HETERODYNE DETECTION OF OPTICAL BIOREPORTERS BASED ON MICRO-OPTO-ELECTRO-MECHANICAL-SYSTEMS (MOEMS) METHODS

By

Noel M. Elman

THESIS SUBMITTED FOR THE DEGREE OF “DOCTOR OF PHILOSOPHY” SUBMITTED TO THE SENATE OF TEL AVIV UNIVERSITY

April 2006
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This Research Work was Carried out at Tel-Aviv University in the Faculty of Engineering

Under the Supervision of Prof. Yosi Shacham-Diamand

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To my wife, Dalya.  
To my parents, Jose and Clelia  
To my sisters, Gala and Lila  
To my brother-in-laws, Sebastian and Emiliano  
To my nephews and nieces, Zoe, Alex, Ema, and Ilan  
To my parents-in-law and sister-in law, Nelson, Stella, and Sheila
HETERODYNE DETECTION OF OPTICAL BIOREPORTER BASED ON MICRO-OPTO-ELECTRO-MECHANICAL-SYSTEMS (MOEMS) METHODS

Abstract

A novel MOEMS (Micro-Opto-Electro-Mechanical-System) modulation method was devised to allow detection of very weak optical signals for "lab on chip applications". The scheme that is presented enhances the signal-to-noise ratio (SNR) of integrated silicon photodiodes that are adapted for the detection of light-emitting bio-reporter signals. Integrated photodiodes are an attractive choice because they are VLSI compatible, easily miniaturized, highly scalable, and relatively inexpensive. Optical modulation prior to photo detection, transfer the signal to higher frequency range, overcomes the inherent low frequency noise of the photodetectors and the system detection circuits. In this work, a new modulation scheme, titled "Integrated Heterodyne Optical System" (IHOS) is introduced as a method to allow low light intensity detection. The key component of IHOS is a transmissive MOEMS modulator that operates in the 1-5 kHz range. In order to implement the transmissive MOEMS modulator, we have developed a two-mask fabrication named MASIS (Multiple Aspect Ratio Structural Integration in Single-Crystal-Silicon). The MASIS process combines high-aspect ratio and low aspect-ratio structures. Long stroke electrostatic comb-drive actuators were fabricated to drive large aperture shutters (low aspect-ratio). Under resonant excitation at approximately 1 kHz, the MOEMS modulators demonstrated maximum displacement of about 50 µm at an actuation voltage of 15 Vp in ambient conditions, and 3.5 Vp in vacuum (8 mTorr). In addition, a new modulation scheme named "Double Harmonic Modulation Technique" has been introduced as a method that up-converts the optical signal to twice and four-times the excitation frequency of the modulator. In this way, the optical signal is modulated above the low-frequency noise and the unwanted coupling between the modulator and the photodetection circuits. This work represents the first attempt for signal enhancement utilizing MOEMS technology for detection of low intensity optical signals, and particularly for detection of optical bio-reporter signals of whole-cell biosensors. Whole-cell biosensors are genetically modified cells that are engineered to act as chemical-optical transducers. As the cells are exposed to toxins, photo-emission (bioluminescence) is triggered, providing optical emission levels per cell proportional to the toxicity concentration in the environment. The most important application that we have investigated is the implementation of whole-cell sensors as an early detection method for water toxicity. Bioluminescence detection becomes a very challenging task, as the maximum photo-emission rate per cell is limited to 100-300 photons per second. The main intended application of the IHOS is to utilize it as a seamless "add-on" that will be placed in between photodiodes and whole-cell sensors, all of which combined into an inexpensive and portable toxicity reader. We believe that the ramifications of this new MOEMS-based method can be also applicable to a vast number of fields of optical systems for low light level slowly varying optical signals, such as luminescence on a "lab on chip" level, or for high performance sensitive imaging systems.
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<th><strong>Technology</strong></th>
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<tr>
<td>APD</td>
<td>Avalanche Photodiode</td>
</tr>
<tr>
<td>CCDS</td>
<td>Charge Coupled Display System</td>
</tr>
<tr>
<td>CIS</td>
<td>Complementary MOS image sensors</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal-Oxide-Silicon</td>
</tr>
<tr>
<td>DRIE</td>
<td>Deep Reactive Ion Etch</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>HF</td>
<td>Hydrofluoric Acid</td>
</tr>
<tr>
<td>ICP</td>
<td>Inductive Coupled Plasma</td>
</tr>
<tr>
<td>IHOS</td>
<td>Integrated Heterodyne Optical System</td>
</tr>
<tr>
<td>MASIS</td>
<td>Multiple Aspect-Ratio Structural Integration in Single-Crystal-Silicon</td>
</tr>
<tr>
<td>MDS</td>
<td>Minimum Detectable Signal</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro-Electro-Mechanical-Systems</td>
</tr>
<tr>
<td>MOEMS</td>
<td>Micro-Opto-Electro-Mechanical-Systems</td>
</tr>
<tr>
<td>MOS</td>
<td>Metal-Oxide-Silicon</td>
</tr>
<tr>
<td>NEB</td>
<td>Noise Equivalent Bandwidth</td>
</tr>
<tr>
<td>PECVD</td>
<td>Plasma Enhanced Chemical Vapor Deposition</td>
</tr>
<tr>
<td>PMT</td>
<td>Photomultiplier</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive Ion Etch</td>
</tr>
<tr>
<td>SCREAM</td>
<td>Single-Crystal-Silicon Reactive Ion Etch and Metallization</td>
</tr>
<tr>
<td>SCS</td>
<td>Single-Crystal-Silicon</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>Silicon Nitride</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>Silicon Dioxide</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
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</table>
SOI | Silicon on Insulator
---|---
**Biology** | **Terms**
ATP | Adenosine triphosphate
AMP | Adenosine monophosphate
FMN | Flavin mononucleotide
FMNH$_2$ | Reduced flavin mononucleotide
IPTG | Isopropyl-beta-D-thiogalactopyranoside
Lux | Bioluminescence Reporter
NADP | Nicotinamide adenine dinucleotide phosphate
NADPH | Reduced nicotinamide adenine dinucleotide phosphate
OD | Optical Density

**Symbols** | **Terms**
---|---
$k_B$ | Boltzmann Constant
$m_{\text{eff}}$ | Effective mass of MOEMS modulator
$h$ | Height of Comb-drive
$\varepsilon_0$ | Permittivity Constant
$k_{\text{tc}}$ | Total Axial stiffness of MOEMS modulator
$\gamma$ | Damping Coefficient in Air
$q$ | Electron Charge
$\Phi$ | Input Photon Flux
$u$ | Number of Shutter
$L_s$ | Length of a Shutter
Quantum Efficiency
$\omega$ | Angular frequency
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>( o )</td>
<td>Resonance angular frequency</td>
</tr>
<tr>
<td>( b )</td>
<td>Width of beam of folded-flexure</td>
</tr>
<tr>
<td>( C )</td>
<td>Capacitance Between Fingers</td>
</tr>
<tr>
<td>( d )</td>
<td>Gap Between Fingers</td>
</tr>
<tr>
<td>( E )</td>
<td>Young's Modulus of Silicon</td>
</tr>
<tr>
<td>( f )</td>
<td>Frequency</td>
</tr>
<tr>
<td>( F_{elec}(t) )</td>
<td>Electrostatic Force of Comb-drive</td>
</tr>
<tr>
<td>( f_o )</td>
<td>Resonance frequency</td>
</tr>
<tr>
<td>( i )</td>
<td>Number of folded flexures</td>
</tr>
<tr>
<td>( k_e )</td>
<td>Negative Electrical Stiffness of Comb-drive actuator</td>
</tr>
<tr>
<td>( k_x )</td>
<td>Axial Stiffness of folded Flexure</td>
</tr>
<tr>
<td>( k_y )</td>
<td>Orthogonal Stiffness of folded Flexure</td>
</tr>
<tr>
<td>( l )</td>
<td>Length of folded flexure</td>
</tr>
<tr>
<td>( n )</td>
<td>Number of Comb-Fingers</td>
</tr>
<tr>
<td>( Q )</td>
<td>Quality factor</td>
</tr>
<tr>
<td>( U )</td>
<td>Energy</td>
</tr>
<tr>
<td>( V(t) )</td>
<td>Applied Voltage</td>
</tr>
<tr>
<td>( V_{max} )</td>
<td>Maximum Voltage of comb-drive actuator</td>
</tr>
<tr>
<td>( x )</td>
<td>Axial displacement</td>
</tr>
<tr>
<td>( x_{max} )</td>
<td>Maximum displacement of Comb-drive actuator</td>
</tr>
<tr>
<td>( y )</td>
<td>Lateral displacement</td>
</tr>
</tbody>
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Chapter 1.
Introduction.

1.1. Integrated Heterodyne Optical System (IHOS)

This research work describes the development of a novel optical detection method for low intensity bio-reporter signals that is based on the integration of Micro-Opto-Electro-Mechanical Systems (MOEMS), whole-cell biosensors, solid-state photo-detectors, and electronics. The fundamentals of this dissertation have been synthesized in the form of design, fabrication, and integration novelties of a unique MOEMS technique, which has been named Integrated Heterodyne Optical System (IHOS).

Whole-cell sensors represent a new family of genetically engineered cells that provide a measurable signal response upon exposure to environmental toxicity [1]. In this research work, we have utilized whole-cells that provide a bioluminescent response in the green spectrum. Real-time detection of bioluminescence using solid-state photodetectors poses a major challenge due to the low photon-rate emission per cell, which ranges 100-300 photons per second [2].

Solid-state photo-detectors are attractive photodetectors for use in a wide number of applications that require VLSI compatibility, low cost, and survival in harsh environmental conditions. This type of photodetectors, however, suffers from various noise mechanisms that limit the photodetection sensitivity. Flicker noise is the most dominant source of noise in the lower frequency spectrum [3]. Currently, photomultipliers (PMTs) are predominantly utilized for applications that require sensing of low-intensity bioluminescence [4]. PMTs do not enjoy VLSI compatibility, cannot be adapted for portable applications, and do not offer a cost-effective solution. Other electronic techniques are designed to decouple the noise from the desired signal after photodetection by means of either electronic modulation, or signal processing filters [5].
Using a complete different approach, IHOS is dedicated to overcome the inherent low-frequency noise of solid-state by means of optical modulation prior to photodetection, as shown in Figure 1.1. The central element of the IHOS is a transmissive MOEMS modulator, which consists of miniature transmissive shutters driven by electrostatic comb-drive actuators. As the shutters are harmonically excited, the input optical signal is modulated spatially before photo-conversion. Three main innovative contributions summarize this research work:

- The design of a transmissive MOEMS modulator placed as an “add-on” between the optical source and the photodetector, drastically increasing the sensitivity of detection system. The design features a transmissive architecture configuration, characterized by its large aperture area, kilohertz operation, and low operation voltage.

- The development of a novel fabrication process, named MASIS (Multiple Aspect Ratio Structural Integration in Single-Crystal-Silicon). The process is tailored for implementation of the transmissive MOEMS modulator. MASIS combines high-aspect ratio actuators with large area shutters. The fabrication process is based on bulk-micromachining, utilizes two photolithographic masks, and is fully VLSI compatible.

- The integration of light emitting whole-cell biosensors with the MOEMS modulator and a photodetection system. This integration creates a unique hybrid system that combines living cells, MOEMS, and electronics as a unique micro-system.
Figure 1.1: Block Diagram of an Integrated Optical Heterodyne System (IHOS). A. Detection of low-intensity signals. B. Detection of bioluminescent signals from whole-cell sensors.

1.2. Description

Modulation of an optical signal can be achieved by means of a transmissive MOEMS modulator. Figure 1.2 shows the schematic modulation process.
The modulation scheme can be ideally represented as the multiplication of an optical signal by a sinusoidal carrier that enjoys a frequency above the low-frequency noise. The carrier signal is generated by the harmonic excitation of the shutters using electrostatic actuators. Modulation can be represented by an elementary set of mathematical equations shown in Figure 1.3.

\[
\begin{align*}
X(\omega) & \quad \text{Input Signal} \\
S(\omega) & = \frac{A}{2} \cdot \delta(\omega - \omega_o) \quad \text{Carrier Signal} \\
Y(\omega) & = X(\omega) * A \cdot \delta(\omega - \omega_o) \quad \text{Modulated Signal}
\end{align*}
\]

**Figure 1.3:** Block diagram of the optical modulation positive-term.

Here, \(X(\omega)\) represents a low intensity signal, \(S(\omega)\) represents the real-part of the Fourier transform of the cosine wave which acts as a carrier with frequency \((\omega_o)\) and amplitude \(A\). \(Y(\omega)\) is the modulated wave, which is the result of the convolution of \(X(\omega)\) and \(S(\omega)\).

The transmissive MOEMS modulator is composed of an array of shutters suspended over an array of optical vias. The shutters are connected to comb-drive actuators, which provide the driving force required for chopping the input optical signal. MASIS combines multiple aspect ratio structures in order to integrate the large area shutters with the high-aspect ratio actuators. MASIS requires standard processing tools, and low temperature (< 250 °C) conditions, thereby offering a VLSI compatible process. It is also possible to introduce independent vias and electrical connections for defining integrated electronic circuits on chip, such as differential amplifiers and filters. The process requires as few as two photolithographic masks, which are designed for the front and backside of SOI wafers. On the
front side, actuators and shutters are defined. On the backside, the optical vias are etched beneath the shutters.

Finally, we have investigated the integration of bacterial cells that have been modified to emit light as a function of toxicity concentration in the environment. Whole-cell sensors have been designed to detect specific chemicals in the environment via the combined use of promoters and bio-reporters [6]. Reporters are expression genes that encode for proteins or enzymes that function as optical sources for monitoring metabolic cell activity [7]. Chemical inducers, such as environmental pollutants, activate promoter genes, providing a genetic signal transduction that not only triggers, but also regulates the intensity of the bio-reporter expression. In the course of this research work, we have utilized the Lux reporter that is characterized as a self-emitting bioluminescent process, which does not require optical excitation signal. The bioluminescent reporter represents an excellent choice for integration with solid-state photodetectors [8], as neither complementary optical excitation sources, nor optical filters are required for on-chip integration.

1.3. Research Goals

The main goal of this research is implementation of standard solid-state sensors in conjunction with the transmissive MOEMS modulator and a lock-in amplifier in order to detect low-intensity bioluminescent signals from whole-cell sensors. Increasing the minimum detectable signal of a solid-state photodetection system allows downscaling of the entire system as a “lab-on-chip”. Minimizing the system noise can be accomplished by reducing the noise equivalent bandwidth using the optical heterodyne detection technique. Therefore, the main research goals are defined as follows:
1. **Design of the transmissive MOEMS modulator.** The modulator represents one of the novel components of the system. The design incorporates a unique MOEMS design that combines long-stroke comb-drive actuators with an array of large-area shutters. The modulator needs to operate in the kilohertz range beyond the low-frequency noise of the photodetectors.

2. **Development of a novel fabrication process.** In order to implement the MOEMS modulators, MASIS has been developed as a process to implement transmissive modulators. The monolithic process is VLSI compatible, and allows the modulators to be seamlessly stacked between the photodiode and the optical source.

3. **Test of the IHOS.** The system must be assembled and tested with a low-intensity optical source. The minimum detectable signal (MDS) needs to be measured in order to quantify the SNR improvement. In addition, emulation of bioluminescence needs to be performed to ensure that the system can be integrated with light-emitting whole-cell biosensors.

4. **Development of a quantitative noise model.** The developed analysis provides the crucial information that relates the sensitivity limit of the photodetection system to the required figures of improvement for implementing a modulation scheme.

5. **Integration of whole-cell biosensors.** Whole-cell sensors are tested as an integral part of the system. Measurement of bioluminescence as a function of time is a crucial requirement for validating the proposed use of the heterodyne detection based on MOEMS methods. This integration represents the proof-of-concept for the future generation of lab-on-chip toxicity detectors using IHOS.
1.4. **Advantages**

IHOS enhances the sensitivity for low-intensity optical signals, resulting in an inexpensive and accessible detection method that offers a significant reduction in size and cost. A micro-system provides great versatility for portable implementation and integration, since its miniature size allows a more efficient optical collection for a limited number of optical emitting biosensors. The economic advantages of a silicon-based fabrication process offer great scalability and a cost-effective mass production for large volumes. The parallel and independent actuation of various micro-systems can enable automation, which is crucial for real-time monitoring of cells in various biological applications. In addition, IHOS scalability will offer an inexpensive option to integrate it with cameras, microscopes, and telescopes for detection of low intensity signals. We believe that the ramifications of IHOS can be applicable to a vast number of applications for optical systems.

1.5 **Organization and Preview**

**Chapter 2** offers a literature review of the existing solutions for detection of low-intensity bio-reporter signals. In addition, this chapter introduces a review for each of the building blocks that compose the final device: whole-cell sensors, photodetectors, MOEMS modulators, MOEMS fabrication methods.

**Chapter 3** provides a comprehensive model of the IHOS by analyzing each component separately. A large portion of this chapter is dedicated to noise analysis of the photodetection system. In addition, the dynamics model of the MOEMS modulator is thoroughly discussed. Finally, the minimum detectable signal of the system is simulated.

**Chapter 4** presents the design of the MOEMS modulator. All the physical equations that govern the behavior of the MOEMS are introduced. The stability analysis is discussed as
part of a 1-DOF model, and the final design values are synthesis. Finally, a finite element
analysis (FEA) is performed to verify and complement the analytical model.

**Chapter 5** presents a new fabrication process specifically tailored to implement
transmissive optical modulators with large aperture areas. The process is a two-mask process,
denominated MASIS for Multiple Aspect Structural Integration in Single-Crystal-Silicon.

**Chapter 6** provides a comprehensive description of the experimental set-up, and the
characterization of the IHOS.

**Chapter 7** presents the bioluminescence measurements as the whole-cell biosensor
are integrated with the IHOS.

**Chapter 8** presents a detailed discussion of all aspects of this research work. The
design, fabrication are reviewed as part of the solution. The integration of whole-cell
biosensors is described as part of the proof-of-concept for a new type of portable toxicity
measurement system.

**Chapter 9** provides the summary and conclusions of this research work
Chapter 2.
Literature Review.

2.1. Introduction

This chapter provides a review of the background topics that are relevant to this thesis. We will focus on methods that integrate light-emitting whole-cell sensors. We first review the field of genetically engineered whole-cell sensors and the existing expression systems designed to provide an optical response that is correlated to the concentration of the toxicity in the environment. A brief discussion of fluorescent and luminescent bio-reporters is presented. The basic mechanisms of promoter-gene detection and the reporter-gene expression are discussed, with specific emphasis on the bioluminescent reporters.

Next, we present a review on the current photodetection systems adapted for bioluminescent detection, including photomultipliers and solid-state detectors. The different noise mechanisms of solid-state photo-detectors are examined. The detection of low intensity signals is affected by low-frequency noise. We also present a review of existing electronic modulators. In addition, we review existing on-chip optical modulators, based on liquid crystals and Micro-Electro-Mechanical-Systems (MEMS) technology. The highlights and drawbacks of such methods are discussed, providing the foundations of this research work. The Integrated Heterodyne Optical System (IHOS) introduces an original approach to low-level signal detection from bio-luminescent bio-chips.

Finally, we present a review of the existing Micro-Opto-Electro-Mechanical-Systems (MOEMS) modulators, which are mostly designed for reflective applications, and current fabrication methods for MOEMS modulators. Although there are various fabrication processes, none are intended for transmissive optical modulators that enjoy large field area and operate beyond the low-frequency noise.

The need to design a transmissive optical modulator using a MOEMS technique to enhance the Signal-to-Noise Ratio (SNR) of solid-state photodetectors becomes apparent,
thereby providing the motivation of this research work. Furthermore, the MOEMS modulator represents the heart of the Integrated Heterodyne Optical System (IHOS), and can be adapted as an add-on device for a wide number of applications. The intended function of the IHOS can be extended to any field that requires detection of slowly-varying, low-intensity signals, such as for example optical bio-reporters, cell markers, all of which have a very slow time response. Based on the results of this research work, we anticipate that the ramifications of this MOEMS-based modulation technique can also be applicable to a number of optical systems that fulfill the following specifications:

- The signal is coming from a known source.
- The signal is slowly varying and low-intensity.
- Improving the SNR is critical to the detection.

For example, the response of whole-cell toxicity sensors is slow, the signal intensity is weak, and the detection time, which depends on the SNR, should be as short as possible in order to allow early warning. The scalability of such solutions will offer an inexpensive solution in a vast number of optical applications ranging from microscopes, telescopes, and any optical detection system that fits these requirements.

### 2.2.1 Biosensors

A biosensor is a chemical sensing device in which a biologically derived recognition entity is coupled to transducer, to allow the quantitative development of some complex biochemical parameter, manifested as a recognition event. In our case, the term biosensor implies that the device is a combination of two parts: a bio-element and a sensor-element. The bioelement may be an enzyme, antibody, antigen, or living cells [9]. The sensor-elements include physical parameters, such as electric current, electric signal, intensity and phase of electromagnetic radiations, mass, viscosity, etc. A specific bio-element recognizes a specific analyte, which the sensor element transduces to a measurable signal. The transducer
mechanism defines the type of biosensor. Among the most basic ones are resonant biosensors [10], optical-detection biosensors [11], Ion-Sensitive FETs (ISFETs) biosensors [12], and electrochemical biosensors [13]. Table 2.1 provides a summary of the types of biosensors.

Table 2.1: Current commonly used biosensors.

<table>
<thead>
<tr>
<th>Type</th>
<th>Bio-Detection</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Affects the resonance frequency, or the bending of a micro-mechanical part</td>
<td>This type of sensor is generally implemented with MEMS cantilever beams; deflection or resonance frequency are usually measured using a laser and interrogating photo-detector circuit, such as in the case of Atomic Force Microscopy (AFM) [11]</td>
</tr>
<tr>
<td>Ion-Sensitive</td>
<td>Affects the electro-chemical properties of an input port</td>
<td>This type of devices are generally based on: Ion-Sensitive-Field-Effect-Transistor; (ISFET) [12], Chemical-Modified-Field-Effect-Transistors (CHEMFET) [14], Carbon-Nano-Tubes (CNT) [15]</td>
</tr>
<tr>
<td>Electro-Chemical</td>
<td>3 Electrode Potentiometry</td>
<td>This type of sensors are generally implemented with miniaturized electrodes [16]</td>
</tr>
<tr>
<td>Optical</td>
<td>Fluorescent and bioluminescent</td>
<td>This type of sensors uses photomultipliers and solid-state photodetectors [17]</td>
</tr>
</tbody>
</table>

There are two general approaches for monitoring chemicals in the environment: a. highly specific chemical-biosensors, and b. non-specific cell-based or animal based sensors. The first approach is based on chemical or physical analysis, and allows highly accurate and sensitive determination of the exact composition of any sample. Most of this type of biosensors relies on biological molecules that are highly specific. For example, successful biosensors are based on measuring some chemical effects related to the interaction between enzymes and substrates [18], recognition between antibodies and antigens [19], accessibility of specific target molecules to their receptors [20], or the high affinity of nucleic acid strands to their complementary sequences [21]. This focus is primarily based on the
specificity between the unique affinity and recognition of two entities: The molecule to be detected and the recognizing molecule or reaction.

The second approach relies on the use of living cells as the biological entity. Rather than targeting specificity, this type of biosensors relies on bioavailability, toxicity, and genetoxicity. Belkin (2003) [22], Souza et al. (2001) [23], Daunert (2000) [24], provide three comprehensive reviews on microbial biosensors, as leading scientists in this field. Microbial biosensors based on light emission from luminescent bacteria are being applied as a sensitive, rapid and non-invasive assay in several biological systems. Bioluminescent bacteria are found in nature, their habitat ranging form marine (Vibrio-fischeri) to terrestrial (Photorhabdus-luminescens) environments. Bioluminescent whole-cell biosensors have also been developed using genetically engineered microorganisms for the monitoring of organic, pesticide and heavy metals contamination. The microorganisms used in these biosensors are typically produced with a constructed plasmid in which genes that code for the luciferase (bioreporter) are placed under control of a promoter that recognizes the analyte of interest.

In summary, the integrated whole-cell biochips require sensitive signal detection. In this chapter, first review the biosensors, and then the background of the proposed MOEMS-based detection systems and related methods.

### 2.2.2. Microbial Whole-Cell Biosensors

Microbial whole-cell biosensors are genetically engineered cells designed to detect such environmental pollutants via the combined use of promoters and reporter genes. Typically E-coli bacteria are used as harboring cells, in which plasmids containing the promoter-reporter gene conjugation are introduced. Reporters are expression genes that encode for proteins or enzymes that function as optical sources for monitoring metabolic cell activity [25]. Promoter genes function as activators of the bio-reporter expression. As environmental pollutants, acting as inducers, activates promoter genes, a genetic signal
transduction triggers and regulates the intensity of the bio-reporter expression. Thus, whole-cells metabolize the pollutants, whereas the genetic control mechanism turns on the synthesis of the reporter.

Optical bio-reporters are designed as either fluorescent protein complexes, or catalysts of luminescent reactions. Green fluorescent protein (GFP) has an excitation wavelength in the blue-green spectrum, whereas the bioluminescence system (Lux) emits in the green-red spectrum. Both reporter systems are widely used in microbiology research. The Lux reporter does not require an optical excitation, whereas GFP requires a complementary optical source for excitation and optical filters for the photo-detection stage. Hence, whole-cell sensors containing the Lux bio-reporter gene are preferable for on-chip integration [26].

A microbial biosensor based on optical detection employs whole-cell microbial sensors to catalyze, sense, and transmit optical signals. The microorganisms can be immobilized either on the transducer or in a separate compartment with the light signal transmitted through an optical medium to the transducer. The use of intact cells instead of isolated enzymes allows lower sensitivity to inhibition by solutes, higher tolerance of suboptimal pH, longer lifetime, and lower costs. Alternatively, response and relaxation times may be longer than those of enzyme electrodes, and storage and maintenance requirement may be more complex.

2.2.3. Whole-Cell Biosensors - Principles of Operation

Whole-cell biosensors are designed to emit a dose dependent optical response upon exposure to environmental pollutants. For example, whole-cell sensors can be used to detect intentional poisoning of water supplies [27]. An important advantage of utilizing biological transducers is the real-time process monitoring, since an effective change in the sampled environment provides a real-time change in the metabolism of the cells. Moreover, microbes are suitable for genetic modifications through standard DNA manipulation technology.
Microbial cell sensors have been constructed by genetically binding the *Lux* gene with an inducible gene promoter for toxicity testing. Genetic promoters have been utilized to act as very precise detectors of environmental toxins [28]. The main function of the bio-reporters is to provide a detectable signal response correlated to the magnitude of the bio-chemical input dose. Figure 2.1 illustrates the promoter exposed to an analyte, transcribing messenger RNA (mRNA) [29], which is subsequently translated into a light emitting reporter.

**Figure 2.1:** Schematic diagram of promoter-reporter gene fusion in the whole-cell biosensors.

The high sensitivity, approximate linear dependence of light intensity on the amount of luciferase, and rapid time response are unique features of luminescence assays [30]. Most other enzymes generally require longer assay times, and often involve separation of reaction products that are radioactive [31], resulting in lower sensitivity levels. In addition, most assays for enzymes from nonluminescent organisms are restricted to relatively narrow limits for the amount of enzyme and time of assay [31].

The absence of endogenous luciferase activity in nonluminescent organisms, such as *E-coli* cells, clearly permits the widespread use of the *Lux* genes as reporters of gene expression. Theoretical lower limits of detection are restricted by the background noise of the photodetectors. Practical limits, as it will be shown later, are determined by the front-end photo-detection interface. The major disadvantage in the use of bacterial luciferase genes as bioreporters of gene expression resides in the necessity to use a monocistromic fused *LuxA-LuxB* genes [31]. Although the bacterial luciferases from *V. harveyi* and *X. luminescens* are
quite stable, the fused luciferase cannot fold efficiently at 37 °C. This property limits the use of the fused bacterial Lux gene in eukaryotic cells, plants, insects, and yeast cells grown at or below 30 °C. Future developments of a new LuxA-LuxB constructions coding for bacterial luciferase, which can refold efficiently at 37 °C, will be necessary to obtain levels of expression in mammalian cells [31]. Given the great number of LuxA and LuxB available, the goal appears attainable. The direct measurement of in-vivo function without disruption of the cell membrane and loss of cell viability has been one of the main reasons for the widespread interest in the application of the Lux genes. The substrate can be applied exogenously as short chain aldehydes can readily cross the cell membrane, while there is a sufficient supply of reduced flavin mononucleotide (FMNH₂), which is a molecule that acts as an electron acceptor available in most bacterial systems [31]. Furthermore, in contrast to other luminescence systems, the genes LuxCDE provide the synthesis of a substrate (aldehyde), eliminating the need for any exogenous additions to generate light. In eukaryotes generation of in-vivo luminescence, it is more difficult because the availability of the FMNH₂ appears to be more limited. Bacterial luciferase is currently the most prevalent system of choice for expression in prokaryotic cells for whole-cell sensors, whereas firefly luciferase has been expressed most often in eukaryotic cells.

2.2.4. Physical Mechanism of Bioluminescence

Bioluminescence refers to the visible light emission in living organisms that accompanies the oxidation of organic compounds, such as luciferin, mediated by an enzyme catalyst, known as luciferase. The enzymes involved in the bioluminescent system, including luciferase and luciferin are coded in the LuxDCABE operon [32]. The bacterial luminescent reaction, which is catalyzed by luciferase, involves the oxidation of a long-chain aliphatic aldehyde (R-CHO) and reduced flavin mononucleotide (FMNH₂) with the liberation of excess free energy in the form of light.
The process is described by the following reaction [32]:

\[
FMNH_2 + R-CHO + O_2 \rightarrow FMN + R-COOH + H_2O + \text{Light} \tag{2.1}
\]

Where \( FMN \) is flavin mononucleotide, and \( R-COOH \) is the fatty acid. Here, the energy for light production is supplied by the oxidation of the aldehyde and \( FMNH_2 \). The \( LuxA \) and \( LuxB \) genes encode the \( \alpha \) and \( \beta \) subunits of luciferase (a heterodimer in the form of \( \alpha \beta \)), with molecular weights of approximately 42,000 and 38,000 Daltons (1 Dalton = \( 1.6 \times 10^{-24} \) gram), respectively [32]. The \( LuxCDE \) genes encode polypeptides-enzymes (Transferase, Synthetase, and Reductase). These enzymes are required for the conversion of fatty acids into the long-chain aldehyde, which is a requirement in the reaction to produce light [32]. The fatty acids for this reductase enzyme (gene \( LuxE \)) complex are removed from the biosynthesis pathway via the enzyme acyl-transferase (gene \( LuxC \)) [32]. This enzyme reacts with acyl-ACP (acyl carrier protein) to release free fatty acids (R-COOH), which are then reduced to an aldehyde by a two-enzyme system via the following reaction:

\[
R-COOH + ATP + NADPH \rightarrow R-CHO + AMP + PP + NADP^+ \tag{2.2}
\]

Where ATP is adenosine triphosphate and AMP is adenosine monophosphate, both of which are molecules that act as energy carriers. \( NADPH \) and \( NADP^+ \) are nicotinamide adenine dinucleotide phosphate molecules in reduced and oxidized forms which facilitate electron transfer, and PP is disphosphate.

One enzyme, acyl-protein synthetase (gene \( LuxD \)) activates the fatty acid via the transition of ATP to \( R-CHO-AMP \). This serves as the substrate for the final enzyme, acyl-reductase (gene \( LuxE \)) that catalyzes the \( NADPH \)-dependent reduction of the activated fatty acid to an aldehyde. Figure 2.2 illustrates the entire \( Lux \)-process [32], and all the pertaining molecules involve in the bioluminescence production. The reported range of the photon-emission rate per cell is 100-300 photons per second [33,34].
In summary, *LuxCDE* genes encode for three enzymes (Transferase, Synthetase, and Reductase) that produce an aldehyde, Luciferin. *LuxAB* genes encode one enzyme, Luciferase, which combined with the aldehyde, $FMNH_2$ and $O_2$ catalyze fatty acid and light production.

### 2.3.1 DC-Detection of Low-Intensity Bio-reporter Signals

Current methods to detect low-intensity bioluminescence are based on direct photodetection by means of either photomultipliers (PMTs), or solid-state sensors, such as silicon photodiodes. Photomultipliers enjoy the highest sensitivity but are bulky, fragile, and expensive, thereby making it inappropriate for low-cost portable applications. Solid-state sensors enjoy scalability and portability, but suffer from various noise mechanisms that limit their photo-detection sensitivity. In this section, we present a review of both types of devices.

Figure 2.3 shows a schematic diagram of dc-photodetection systems. There are mainly two alternatives. The first one is based on direct photo-detection, which implies that a change in either voltage or current is measured directly as a function of the intensity of the optical...
signal. The second alternative is based on indirect measurement by means of an integrating circuit. In this case, the photo-signal is not detected directly, but rather integrated over time after photodetection in order to measure the time-average. In this section, we also present a description of both techniques.

**Figure 2.3:** DC detection technique.

### 2.3.2. Direct Photodetection using Photomultipliers

Photomultiplier tubes are the most sensitive photodetectors for visible optical range, representing the most popular choice for sensing optical bio-reporter signals in laboratory settings. The main principle in PMTs is the photoelectric effect combined with electron-multiplication. Figure 2.4 illustrates a schematic view of the device. Photons enter through an input window impinging on a photocathode, which absorbs the photons and emits electrons into a vacuum chamber. Thereafter, the electrons are accelerated and focused on a series of dynodes. Each dynode multiplies the electron through secondary electron emission. Subsequently, as the electrons travel down through the series of dynodes, and multiplied each time, all the electrons are collected by the anode. The major sources of noise for this type of
photodetectors are the dark-current, which is mostly due to the random nature of thermionic emission of electrons from the photocathode and dynodes, and multiplication noise (excess noise). Shot noise is another source that arises from the fluctuations in the arrival rate of photons [35]. Electron multiplication in PMTs is a single carrier multiplication process. PMTs are often compared with avalanche photodiodes (APDs). The multiplication process in APDs, however, is a two carrier process since it involves holes and electrons. Therefore, PMTs enjoy less excess noise when compared with APDs operating under similar nominal conditions.

![Photomultiplier structure](image)

**Figure 2.4:** Photomultiplier structure [34].

PMTs are not the best choice for fully integrated micro-systems due to the high operating voltages, fragility, large size, and cost. These limitations eliminate the use of PMT as a viable solution for detection of low-intensity bio-reporter signals in inexpensive portable applications [35].

### 2.3.3. Bioluminescence Detection using PMTs

To this date, there are two main approaches low-intensity bioluminescence detection using PMTs. The first approach relies on direct detection of the light-emission by direct sensing utilizing photomultipliers (PMTs). In this approach, the light-emitting samples are placed in close proximity to the active area of the PMT using a mechanical arm. This
approach represents the most common method, as virtually all laboratory equipment tools for precise photodetection of bioluminescence utilize PMTs [36,37]. Several companies have developed detectors for low-intensity signals for parallel detection, such as PerkinElmer Corporation and Berthold Technologies, Inc., USA. This type of equipment is bulky, aimed for microplate applications, designed as bench-top applications.

The second approach is based on the use of fiber optics. In this case, the whole-cell sensors are entrapped in a polymer, and connected to the tip of a fiber optic, which itself is connected to the active area of a PMT. Although this method allows physical separation between the biological samples and the photodetector, the optical collection is not efficient due to the insertion losses of the fiber optic. Several authors have reported successful measurements using this approach. R.S. Marks et al. [38] demonstrated this concept by attaching bioluminescent bacterial sensors in close proximity to an optical fiber waveguide transducer, so as to produce an optical whole-cell biosensor. The harvested bacteria were trapped into a calcium alginate matrix, and attached to the tip of a multimode fiber. In order to measure the low intensity bio-reporter signal produced by the bioluminescent bacteria, the other end of the fiber was connected to a photon counting system based on a PMT, which enjoyed a 21 mm-diameter active area. The entire instrumentation was placed inside a light-tight box in order to prevent damage of the PMT by the environmental light. The tips of the fibers with the entrapped bacterial cells sensors were exposed to varying concentrations of mitomycin C, a toxicant emulator, by multiple immersions, thereby creating several layers of entrapped bacteria. As the optical signal was measured every 15 minutes with a mean value of photon counts per measurement length of 20 seconds, a dose-dependant bioluminescence response was obtained. The minimum detectable dose was approximately 100 ppm, which corresponded to a signal value of approximately 100 photon counts. The main drawback of this PMT-based detection method is the diffusion of the analyte through the immobilized matrix, limiting the response. In addition, the efficiency of the cell-attachment process is
limited to 8 multiple immersions per fiber, which limits the number of cells that can be used per fiber. Although this system is quite reliable, its photonic sensitivity relies ultimately on the use of PMTs, which directs its applications to larger immobile systems, or mobile systems for large carriers, i.e. cars, ships, etc.

2.3.4. Direct Photodetection using Solid-State Sensors

In this section, we focus on silicon photodiodes as an attractive solid-state photodetectors for use in biological applications. Photodiodes are inexpensive, easily miniaturized, exist in every CMOS circuit, and can be fabricated in large arrays. In addition, photodiodes exhibit a response range extending from the ultraviolet (UV) to the near infrared (IR) part of the spectrum, which is appropriate for sensing bio-reporter signals. The basic mechanism of photodetection in a PN junction is based on internal photoelectric effect [39].

For a given illumination level, in reverse bias the photodiode current is given by:

$$I_D = -I_{sat} - I_p.$$ \hspace{1cm} (2.3)

Where $I_{sat}$ is defined as the saturation current, and $I_p$ is the photocurrent. The magnitude of the photocurrent is dependent on the number of incident photons, and the quantum efficiency, which depends on the wavelength of the incoming optical signal. As the active area of a photodiode is exposed to a photon-flux, the current due to photon generation [40] is given by:

$$I_p = \Phi q \eta A,$$ \hspace{1cm} (2.4)

where $\Phi$ is the incident photon-flux [photons/sec-cm$^2$], $\eta$ is the quantum efficiency (typical values for commercial devices are in the range of 0.5-0.9), $q$ is the electron charge, and $A$ is the active area of the photodiode. The detection limit of optical signal processing depends strongly on the noise features of photodiodes. Therefore, detectable bio-reporter signals must be greater than the noise level of the photodiode. The total noise of the photodiode includes thermal noise (Johnson noise) from the parasitic series resistance, shot noise, low-frequency noise (1/f noise), and generation-recombination (G-R) noise [41,42]. The flicker noise
dominates at low frequencies due to traps in the depletion layers, surface defects, and metal contacts. The low-frequency noise is the main limiting factor in detection sensitivity for biological applications, as typical optical signals have a frequency range of 0.01-1 Hz. In a photodiode, the total spectral density is described in the following expression [42]:

$$S_i = S_{i,\text{shot}} + S_{i,\text{thermal}} + S_{i,\Delta f}.$$  \hspace{1cm} (2.5)

Where $S_{i,\text{shot}}$ is the spectral density of the shot noise, $S_{i,\text{thermal}}$ is the spectral density of the thermal noise due its parasitic resistance, and $S_{i,\Delta f}$ is the spectral density of the flicker noise.

In wide-band operation the total noise is the integral of the spectral density over the frequency of interest. In our system we deal with narrow-band measurements, therefore [43]:

$$\langle I_{\text{total}}^2 \rangle \approx \frac{\Delta f K I_D^\beta}{f^\gamma} + \frac{4k_B T \Delta f}{R_{\text{PD}}} + 2qI_D \Delta f.$$  \hspace{1cm} (2.6)

Where $\Delta f$ is the noise equivalent bandwidth (NEB), and $I_D$ is the diode current. In the first term, the flicker noise is represented for $\Delta f \ll f$ (frequency at which the noise is measured); $K$ and $\gamma$ are coefficients that depend on the photodiode fabrication process (quality and technology), $\beta$ value is an empirical constant related to doping profile. In the second term, the thermal noise is represented; $k_B$ is the Boltzmann constant, $T$ is the operating temperature, $R_{\text{PD}}$ is the parasitic series resistance of the photodiode. In the third term the shot is represented; $q$ is the electron charge. Photodiode outputs can be measured as a current, or converted into a voltage. After photo-detection, the output signal can be fed into a pre-amplifier for subsequent signal conditioning.

Typical photodiodes have no internal gain. On the other hand, special devices such as avalanche photodiodes (APDs) enjoy some internal gain. APDs are among the most sensitive solid-state device available. APDs are basically PiN diode structures that are operated at large bias voltages [44]. Signal multiplication is obtained as photogenerated carriers gain enough energy from the electric field to generate secondary carriers through impact ionization. These secondary carriers are also accelerated by the electric field and generate
other electron-hole pairs. The output current is the primary photocurrent multiplied by the avalanche multiplication factor is dependant on the bias voltage. The avalanche multiplication process also introduces excess noise due to the random nature of the avalanche multiplication process since every electron-hole pair generated at a random location within the depletion region does not experience the same multiplication. The high reverse bias used in APDs requires very uniform doping and sometimes elaborate doping profiles to prevent local variations in the electric field and premature breakdown. The drawbacks of the APDs are the high voltage requirements, making them unsuitable for portable applications. In addition, the custom fabrication steps, and dependency on complicated supporting circuits may also limit its usefulness in integrated modules [35].

![Photodiode cross sections of a silicon photodiode.](image)

**Figure 2.5:** Photodiode cross sections of a silicon photodiode.

### 2.3.5. CCD and CIS Detectors

Recent advances in Metal Oxide Silicon (MOS) technology has allowed the development of array photo-detectors. Two of the most common array-sensor devices include Charge Couple Devices (CCDs) [45], and complementary MOS image sensors (CIS) [46].

CCDs consist of an array of metal-insulator-semiconductor (MOS) structures that can detect, store, and transfer photogenerated charge. The basic structure is a metal or polysilicon gate above a dielectric and semiconductor substrate below, forming an MOS capacitor which is charged up from photogenerated carriers. The gate is biased to place the semiconductor into deep depletion. The accumulated carriers are transferred out from the well fills up
completely. As the photons are absorbed, an electron-hole pairs are created, the electrons are swept toward the gate where they are stored until the charge is transferred out. The wells are arranged side by side and the photogenerated charge packets are transferred from well to well to the charge sensors and finally to the output.

CCDs have become a popular choice for use in biological systems. The main advantage of CCDs over other photodetectors is that they provide spatial information about the system. Although CCDs have a relatively slow response time, this is often not a critical factor in biological experiments, which are inherently slow. The device requires cooling in order to reduce the noise, and obtain the required sensitivity to detect low-intensity signals. External coolers are an impediment for complete miniaturization.

CIS offer a comparable performance to CCDs, as they are also implemented in arrays. Typical pixels in CMOS imagers consist of a photodiode and MOS transistors that are used to switch the photo-detected signal to a video line via some specific circuitry [45]. The photodiode is implemented in a CMOS process, and is usually based on a standard PN junction. In some other designs, the photodetector structure consists of shallow and deep PN junctions, which are sensitive to short and long wavelength. The sum of the two currents is representative of the total impinging power. The shallow junction photocurrent is proportional to the impinging optical power at the wavelength between 400 nm and 650 nm, whereas the ratio of the photocurrents provides information about the wavelength of the impinging light. CIS usually have a lower fill factor than CCDS [35]. Designs of CCDs include amplification circuits at the end of every row to conserve space and fill factor for maximum image resolution. In biological applications that required sensing intensity, high image resolution is not a priority. Due to the decreasing feature size in CMOS technology, CIS photodetectors can be designed for sensing of low intensity signals, as each pixel includes amplification circuitry, rather than per array line. Hence, photodetectors in these active pixel architectures experience lower capacitance on the input transistor channel,
thereby exhibiting a reduced switching noise level. The spectral sensitivity of a CMOS photodetector can be adjusted with the bias voltage. Therefore, CIS photodetectors provide an alternative for bio-chip sensors.

![Diagram of CCD and CMOS structures](image)

**Figure 2.6:** A. Cross Section of CCD Structure. B. Cross-section of CMOS structure.

Both CCD and CMOS photodetectors suffer from the same noise mechanisms as discussed for simple PN photodiodes, in addition to the electronic noise of the on-chip circuits and the switching noise. A cooling device can be added in order to further reduce the thermal noise. Low-frequency noise, however, can be the limiting factor for detection of low-frequency signals. Therefore, similar considerations should be taken into account in order to assess the performance of these photodetectors for measuring low intensity signals, such as bioluminescence from whole-cell sensors.

### 2.3.6. Bioluminescence Detection using Solid-State Detectors

Few authors have attempted to measure bioluminescence using photodiodes. Simpson et al. demonstrated the first bioluminescent bioreporter integrated circuit (BBIC), which utilizes a CMOS microluminometer for sensing low-level luminescence [45,46,47]. In this work, genetically engineered whole-cell bioreporters were placed directly on top of a CMOS detector. Low level currents were measured by means of complementary circuits, which increase the SNR by integration methods. The author reports that for the given imager, leakage current limits the minimum bioluminescence detection, compensated with low dc-bias which reduces the dependence of the leakage current on temperature fluctuations. The power spectral density of the CMOS detector white noise depends directly on the magnitude
of the dc leakage current. The complementary circuit improves the SNR as a function of integration time, thereby limiting the real-time response of the circuit. This promising technology could be further improved by means of optical modulation. Furthermore, the authors even suggest that modulation of low-intensity optical signals prior to photodetection is not a practical option as apparently there are no existing solutions for a modulator integrated with a photodetector as a single-chip analytical instrument at the time they published their work.

2.4.1. Modulation

Modulation provides a solution to overcome low-frequency noise of photodetectors by shifting up the desired spectral section to a higher frequency range characterized by a lower background noise. Several modulation methods have effectively proven to enhance the sensitivity of the photodetection system. Modulation methods can be implemented either electronically, or optically. Figure 2.7 shows a sketch of both alternatives.

**Figure 2.7:** AC Detection method. A. Modulation prior to photodetection. B. Modulation after photodetection.
Correlated double sampling (CDS) is one of the most popular electronic techniques for overcoming electronic noise [50]. Basically, this circuit technique translates the noise energy from the baseband to some higher frequency so that the signal of interest is not contaminated. Another commonly implemented electronic technique is based on chopper stabilized amplifiers, which are used to overcome low-frequency noise by means of electronic modulation. This technique makes use of a square wave to multiply the signal of interest, using a switching circuit. The main drawback of these methods is that the modulation process is performed after the optical signal has been photo-detected. Hence, all noise mechanisms are added to the photo-detected signal in the spectrum of interest, and subsequently the technique aims to spectrally decouple the baseband noise from the signal of interest. In addition, the switching noise and thermal noise of the implemented circuited contributes significantly to the overall noise. Thus, electronic modulators are impractical to implement in order to increase the sensitivity of solid-state photodetection for low intensity optical signals.

Optical modulators provide a way to overcome the unwanted contribution of the photo-detector low-frequency noise. Optical modulation of a low signal signals is achieved by periodic sampling in the optical domain, thereby shifting the information in frequency domain. Hence, the electronic noise is not modulated, and the spectrum where the desired signal is located enjoys a lower noise floor. Therefore, in the demodulation process the desired signal is detected, whereas the noise is minimized significantly. Conventional methods make use of a mechanical chopper that modulates the signal prior to photodetection [51]. Subsequently, the signal is photodetected, amplified, and demodulated electronically. A lock-in amplifier, synchronized with excitation signal of the chopper, is often used to demodulate the signal. Lock-in amplifiers achieve highly accurate demodulation frequency which is effectively translated to small noise equivalent bandwidth (NEB) and overall low
noise. Large size, high-voltage signal, and low-frequency limit the overall implementation of the electro-mechanical-optical choppers. These bulk modulators cannot be easily adapted for on-chip applications that require modulation of very low intensity signals.

2.4.2. MOEMS Modulators

Several MEMS-based modulators have been produced, most of which are based on reflective technologies, such as micro-mirrors. Few references, however, have been found that deal with transmissive modulators, enjoying a vertical architecture, and large aperture shutters. Transmissive architecture provides several advantages over reflective architecture, such as an easier integration between optical sources and photodetectors, and a reduction in integrated bulk-optics complexity. Current on-chip optical shutters include liquid crystal-based, and micro-choppers, which provide up to 50 percent in optical efficiency for modulation [52]. Optical efficiency can be defined as the intensity ratio of the modulated signal and the unmodulated signal.

2.4.3. Reflective Modulators

Recent advances in micromachining have allowed the implementation of optical modulators, most of which have been designed for projector display technology and are based on reflective modulation. The most advanced optical modulators are based on torsional electrostatic micromirrors [53]. Texas Instruments, Inc., developed the digital micromirror devices (DMD). Arrays of aluminum micromirrors suspended above a silicon substrate by very thin torsional hinges are designed to rotate once an electric potential is applied between the mirror plate and the underlying electrode, thereby deflecting the incident light. One of the greatest challenges in torsional and out-of-plane MOEMS modulators is to achieve a large static tilting-angle from large mirrors and low driving voltage because of the constraints on the geometry associated with mirrors and electrostatic actuators. As of this date, it is not
possible to find any electrostatic micro-mirror that can achieve 90 degree out-of-plane deflection. Several complementary solutions have been implemented such as the use of magnetic actuation [54].

Electromagnetic actuators represent an alternative to electrostatic actuation due to the large forces that can be obtained from magnetic field. One of the main drawbacks is the high power levels, as an external permanent magnet is used to provide a field against which micromachined coils can generate a force when energized. The main drawbacks of this type of actuation are the high power consumption and the off-chip external magnets required to drive the actuator, limiting the overall scalability [55].

Other reflective modulators are based on optical gratings [56], which are based on arrays of beams that can be pulled down from planarity with the surrounding reflective surface to change from a fully reflective surface to a diffraction grating, scattering light to the sides. Contrast ratios as high as 200:1 can be achieved, as the gap between the beams can be selectively changed from half wavelength to a quarter of wavelength.

Nonetheless, whichever reflective modulator technology is chosen, it does not apply to modulation of bioluminescence, as such low intensity emission occurs at wide spatial angles. Reflective modulators do provide the precedence for future design of transmissive architecture configuration.

2.4.3. Transmissive Modulators

Various types of optical modulators are feasible, including those using mechanical or non-mechanical means. Liquid crystal technology is one of the dominant approaches to optical modulators [57]. Liquid crystals provide a simple, low-power and inexpensive type of optical modulators. Modulation is based on gating the passage of light through an electrically controlled cell. Each cell contains liquid materials that are partially ordered as opposed to fully ordered crystals. Nematic liquid crystals are among the most prevalent type of crystals,
which are rod-shaped molecules (typically 2 x 0.5 nm in diameter) that maintain a degree of parallel alignment despite disruption by thermal energy. The operation is based on the interaction between polarized light and the oriented molecules, leading to a modulation efficiency of 50 percent. Typically response time is between 10 ms to 100 ms, thereby making it unsuitable to overcome the low-frequency noise of photodiodes that is typically in the frequency range of 1-10 kHz.

The solution for on-chip modulation lies with the implementation of a transmissive MOEMS modulator. The use of a MEMS electrostatic motor to serve as a rotating transmissive light modulator, or shutter, for IR detectors was successfully demonstrated by Kraus, et al. [58]. Figure 2.8 shows an image of the device. A standard sacrificial oxide, polysilicon mechanism process, combined with the deposition of a gold layer on pie-slice-shaped regions of the center of the rotor. Backside KOH bulk-etch was required to form a path for light to travel through the substrate. Once these steps were completed, the surface microstructures were released using an HF etch followed by a p-dichlorobenzol sublimation step to prevent stiction. Rotor diameters of 800 µm and 1.2 mm were demonstrated, with drive voltages ranging from 35 to 60 V (starting voltages ranged from 60 to 100 V), and rotation rates of 0 to 7,000 RPM. The 50 nm gold layer used to block light showed a transmittance of less than 0.1 percent over the wavelength range of 2.5 µm to 25 µm. It should be noted that for operation above a few microns of wavelength, the backside via may not be necessary, since IR light of those wavelengths passes readily through silicon; although with a wavelength-dependent attenuation. Such a MEMS device, however, had a constrained aperture, limited scalability and required complex electronic drive circuitry. This type of shutters, however, suffers from low modulation speed, high operating voltage, and lack of scalability. Furthermore, this type of devices suffered from unwanted stiction effects, as the suspended rotor is separated from the substrate by a gap of less than 1 µm.
Perregaux et al. [59], demonstrated the use of an in-plane spring to move a polysilicon shutter blade along a circular path to modulate visible light (200 to 500 nm). Figure 2.9 shows an image of the device. Lateral shutters were fabricated using a sacrificial oxide, polysilicon mechanism process with a back-side etch to form vias for light transmission. Shutters were fabricated as of 30 µm x 90 µm attached to a 190 µm long, 2.5 µm wide, 2 µm thick polysilicon beams. The shutters were suspended over an optical vias etched from the backside, characterized by a resonant frequency of 9.5 kHz, a quality factor of 33, and high switching voltage of approximately 70 V. Several arrays of these devices were fabricated but were constrained by the pitch as it was greater than the shutter area. Therefore, this type of shutters suffered from a limiting optical aperture and overall modulation efficiency. As such shutters were fabricated in polysilicon, stiction was one of the main fabrication drawbacks. In addition, the shutters were actuated using parallel plate actuation, leading to non-harmonic modulation.
Bohringer et al., designed a transmissive optical shutter, called transmissive zigzag electrostatic micro-optical switch (TMOS) [60]. Figure 2.10 shows an image of the device. In this case, a shutter of approximately 20 µm x 20 µm is driven by a set of zigzag actuators over an optical vias etched from the backside. The operating voltage range was 38-138 V, achieving a natural frequency of 18.6 kHz. The main drawback of this design is the small aperture area, which is inadequate for modulation of wide-angle optical signals, and the large operating voltages. In addition, the fabrication process is based on suspension of polysilicon structures, making it also prone to unwanted stiction effects.
2.5.1. MOEMS Fabrication Processes

Several fabrication processes for MOEMS modulators have been published in recent years. Most of these fabrication techniques, however, are either dedicated to reflective architectures, or based on small aperture transmissive shutter configurations. Therefore, currently there is no published work demonstrating the fabrication of transmissive modulators that enjoy large aperture shutters at low operating voltages, and high resonant frequencies, particularly implemented using bulk-micromachining. Bulk micromachining allows to fabricate structures that enjoy higher mechanical stability due to high-aspect ratio (defined as the width of divided by the depth of the structure), are virtually unaffected by unwanted stiction effects, and can sustain harsher environmental conditions.

Silicon micromachining can be realized using two main approaches. The first one is based on surface micromachining, making use the silicon substrate as platform upon which several layers are deposited, such as insulators, metals, and semiconductor materials. Figure 2.11 illustrates a simple surface micro-machining process. The structures are released by wet etching of sacrificial layers, e.g. silicon dioxide, allowing selective suspension of structures. Although there are several surface micromachining processes that have been successfully
proven, transmissive optical modulators cannot be achieved as optical vias need to be etched in the silicon bulk. Moreover, this type of processes suffers from unwanted stiction effects, as the devices are characterized by the low aspect-ratio structures. One of the most commonly surface micro-machining processes is the Multi-User-MEMS-Process (MUMPS), which was originally funded by DARPA [61]. MUMPS allows low-cost manufacturing with known design rules for CAD, such as minimum feature size of fixed structures and suspended structures, size of pads, critical gaps, etc. Such process makes use of multiple depositions of poly as the material for the mechanical structures, metals to connect between layers and external connections, and oxide as a sacrificial layer.

![Surface Micro-machining process](image)

**Figure 2.11:** Surface Micro-machining process.

Bulk micromachining is the prevalent choice for implementing high aspect-ratio structures that are inherently more stable, robust, and therefore allows easier assembly. Several processes exist to this date that can achieve high-aspect ratio structures. Rapid prototyping of the MEMS devices can be implemented via SCREAM (Single Crystal Silicon Reactive Etching and Metallization) [62], or by a SOI process [63]. Figure 2.12 illustrates the outline of SCREAM process, originally developed at Cornell University [64] by the N.C. Macdonald research group. The main advantages of this process are the use of a single-photomask to define all components of the device, and its VLSI compatibility. SCREAM
allows fabrication of suspended beams with aspect ratios greater than 30 to 1 (height to width). A large class of functional structures has been demonstrated that provides excellent mechanical stability [65]. Moreover, this process can be complemented to include optical vias implemented by selectively etching windows through the entire silicon substrate. This process, however, cannot be used for fabrication of large area shutters, as that the suspended structures cannot be greater than 4 µm. Therefore, this process cannot be use to fabricate suspended large area shutters combined with standard actuators.

Several Silicon-on-Insulator (SOI) micromachining techniques have been investigated. SOI wafers consist of a device layer bonded on an oxide layer on top of thick silicon handle (substrate). Typical thickness dimensions of the SOI wafers for MEMS applications are 30 µm for the device layer, 2 µm for the oxide layer, and 300 µm for the silicon handle. High and low aspect-ratio structures can be defined in the device layer by deep reactive ion etch (DRIE). In addition, release is defined by critically timing the etching
of the sacrificial oxide layer using HF. Backside etch of the silicon handle allows to selectively open windows that can be used as optical vias. The main drawback in defining structures in the handle is that the process depends on the DRIE non-uniformity (usually at least 10 percent), limiting the precision in aimed structural thickness. Milanovic et al. demonstrated a multi-level process [67] for torsional mirrors that enjoy multiple thicknesses by selectively etching the front and the backside of the wafer. Although SOI processes allow in-plane actuators to provide out-of-plane deflection by means of torsional beams, the mirrors do not achieve large angle deflection, making impractical for transmissive modulation. Moreover, currently most SOI-based processes are highly complex multi-level photolithography is required. Table 2.2 shows a comparison of the fabrication processes.
Table 2.2: Comparison of Processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>Process Characteristics</th>
<th>Device Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scream [62]</td>
<td>Standard SCS wafers</td>
<td>In-plane resonators</td>
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<tr>
<td></td>
<td>High-Aspect Ratio Structure</td>
<td>Long Stroke actuators 1-50 um</td>
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<tr>
<td></td>
<td>One Photolithography</td>
<td>Linear springs</td>
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<tr>
<td></td>
<td>No Sacrificial layer</td>
<td>Low Voltage (1-50 V)</td>
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<td></td>
<td>Wafer front-side micro-machining</td>
<td>High Frequency (1-100 kHz)</td>
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<tr>
<td></td>
<td>Feature size of suspended device &lt; 5 um</td>
<td>Comb-drive actuator</td>
</tr>
<tr>
<td></td>
<td>VLSI Compatible</td>
<td>Parallel Plate actuators</td>
</tr>
<tr>
<td></td>
<td>Dry release – No stiction</td>
<td>Reflective Architecture</td>
</tr>
<tr>
<td>SOI [63]</td>
<td>SOI Wafers</td>
<td>Out-of-plane mirrors</td>
</tr>
<tr>
<td></td>
<td>Multi-level photolithography</td>
<td>In-plane resonators</td>
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<tr>
<td></td>
<td>High-Aspect Ratio and Low-Aspect Ratio</td>
<td>Small deflection angle (&lt; 15 deg)</td>
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<td></td>
<td>Wafer front and back-side micro-machining</td>
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<td></td>
<td>Buried oxide as sacrificial layer</td>
<td>High Frequency (1-100 kHz)</td>
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<td></td>
<td>Suspended feature size depends on etch-time</td>
<td>Comb-drive actuator</td>
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<td></td>
<td>VLSI Compatible</td>
<td>Parallel plate actuators</td>
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<td></td>
<td>Wet release – Low-moderate stiction</td>
<td>Reflective architecture</td>
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<tr>
<td>MUMPS [61]</td>
<td>SCS Wafers</td>
<td>Out-of-plane mirrors</td>
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<td></td>
<td>Multi-level photolithography</td>
<td>In-plane resonators</td>
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<tr>
<td></td>
<td>Polysilicon devices</td>
<td>Large deflection angle (&lt; 90 deg)</td>
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<td></td>
<td>Low-aspect ratio</td>
<td>Hinges, rotors can be fabricated</td>
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<tr>
<td></td>
<td>Oxide, or photoresist as sacrificial layer</td>
<td>Torsional and linear springs</td>
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<td></td>
<td>Wafer front-side micro-machining only</td>
<td>High Frequency (1-100 kHz)</td>
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<td></td>
<td>Suspended feature depends on sacrificial layer</td>
<td>Comb-drive actuator</td>
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<td></td>
<td>VLSI Compatibility depends on process temp.</td>
<td>Parallel plate actuators</td>
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<td></td>
<td>Wet-release - prone to stiction</td>
<td>Reflective architecture</td>
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</table>
2.6. Summary

In this chapter, we have presented a comprehensive review of several existing technologies that constitute the foundations for the Integrated Heterodyne Optical System (IHOS). Firstly, we have described whole-cell biosensors as a new family of genetically engineered sensors for real-time detection of environmental toxicity. We also described the principles of gene expression and the physical mechanism for bioluminescence.

Furthermore, we have presented current methods for the photodetection of low intensity signals. Photomultipliers (PMTs) have been described as the most sensitive of all photodetectors. PMTs, however, cannot be implemented for portable applications, as they are fragile, bulky, and expensive. On the other hand, solid-state photodetectors can be adapted for portable applications. Several types of photodetectors are presented, such as PN photodiodes, Avalanche photodiodes, CCDs, and CMOS imagers. The most limiting factor, however, is the photo-sensitivity affected by low-frequency and thermal noise. Thermal noise, switching noise, and dark current can be reduced using a cooling system, whereas low-frequency noise can be overcome by a modulation scheme.

Although several on-chip modulators exist, none satisfy the requirement of high resonant frequency operation, low actuation voltage, large field area, and a transmissive architecture. Several technologies have been reviewed in detail. Liquid-crystals are limited by low frequency operation.

The MOEMS modulators use electrostatic actuation. Most MOEMS modulators are characterized by their reflective architecture, and operate as torsional mirrors, or diffractive gratings. Torsional mirrors require high actuation voltages, and cannot achieve large out-of-plane deflection. The MOEMS modulators that use electromagnetic actuation require high power and an external magnet to apply the field, thereby limiting scalability and batch production.

The few transmissive MOEMS modulators that have been implemented to this date experience several faults. The current modulators implemented by surface micromachining require high actuation voltages, suffer from unwanted stiction effects, making them unreliable for portable applications. The existing transmissive modulators implemented by bulk micromachining suffer from small field area, cannot be scaled up in arrays, and required high operating voltages.

Moreover, two main fabrication processes were presented. The first process was SCREAM (Single-Crystal-Reactive-Ion-Etch-and-Metallization), which relies on a bulk micromachining technique and requires one photolithographic mask. This process allows the fabrication of high aspect-ratio structures, and can be modified to include backside etch vias.
to achieve an optical path for the shutters. SCREAM, however, is limited by the width of the suspended features, and therefore limits the field area of the shutter. Other existing bulk micromachining processes are based on SOI (Silicon-on-Insulator). The combination of SCREAM with SOI-based processes will provide the precedence for MASIS (Multiple-Aspect Structural Integration in Single-Crystal-Silicon), a novel process designed specially tailored for transmissive modulators. The reader is referred to Chapter 5 for detailed discussion of MASIS.

In summary, although there are several existing technologies for implementing optical modulators, as of this date none are exactly applicable to implement an optical modulator for photodetection enhancement of low intensity signals, such as bioluminescence from whole-cell sensors. In the subsequent chapters, we present the firstly reported MOEMS modulators that enjoy large area shutters and operate in the low kHz at low operating voltages. Such modulators can be seamlessly adapted to photodetectors using a transmissive architecture.
Chapter 3.
IHOS MODEL.

3.1. Introduction

The goal of this chapter is to present a comprehensive model for the IHOS (Integrated Heterodyne Optical System). The chapter provides an introduction to the MOEMS (Micro-Opto-Electro-Mechanical-System) modulator, the photodetector, and the amplifier.

First, we discuss the system electrical parameters. We model the signal and noise for the various components of the system. We introduce the background for the noise mechanisms of the silicon photodetector and the transresistance amplifier. In addition, we simulate the photodetector and amplifier stages in order to predict the signal and noise voltage spectral densities at the output of the system. Next, we provide the model for the MOEMS, which is used as the basis for the design chapter. Figure 3.1 illustrates the four stages that will be described in detail.

The novelty in modeling the entire system is based on the unique representation of different physical variables that describe the combined behavior of MOEMS, and semiconductor parameters into a single model that can be utilized as a design tool.

Thermal noise and shot noise are present mainly in the photo-detecting stages generally showing a uniform spectral distribution. Thermal noise is also present at the input of the amplifier and in the feedback network. The electronic system can be cooled down in order to reduce the thermal noise. Modulation prior to photodetection provides the most effective method to overcome the low-frequency noise (flicker noise) manifested in the subsequent stages. The low-frequency noise of the photodiode and amplifier stages can be overcome by modulating the input signal in the low kHz. A bandpass filter further improves the SNR as the system bandwidth is reduced to the desired frequencies of interest. Such filter can be implemented with a lock-in amplifier operating synchronously at the same frequency as the MOEMS modulator.
3.2. Noise in the Photodetection Stage

The photodetector stage is implemented by a photodiode in reverse bias connected to a transimpedance amplifier with a resistor and capacitor in the feedback loop. The feedback network is based on the parallel connection of the capacitor with the resistor, which provides frequency compensation. Figure 3.2 shows a schematic diagram of an amplifier with the integrated noise sources. The transresistance amplifier, however, also suffers from various types of noise mechanisms. We have used the noise model developed by Hamstra and Wendland [67]. Herein, we refer the reader to Appendix I for comprehensive discussion of the noise in photodiodes and amplifiers, and all corresponding definitions. In this chapter, we simply summarize the results.

The actual magnitude of the noise at the output of the amplifier can be calculated using the following expression:

$$
\bar{v}_{\alpha_{\text{noise}}}^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left| a_1(f) (i_{\text{phd}}(f) + i_n(f)) \right|^2 + \left| a_2(f) e_n(f) \right|^2 + \left| a_3(f) i_{\text{ref}}(f) \right|^2 df.
$$

(3.1)
Where $a_1$ is the transfer function of the amplifier for the input current noise due to the photodiode, $i_{npd}$, and the input current noise of the amplifier, $i_n$; $a_2$ is transfer function of the amplifier for an input voltage noise, $e_n$; and $a_3$ is the transfer function due to the feedback network noise, $i_{n_f}$. The total output voltage noise is obtained by integrating over the entire system bandwidth ($f_1 - f_2$).

\[ a_0 \]

\[ \text{Figure 3.2: Photodiode connected to a transresistance amplifier.} \]

In order to calculate the SNR ratio, we formulate the ratio of the output voltage due to the photocurrent, $i_{pd}$, that enjoys a specific operating frequency determined by the transmissive MOEMS modulator, and output noise voltage integrated over the desired frequency range. Such expression is given by:

\[
\text{SNR} = \frac{\int_{f_1}^{f_2} \left( a_1(f) i_{pd}(f) + a_2(f) i_n(f) + a_3(f) i_{n_f}(f) \right)^2 df}{\int_{f_1}^{f_2} \left( a_1(f) i_{npd}(f) + a_2(f) v_n(f) + a_3(f) i_{n_f}(f) \right)^2 df}
\]  

(3.2)

The bandpass filter can be implemented electronically using a standard filter that provides a selective bandwidth. Among the several options exist to implement a lock-in amplifier provides a very narrow bandwidth and a simple method to demodulate the signal. The selectivity of the bandpass filter allows to further reduce the noise. Furthermore, a MEMS filter can also be implemented in order to obtain a high-$Q$, several references can be found in
The SNR is the figure that ultimately determines the performance of the system.

Next, we have simulated the noise contribution of each stage in order to predict the minimum detectable signal (MDS). In order to achieve this task, we simulated the noise of the photodetector and transresistance, using Matlab (Matlab Corporation, USA). Table 3.1 summarizes all the physical values used for the system. Figure 3.3 illustrates the noise sources for each stage. In this first model, we have neglected the noise contribution of the MOEMS modulator.

![Block diagram of the IHOS including different noise source. Modulation is performed prior to photodetection. Noise is added in the photodiode and amplifier stages.](image)

**Figure 3.3:** Block diagram of the IHOS including different noise source. Modulation is performed prior to photodetection. Noise is added in the photodiode and amplifier stages.

In order to estimate the noise magnitude it is necessary to integrate the total of the square voltage spectral density over the desired frequency range. A simple method to estimate the magnitude of the noise at the output of the amplifier is based on multiplying the noise equivalent bandwidth (NEB) by the magnitude of the voltage density at each frequency. In this way, it is possible to estimate the minimum detectable signal by dividing the output noise by the gain of the amplifier. Figure 3.4 shows minimum detectable signal (MDS) of the
photocurrent as a function of the bandpass filter bandwidth, which was simulated as 25 mHz, 100 mHz, 1 Hz, 5 Hz, and 10 Hz. A lock-in amplifier can implement such narrow bandwidth.

Figure 3.4: Calculated minimum detectable signal as a function of bandwidth. Green is 25 mHz, cyan is 100 mHz, Red is 1 Hz, Blue is 5 Hz, and Yellow is 10 Hz.
Table 3.1: Values of the photodiode and amplifier used for the simulations.

<table>
<thead>
<tr>
<th>Stages</th>
<th>Physical Variables</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photodiode</td>
<td>Active Area ($A$)</td>
<td>8 mm$^2$</td>
</tr>
<tr>
<td></td>
<td>Operating Voltage ($V_d$)</td>
<td>-1 V</td>
</tr>
<tr>
<td></td>
<td>Saturation Current ($I_{sat}$)</td>
<td>$10^{-11}$ A</td>
</tr>
<tr>
<td></td>
<td>Quantum Efficiency ($)</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Parallel Resistance ($R_d$)</td>
<td>10 GΩ</td>
</tr>
<tr>
<td>Amplifier</td>
<td>Capacitance ($C_d$)</td>
<td>$10^{-9}$ F</td>
</tr>
<tr>
<td></td>
<td>Input Impedance ($R_{in}$)</td>
<td>100 MΩ</td>
</tr>
<tr>
<td></td>
<td>Input Capacitance ($C_d$)</td>
<td>$10^{-12}$ F</td>
</tr>
<tr>
<td></td>
<td>Feedback Resistor ($R_f$)</td>
<td>15 kΩ</td>
</tr>
<tr>
<td></td>
<td>Feedback Capacitance ($C_d$)</td>
<td>$10^{-9}$ F</td>
</tr>
<tr>
<td></td>
<td>Open loop Gain ($R_f$)</td>
<td>15 kV/A</td>
</tr>
<tr>
<td></td>
<td>Gain Product Bandwidth ($\omega_H$)</td>
<td>10 MHz</td>
</tr>
<tr>
<td></td>
<td>Amplifier Input Noise ($e_n$)</td>
<td>$10 \frac{pV}{\sqrt{Hz}}$</td>
</tr>
<tr>
<td></td>
<td>Amplifier Input Noise ($i_n$)</td>
<td>$0.5 \frac{pA}{\sqrt{Hz}}$</td>
</tr>
</tbody>
</table>
3.3. MOEMS Modulator

The MOEMS modulator is based on the design presented in the Chapter 4, which its schematics are shown here. The device is comprised of a comb-drive actuators connected to set of shutters that resonate in plane to allow transmissive modulation. The modulator is excited using a time dependent voltage signal $V(t)$, which is composed of a dc-offset signal and an ac-sinusoidal signal in such a way that $V(t) = V_{dc} + V_{ac} \cos(\omega t)$. Here $\omega$ denotes the "electrical" frequency of the electrical signal applied to the transducer as the excitation. Since the mechanical force produced by the comb-drive-based transducer is proportional to the square of the voltage, the transducer is characterized by the following force-voltage relation:

$$F(t) = \frac{n_\varepsilon h}{d} V^2(t) = \frac{n_\varepsilon h}{d} \left( V_{dc}^2 + \frac{V_{ac}^2}{2} + 2V_{ac}V_{dc} \cos(\omega t) + \frac{V_{ac}^2}{2} \cos(2\omega t) \right).$$

(3.3)

Where $\varepsilon_0$ represents the permittivity of the free space, $h$ represents the height of the actuator, $d$ is the gap between the comb fingers, and $n$ is number of combs. One observes that as the electro-static transducer is driven by a single frequency electrical harmonic signal, the mechanical force, which is related to the voltage squared, is produced at two frequency scales:

a. the excitation frequency and b. twice this frequency.

The mechanical dynamic behavior of the modulator under harmonic excitation is described using a simplest one degree of freedom model:

$$m_{eff} \ddot{x} + \gamma \dot{x} + k_{ts} x = F \cos(\omega t).$$

(3.4)

Where $m_{eff}$, $k_{ts}$, $\gamma$ are the effective mass of the modulator, the total suspension stiffness in the stroke direction (axial displacement), and the damping coefficient (the typical value is $1.86 \times 10^{-5}$ [N.S/m²]), respectively. $F$ is the amplitude of the excitation force; an example for the calculation of the effective mass of a comb-drive actuator and stiffness of the folded suspension. The steady state solution of Equation (2) can be written in the form [73]:

$$x(t) = X(\omega) \cos(\omega t - \varphi),$$

(3.5)
where

\[ X(\omega) = \frac{F/k_{\text{e}}}{\sqrt{[1-(\omega/\omega_0)^2]^2 + (\omega/Q\omega_0)^2}}, \]  

(3.6)

is the amplitude, and

\[ \varphi = \tan^{-1} \left( \frac{\omega/Q\omega_0}{1-(\omega/\omega_0)^2} \right) \]

(3.7)

is the phase angle. Here, \( \omega_0 = \sqrt{k_{\text{e}}/m_{\text{eff}}} \) is the "mechanical" natural frequency of the modulator and \( Q = \sqrt{k_{\text{e}}m_{\text{eff}}/\gamma} \) is the Q-factor. Substituting Equation (1) for the mechanical force into Equation (2) and taking into account Equations (3)-(5), we obtain the steady-state response of the modulator:

\[ x(t) = X_{\text{st}} + X_1(\omega_e)\cos(\omega t - \varphi_1) + X_2(2\omega_e)\cos(2\omega t - \varphi_2), \]

(3.8)

where

\[ X_{\text{st}} = \frac{n\varepsilon_o h}{d} \left( V_{dc}^2 + \frac{1}{2} V_{ac}^2 \right) \]

(3.9)

is the static displacement,

\[ X_r(\omega_e) = \frac{F_r/k_{\text{e}}}{\sqrt{[1-(\omega_e/\omega_0)^2]^2 + (\omega_e/Q\omega_0)^2}}, \quad r = 1, 2, \]

(3.10)

\[ \varphi_r = \tan^{-1} \left( \frac{\omega_e/Q\omega_0}{1-(\omega_e/\omega_0)^2} \right) \quad r = 1, 2, \]

(3.11)

and

\[ F_1 = \frac{2n\varepsilon_o h}{d} V_{ac} V_{dc}, \quad F_2 = \frac{n\varepsilon_o h}{2d} V_{ac}^2. \]

(3.12)

The first mechanical scale occurs at the electrical signal frequency, \( \omega_e \), while the second one occurs at twice that frequency, \( 2\omega_e \). As a result, the resonant excitation can be achieved as the device is driven by an electrical harmonic signal at half damped resonant frequency of the modulator, i.e. \( 2\omega_e = \omega_0 \sqrt{1-1/(2Q^2)} \), as well as at the damped resonant frequency itself, i.e.
\( \omega_e = \omega_b \sqrt{1-1/(2Q^2)} \). In the former case, the mechanical response frequency differs significantly from the frequency of the electrical signal. The effective mass of such comb-drive actuator can be calculated according to the following expression [74]:

\[
m_{\text{eff}} = m_{\text{shuttle}} + \frac{m_{\text{beam}}}{2} + \frac{96m_{\text{truss}}}{35}.
\]

(3.13)

Where \( m_{\text{shuttle}} \) is the mass of the actuators, shutters and moving portion of the actuators; \( m_{\text{beam}} \) is the mass of a single beam of the folded flexure; \( m_{\text{truss}} \) is the mass of the truss of the folded suspension (typical design values are described in the subsequent in Chapter 4). The suspension stiffness can be calculated from the expression of a folded flexure [75]:

\[
k_{i} = ik_{s} = i2Eh \frac{b^3}{l^3}, \quad i = 8,10
\]

(3.14)

where \( i \) is the total number of spring structures (generally taken in pairs), and \( b \) and \( l \) are the height and length of the folded-flexure beam, \( E \) is the Young’s modulus of silicon (the value is taken as 169 GPa). If we take into account that the MOEMS design is comprised of either 8 or 10 springs (the reader is referred to Chapter 5), then the natural frequency of the system can then be calculated as:

\[
\omega_o = \left( \frac{k_{i}}{m_{\text{eff}}} \right)^{\frac{1}{2}} = \left( \frac{i2Eh \frac{b^3}{l^3}}{m_{\text{shuttle}} + \frac{m_{\text{beam}}}{2} + \frac{96m_{\text{truss}}}{35}} \right)^{\frac{1}{2}} \quad i = 8,10
\]

(3.15)

3.4. Photodetection of Modulated Signal

As described earlier, the mechanical response of the device enjoys two main frequency scales. The first one occurs at the frequency of electrical excitation, \( \omega_e \), whereas the second one occurs at twice that frequency, \( 2\omega_e \). Figure 3.5 shows the cross-section of MOEMS modulator, where the shutters are driven by the actuators over the etched cavities that act as optical vias. Given this configuration, the frequency of the photodetected signal doubles the
mechanical frequency. Therefore, the photodetected signal enjoys two main spectral components that occur at twice the electrical excitation frequency, $2\omega_e$, and at four times the electrical excitation frequency, $4\omega_e$. Figure 3.6 shows a schematic representation of the frequency response of the modulated signal. Note that the arrows represent the Fourier components for the frequency spectrum of the electrical, mechanical, and optical responses.

As the active area of a photodiode is exposed to a photon-flux, the current due to photon-generation is defined as:

$$I_p = \Phi q \eta A,$$

(3.16)

where $\Phi$ is the incident photon-flux [photons/sec-cm$^2$], $\eta$ is the quantum efficiency (i.e. 0.9), $q$ is the electron charge, $A$ is the active area of the photodiode. Since the active area of the photodiode is shuttered periodically as described by Equations 6-7, the photodetected signal varies as a function of time.

As discussed later in Chapter 4, the design of the MOEMS modulator is comprised of either 20 or 40 shutters. Hence, the photodetected signal can be calculated from the following expression:

$$I_p(t) = \Phi q \eta L_s u \left( X_{st} + X_i(\omega_e) \left| \cos(2\omega_e t - \varphi_i) \right| + X_j(2\omega_e) \left| \cos(4\omega_e t - \varphi_2) \right| \right).$$

(3.17)

Where $L_s$ is the length of the shutters, $u$ is the number of shutters. We have assumed that the displacement magnitude of the shutters is 50 µm, which is exactly the width of the optical vias. At an excitation frequency of half resonance, the photodetected signal can be expressed as follows:

$$I_p(t) = \Phi q \eta L_s u \left( X_{st} + X_i(\frac{\omega_e}{2}) \left| \cos(\omega_e t - \varphi_i) \right| + X_j(\omega_e) \left| \cos(2\omega_e t - \varphi_2) \right| \right),$$

(3.18)

$$i = 8,10, \quad u = 20,40.$$

In this expression we disregarded the phase since it is not relevant for measuring bioluminescence from whole-cell biosensors.
Figure 3.5: Cross section of shutter configuration showing the input and output fluxes.

Figure 3.6: Frequency Spectrum of the electrical excitation (red), mechanical (blue) and optical (green) responses.

Note that the second harmonic of the optical response is at $4 \epsilon$, which is much higher than $\epsilon$. Hence, the unwanted electrical coupling from the modulator at $\epsilon$ can be avoided.

3.7. **Summary**
This chapter offers an overview of the physical model that governs the photodetector, electronics and the MOEMS modulator, which constitute the IHOS. As we formulated all the equations that define the system, this chapter can be considered as the foundations for the development of a CAD tool. First, we introduced all the noise mechanisms that limit the sensitivity of silicon photodiodes. Flicker noise is the most dominant source of noise, as it is characterized by its 1/f noise distribution. Hence, the motivation for modulation is to overcome the low-frequency noise content that limits the sensitivity of the photodiodes.

Furthermore, we introduced the noise mechanism of the transresistance amplifier integrated with a photodiode. The model was based on Hamstra and Wendland [67], which neglects the series resistance of the photodiode. This chapter has been complemented with Appendix I. In addition, the noise due to the power supply variations was also neglected since the system will be connected to batteries. We have simulated the total noise of the system in order to estimate the minimum detectable signal.

Finally, we presented the model of the MOEMS modulator, which is the heart of the IHOS, and can be implemented as a simple add-on device. We introduced all the equations of motions that define the comb-drive actuator, including the electro-static and mechanical stages. In addition, we explain how the modulator works as a mechanical-electrical-optical transducer in order to achieve optical modulation at different frequency scales, which are electro-mechanically decoupled from the excitation signal of the modulator (the reader is referred to the experimental chapter, Chapter 6, for a description of the Double Harmonic Modulation Technique.

In order to realize the integration of the IHOS with light-emitting whole-cell sensors, simulations for the noise figures were required to estimate the minimum detectable signal (MDS). This chapter provides the basis for the Design Chapter.
Chapter 4.

4.1. Introduction

This chapter provides a detailed description of the MOEMS (micro-opto-electro-mechanical-system) design for the implementation of the Integrated Heterodyne Optical System (IHOS). Firstly, we introduce a short description of basic building blocks for the design of linear electrostatic MOEMS actuators, as described in Figure 4.1. Secondly, we introduce the design considerations in order to adapt the basic MOEMS building blocks into a novel device capable of providing an optical modulation function. Furthermore, this section discusses the physical parameters and corresponding engineering trade-offs involved in the design optimization. This discussion includes requirements for efficient optical modulation, mechanical and electrical parameters that define the microstructures and the electrostatics of the actuators. Next, first-order stability analysis and finite element analysis (FEA) simulations are presented as part of the overall design plan. Lastly, the design synthesis is presented, which includes all the final design dimensions, summarized in Tables 4.1-4.2.

![Figure 4.1](image.png)

*Figure 4.1:* The main three components of the IHOS: Comb-drive Actuators, Folded Flexures (spring structures), and Shutters.
4.2. MOEMS Design Considerations

The physical considerations involved in the MOEMS design are introduced in this section. Several aspects need to be taken into account when designing a MOEMS-based device that performs a predetermined function, such as optical modulation. First, the functional requirements must be considered from the initial design stage. The device must modulate the amplitude of an optical signal using a vertical architecture in order to attain transmissive spatial modulation. The main design challenge is to achieve high modulation efficiency by means of changes in the aperture area at frequencies well above the low-frequency noise of the photo-detector. Optical efficiency can be defined as the intensity ratio of the modulated signal and the unmodulated signal. Hence, it is crucial to obtain maximum chip area dedicated to shutter the incoming optical signal over the active area of the photo-detector.

The MOEMS design has been conceived as an integration of an array of suspended shutters with driving electrostatic actuators. Electrostatic actuators make up the engine for the optical shutters, which are based on a comb-drive configuration that is described in a subsequent section in detail. The comb-drive actuators need to be fabricated as high-aspect ratio (narrow over deep features) structures, providing robustness and stability. The requirements for high-frequency, large-aperture MOEMS modulators are, however, quite stringent. The wide majority of large stroke comb-drive actuators are designed to operate either under static loading, such as variable optical attenuators (VOAs) [76], or transient excitation applications, such optical switches [77] which do not require resonance operation. On the other hand, most comb-drive based resonators designed to operate at high frequency do not require large displacement, as for example in the field of RF [78,79,80] or angular rate sensors [81]. Therefore, the combination of large-displacement actuators, operating in resonance in the low kHz range does represent in a sense a unique design challenge.
In order to implement transmissive optical architecture, a new fabrication process was conceived and designed named MASIS (Multiple-Aspect Ratio Structural Integration in Single-Crystal-Silicon). The reader is referred to Chapter 5 for a comprehensive description of the fabrication process. The novel process integrates standard electrostatic actuators with large area shutters in the same device layer, thereby meeting the demands for efficient optical modulation. The design of the device involves an iterative process for which design considerations of the fabrication process must be included from an early design stage.

4.3. Comb-drive Actuators.

The electrostatic engine of the modulator is based on the design of lateral comb-drive actuators for large displacements. Figure 4.2 shows a schematic diagram of a comb-drive actuator, which is composed of electrostatic drivers connected to the mechanical springs. The comb-drive actuators are responsible for providing the actuating force for the shutters. The electrostatic part of the comb-drive actuators consist of inter-digitated structures (comb-fingers), where one set of arms is fixed (the stator), and the other arm (the rotor) is connected to a movable and compliant suspended structure. As a voltage potential is applied between the comb electrodes, deflection of the suspended comb-drive structure is achieved as a result of the developed electrostatic forces. The compliant structure is based on folded flexures that provide a restoring force that works against the electrostatic force. Overall, the comb-drive actuator behaves as a resonator that is excited by a harmonic electrostatic force. The resultant resonant behavior of the shutters determines the carrier signal by which the input optical signal is multiplied in time domain. Ideally, the carrier signal is a pure sinusoidal wave in time domain, allowing an accurate and deterministic modulation. On the other hand, if the mechanical behavior of the shutter is not harmonic but rather nonlinear, the resultant modulated signal will not enjoy a unique spectral location, thereby making the modulation and subsequent signal demodulation quite complex. The key is to design a large displacement
actuator capable of driving an array of optical shutters, while avoiding any nonlinear behavior that may lead to non-harmonic motion.

Figure 4.2: Schematic diagram of a comb-drive actuator.
4.4. Folded Flexures

In order to achieve maximum linear displacement, a folded flexure has been implemented as the spring structure of choice for the comb-drive actuator [82]. Folded flexures enjoy a relatively simple geometry that provides a very large linear force-displacement response. Figure 4.3 shows a schematic diagram of the folded flexures. This type of spring structure has been extensively studied, as it represents one of the most commonly used springs for MEMS actuators. The key concept in using this spring configuration is that the resultant structure is very flexible in the axial direction (direction of displacement), while it is be very rigid in the lateral direction (orthogonal to direction of displacement). The analytical expressions for the spring constants in the lateral and axial directions have been extensively modeled in previous works [62,74,75], and can be respectively found from:

\[ k_y = \frac{2Ebh}{l}, \]  
\[ k_x = \frac{2Eb^3h}{l^3}. \]  

The overall stiffness ratio is given by the following expression [74]:

\[ \frac{k_y}{k_x} = \left( \frac{b}{l} \right)^2. \]  

Where \( b \) is the width of the spring beams, determined by the fabrication technology, \( h \) is the height of the spring beams, \( l \) is the length of the spring beams, \( E \) represents the Young’s modulus of single crystal silicon, approximately 169 GPa for (110) single crystal silicon [83]. Furthermore, if we take into account a more accurate definition for the orthogonal stiffness, a spatial dependence on the axial direction is observed, as described by the following expression [74,75]:

\[ k_y = \frac{200EI}{3lx^2}. \]
This Equation clearly shows that the orthogonal stiffness decreases as a function of axial displacement.

Figure 4.3: Folded Flexures. A. Top view of folded flexure composed of beams. B. The stoppers provide the required support in order to prevent stiction.
4.5. **Electrostatic Behavior**

In a comb-drive actuator a movable arm of fingers (rotor) is engaged with a stationary arm of fingers (stator). A ground plane is located under the comb fingers, which are connected to the same potential of either the stator, or the rotor arm. Figure 4.4 shows engaged pairs of fingers. A two-dimensional analysis provides a very accurate and simplified solution to investigate linear force-displacement behavior in electrostatics, which can be adapted as the baseline values for a subsequent dynamic analysis.

![Figure 4.4: Engaged comb-drive, characterized by a stator (fixed) and rotor.](image)

Three dimensional effects, such as fringing fields, comb-finger ends, and ground plane levitation are neglected, as it is estimated that those contributions correspond to less than 5 percent of the overall behavior [74]. The capacitance between a pair of rotor and the stator fingers is given by the following expression [74]:

\[ C = \frac{2\varepsilon_0 h(x + x_o)}{d}, \]  

(4.5)
Where $x$ is the displacement in the axial direction, $x_o$ is the initial overlap, $h$ is the thickness of the fingers, and $d$ is the gap between the fingers. The stored energy of such system is determined by following expression:

$$ U = \frac{CV^2}{2}. \quad (4.6) $$

As the lateral forces cancel each other due to the structural symmetry, the resultant force in the axial direction is given by [74]:

$$ F_{elec} = -\frac{\partial U}{\partial x} = -\frac{\partial C}{\partial x} V^2 = -\frac{n\varepsilon_c h V^2}{d}. \quad (4.7) $$

Where $F_{elec}$ is the negative gradient of the energy, $V$ is the applied voltage signal, $\varepsilon_o$ is the electric permittivity, $h$ is the height of the fingers, $d$ is the gap between fingers, $n$ is the total number of finger cells engaged in the comb-drive array. The displacement in the axial direction achieved by the electrostatic force is, therefore, given by the following expression [74]:

$$ x = \frac{n\varepsilon_c h V^2}{k_o d}. \quad (4.8) $$

### 4.5. Stability and Maximum Range of Motion

The maximum range of motion of comb-drive actuators is limited by the stability of the system. The linear behavior displacement and the proper operation can only be guaranteed as long as the system is stable. Thus, it is imperative to analyze the parameters that affect the natural stability of the system. First, the lateral compliance of the spring structures provides one of the main contributors to the side stability. The orthogonal forces pulling the stator and rotor fingers in the orthogonal direction can be defined by the following expression [74]:

$$ F_{elec} = \frac{n\varepsilon_c h(x + x_o) V^2}{2(d - y)^3} - \frac{n\varepsilon_c h(x + x_o) V^2}{2(d + y)^3}. \quad (4.9) $$

Where $y_o$ is the initial overlap between stator and rotor fingers, $y$ is the displacement in the axial direction, $x$ is the displacement in the lateral direction. Under perfect spatial symmetry,
the gap between fingers is equal, leading to a cancellation of the forces between the fingers in
the orthogonal plane. The stable operation range of the comb-drive actuator is, however,
limited when the forces due asymmetrical gaps is greater than the stiffness of the springs in
the orthogonal direction. Therefore, the stability is bounded by the following expression [74]:

\[ k_y > \left[ \frac{\partial E}{\partial y} \right]_{s \to 0} = k_e = \frac{2n \varepsilon_o h(x + x_o) V^2}{d^3}. \]  \hspace{1cm} (4.10)

Where \( k_e \) can be thought of as an equivalent negative stiffness that leads to a contributing
force of instability [74]. Combining Equations 9-7, \( k_e \) can be expressed as:

\[ k_e = \frac{2k_s (x + x_o) x}{d^2}. \]  \hspace{1cm} (4.11)

In this expression, \( k_e \) is independent of voltage. In order to calculate the maximum
displacement, i.e. \( k_y = k_e \), we combine Equations 8-10, and express the voltage at which side-
instability occurs [74]:

\[ V_{\text{max}}^2 = \frac{d^2 k_s}{2 \varepsilon_o h n} \left( \frac{2 k_y}{k_s} + \frac{x_o^2}{d^2} - \frac{x_o}{d} \right) \]  \hspace{1cm} (4.12)

This upper voltage limit is widely referred as the critical applied voltage, and is otherwise
known as the pull-in voltage. As described by Legtenberg et al. (1995) [74], the spring
constant \( k_s \) refers to the value in the deflected state, since side instability occurs only when a
voltage signal is applied. If we neglect the second term of Equation 12 (\( k_y \gg k_s \)), and combine
Equations 8-12, the simplified expression for maximum deflection is given by [74]:

\[ x_{\text{max}} = d \sqrt{\frac{k_y}{k_s}} \frac{y_o}{2}. \]  \hspace{1cm} (4.13)

In this simple expression, one can observe that the maximum deflection is limited by the gap
spacing, \( d \), between the rotor and stator fingers, and the stiffness ratio between the spring
constants in the axial and lateral directions. In order to properly design a comb-drive actuator
for large displacement range, it is necessary to obtain an in-depth understanding of the trade-
offs between the physical and structural parameters. If we combine Equations 4-13, and disregard the initial overlap, we obtain the very simplified expression [84]:

\[
x_{\text{max}} = \sqrt{\frac{5}{3}} dl
\]  

(4.14)

Surprisingly, this expression shows that the gap, \(d\), between fingers and the length, \(l\), of the springs are the actual structural parameters that define the maximum displacement in a comb-drive actuator that utilizes folded-flexures as the main spring structures. It is noteworthy that this simplified stability analysis is valid in static conditions, and provides baseline values for displacement magnitudes in resonance. Therefore, it is possible to conclude that comb-drive structures with small gap spacings are more prone to side pull-in instability. Moreover, implementation of spring structures with high spring stiffness ratio is required to minimize this effect. On the other hand, if larger gaps and stiffer springs are required, greater voltage magnitudes are required in order to supply the excitation forces necessary for large displacements in the axial direction. In addition, if the initial overlap between the stator and rotor fingers is decreased, the voltage threshold for stability is increased, leading to a greater actuation voltage range. Furthermore, if the number of fingers is increased, a lower actuation voltage is required as more comb-units are engaged at once. The main drawback in increasing the number of fingers is the increase in mass, leading to a lower natural frequency.

4.6. Dynamic Behavior

The dynamic behavior MOEMS system can be modeled using a second order differential equation that relates all the structural parameters of the system with the driving force:

\[
m_{\text{equiv}} \alpha k_x x = F_{\text{elec}} = \frac{n e_x h}{2 \cdot d} V(t)^2.
\]  

(4.15)

Where \(m_{\text{eff}}\) represents the effective mass of the entire system, \(\alpha\) represents the damping coefficient, \(k_x\) represents the stiffness in the axial direction, \(F_{\text{elec}}\) represents the electrostatic
force, $V(t)$ is the excitation voltage signal, which can be considered as a summation of sine wave and a dc-offset. The equivalent mass of the entire system can be calculated using the Rayleigh’s method [74], described by the following expression:

$$m_{\text{eff}} = m_{\text{shuttle}} + \frac{1}{2} m_{\text{truss}} + \frac{96}{35} m_{\text{beam}}.$$  \hfill (4.16)

The fundamental frequency of the system is given by [73]:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{k_{\text{ax}}}{m_{\text{eff}}}},$$  \hfill (4.17)

and the Q-factor is defined as [73]:

$$Q = \frac{\sqrt{k_{\text{ax}} m_{\text{eff}}}}{\gamma}.$$  \hfill (4.18)

Where $m_{\text{eff}}$, $k_{\text{ax}}$, $\gamma$ are the effective mass of the modulator, the suspension stiffness in the stroke direction (axial displacement), and the damping coefficient (the typical value is $1.86 \times 10^{-5}$ [N.S/m²]) [72], respectively. Clearly, the mass of the shutters needs to be minimized as much as possible in order to increase the resonance frequency and decrease the actuation voltage. The main dimensional parameter that can be adjusted is the thickness of the shutters. The reader is referred to the fabrication Chapter 5 for further information about the fabrication process. In addition, the actuation voltage can be decreased by driving the device in vacuum. In vacuum conditions, however, the damping coefficient also decreases substantially, and the main contributing mechanisms of losses are fatigue and heating. Therefore, it is preferable to drive the device in vacuum, if it is required to increase the $Q$-factor and decrease the driving voltage significantly.

4.6. Design Requirements and Tradeoffs

This section introduces the required design parameters necessary to implement a MEMS resonator capable of driving a large array of optical shutters. The design has been tailored to comply with the following requirements:
The frequency of modulation needs to be higher than 1 kHz in order to overcome low-frequency noise of the photodetector systems, which is mainly dependent on the flicker (1/f) noise. As the resonance frequency is proportional to the square-root of the effective mass of the system, it is necessary to design a fabrication process that reduces the payload mass of the shutters in order to obtain a high modulation frequency.

The light collection needs to be optimized by maximizing the range of motion, which improves the optical aperture area of the shutters. Therefore, the comb-drive design needs to enjoy a long stroke actuation range. As previously demonstrated, the stable range of comb-drive actuators is limited mainly by the gap between comb-fingers and the length of the folded-flexures. This value is taken as a baseline for dynamic operation.

The operating voltage needs to be as low as possible. One way to reduce the operating is to decrease the stiffness of the folded-flexures. Decreasing the stiffness, however, implies decreasing the resonance frequency. Decreasing the mass can also help reduce the voltage when the device operates in atmospheric conditions. Lastly, another alternative is to increase the total number of comb-fingers in order to decrease the operating voltage. This alternative, however, implies an increase in mass, thereby a decrease in resonance frequency. Therefore, in order to decrease the voltage, it is important to take into account the effects on the resonance frequency.

4.7. Design Synthesis

The design of the shutters is comprised of an array of rectangular masses suspended above etched windows connected to the comb-drive actuator via a central backbone. The shutters are driven by the comb-drive actuator, providing a maximum optical transmission efficiency of 50 percent. Three main topologies have been designed, shown in Figure 4.5.
The first one is based on a single array of 20 shutters connected symmetrically to comb-drive actuators, Figure 4.5.A. The second topology is based on a single array of 40 shutters, shown in Figure 4.5.B. The third topology is based on two arrays of 20 shutters, symmetrically separated by folded flexures, Figure 4.5.C.

The engineering trade-offs that differentiate these three designs are:

- Natural frequency
- Maximization of the optical aperture.
- Robustness

The first topology is considered the most stable and enjoys the highest natural frequency, as the structure is the most simple, and the fewer number of shutters provides a lower payload, allowing a higher natural frequency. The only drawback is the reduced optical aperture, which is about 1 mm$^2$.

The second configuration provides the largest aperture at the expense of greater payload mass. The optical aperture has been defined as 2 mm$^2$. The only drawback is that the greater number of shutters slightly reduces the operating frequency.

The third topology provides a large aperture at the expense of greater payload mass, while it enjoys an extra pair of folded-flexures. Therefore, the natural frequency is slightly reduced as the extra pair of springs compensates the increase in mass. In addition, the greater number of shutters and folded flexures increases the operating voltage. In addition, the spring structure that separates the arrays of shutters decreases the overall optical efficiency.

We have designed folded flexures that are 3.5 μm wide, 900 μm long and 30 μm deep, which provide the restoring force for an array of 1440 comb-fingers that are 2.5 μm wide, 65 μm long, 30 μm thick, separated by a 3 μm gap, and enjoy a 5 μm initial overlap. Each shutter is defined as 50 μm wide and 1 mm long. All the dimensions for each topology of the transmissive MOEMS modulator are summarized in Table 4.1.
Figure 4.5: Layout-of design of the three design topologies.
Once all of the topologies have been optimized analytically using the Equations described in Sections 4.4-4.6, it is possible to obtain the overall parameters for the calculation of the maximum linear displacement. Figures 4.6-4.7 illustrates the maximum mechanical stiffness and electrical stiffness as a function of displacement obtained by plotting equations 4.1 and 4.9 as a function of axial displacement for the dimensions shown in Table 4.1. Figure 4.6 corresponds to topologies I-II, as the only difference between the two designs is the mass size, which does not make an impact in the instability. Figure 4.7 corresponds to topology III. The maximum range of stability is determined as the point where both curves meet. The maximum displacement is calculated as 58 µm for the first two topologies, and 52 µm for the third topology.
Figure 4.6: Plot of negative electrical stiffness, $k_e$, and the orthogonal stiffness of the folded flexure, $k_y$, as a function of displacement for Topologies I-II, independent of voltage.

Figure 4.7: Plot of negative electrical stiffness, $k_e$, and the orthogonal stiffness of the folded flexure, $k_y$, as a function of displacement for Topologies III, independent of voltage.
Further sources for instability are provided by the imperfections during the fabrication process providing unwanted roughness on the sidewall that can reach up to 50 nm in sidewall noise topography, manifested as ripples and striation effects (the reader is referred to the Fabrication chapter for further information). A lack of spatial symmetry between the stator and rotor fingers further contributes to the instability of the system, which in turn limits the overall linear performance of the actuator.

4.9. Finite Element Analysis Simulation

The goal of this section is to corroborate and complement the analytical calculations for the MOEMS design with finite element analysis (FEA) by means of COSMOSWorks software simulator, which is a subcomponent of SolidWorks (Solidworks Corporation, USA). First, we incorporated the design in the software interface, for which separate components were introduced as parts. Only the movable parts were defined: the folded flexure, the backbone, the shutters, and rotor part of the comb-drive actuators. Subsequently, assemblies were constructed for which all of the parts were put together to form the main three design topologies.

Thereafter, boundary conditions were defined. The material properties for single crystal silicon (SCS) were also introduced, including the Young’s modulus, the material density, and the yield strength. These parameters were required in order to define the mesh composed of approximately 100,000 nodes, each defined as 5 µm³. The program provides an iterative array of calculations per element to make up for the overall structural behavior. Figures 4.8-4.9 illustrate the three-dimensional structural assembly that integrates all components for the second design topology, and the view of the finite elements.

In addition, fixed-type constraints were defined as part of the boundary conditions set at the folded flexure supports. A 10 micro-Newton probe force was defined to calculate the
impulse response to obtain mode shapes, maximum displacement, and resonant frequencies. Figures 4.10-4.12 show the simulated mode shapes of second topology.

Table 4.2 summarizes the results for all topologies, showing that the first mode, is spectrally spaced far from the other modes, ensuring that the devices will not suffer from mechanical interference from other modes during operation in their natural frequencies.

**Figure 4.8:** Rendered Image of IHOS. Shutters and Folded Flexures.

**Figure 4.9:** Mesh showing the solid elements of FEA simulation.
Figure 4.10: FEA simulation for first mode shape and resonance frequency.

Figure 4.11: Second Mode Shape Simulation and Frequency Value.
Figure 4.12: Third Mode Simulation and Frequency Value.

Table 4.2: Summary of FEA simulations, and analytical calculations for the three topologies.

<table>
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<th>Topology II</th>
<th>Topology III</th>
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4.10. Summary

In this chapter we have introduced the methods for design of the transmissive MOEMS modulators. First, we divided the main design into two parts: comb-drive actuators, and optical shutters. The comb-drive actuators act as the electrostatic engine of the system that provides the actuation for the shutters. The comb-drive actuators are comprised of an array of inter-digitated electrodes that supply an approximate constant electrostatic force as a function of displacement. The spring structures are based on folded flexures configuration that provide the restoring force. In this fashion, we have designed MEMS resonators that provide a displacement of at least 50 µm in static conditions. Such values can be regarded as baseline for dynamic operation. The shutter arrays consist of building blocks that are suspended over rectangular cavities of the same dimensions. As the shutters are connected to the MEMS actuators via a backbone structure, an in-plane transmissive MOEMS modulator has been conceived.

In addition, the combination of long-stroke actuation and resonance operation in the frequency range of 1-3 kHz poses a unique design challenge. In order to increase the resonance frequency, the MOEMS modulators will be fabricated using a novel technique that reduces the shutter mass by selective backside etching (the reader is referred to Chapter 6 for a detailed discussion of the fabrication process). In order to reduce the operating voltage, we have increased the number of comb-fingers at the expense of a slight decrease in the resonance frequency.

Three design topologies have been introduced that enjoy minor dimensional variations, such as the total number of shutters, and the total number of springs. All the MOEMS designs enjoy natural frequencies greater than 1 kHz that allow overcoming the low-frequency noise of photodetectors, discussed in Chapter 3. Furthermore, we have formulated the standard analytical methods to analyze the behavior of the device. The maximum displacement and maximum operating voltage under stable conditions have been calculated.
We have also corroborated the analytical solutions with finite element analysis (FEA) simulations. We obtained similar results for the resonance and stiffness values of the three design topologies. In addition, we have simulated the dynamic behavior of the structures, in order to obtain the shape of higher mechanical modes.

Overall, this chapter has utilized standard analytical methods to design unique MOEMS modulators that enjoy a transmissive architecture. Such devices are the key components of the Integrated Heterodyne Optical System (IHOS).
Chapter 5.
Fabrication Process.

5.1. Introduction

This chapter is devoted to a detailed description of the new fabrication process developed especially as part of this research work, named Multiple Aspect Ratio Structural Integration in Single-Crystal-Silicon, or MASIS. The main motivation to conceive this new process is to fabricate a transmissive MOEMS modulator that enjoys large aperture area and operates at kHz frequencies. Currently, there is no bulk-micromachining process that can support the fabrication of the MOEMS design that has been described in Chapter 4. Figure 5.1 shows the cross section of the process illustrating the implementation of the MOEMS modulator.

![Cross-section of transmissive MOEMS modulators implemented with MASIS.](image)

**Figure 5.1:** Cross-section of transmissive MOEMS modulators implemented with MASIS.

Design rules for this process are introduced and thoroughly discussed, as well as the rationale behind each fabrication step in order to make it an effective process for combining multiple aspect-ratio structures within the same device layer. The aspect-ratio is defined as the width of a structure divided by its thickness. The main goal is to fabricate suspended structures that support high-aspect ratio actuators and large area low-aspect ratio shutters, while reducing process complexity by minimizing the number of photolithographic masks. MASIS introduces a simple approach to the fabrication of a variety of micro-systems using
Silicon-on-Insulator (SOI) wafers. MASIS is a multi-level bulk-micromachining fabrication process, specially tailored to address the need for transmissive modulators, driven by long-stroke actuators. The MEMS architecture allows integration of very stiff actuators with very large area shutters. The process addresses the need to reduce the payload mass of the shutters, while maintaining high-aspect ratio of suspension springs and comb fingers of the transducers. Large aperture shutters are selectively thinned down significantly to achieve the high-frequency low voltage operation. Furthermore, two process variations derived from SCREAM (Single-Crystal-Reactive-Ion-Etch-and-Metallization) [64] are also discussed, as well as the advantages of different step sequences. MASIS II is introduced as the first alternative that utilizes SOI wafers and requires only a dry-release step. Next, we introduce MASIS III, which requires standard silicon wafers, and also relies on a dry-release step. Both of these processes provide an alternative to MASIS. Lastly, Appendix II includes a number of process details pertaining to fabrication recipes and characterization steps.

5.2. Overview of MASIS

As an introductory overview to MASIS, the end-result of the process is shown as a series of SEM images, Figures 5.2-5.6. Herein the powerful new concept is introduced in order to illustrate the advantages of combining multiple aspect-ratios of suspended structures in a single device layer. Moreover, different structural components of the optical modulator on-chip are demonstrated as illustrative examples of the process flow.
Figure 5.2: Shutters, Combs, and Folded Flexures fabricated by the MASIS process.

Figure 5.3: Arrays of suspended shutters over slits fabricated by the MASIS process.
Figure 5.4: Array of comb-drive structure, showing engaged comb-fingers fabricated by the MASIS process.

Figure 5.5: Backbone connecting the spring fabricated by the MASIS process.
5.3.1. Fabrication

MASIS introduces a simple approach for the fabrication of the transmissive optical modulators that enjoy a vertical architecture, and can be subsequently integrated as a device layer between an optical source and a photo-detector in order to implement the IHOS. As shown in Figure 5.1, an optical signal travels through the silicon slits, which are alternately shuttered in order to accomplish modulation before photo-detection. The MEMS architecture based on MASIS allows integration of high aspect-ratio actuators with low aspect-ratio shutters. The process is essentially divided into two mask layers. The front mask design, called the Device layer, defines high-aspect ratio structures. In this layer, springs and actuators are defined using the same beam width units, in the 2-4 µm range, while keeping the same thickness of 30 µm. The design rule for the beam width allows all the structures that are below this critical lateral dimension to be suspended above the substrate at a later process release step by a critically timed isotropic etch. In addition, the shutters are defined in this layer, although at a subsequent step the thickness is thinned down to reduce the overall effective mass of the IHOS. The backside mask design, called the Shutter layer, achieves two functions. The first one is to open the slits through which the optical signal will propagate and will be subsequently shuttered. The second function is to suspend and reduce the mass of the shutters in order to reduce the actuating force as well as to increase the operating frequency. As the mass of the shutters is decreased by an anisotropic silicon etch, the aspect ratio of the shutters, defined by Device layer, is drastically reduced, creating very wide over narrow structures. Hence, as both photolithographic masks are defined two aspect ratio structures are created, as illustrated in Figure 5.6.
5.3.2. Fabrication Process Flow

The process starts with standard double-sided polished silicon-on-insulator wafers (SOI) as substrates, which have a device layer of 30 µm, a 2 µm buried oxide layer, and a 300 µm silicon handle. The SOI alternative neither requires passivation, nor sputtering metal, as the device layer is doped heavily. In order to obtain metal contacts, it is possible to deposit metal on a very thin layer all over the device. This step guarantees resistive contacts, avoiding any possible Schottky junctions. All the steps hereinafter mentioned are illustrated in Figure 5.6. For specific details related to the recipes, the reader is also referred to the Appendix II.

1. **Oxide Mask**, step 1 in Figure 5.6. The first step is to grow 2 µm of thermal oxide that act as a mask layer for a subsequent etch of the bulk silicon, for both the device and handle layers of the SOI wafers. Thermal oxide provides a higher quality oxide on each side of the wafer, although it does indeed introduce some residual stress. Depending on the design geometry, in some instances it may be more recommendable to replace the thermal growth by a PECVD oxide. Although this type of oxide is characterized by lower quality, in terms of uniformity and etch selectivity to silicon, it contains less residual stress as the process requires lower temperature.

2. **Backside Photolithography**, step 2 in Figure 5.6. The initial photolithographic step involves the backside etch that takes place by spin-coating photo-resist on the backside of the wafer, thereafter developing and exposing the Shutter layer. This mask essentially provides the transmissive architecture for the optical modulation, as it will connect the front and backside of the chip. The goal is to define the transmissive optical windows that will be located underneath the shutters. Once these windows are defined by a backside etch, then the shutters are thinned down 10 µm further by an extended anisotropic etch.
3. **Pattern Transfer I**, steps 2 in Figure 5.6. The first pattern transfer of the design defined from the photo-resist layer to the oxide layer is achieved by anisotropic etch of the oxide utilizing a reactive-ion-etch (RIE), which contains CF$_4$-based plasma. Subsequently, the pattern is defined into silicon by utilizing an inductive-coupled-plasma (ICP) etcher that runs with the Bosch process [85].

4. **Shutter Etch**, step 3 in Figure 5.6. The deep silicon etch stops at the buried oxide, which provides a stop-mask in order to compensate for the etch non-uniformities. This is the main reason that SOI wafers have been preferred to standard silicon wafers. The etch variations of the Bosch process lead to 10 percent non-uniformity that is represented as differences in depth of the same design features located in different places on the wafer. A buried oxide layer offers a solution to overcome the Bosch process non-uniformity. The high selectivity of oxide to silicon buffers the variations in etched depths, as all structures attain the same depth after sometime. At this stage some footing effect occurs. The next step is to etch the buried oxide by using a CF$_4$-based RIE, using the same technique described in step 3.

5. **Shutter Thinning**, step 4 in Figure 5.6. Once the buried oxide under the shutters is etched completely, the thinning down process commences. Without an SOI wafer, the etch non-uniformities would not allow to control the shutter thickness accurately. This step is time critical, as the Bosch process will thin down the shutter mass at a rate of about 2 µm per minute. The goal is to thin down to mass leaving only about 10 µm thick shutter.

6. **Front-side Photolithography**, step 5 in Figure 5.6. The next step involves the front-side device mask. Up to this stage, the wafer front-side had a 2 µm oxide layer, which also serves as anti-scratching layer. Thereafter, the wafer is subject to its second
photolithographic step. This time, however, a thinner photo-resist is utilized since smaller critical dimensions (< 4 µm) are required.

7. **Pattern Transfer II**, step 6 in Figure 5.6. The next step is to transfer the front-side pattern to the oxide layer. This step is achieved again by the use of a CF$_4$-based RIE that provides the required anisotropic etch. Subsequently, the silicon is patterned using the Bosch process. The structures are defined down to the buried oxide layer. Again the exposed buried oxide layer is etched using CF$_4$-based RIE. Next, the photoresist layer is removed by using O$_2$-plasma based RIE. This is required as the wafer will be subject to higher temperatures subsequently.

8. **Silicon Substrate Opening**, step 7 in Figure 5.6. The next step involves etching the top and buried silicon dioxide layer. This step leaves a conformal and protective oxide layer on the structures, while silicon windows become exposed in the silicon handle.

9. **Release**, step 7 in Figure 5.6. The release step was achieved by using HF (49 %) for approximately 10 minutes. In order to prevent stiction, the chips were immersed in DI water, and isopropanol. The devices were dried using an oven at 80 C, which was in low vacuum. This was performed in order to avoid the liquid-air interface, and rather obtain a liquid-vacuum interface until all the remaining solutions on the chip surface were evaporated.

10. **Metallization**, step 8 in Figure 5.6. This step is required to achieve metal contacts for the devices, as mentioned earlier. If wire-bonding and an ohmic (non-rectifying) contacts are necessary, then a simple solution to obtain metal pads is based on evaporating a thin layer
of metal (<100 nm), such as gold. Such layer guarantees metallic contacts, without compromising the release step or electrical isolation between separate pads.

1. SOI wafer with 2 um oxide on both sides
2. Backside photolithography of Shutter Layer and oxide pattern transfer using RIE
3. Deep silicon etch to open slits using the Bosch process
4. RIE of buried oxide layer and controlled silicon etch to thin down the shutters
5. Front side photolithography of MEMS Layer and oxide pattern transfer using RIE
6. Silicon Etch using the Bosch Process
7. RIE of buried oxide layer using RIE and subsequent HF based release
8. Evaporation of a thin metal layer less than 50 nm to obtain ohmic contacts

Figure 5.6: MASIS fabrication process flow.
5.4.1. Critical Steps during the Fabrication Process

The MASIS process depends on critical parameters that allow the integration of different aspect-ratio structures in the same device layer. The first critical parameter is related to the photolithographic alignment between the front and backside patterns. This step is crucial in order to match the front design of the actuators with the backside design of the shutter windows.

Another critical parameter is the verticality of the silicon deep reactive ion etch (DRIE) that defines the shutter windows. The angle of the walls of the backside windows needs to be taken into account to assure a proper structural match between the front and backside patterns. Moreover, the connection between different aspect-ratio structures is another critical parameter that needs to be considered. The transition between the different
aspect-ratio devices is dependent on the Transition Beams, which are also released using the same critically time release step.

The last critical parameter is related to the release of the actuators in order to obtain high-aspect ratio suspended structures. The release step is based on a critically timed isotropic etch of the buried oxide layer, using HF.

In this section each of these critical parameters is thoroughly discussed in order to demonstrate the successful implementation of the process.

5.4.2. Alignment

The first critical step of the process is to accurately align the backside design with the front-side design. Alignment marks provide an accurate method to achieve this requirement. The acceptable estimated error between the front and backside patterns is +/- 3 μm. We utilized a Karl-Suss MI6 mask aligner to expose the patterns. Figure 5.8 shows an image of both front and backside alignment marks. The key is to control the placement between front and backside alignment marks. This is one of the reasons that the Shutter Layout mask is firstly defined in the process. As the backside etch is concluded, the front side mask needs to be aligned to the backside design, which is only 10 μm apart from the wafer top. Therefore, higher alignment accuracy can be accomplished by etching the backside first, and then aligning the front-side and the backside designs. Figure 5.9 shows a failed alignment between the front and backside etched patterns.
5.4.3. **Verticality of the Backside Etch**

The goal of this step is to define the shutter openings by etching silicon windows underneath the shutters. The critical aspect of this step is that the etched windows need to coincide with the corresponding front-side design of the shutters. As the deep silicon etch does not provide a perfectly vertical profile, it is necessary to customize the etch to the required device lateral dimensions. The windows (optical vias) are etched using the Bosch™
process, which is based on a sequence of combinations of a SF$_6$-based isotropic etch and a subsequent deposition of Teflon-like layer. While several works have dealt with various aspects related to the etch verticality, uniformity, loading-factor effect, and sidewall smoothness [86,87], the issues related to the characterization goes beyond the scope of this work. Herein we only intend to provide a quick summary of the critical parameters of the Bosch process.

Mainly, the verticality can be controlled by variations in the etching and deposition times. Smoothness can be controlled by the addition of O$_2$ and by reduction of the overall etch and deposition cycles, thereby decreasing the ripple sizes. The average etch-rate is 2 µm per minute, and can be controlled by the power level, while it also contributes to the sidewall smoothness. Finally, the loading-factor effect makes the device layout relate to the etch profile, as differences in trench lateral dimensions lead to variations in the etch verticality and sidewall profile. The interdependence of all these parameters affects the anisotropic properties of the entire etch, and therefore any single variation of a parameter affects the overall profile. Sidewall roughness is not of concern since the wavelength is not a critical parameter for spatial optical modulation. The only parameter of true concern is the verticality and the etch uniformity across the wafer that mainly depend on the device layout and the times of the etch-deposition cycle. As the Bosch™ process provides undesirable non-uniformity that depends on the layout and wafer location [88,89], it was necessary to run a calibration mask to customize the profile to the device layout. The calibration design consisted of variations in dimensions of shutter windows for the Shutter layer. The front-side design dimensions required shutter arrays of 50 µm wide separated by 50 µm gaps. The calibration mask varied the shutter widths from a 35 µm to 65 µm in steps of 5 µm, while constantly keeping the same 100 µm pitch. As the etching for the calibration mask was concluded, an approximate 89 degree-profile verticality was obtained. Figures 5.10-5.12 show the different cross-sections of samples with varying trench widths for a 200 µm deep etch. The actual Shutter layer design
needed to accommodate compensated lateral features, which resulted in shutter windows that were 60 µm wide separated by a 40 µm gap. This final design compensation is depicted in Figure 5.13, showing the mask layout and the cross-section of the trenches.

**Figure 5.10:** Backside etch profile for different trench widths: A.65 µm. B.60 µm. C.55 µm.

**Figure 5.11:** Backside etch profile for different trench widths: A.50 µm. B.45 µm. C.35 µm.

**Figure 5.12:** Backside etch profile for different trench widths: A.30 µm. B.25 µm. C.20 µm.
5.4.4. Transition Beams

The Transition Beams provide the seamless connection between the two distinct aspect ratio structures, and are among the innovative aspects of MASIS. The beam dimensions are 2-4 µm wide and 30 µm long. This critical width is required to release the beams at the same time as the actuators are released. The length of the beam provides the adequate separation between the shutters and the actuators in order to prevent any unwanted etching of actuators. Therefore, the Transition Beams guarantee that the actuators will have the correct thickness, and prevent any unwanted etching. Figures 5.14-5.16 show the Transition Beams connecting suspended with different aspect-ratios.
**Figure 5.14:** SEM image illustrates the transition beams that allow to bridge two distinct aspect ratio structures.

**Figure 5.15:** Top view of suspended optical shutters before release step.
5.4.5. Release Step

The buried oxide layer can be etched using hydro-fluoric acid (HF)-based wet chemistry. The main drawback of this method is that as the gap is very small, capillary forces lead to stiction, which is the main problem for releasing micro-machining structures. Several authors have dealt with various techniques and models to avoid stiction, such as the use of anti-stiction coatings based on self-assembly-monolayers (SAMs) [90,91], vapor HF combined with alcohol [92], HF bath combined with hexane [93,94], and a recent high temperature technique called Flash Release are among the newest methods to release MEMS devices that utilize a buried silicon dioxide sacrificial layer [95]. Nonetheless, there is not a universally recognized standard technique to avoid stiction. We used HF and subsequently replaced it with very low surface tension liquids [96], such as isopropanol, to prevent stiction. As the devices are immersed in solution for about 10 minutes, the HF is replaced with DI water, and subsequently replaced by isopropanol. The next step is to replace the isopropanol with hexane, which offers a lower surface tension. The final step is to use an oven in vacuum.
to evaporate the hexane at 85 °C, subsequently the chamber is vented gradually until atmospheric pressure is achieved. This step has proved to be repeatable and reliable.

5.5. **MASIS II**

An alternative process to MASIS process using SOI wafers is derived from SCREAM (Single-Crystal-Silicon Reactive Ion Etch and Metallization) [62], which makes use of a passivation technique and a subsequent SF$_6$ based etch to release the silicon devices. Although this proposed process requires a more thorough characterization and it includes more process steps, the main benefit is based on the use of plasma-based chemistry to avoid wet etching. The process runs at low temperature, and also utilizes standard VLSI processes. Figures 5.17-5.18 show all the steps of the process flow. This process can be considered as an alternative for future implementation. The main difference with the standard MASIS process resides in the use of a passivation step and the dry release step. The major distinction factors are summarized as follows:

1. **Passivation**, steps 9 in Figure 5.18. The release step involves passivating the sidewalls of the structuring by means of plasma-enhanced chemical vapor deposition (PECVD) performed at 250 °C. This step is required in order to protect the structures from a subsequent isotropic SF$_6$ during the release step. A 1 µm layer of PECVD is deposited on the topside and bottom sides of the structures, while a layer of approximately 150 nm is deposited on the sidewalls. The low temperature process minimizes the residual stress. The devices that are densely positioned are subject to less sidewall deposition than those that are position in open areas. Problems such as unwanted bending may be an issue for fingers structures that are on one side exposed to large openings, and on the other closely position to other structures. Dummy structures may be required in this case to provide a uniform conformal deposition.
2. **Extension Etch and Release**, steps 10-11 in Figure 5.18. This useful step is called extension etch, which is required to etch 10 µm down using the Bosch process. The silicon windows become further exposed. The next step is the release step, which is the most critical of all steps. The structures are released by using SF₆-based plasma etch. This step is time critical as SF₆ etches the structures isotropically. The structures are released, and therefore suspended over the silicon substrate. It is critical to characterize the time of the etch, otherwise an over-etched structure can be obtained. Figure 5.19 shows a SEM image of a comb-drive structure released using SF₆. This step is critically timed, implying that an over-etch may signify a complete structural loss. Figure 5.20 shows an over-etched structure, the silicon has been completely etched, and only the silicon dioxide shell has been preserved.

3. **Electrical Isolation and Metallization**, step 10 in Figure 5.18. This step is required to provide electrical isolation by deposition of a conformal oxide layer using PECVD. A 500 nm layer oxide is deposited horizontally, while a 50 nm oxide layer is deposited on the sidewalls. Finally, the last step involves metallization of the structures by sputtering metal. The metal of choice is aluminum as it does not require any inhesion layer to the oxide. A 200 nm of aluminum is deposited.
1. Double polished single-crystal-silicon Wafers with 2 micron thermal silicon dioxide on both sides

2. Backside Photolithography for Shutter Layer and RIE to transfer the pattern into the silicon dioxide

3. Backside deep silicon anisotropic etch using Bosch Process to open slits and define shutters

4. RIE of buried layer and thin down of shutter

5. Front-side photolithography and pattern transfer to the oxide using RIE

**Figure 5.17**: MASIS II. The first five main steps of process flow for fabrication process.
6. Deep silicon etch using Bosch process to define actuators

7. RIE of buried oxide layer

8. Extension etch of floor using Bosch process

9. Conformal passivation using silicon dioxide PECVD

10. RIE to etch PECVD oxide to remove oxide from floor and open up windows in silicon bulk

11. Anistropic etch using Bosch process to extend floor and enlarge expose silicon windows

12. Isotropic etch to release actuators and springs using SF6 based plasma

13. Sputter of metal in order to metallize structures conformally, while obtaining overhang to guarantee electrical isolation

Figure 5.18: MASIS II. The last five steps of fabrication process denominated.
**Figure 5.19:** Isotropic Release using SF$_6$. Properly released structure.

**Figure 5.20:** Isotropic Release using SF$_6$. Over-etched structure.
5.6. MASIS III

Another variation of the standard MASIS is based on the use of standard silicon wafers with a silicon nitride layer as the material for the shutters. Although the process sequence is similar to the one for standard MASIS, it does not require the use of a buried layer as a stop mask. The silicon nitride layer maintains structural support for the shutters, proving the adequate structural rigidity. A clear advantage of this proposed process is that the shutter mass is mainly composed of silicon nitride, thereby increasing the operating modulation frequency. In addition, the process only requires standard wafers, which substantially decrease the fabrication cost, and can be integrated directly on standard VLSI base-line processes. Finally, the opacity of the shutters is achieved by either depositing a thick silicon nitride, greater than 500 nm, or by a subsequent metallization process. In both instances, light can be blocked, achieving a high contrast, maximizing the modulation efficiency. Figure 5.21 provides an overview of the proposed process that also can be considered for future implementation.
<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Silicon wafer with silicon nitride on top side and silicon dioxide layers</td>
</tr>
<tr>
<td>2.</td>
<td>Photolithography of Shutter Layer and pattern transfer into the oxide using RIE (CHF3-based)</td>
</tr>
<tr>
<td>3.</td>
<td>Deep Silicon etch using the Bosch process</td>
</tr>
<tr>
<td>4.</td>
<td>Photolithography of Device Layer and pattern transfer into the oxide and nitride layers using RIE</td>
</tr>
<tr>
<td>5.</td>
<td>Silicon Etch using the Bosch process to define depth of MEMS devices</td>
</tr>
<tr>
<td>6.</td>
<td>Sidewall passivation using PECVD oxide</td>
</tr>
<tr>
<td>7.</td>
<td>RIE of oxide to open of silicon windows</td>
</tr>
<tr>
<td>8.</td>
<td>Extension etch to expose silicon structures to be released</td>
</tr>
<tr>
<td>9.</td>
<td>Release of structures using SF6</td>
</tr>
<tr>
<td>10.</td>
<td>Metallization of structures using sputter deposition</td>
</tr>
</tbody>
</table>

**Figure 5.21:** MASIS III. Fabrication process flow.
5.7. **Summary**

MASIS (Multiple-Aspect-Structural-Integration) introduces a simple approach to the fabrication of a variety of microsystems, which in the present work it is implemented for fabrication of a transmissive optical modulator that enjoys a vertical architecture. MASIS is a multi-level bulk-micromachining fabrication process, specially tailored to address the need for transmissive modulators, driven by long-stroke actuators that operate dynamically. The MOEMS architecture allows integration of very stiff actuators with very light and large shutters. The process addresses the need to reduce the payload mass of the shutters, while maintaining high-aspect ratio of suspension springs and comb fingers of the transducer. MASIS allows selective backside etching in order to thin down large areas of silicon structures, thereby increasing the natural frequency and reducing the actuation voltage.

Furthermore, it is also option to thin down the springs in order to decrease the stiffness of the spring structures, in order to achieve larger stable travel. MASIS provides a solution to DRIE non-uniformity by utilizing the buried oxide layer of the SOI as a stop-mask layer. The process is VLSI compatible as all of the fabrication steps are low temperature and can also be integrated with CMOS process. In addition, two process variations have been discussed as alternative for future implementation, derived from SCREAM, a fabrication process designed at Cornell University. The first variation is based on the use of a passivation step, and a SF$_6$ release step, avoiding the use of wet chemistry. The second process variation relies on the use of standard silicon wafers that are coated with a silicon nitride and silicon dioxide layer on the front side. This process is very promising as it only requires standard silicon wafers. Table 5.1 summarizes MASIS, and both of its proposed variations.

MASIS allows seamless integration of transmissive MOEMS modulators as add-on devices placed directly on photo-detectors [84].
Table 5.1: MASIS and its process alternatives.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>MASIS</th>
<th>MASIS II</th>
<th>MASIS III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer</td>
<td>SOI</td>
<td>SOI</td>
<td>Double Polished SCS</td>
</tr>
<tr>
<td>Num. Photomasks</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Aspect-Ratio</td>
<td>High and Low</td>
<td>High and Low</td>
<td>High and Low</td>
</tr>
<tr>
<td>Release</td>
<td>HF</td>
<td>HF</td>
<td>Dry-SF$_6$</td>
</tr>
<tr>
<td>Passivation</td>
<td>Not Required</td>
<td>Required</td>
<td>Required</td>
</tr>
<tr>
<td>Metallization</td>
<td>Evaporation</td>
<td>Conformal Sputter</td>
<td>Conformal Sputter</td>
</tr>
<tr>
<td>Number of Steps</td>
<td>8</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>VLSI</td>
<td>Compatible</td>
<td>Compatible</td>
<td>Compatible</td>
</tr>
<tr>
<td>Major Drawback</td>
<td>Wet-Release</td>
<td>Process Complexity</td>
<td>Backside DRIE</td>
</tr>
<tr>
<td>Major Advantages</td>
<td>Simplicity</td>
<td>Backside uniformity and Dry-Release</td>
<td>Standard SCS wafers, and dry-release</td>
</tr>
</tbody>
</table>
Chapter 6.
Device Characterization.

6.1. Introduction

This chapter provides a comprehensive description of the characterization of the IHOS. Firstly, the experimental set-up is presented, including the testing equipment apparatus for both the signal and noise of the system. Secondly, the transmissive MOEMS modulator is characterized as its frequency response is tested under different applied voltage signals in order to investigate the comb-drive actuator characteristics.

In addition, a new modulation scheme, called the Double Harmonic Modulation Technique, is presented as an alternative method to overcome the low-frequency photodetector noise and unwanted electrical coupling.

Moreover, the optical sensitivity of the IHOS is characterized in terms of the minimum detectable signal (MDS), which represents the figure of merit. This experiment provides empirical data about the detection sensitivity, as the IHOS is utilized to detect very low-intensity signals.

6.2. Experimental Set-up

The experimental set-up is introduced in this section introducing details related to the testing equipment and assembly of all the elements that comprise the IHOS. Figure 6.1 shows the experimental set-up of the device. Subsequent to the fabrication process, the wafers were diced into chips, and the MOEMS modulators were tested by placing them on top of a standard packaged PN silicon photodiode (Hamamatsu 1226). The photodetector was connected to a transresistance amplifier (Hamamatsu PCB 9052) board characterized by a 15 kV/A gain, see Table 3.2 in Chapter 3. The output of the transresistance amplifier was connected in parallel to a spectrum analyzer (Stanford Research Systems Inc. SR780), to an oscilloscope (Tektronix Inc., model TDS210), and to a lock-in amplifier for very low-
intensity signals (Stanford Research Systems Inc., model 870). The MOEMS chip was placed on a small platform with a centered hole in order to seamlessly fit it directly on top the active of photodiode. The schematic cross section is shown in Figure 6.2. The MOEMS modulator was connected via probe-station excited by a signal generator with a 15 Vp sinusoidal signal and 0.2 V dc-offset. Figure 6.3 shows a photograph of the system. A halogen lamp was utilized as an optical source, which was connected to a 500 nm optical filter with a 4 nm bandwidth, used to emulate the light emission from bioluminescent bacteria. In addition, a spatial variable optical attenuator (VOA) was utilized to calibrate the optical intensity of the light source. A CCD camera (model CNB-GP258DNG, CNB Technology, Inc., Korea) was used to capture the motion of the MEMS devices and tape-record with a VCR for measuring the spatial response per video frame for subsequent image analysis.

**Figure 6.1:** Schematic diagram of experimental set-up for the characterization of the IHOS.
6.3. **MOEMS Characterization.**

In this section the goal is to characterize the Input vs. Output response of the IHOS. This step was achieved by measuring the linearity of the MOEMS modulator driven by the set of comb-drive actuators in resonance. The linearity was measured in terms of magnitude of...
input voltage signal at the natural frequency of the device versus displacement for the following excitation signal:

\[ V(t) = V_{dc} + V_{ac} \cos(\omega_0 t), \]  

(6.1)

Where \( V_{dc} \) was 0.2 V and \( V_{ac} \) was varied from 0 to 15 V; \( \omega_0 \) is the resonance frequency. Note that the resonance operation and dc-value were chosen in order to excite the system for the first frequency scale, which is linearly dependent on the dc and ac voltage magnitude (the reader is referred to Equation 3.3 in Chapter 3). Such low dc-level was experimentally found to be the minimum required potential for excitation. The amplitude is linearly dependent on the displacement, as we have referred to Equations 3.22-3.24 for the resonance case, i.e. \( e = \omega_0 \), expressed as:

\[ X(\omega_0) = \frac{2ne_o hV_{ac}V_{dc}Q}{dk_{tx}} \]  

(6.2)

Where \( n \) is the number of fingers, \( h \) is the thickness of the comb-fingers, \( d \) is the gap between fingers, \( k_{tx} \) is the total stiffness in the stroke direction, and \( Q \) is the quality factor.

The resonance point was found by image analysis, as the frequency dial of the signal generator was changed while the image was being captured with the CCD camera and recorded with VCR for a given input optical intensity of approximately 1 mW/cm\(^2\). Due to the fact that the acquisition frequency of the video signal is lower than the frequency of operation of the MOEMS resonator, the displacement of the shutters is captured as a collection of blurred images. The width of such blur is proportional to the amplitude of vibration, with a precision of +/- 1 \( \mu \)m. The maximum displacement, displayed as a blur on the video data, was captured per given input voltage. The results are illustrated in Figure 6.4. The measured maximum displacement was approximately 50 microns for a natural frequency of 990 Hz.
Next, we characterized the output voltage signal at output of the transresistance amplifier as a function of the input signal. In this case, we repeated the previous experiment but rather than measuring displacement, the magnitude of the output voltage was registered as a function of the ac-voltage at resonance. Figure 6.5 shows the results.

**Figure 6.4:** Displacement vs. input magnitude of the ac-signal. Resonance operation.

**Figure 6.5:** Output signal magnitude vs. input magnitude of the ac-signal. Resonance operation.
Figures 6.4-6.5 clearly show the linearity of the system at resonance, as it is then possible to extrapolate and plot the displacement vs. output voltage values at resonance, illustrated in Figure 6.6. This curve is crucial in order to obtain the transfer function of the system. Hence, a given output voltage value can be interpreted as a given displacement for a given intensity level from the optical source.

![Displacement vs. Output voltage. Resonance operation.](image)

**Figure 6.6:** Displacement vs. Output voltage. Resonance operation.

Furthermore, the quality factor ($Q$-factor) of this device was measured to be 20 in atmospheric conditions. This step was achieved by measuring the signal magnitude at resonance for $V_{dc}$ equal to 0.2 V and $V_{ac}$ equal to 15 V, and the frequencies at which half of this magnitude occurs, otherwise known as the cut-off frequencies. Figure 6.7 shows the recorded experimental data of the frequency response of the MOEMS modulator, the 3 dB points, and the corresponding bandwidth, which was measured approximately as 50 Hz. A Lorentzian fit, shown in red, has also been plotted. It is worth mentioning that the reason for the asymmetry of this curve is due to the minor non-linear behavior of the resonator. The goal is to operate the MOEMS modulator in the linear regime in order to obtain harmonic
oscillation, which in turn provides linear amplitude modulation. In order to minimize any non-linear behavior, which can be manifested as hysteresis in the frequency response measurements, the excitation magnitudes were minimized as much as possible, while trying to obtain maximum displacement at resonance.

**Figure 6.7:** Frequency response of the device.

Next, the frequency response was measured in vacuum conditions at 8 mTorr, using a probe station that includes a vacuum chamber. A new device with the same design dimensions was employed for this experiment. This time, however, only an image processing method was implemented to assess the frequency response, with a precision of +/- 1 µm. In this case, the resonance frequency was slightly different from the previously measured device, as there was probably a variation in mass and stiffness of the new device. The shutters resonate at 944 Hz with an excitation voltage of 2.5 V peak, and dc-offset of 0.05 V, demonstrating a significantly reduction of the applied voltage due to the low loss medium. The measured $Q$-
factor was approximately 100, illustrated in Figure 6.8. The frequency response shows symmetrical curve as the magnitude of excitation required to obtain maximum displacement was very low, minimizing non-linear effects.

**Figure 6.8:** Frequency response in vacuum conditions.

The experimental measurements for resonance frequency and maximum displacement are in close accordance with the analytically calculated and FEA simulated values that were obtained in Chapter 4, as shown in Table 6.1.

**Table 6.1:** Comparison of Theoretical and Experimental Values for the second topoly.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Theoretical Value</th>
<th>Experimental Value</th>
<th>Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_o$</td>
<td>1.36 kHz</td>
<td>1.05 kHz</td>
<td>-22</td>
</tr>
<tr>
<td>$Q$-factor</td>
<td>30</td>
<td>20</td>
<td>-33</td>
</tr>
<tr>
<td>Max. Displacement</td>
<td>58 µm</td>
<td>55 µm</td>
<td>6</td>
</tr>
<tr>
<td>Max. Voltage</td>
<td>41 V</td>
<td>38 V</td>
<td>7</td>
</tr>
</tbody>
</table>
6.4. Noise Characterization

The goal of this section is to characterize the overall spectral noise response of the system. The noise of the system was measured with a given system bandwidth of 16 Hz, using the spectrum analyzer, shown in Figure 6.9. In this case, the output noise was measured in dark conditions, without any excitation for the MOEMS modulator. It is possible to observe that the low-frequency noise of the system defines the detection sensitivity (for a detailed discussion about the noise model, the reader is referred to Chapter 3). Given a system bandwidth of 16 Hz, the difference in noise levels between low-frequency noise at about 1 Hz and a noise level at 1 kHz can be extrapolated from Figure 6.9, as approximately 30 dB. The second noise measurement was conducted with the signal driving the MOEMS modulator in dark conditions. Such noise signal is characterized by the low-frequency noise, and also by an unwanted electrical coupling between the excitation signal that drives the MOEMS modulator and the detection electronics. This unwanted coupling can be minimized by proper shielding and ground connections, but not completely eliminated.

![Data (1)](image)

**Figure 6.9:** Spectral noise in photodiode, measured with $f$ equal to 16 Hz.
6.5.1 Double Harmonic Modulation Technique

IHOS, as other modulator systems, suffers from unwanted electrical coupling between the electrical excitation source and the detector at the desired modulation frequency. This unwanted electrical coupling from the modulator excitation source can become comparable to the signal levels of photodetected signals at the desired modulation frequency, thereby limiting the overall detection, as it is shown in Figure 6.10. In order to overcome this common problem, we introduce an operational mode of the IHOS that not only modulates, but also electro-mechanically decouples the photodetected modulated signal from the driving signal. The operational mode is based on the intrinsic feature of the electrostatic transducer to produce the output signal at two frequencies scales under application of a single frequency driving signal, as it is described in Chapter 3.
The mechanical response function consists of two frequency scales. The first scale occurs at the electrical signal frequency, $\omega_e$, while the second one occurs at twice that frequency, $2\omega_e$. As a result, the resonant excitation can be achieved as the device is driven by an electrical harmonic signal at half the damped resonant frequency of the modulator, i.e. $2\omega_e = \omega_0 \sqrt{1 - 1/(2Q^2)}$, as well as at the damped resonant frequency itself, i.e. $\omega_e = \omega_0 \sqrt{1 - 1/(2Q^2)}$. In the former case, the mechanical response frequency differs significantly from the frequency of the electrical signal. In addition, due to the geometric configuration of the optical shutter design, the photo-detected signal frequency doubles the mechanical frequency, as the shutter travels twice over the etched window per cycle of the mechanical motion. Hence, in the case that the device is driven at half the resonant frequency, the photo-detected signal frequency is four times higher than that of the excitation electrical signal frequency. Therefore, the presented modulation technique makes use of the second frequency scale not only to further decrease the low-frequency noise, but also to isolate the modulated signal from the unwanted modulator electrical coupling. Figure 6.11 sketches the spectrum of this new technique.

![Diagram](Figure 6.11: Double Harmonic Modulation Technique.)
6.5.2 Measurements using the Double Harmonic Modulation Technique

The photodetected signal enjoys two main spectral components. The first one occurs at twice the electrical excitation frequency, $2\omega_e$, while the second one occurs at four times the electrical excitation frequency, $4\omega_e$, as shown in Figure 6.12. Hence, the Double Harmonic Modulation Technique makes use of the second frequency scale. We have referred to Equations 3.22-3.25 to obtain the expression for the displacement at the second scale when the modulator is excited at half the resonance frequency, given by:

$$X(2\omega_e) = \frac{n\varepsilon hV_{ac}^3 Q}{2dk_e}$$  \hspace{1cm} (6.3)

Where $n$ is the number of comb-fingers, $h$ is the thickness of the comb-fingers, $d$ is the gap between fingers, $k_e$ is the total stiffness in the stroke direction, and $Q$ is the quality factor.

The second harmonic of the photocurrent is related to the displacement by the following equation:

$$I_{ph}(t) = \Phi q \eta A X_2(2\omega_e) \cos(4\omega_e t + \phi_2).$$  \hspace{1cm} (6.4)

Where $\Phi$ is the photon flux of the source given in photons/sec-cm$^2$, $q$ is the electron-charge $(1.672 \times 10^{-19})$, $\eta$ is the detector quantum efficiency (~0.9), $A$ is the active area of the photodetector after the modulator mask. Note that Equation (4) is written for the case that the shutter area is equal to the opening window area such that the optical signal is zero for zero displacement of the modulator. The time-dependent photocurrent function is proportional to $\cos(4\omega_e t - \phi_2)$ since the modulator output frequency is doubled as the shutter travels over the etched windows twice per excited cycle, thereby doubling the optical frequency. Therefore, the desired signal can accurately be detected with a lock-in amplifier at four-times the electrical excitation frequency, without suffering unwanted electrical coupling from the modulator signal, or from low-frequency noise. As the optical intensity is decreased beyond
the noise limit of the spectrum analyzer, the output response is followed by a lock-in amplifier, which is triggered by four times the electrical driving signal frequency.

![Graph showing spectrum with markers for Unwanted Coupling, Modulated Signals, and Low-frequency noise, i.e. 50 Hz power-lines.](image)

**Figure 6.12.** Spectrum: low-frequency noise, unwanted coupling, and modulated signals.

### 6.5.3 Minimum Detectable Signal of the IHOS

The goal of this section is to measure the minimum detectable signal (MDS) of the IHOS. In this experiment we used a topology II design, which enjoys a larger aperture area (the reader is referred to Chapter 3 for description of the different design topologies). As the input optical intensity is decreased drastically, the noise level needs to be characterized in order to measure the sensitivity limit of the system. This key step is necessary in order to demonstrate the optical sensitivity of the IHOS and its corresponding enhancement step. In order to measure a very low signal magnitude, a lock-in amplifier was connected to the output of the transresistance amplifier, with a bandwidth of 26 mHz. Figure 6.13 shows the response...
per optical intensity as function of time, the equivalent photodetected currents are also shown per step. The variable optical attenuator was used to systematically decrease the intensity of the monochromatic signal. It is possible to observe that the MDS was 100 nV, shown in Figure 6.14. The values were calibrated by taking the ratio of the voltage magnitude to the transresistance amplifier gain (15 kV/A). As the IHOS makes use of the second harmonic, the detection limit of the photodiode is practically increased by at least two orders of magnitude. Hence, the photodiode sensitivity becomes comparable to signal levels required to detect bioluminescence from whole-cell bioluminescence in volumes 1 cm$^3$ (for more information about bioluminescence, the reader is referred to Chapter 2).

![Figure 6.13: Response as the intensity of the optical source was varied using a VOA.](image)

Figure 6.13: Response as the intensity of the optical source was varied using a VOA.
Figure 6.14: Very low signal intensity measurements of the IHOS determining the MDS.

6.6. Twin Modulation Technique

This section introduces another modulation technique based on two identical modulators operating at the same time at slight different frequencies. The modulation technique called Frequency Analyzer based on Twin Optical Modulators (FATOR) generates optical beats that provide information about the modulated optical signal. A beat is defined as the superposition of two harmonics at very close frequencies. Figure 14 shows the layout of the modulators, which are placed on top of the same photodiode connected to a transresistance amplifier, following the experimental set-up of Figure 1.

A low-frequency optical signal is modulated separately by each MOEMS modulator, and subsequently photodetected, amplified, and connected to the spectrum analyzer.
Figure 6.15: Two MOEMS modulators are implemented in parallel to generate beats.

Figure 6.16 shows the modulated signals. The first modulator operates at 960 Hz, while the second operates at 910 Hz. Figure 6.16 shows the modulated signals as the frequency of modulation of one of the MOEMS modulators is set to 935 Hz, moving it closer to the operating frequency of the second modulator. Figure 6.17 shows the generated beats in time domain, enjoying beat frequencies of 50 Hz and 25 Hz, respectively. As the operating frequencies of the MOEMS modulators move closer, the frequency of the beats decreases. Beats are quite sensitive to intensity variations, thereby making this alternative technique a good candidate for future implementation of photodetected signals. In addition, the use of multiple modulators allows the increase in the field area, in the case that a photodetector with a large active area is required.
Figure 6.16: Frequency response of two modulated signals. A. The first clearly shows the two separate modulations. B. The frequency scales are almost superimposed.
Figure 6.17: Beats shown in time domain. A. The beat frequency is 50 Hz. B. The beat frequency is 25 Hz.
6.9. Summary

This chapter presents a thorough discussion of the characterization of the IHOS. First, the comb-drive actuators were characterized and tested at resonance in order to obtain the linearity of the transfer function, ultimately expressed as the displacement of MOEMS actuator versus the amplified output of the photodetected signal. In this way, it is possible to make direct measurements of the device by just obtaining the photodetected signal for a known intensity. The frequency response of the device in atmospheric conditions was also measured, obtaining a Q-factor of 14. In addition, the device was tested in vacuum conditions, showing a Q-factor of 100, and a sharp decrease in the actuation voltage.

As the noise of the system was measured using a spectrum analyzer, the double harmonic modulation technique was introduced as a new method to further increase the SNR of modulated low-intensity signals. This technique proved to be extremely valuable in order to overcome low-frequency noise and unwanted electromagnetic coupling from the driving modulator circuit. Moreover, the device was tested as an efficient transmissive optical modulator. This device represents the first reported transmissive MOEMS modulator characterized by its large aperture. As the intensity of the input optical signal was decreased in a calibrated fashion by means of a VOA, the minimum detectable signal (MDS) was measured at the output of the transresistance amplifier. The MDS was approximately 100 nV, which corresponds to a photocurrent of approximately 5 pA.

In addition, two optical modulators were implemented at the same time, operating at slight different frequencies in order to obtain beats. This promising technique can be further explored for signal processing and for increasing the field area when a photodiode with a large active area is required.
Chapter 7.
Measurements of Bioreporter Signals.

7.1. Introduction

This chapter provides a description of the bioluminescence measurements as the IHOS has been integrated with light-emitting whole-cell biosensors. First, we present the experimental set-up, and explain how the whole-cell biosensors were adapted to the IHOS.

Next, we introduce a short description of the preparation process necessary to grow the whole-cell biosensors. Subsequently, biosensors are exposed to a chemical inducer in order to emulate a bio-chemical response. Thereafter, the bioluminescence response per inducer concentration is measured as a function of time. Finally, we present the maximum bioluminescence response as a function of inducer concentration.

In summary, we present the IHOS as a system capable of measuring very low intensity signals for a number of applications. More specifically, the IHOS can be integrated with light-emitting whole-cell biosensors for portable, inexpensive, and massive deployment as a new generation of biochips tailored for rapid detection of environmental toxicity.

7.2. Bioluminescence Detection

The goal of this section is to describe the integration of the whole-cell sensors with the IHOS in order to measure bioluminescence from whole-cell biosensors. Firstly, we provide information about the preparation procedure for cell growth, and the induction of the cells, which emulates specific levels of environmental toxicity. As the whole-cell biosensors are induced, we place them inside of small containers that are placed atop of the MOEMS modulator, as shown in Figure 7.1. The entire experimental set-up is similar to the one described earlier, except that the optical source is replaced by the bio-containers, as shown in Figure 7.2. The microscope of the probe-station was utilized as a 3-dimensional stage, as the containers with the biosensors were adapted to fit in one of the vacant holders of the optical
lens. In this way the cells were placed in close proximity, approximately 2 mm, to the MOEMS modulator. Figure 7.3 shows a photograph of the new system.

**Figure 7.1:** Sketch of cross-section.

**Figure 7.2:** Schematic diagram of experimental set-up for detection of bioluminescence. Note that the optical source is replaced by light-emitting whole-cell biosensors.
7.3. **Cell Preparation**

Bacterial cultures in agar plates containing the whole-cell biosensors were developed at Belkin’s laboratory in Hebrew University, Israel. E. coli strain DPD2794 harbors a plasmid, which contains a fusion of the E. coli recA-promoter to the Lux gene (V. fischeri lux). As we received the plates, shown in Figure 7.4, cells were grown to densities that would allow highest possible photon-rate emission per cell. Bacterial cultures containing the bioluminescent strains were grown in 1 ml Luria-Bertani (LB) broth for 12 hours at 37 °C in the presence of ampicilin (100 mg/ml) to ensure plasmid maintenance. Overnight cultures were diluted 100-fold into a fresh medium without the presence of the antibiotic, and allowed to re-grow for a few generations for 2 hours at 30 °C. When the cultures reached a density of approximately 10^8 cells/ml, they were placed into 3 ml transparent bio-containers. The cell-density was measured by checking the optical density (OD) at 600 nm, using a Viktor luminometer (Perkin Elmer Inc., USA). All experiments were carried out in duplicate and were repeated at least three times. Variations between duplicates and between different experiments were not greater than 5 and 15%, respectively.
Figure 7.4: Bacterial cultures of bioluminescent whole-cell biosensors.

After the cells were prepared, IPTG (isopropyl-beta-D-thiogalactopyranoside) was used as genotoxicant to emulate environmental toxicity. This inducer binds and inhibits the Lac repressor, promoter gene, leading to expression of the Lux reporter. The IPTG compound predominantly induces DNA intrastrand cross-linking [30], causing a high induction of the bioluminescence in the genetically modified E. coli strain used in these experiments. The molecular weight of IPTG is 238 gram/mol. The cells in volumes of 3 ml were placed in bio-containers, which were completely sealed and wrapped with aluminum foil in order to maximize the photon flux in the vertical direction that points towards the MOEMS modulator.

7.4. Bioluminescence Measurements

This section describes the bioluminescence measurements that were performed as the whole-cell sensors were exposed to different concentrations of IPTG inducer. Bioluminescence was measured as a function of three IPTG different concentrations in independent experiments. The real-time signal was recorded by the lock-in amplifier, which registers the data at a sample frequency of 1 Hz. Such signal suffers from unwanted noise as it was shown earlier in the Chapter 6. Once the real-time signal was acquired, two signal processing techniques were implemented in order to obtain smoother curves, using Origin (Originlab Corporation, USA). The first technique, the average data method, consists of a smoothing procedure that provides a more clear view of the signal as a function of time. In
this case, the data points are averaged for every 5 minute periods. The second technique was based on the low-pass filter method, which filters out spurious signals by implementing a signal processing RC filter characterized by a cut-off frequency of 8 mHz. This technique allows to observe the overall trend.

The first experimental step was to measure the noise in order to calibrate the device for subsequent bioluminescence measurement. As seen in Figure 7.5, the average data and the low-pass filtered data are shown in red and blue, respectively. The noise level averaged approximately 40 nV.

![Figure 7.5](image)

**Figure 7.5:** Noise measurement (trace), average (red) and low-pass filtered noise (blue).

The next steps consisted of measuring the bioluminescence immediately after whole-cell biosensors were exposed to different IPTG concentrations. Three separate solutions were tested, each with a total volume of 3 ml, and final inducer concentrations of 20 µM, 100 µM, and 500 µM. Given the molecular weight of IPTG (238.3 g/mol), such concentrations are equivalent to 4 ppm, 20 ppm, and 100 ppm, respectively. The cell light emission was measured during the steady-state of the cell proliferation, where the cell density remains
approximately constant. As described in Chapter 2, oxygen is involved in the reaction that produces light in the *Lux* process. Hence, moderate shaking was implemented for approximately 1 minute prior to taking any measurements in order to supply enough oxygen to the cells.

In the first experiment bioluminescence was measured in the solution as the cells were exposed to a concentration of 10 µM of IPTG inducer. Figure 7.6 shows the five minute data average (red trace) displayed together with the low-pass filtered data (blue-trace) using a cut-off frequency of 8 mHz. The data average shows the amplitude growing from a minimum signal level approximately 70 nV to the 280 nV plateau. Thereafter, the signal stays constant for approximately 50 minutes, until it decays back to the minimum signal level, near the noise floor.

![Figure 7.6: Bioluminescence measurements for 0.1 mM of IPTG concentration.](image)

Two main reasons are seemingly related to the bioluminescence decay. The first one is related to the oxygen, which is a reactant in the light producing reaction in the *Lux* system. The depletion of oxygen leads to a decay in bioluminescence. The second reason for the bioluminescence decay is due to the cell proliferation cycle. Cell concentration is linearly
correlated to the optical density of the sample, which can be measured optically by measuring the turbidity of the sample. Figure 7.7 shows an optical density (O.D.) graph of the whole-cell sensors as a function of time per various inducer concentrations. The O.D. data was obtained using a Victor-2-luminometer (Perkin Elmer, Inc., USA), determined by measuring the optical absorbance of a laser beam at a wavelength of 660 nm. It can be seen in Figure 7.9 that the cell growth is characterized by approximately linear and constant regions. In the linear region, the cells growth is higher than the cell apoptosis (death), which implies that the cells proliferate at maximum rate. It can be deduced from the approximately constant region that cell proliferation almost equals apoptosis. It is also possible to observe that the cell-growth is affected by the inducer concentration. Hence, it is evident that as the inducer concentration increases, the growth rate diminishes. It is important to measure the bioluminescence from various whole-cells consistently at approximately the same region of interest.

**Figure 7.7**: Optical Density per inducer concentration as a function of time.

In the next experiment bioluminescence was measured in the solution as the cells were exposed to a concentration of 50 µM of IPTG inducer. Figure 7.8 shows the real-time signal (black trace), the average signal (red trace), and the low-pass filtered signal (blue-trace). In this case, the sample was purposely removed and put back in place in order to demonstrate
that bioluminescence was in fact being measured. Shortly after induction, the average signal trace shows the signal level increasing from the minimum signal level of approximately 80 nV to the first plateau of 160 nV. Subsequently, as the bio-container was removed the signal level dropped back to the minimum signal level, and as the bio-container was put back in place, the signal reached the second plateau of 180 nV. The signal level dropped to the minimum level after 20 minutes. In this case, it is possible to extrapolate that the signal remains at maximum intensity for approximately 50 minutes.

Figure 7.8: Bioluminescence measurements for 0.05 mM of IPTG concentration.

The last experiment was performed by exposing the cells to 5 µM of IPTG concentration. Figure 7.9 shows the real-time signal (black trace), the average signal (red trace), and the low-pass filtered signal (blue trace). In this case, it is possible to note that the signal level increases from the minimum signal of 60 nV to a plateau of 90 nV for approximately 20 minutes.
Figure 7.9: Bioluminescence measurements for 0.5 mM of IPTG concentration.

Figure 7.10 compares the average bioluminescence data of the three previously described experiments. The data average values were computed in 15 minute intervals. It is important to notice that the concentration of IPTG does in fact affect the bioluminescence. As shown in Figure 7.7, the cell-growth is also dependant on the inducer concentration. The cell growth can be limited if the inducer concentration is very high, thereby affecting the overall bioluminescence. Figure 7.11 shows the maximum bioluminescence level per inducer concentration. The bioluminescence increases as a function of inducer concentration up to the point that the inducer itself limits the multiplication rate of the cells. An error bar is indicated in this graph showing the amplitude variation due to the noise.
Figure 7.10: Bioluminescence measurement as a function of time per inducer concentration implemented. Measurements were averaged for 15 minute periods.

Figure 7.11: Maximum bioluminescence as a function of inducer concentration (IPTG).
7.5. **Summary**

In this chapter we integrated the whole-cell biosensors with the IHOS, obtaining a hybrid bio-chip. The biosensors were placed in bio-containers, which were positioned in close proximity to the IHOS. The biosensors were chemically induced with IPTG, emulating a sharp increase in the environmental toxicity. Bioluminescence as a function of time and IPTG concentration was measured, clearly showing a high sensitivity of photodetection. The experimental data was also signal-processed in order to further reduce the noise. Such signal processing tools can actually be implemented with the IHOS at a chip level using DSP technology. Finally, we have shown the maximum bioluminescence as a function of inducer concentration. This graph can serve to predict environmental toxicity.

IHOS has been successfully utilized to measure low intensity signals, and can be easily integrated with light-emitting whole-cell biosensors. We believe that this silicon-based solution provides enough motivation to implement a portable and inexpensive device capable of sensing environmental toxicity in a very rapid fashion for massive applications.
Chapter 8. Discussion.

8.1. Introduction

This chapter presents a discussion related to the innovative aspects of this research work. First, we provide the rationale for the optical modulation scheme based on the MOEMS methods. Thereafter, we describe specific design challenges for the MOEMS modulator as the key component of the IHOS. In addition, we have complemented the analytical calculations with finite element analysis in order to simulate the stability and structural integrity of the device that will be implemented with MASIS. Subsequently, we discuss the advantages of MASIS as a fabrication process specially tailored for transmissive optical modulators. Moreover, we provide the highlights of the integration with whole-cell biosensors. Finally, we introduce a short description of the potential applications.

8.2. General Discussion

Solid-state photo-detectors are attractive photodetectors for use in a wide number of applications that require VLSI compatibility, low cost, and survival in harsh environmental conditions. This type of sensors is mostly based on PN junctions that can be arranged in a number of configurations to generate photocurrents. Photodiodes can be integrated in arrays, and fabricated in standard silicon batch manufacturing processes. Currently photodiodes cannot be used for applications that require detection of low-intensity signals as the noise limits the photo-sensitivity.

The total noise of a photodetector involves shot noise, thermal noise (Johnson noise), low-frequency noise. Flicker noise and generation-recombination noise contribute to the low-frequency noise. A typical equivalent circuit for a reverse bias photodiode is shown in Figure 8.1. In this case, \( \bar{i}_{npd} \) is the current noise intrinsic in the photodiode, which includes a
resistor, $R_d$, in parallel with a capacitor $C_d$, $v_{npd}^2$ is the voltage noise due to the contact and parasitic series resistor, $R_s$. A discussion of noise model appears in Appendix I.

**Figure 8.1:** Equivalent circuit of photodiode noise.

In low-frequency measurements, flicker noise is the most dominant source of noise in the lower spectrum. Surface defects and metal contacts are among the main contributors to the low-frequency noise. Although the physical mechanisms are not completely understood, this type of noise is related to variations in the manufacturing process, proportional to the photodiode current, and its spectral power is inversely proportional to the frequency. The spectral distribution of this noise decays 10 dB per decade and becomes almost negligible above 1 kHz.

The use of integrating amplifiers provide a limited solution as the thermal noise is also added in the amplification stage, as well as long integration times compromise the real-time performance. The low-frequency sensitivity of solid-state photodetectors can be increased drastically if the signal frequency is up-converted from the low-frequency noise to a frequency above 1 kHz. Several techniques attempt to overcome the flicker noise using electronic methods. Another SNR enhancement technique is based on Correlation Double Sampling (CDS), which translates the noise energy from a baseband to some higher frequency so that the signal of interest is not contaminated in its entirety. Another commonly implemented electronic technique is based on chopper stabilized amplifiers, which modulate
the desired signal in electronically. This technique makes use of a square wave to multiply the
signal of interest, using a switching circuit, to a higher spectral location. The switching
circuits, however, supply excess noise that limits the minimum detectable signal (MDS).

The main drawback of these electronic methods is that the modulation process is
performed after the optical signal has been photo-detected. Although several existing
electronic techniques are designed to overcome the low-frequency noise, all of them suffer
from one major disadvantage: noise is added to the signal in the electrical domain.
Consequently, all the techniques have the basic premise of decoupling the added noise after
the photodetection stage. Thus, it is inevitable that the complementary circuits that are
required for SNR enhancing techniques ultimately contribute to the overall noise.

This basic limitation restricts the use of photodiodes for applications that demand very
sensitive photodetection. Photomultipliers (PMTs) have been the prevalent choice for
detection of low-intensity signals as the detection sensitivity is far superior to solid-state
photodetectors. Almost all the photodetectors used for optical measurements of biological
signals, such as bioluminescence, depend on PMTs. This type of photodetectors, however,
suffers from a variety of disadvantages. PMTs are not solid-state devices, but rather
manufactured using vacuum technology. Hence, PMTs are bulky and fragile, require high
voltages, and cannot be used for portable applications. In addition, PMTs are not VLSI
compatible, cannot be manufactured in large arrays, and are expensive for mass production.

Thus, there is a very strong need to improve the sensitivity of silicon solid-state
photodetectors using a cost effective solution that allows VLSI compatibility, does not add
manufacturing complexity, and can be ultimately utilized in portable applications.

The Integrated Heterodyne Optical System (IHOS) is a new MOEMS-based technique
that addresses this very specific need. The IHOS is radically different from other SNR
enhancement methods since it does not aim to decouple the electronic noise after
photodetection. Rather, this technique is based on modulation of the optical signal prior to
photodetection. In this manner, the low intensity signal does not combine with the electronic noise within the same frequency spectrum. The optical signal is shifted up from its base-band to a higher spectrum before the photo-electric conversion. Hence, the optical signal is transferred to a zone in the spectrum where the floor noise drops by at least by 30 dB. Therefore, the SNR enhancement is justified even at the expense of some losses in the spatial modulation process, as the floor noise is reduced dramatically. In addition, the modulated optical signal is recovered using a bandpass filter, such as a lock-in amplifier that is synchronously operating at the frequency of excitation. The heart of IHOS is founded on a transmissive MOEMS modulator that enjoys large area shutters that operate at relatively high frequencies. The MOEMS modulator can be implemented as a seamless add-on, placed on top of the active area of the solid-state photodetector. The transmissive MOEMS modulators have been implemented using a novel manufacturing technique, named MASIS (Multiple Aspect-Ratio Structural Integration in Single-Crystal-Silicon). This bulk micro-machining process is VLSI compatible technique, permitting a facile integration with current solid-state photodetectors and complementary circuits for subsequent signal conditioning.

8.3. Design and Implementation

The transmissive MOEMS modulator constitutes the key component of the IHOS. The main requirements for such device are: operation frequency of at least over 1 kHz, large field area, low operating voltage, and a transmissive architecture.

In order to implement a transmissive MOEMS modulator, we have explored few geometric configurations. Ideally, out-of-plane actuation can achieve a 100 percent transmissive modulation efficiency by periodically deflecting a shutter between a closed position, defined horizontally (in-plane), to an open position, defined vertically (out-of-plane). Although most MOEMS micro-mirrors rely on out-of-plane actuation, the maximum angle of deflection that can be achieved with torsional springs does not exceed 15 degrees.
The main reason for such constraint is that out-of-plane motion relies on torsional springs that are very stiff structures. Hence, the required theoretical voltages for these actuators are extremely high, making out-of-plane motion impractical for transmissive optical modulation. Therefore, most of these devices are restricted to reflective applications for which the required deflection angles are far less than 90 degrees.

We have designed transmissive MOEMS modulators that rely on in-plane actuation. The design of the in-plane modulator is defined by a set of electro-static comb-drive actuators that harmonically drive an array of shutters over an array of optical vias. These actuators are characterized by their linear-force displacement relation. The MOEMS modulator is placed between the optical source and the photodetector. In this manner, an incoming optical signal in the vertically direction is chopped as the shutters are driven by the in-plane actuators.

In chapter 4, we have calculated that the maximum range of motion of the comb-drive actuators is approximately 50 µm. The efficiency of such in-plane modulator is defined by the maximum range of stable displacement that the electrostatic actuators can support. The field area of the shutters has been segmented into 50 µm wide and 1 mm long, spaced by 50 µm gaps that are suspended above etched cavities, acting as optical vias with the same dimensions. Therefore, in-plane modulation can provide a maximum of 50 percent efficiency, 3 dB below the optical signal level.

The final design consisted of an array of shutters held by the backbone, which itself was connected to a set of electrostatic comb-drive actuators supported by folded flexures. In order increase the natural frequency of the device and decrease the applied voltage, the mass of the shutters was reduced by selectively thinning down the shutters using. By means of analytical calculations and Finite Element Analysis (FEA) simulations using CosmosWorks simulator (SolidWorks Corporation. USA), we demonstrated that the structures enjoyed a linear long-stroke displacement of 50 µm. In addition, FEA analysis corroborated the calculations for natural frequency, and verified that the large structures preserve their
structural integrity during in-plane motion at resonance, as seen in Chapter 4. In addition, FEA simulated the shape and the values of other mechanical modes, showing that the natural frequency in the in-plane direction does not suffer from any mode interference.

MASIS has been developed with the specific aim to implement MOEMS modulators that enjoy a transmissive architecture for large area shutters that operate at high frequencies. The process incorporates several innovations. Since most of the effective mass of the MOEMS modulator is composed of the large area shutters, the process selectively thins down the mass of the shutters by means of a backside etch in order to increase the natural frequency. MASIS is based on a two photolithographic-mask process that defines the comb-drive actuators on the front side of the wafer, and the optical vias on the backside of the wafer. The backside etch defines the optical vias just underneath the shutters, and provides two main functions. The first one is to suspend the large area shutters, whereas the second one is to thin down the shutters in order to increase the natural frequency. The comb-drive actuators are defined as high aspect-ratio structures that are connected to the arrays of large area shutters by means of connectors, called Transition Beams. The Transition Beams represents one of the innovative aspects of MASIS. These connectors are beams that connect high-aspect ratio structures with low aspect-ratio structures. Figure 2 shows the transition beams, and their corresponding thickness. The length of the Transition Beams guarantees enough separation between the structures that are thinned down from the backside and the high aspect-ratio structures that are defined from the front side.

As discussed in Chapter 4, the natural frequency is proportional to the inverse of the square root of the mass. Most of the effective mass of the MOEMS modulator is composed of the shutter mass. Therefore, if the mass of shutters is reduced to one third of the original, by selectively thinning down the shutter thickness from 30 $\mu$m to 10 $\mu$m, the natural frequency will be approximately 70 percent greater. This significant increase in the natural frequency is one of the main advantages of the MASIS process. Moreover, a reduction in mass implies a
reduction in the required potential. In static conditions, the displacement is proportional to the square of the applied voltage. In resonance, the displacement is proportional to the static displacement multiplied by the $Q$-factor. Following the equations in Chapter 3, the $Q$-factor is proportional to the square root of the mass. Therefore, if the thickness of the shutters is reduced to one third of the original, the voltage is reduced approximately by 12 percent. Furthermore, this process allows an easy monolithic integration for a subsequent adaptation with photodiodes.

8.4. Characterization

We have tested the transmissive MOEMS modulator on top of a photodiode connected to a transresistance amplifier. The connected building blocks constitute the IHOS. The output of the amplifier was connected in parallel to a spectrum analyzer and a lock-in amplifier. The MOEMS modulators were operated continuously for 10 hours without any malfunction, proving that the devices are extremely reliable. The spectrum analyzer revealed that the spectral noise of the entire system, showing the noise content falling 10 dB per decade. We observed an additional coupling noise was present as the IHOS operated in dark conditions. Unwanted coupling was present at the amplifier stage at the frequency of excitation of the MOEMS modulators.

In order to overcome the unwanted coupling, we have developed a new detection method called the Double Harmonic Modulation Technique. First, this technique makes use of the transducer as the force is proportional to the square of the voltage. As the modulator is excited with a sinusoidal signal at half the natural frequency and a dc-offset, the mechanical response occurs at two scales. The first one occurs at the excitation frequency scale, whereas the second scale occurs at twice that frequency. In addition, the optical frequency doubles the mechanical frequency as the in-plane modulation forces the shutters to travel over the optical
vias twice per cycle. Therefore, the double-modulation technique performs optical modulation at twice and four times the excitation frequency of the modulator signal. In this unique fashion, we have demonstrated that the IHOS can detect very low intensity signals.

Furthermore, we connected a variable optical attenuator (VOA) to a monochromatic optical source in order to measure the minimum detectable signal of the system. Effectively, we emulated bioluminescence as the VOA attenuated the signal in discrete steps. The MDS that was detected was 5 pA, which represents at least a 25 dB improvement over direct photodetection.

8.5. Bioluminescence Measurements

Whole-cell sensors are a new family of environmental sensors that are based on genetically engineered bacteria. These biosensors can be designed to express a light-emitting bio-reporter signal upon exposure to pollutants in the environment. Conventional methods for sensing toxicity rely on the chemical specificity of an antigen, acting as sensor and an analyte. These conventional chemical techniques demand lengthy testing processes that limit the real-time response, cost-effectiveness, and portability. Using a complete different approach, the use of whole-cell sensors makes use of the cells as the biological entities. Upon exposure to environmental toxicity, the metabolic changes of the cells are monitored. Hence, rather than specific chemical testing, a general metabolic response is tested. The whole-cells that we have utilized include the Lux bio-reporter genes that encodes for a bioluminescent process. The main limitation the light-emitting whole-cells biosensors is that the low emission rate per cell, which ranges between 100-300 photons/sec. Therefore, the integration of this type of biosensors has predominantly been performed with PMTs, as current solid-state photodetectors are not sensitive enough for direct measurement of bioluminescence in real-time. The use of IHOS as a method to measure bioluminescence from whole-cell biosensors using solid-state photodetectors represents another innovative aspect of this research work.
We have tested whole-cell sensors in volumes of 3 ml, using IPTG as the inducer emulating environmental toxicity. We have proven that IHOS can measure various optical emission levels of whole-cell sensors subject to different inducer concentrations.

Furthermore, we implemented a signal processing filters on the experimental data in order to further condition the signals. Two types of filters were implemented using signal processing tools from Origin statistical program (OriginLab Corporation, USA). The first one is an average filter, which calculates the mean of the data in 5 minute periods. The average filter clearly shows the emission levels as a function of inducer concentrations. In addition an RC filter was also implemented using a signal processing, showing the overall trend of the bioluminescence as a function time. Such filters can be implemented using analog circuits, such as an integrating RC circuit, or with complementary DSP chips.

We have successfully demonstrated the integration of whole-cells sensors with the IHOS, and detected low bioluminescence levels, as the cells were exposed to different concentrations of inducer. It is possible to observe the growth, a plateau, and decay per each inducer concentration. We presume that bioluminescence response is also dependant on the aerobic conditions of the bacteria and the growth rate. As seen in Chapter 2, the reaction for light production requires oxygen as a reactant. Therefore, in order to ensure enough oxygen supply, the samples were shaken prior to taking any measurements. The growth-rate of bacteria as a function of time is characterized by a linear and saturation regions. The linear region is where the growth rate is at its maximum, and the saturation region is when the growth rate becomes limited. The growth rate varies as a function of inducer. If the inducer concentration is very high, all the bacteria will be intoxicated and only apoptosis will take place. If no inducer concentration is added the bacteria will multiply at its maximum rate. In addition, we conducted the experiments consistently during the same stage of cell-growth.
8.6. Applications

The use of IHOS for improving detection sensitivity of solid-state photodetectors has been demonstrated successfully. IHOS can be utilized for a wide variety of applications that require real-time detection of low intensity signals in massive portable applications. Moreover, we have shown that light-emitting whole-cell biosensors can be integrated with the IHOS as lab-on-chip for rapid toxicity detection as part of a handheld monitor. Detection of fluorescent markers in portable laboratory settings can also be implemented using IHOS with the addition of optical filters to separate the excitation signal from the photodetectors. Portable monitor toxicity sensors can be implemented using this technology.

In addition, the IHOS can be implemented for imaging systems that operate in very low light conditions. Cameras that use CCDS and CMOS can be seamlessly integrated with the transmissive optical modulators, increasing the SNR significantly. Furthermore, on chip lock-in DSP can be implemented to further increase the sensitivity of the system, offering an inexpensive portable solution.

8.7. Conclusions

In this chapter we have highlighted the innovative aspects of this research work. First, we have presented the current needs to improve the detection limit of solid-state photodetectors using a cost-effective solution. Current enhancement methods rely on decoupling the signal from the noise after photo-conversion. The IHOS is based on an optical modulation scheme that shifts up the signal to a higher frequency where noise floor is significantly lower. Then, we have presented the design rationale for designing an in-plane transmissive MOEMS modulator. We complemented analytical calculations with finite element analysis simulations in order to simulate stability, structural integrity, and mechanical modes of the MOEMS structure. The IHOS has successfully improved the SNR of photodetectors by at least 25 dB, which allowed to detection of a minimum photo-signal level
of 5 pA. In addition, the IHOS can be integrated with whole-cell biosensors for toxicity detection in the environment. Finally, we have explored few applications for the IHOS, such as portable toxicity sensors using lab-on-chips, affordable detectors for biomarkers, and seamless add-on for improving the detection limit of imaging systems.
Chapter 9. 
Summary and Conclusions.

The following conclusions represent a summary of the presented research work that has been derived from the Model, Design, Fabrication, and Experimental chapters:

1. **A new concept.** The Integrated Heterodyne Optical System (IHOS) is a new modulation scheme that allows a significant improvement in sensitivity of solid-state photodetectors. At present photomultipliers (PMTs) are the predominant choice for applications that demand sensing of low-intensity optical signals, such as for biological applications that require measurement of bioluminescence. Currently, the sensitivity of solid-state photodetectors is limited by the dominant flicker noise that affects the lower spectrum. We have simulated the spectral noise distribution of a photodiode connected to a transresistance amplifier, showing that the noise floor falls 10 dB per decade, resulting in a 30 dB difference between the noise-levels at 1 Hz and above 1 kHz. Therefore, a modulation scheme can be implemented to drastically increase the SNR. Existing electronic techniques decouple the low-frequency noise from the desired signal in the electrical domain. Using a complete different approach, IHOS performs modulation in the optical domain before photo-conversion, entirely avoiding the unwanted low-frequency noise contribution.

2. **MOEMS design.** The central component of the IHOS is a transmissive MOEMS modulator that is placed on top of the solid-state photodetector as a seamless add-on. The in-plane modulator enjoys a large field area of approximately 1 mm², requires a sinusoidal excitation with a frequency of approximately 1 kHz. In atmospheric conditions the operating voltage is approximately 15 Vp combined with a dc-offset of approximately 0.5 V, whereas in vacuum conditions the operating voltage is 3.5 Vp. This design can
achieve a maximum modulation efficiency of 50 percent as the actuators are constrained
to an in-plane motion of 50 µm. Analytical calculations and finite element analysis (FEA)
were performed to simulate maximum displacement, stability, natural frequencies, higher
modes, and structural integrity. One of the key innovations of this design is that the in-
plane modulator can be stacked between the photodetector and the optical source without
compromising structural integrity.

3. MOEMS Fabrication. MASIS (Multiple Aspect Ratio Structural Integration in Single-
Crystal-Silicon) has been developed as a novel bulk-micromachining, compatible process
specially tailored for transmissive optical modulators. The process requires as few as two
photolithographic masks to combine high-aspect ratio actuators with large area shutters in
a transmissive architecture configuration. The process defines optical vias from the
backside of the wafer beneath the shutters. In addition, the process allows increasing the
natural frequency of the modulator by reducing the effective mass of the shutters. The
process also uses the buried oxide layer of the SOI to compensate for etch non-
uniformities of the DRIE in order to thin down the mass of the shutters in a precise self-
aligned fashion. MASIS is VLSI compatible, and can be integrated along with CMOS
circuits.

4. Experimental Results. The transmissive optical modulator was placed on top of a
photodiode connected to a transresistance amplifier. The spectral output of the modulator
was connected to a spectrum analyzer, revealing an additional source of noise due to
unwanted electrical coupling from the modulator excitation manifested as a spurious
harmonic. Such coupling was overcome using the Double Harmonic Modulation
Technique, which makes use of the intrinsic transduction stages of the MOEMS
modulator. The first transduction translates the electrical signal of excitation to
displacement, since the mechanical force is proportional to the square of the amplitude. Hence, the mechanical response enjoys two frequency scales. The first one occurs at the frequency of the electrical excitation, whereas as the second one occurs at twice that value. Therefore, the mechanical frequency is doubled. The second transduction stage translates the mechanical response to an optical signal, as the input optical signal is chopped by the shutters. The comb-drive actuators drive the shutters periodically over the optical vias twice per cycle, thereby the resultant modulated frequency response of the optical signal doubles the mechanical one. Therefore, the optical signal ideally enjoys two frequency scales spectrally located at twice and four times the frequency of the excitation electrical signal. The final transduction stage translates the optical modulation to an electrical signal by means of the photodiode. In this case, both the optical and photodetected signals share the same spectrum. We tested the performance of the modulators for 10 hours continuously, demonstrating the high reliability. An alternative modulation technique that involved twin MOEMS modulators was also presented. This promising technique is based on operating two separate modulators at slight different frequencies in order to generate beats, which are very sensitive to intensity variations. This technique can be utilized for future applications.

5. **Sensitivity Improvement.** The minimum detectable signal (MDS) of the modulator was measured by connecting lock-in amplifier to the output of the transresistance amplifier. A variable optical attenuator (VOA) was used to decrease the intensity of the monochromatic source in order to emulate low-intensity bioluminescence. The MDS corresponded to a photocurrent of approximately 5 pA, which is at least 25 dB below the detection limit of the photodiode.
6. **Biosensors.** Whole-cell biosensors were integrated as part of the IHOS. Whole-cell sensors represent a new family of genetically engineered cells that provide a measurable response upon exposure to environmental toxicity. We have used whole-cell sensors that contain the *Lux* bio-reporter, providing a bioluminescence response upon exposure to IPTG inducer that emulates an environmental toxin. Using the novel IHOS approach, the bioluminescence response of whole-cell sensors was measured as function of time and inducer concentration. A family of curves reveals that the minimum detectable inducer concentration was approximately 10 ppm.

7. **Future Implementation.** The integration of whole-cell sensors with the IHOS represents a successfully implemented proof-of-concept. Portable detectors can be deployed for monitoring toxicity in public water-supply systems. Such cost-effective solution combines the transmissive MOEMS modulator with inexpensive solid-state photodetectors for low-intensity bioluminescence measurements. Furthermore, IHOS can be utilized for enhancing the sensitivity of a number of imaging systems that depend on solid-state photodetectors. The transmissive MOEMS modulators can be implemented for improving the SNR of cameras, telescopes, and microscopes that utilize CCD, CMOS, or any other solid-state photodetectors.
10. References


77. Cornel Marxer and Nicolaas F. de Rooij “Micro-Opto-Mechanical 2x2 Switch for
Single-Mode Fibers Based on Plasma-Etched Silicon Mirror and Electrostatic Actuation”


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Appendix I: System Noise Modeling

A.1. Noise in Photodiodes: The Motivation for Modulation

The detection limit of the optical signal sensing depends strongly on the noise features of the optical sensors, in our case photodiodes. Several sources contribute to the overall photodiode noise: shot noise, thermal noise (Johnson noise), flicker noise (1/f noise), and generation-recombination (G-R) noise [39].

![Equivalent noise circuit for a photodiode connected to trans-resistance pre-amplifier](image_url)

Figure A.1. The equivalent noise circuit for a photodiode connected to trans-resistance pre-amplifier.

The photodiode is represented as an equivalent resistor, $R_d$ in parallel with a capacitor, $C_{d}$. The total noise of the diode is the sum of all its components. First, there is the shot noise which is the result of the fluctuations in the flux of the electron and hole currents that carry the electrical current. For a photodiode in reverse bias, the shot noise current is described by the following expression [43]:

$$\overline{i_{\text{shot}}^2} = 2qI_D \Delta f.$$  \hspace{1cm} (A.1)
Where $q$ is the electron charge, $I_D$ is the photodiode current, and $\Delta f$ is the noise equivalent bandwidth (NEB).

The noise at low frequency may have two other sources. One is the generation-recombination (G-R) noise [39]. The source of this noise is based on fluctuations in the carrier flux due to generation, recombination, and trapping of carriers in semiconductors. These fluctuations cause the number of free carrier to vary, thereby leading to random variations in conductivity that manifest as noise. The spectral response of G-R noise is almost uniform up to a frequency determined by the lifetime of the carriers in the photodetectors. In most cases, this noise mechanism is negligible.

The second low-frequency noise is due to flicker noise that usually dominates at low frequencies. Surface defects and metal contacts are among the main contributors to the low-frequency noise [40,41,42], which is the limiting factor in detection sensitivity. The current spectral density of the flicker noise can be determined by the following semi-empirical expression:

$$S_{i,f} = \frac{I_{\text{dark}} K}{f^\gamma},$$  \hspace{1cm} (A.2)

Where $I_{\text{dark}}$ is the diode-dark current, $K$ and $\gamma$ (approximately 1) are the coefficients of the photodiode that depend on the fabrication process (quality and technology), $\beta$ value is an empirical constant related to doping profile (approximately 2), $f$ is the frequency. The difference in the noise spectral density amplitude between low-frequency detection (~1 Hz) and frequencies higher than 1 kHz is at least three orders of magnitude (30 dB).

The full model is represented in Fig. AI.2 where we also added a series resistance and its associated thermal noise.
Figure A.2: Equivalent circuit for the photodiode.

For low-frequency signal detection, Flicker noise is the most dominant noise mechanism. In addition, measurement systems composed of connectors, coaxial cables, amplifiers all seem to demonstrate high noise content at low frequencies, such as the power line coupling (50 or 60 Hz). Thus, it is preferable to overcome the low-frequency noise source entirely when measuring low intensity signals, such as bioluminescence.

We have modeled the noise following the work developed by Hamstra and Wendland [67], which neglects the series resistor of the photodiode. The photodiode noise can be approximated by the following expression:

\[ \frac{i_{pd}^2}{i_{th}^2} = \frac{i_{1/f}^2}{i_{th}^2} + \frac{i_{shot}^2}{i_{th}^2} \]  

(A.3)

A.2 Amplifier Noise.

Figure A.2 shows a schematic diagram of an amplifier with the integrated noise sources. The transresistance amplifier, however, also suffers from various types of noise mechanisms. The noise present at the amplifier circuit output must be taken into account as integral part of the analysis. Fluctuations in voltage from the power supply are not considered as part of this analysis. Assuming a dominant pole, an amplifier forward transfer function (output voltage versus input voltage) can be modeled as follows:
Where \( a_o \) is the low frequency gain (V/V), \( \omega_c \) is the cut-off frequency. The next step is to formulate the expression for the output voltage due to photocurrent is defined as follows:

\[
\overline{v_{out}^2} = i_{pd}^2 a_1,
\]

(A.4)

Where \( a_1 \) is defined as the transfer function of the amplifier to an input current, which is defined as follows:

\[
a_1 = \frac{-R_f}{\omega^2 \left( \frac{R_f}{\omega_H} \left( C_i + C_f \right) + j\omega \left( \frac{R_f C_f}{\omega_H} + \frac{1}{\omega_H} + \frac{R_f}{\omega_H} \right) + 1 \right)},
\]

(A.7)

Where \( R_f \) is defined as the feedback resistor, \( C_i \) is the input capacitor, \( C_f \) is defined as the feedback network capacitor, and \( \omega_H \) is defined as the bandwidth-gain product when the gain, \( a_o \) (V/V), equals unity.

The amplifier suffers from three main noise sources: \( i_n \) is the amplifier input current noise, \( v_n \) is the amplifier input voltage noise, which are given by the manufacturer, see Table 3.1. In addition, we need to take into account the current noise in the amplifier feedback network, \( i_{nf} \), defined by the following expression:

\[
\overline{i_{nf}^2} = \frac{4K_T T \Delta f}{R_f}.
\]

(A.8)

The output voltage noise due to these noise sources is defined as follows:

\[
\overline{v_{o\_noise}^2} = a_1 \left( \overline{i_{pd}^2} + \overline{i_n^2} \right) + a_2 \overline{e_n^2} + a_3 \overline{i_{nf}^2}
\]

(A.9)

Where \( a_1 \) has already been defined as the transfer function for an input current (Equation 1), \( a_2 \) is the defined as the transfer function due to an input voltage, \( a_3 \) is the transfer function due to feedback network noise. The corresponding transfer functions defined as follows:
The actual magnitude of the noise at the output of the amplifier can be calculated using the following expression:

\[
\frac{v_{o,\text{noise}}^2}{f_2} = \int_{f_1}^{f_2} \left[ \left| a_1(f) i_{pd}(f) + i_n(f) \right|^2 + \left| a_2(f) e_n(f) \right|^2 + \left| a_3(f) i_{nf}(f) \right|^2 \right] df. \tag{A.12}
\]

Where \(a_1\) is the transfer function of the amplifier for the input current noise due to the photodiode, \(i_{pd}\), and the input current noise of the amplifier, \(i_n\); \(a_2\) is transfer function of the amplifier for an input voltage noise, \(e_n\); and \(a_3\) is the transfer function due to the feedback network noise, \(i_{nf}\). The total output voltage noise is obtained by integrating over the entire system bandwidth \((f_1 - f_2)\).

**Figure A.2:** Photodiode connected to a transresistance amplifier.
In order to calculate the SNR ratio, we formulate the ratio of the output voltage for due to photocurrent that enjoys a specific frequency determined by the modulator, and output noise voltage integrated over the desired frequency range. Such expression is given by:

$$
SNR = \frac{i_{pd}(f)a_1(f)}{\int_{f_1}^{f_2} \left( |a_1(f)(i_{pd}(f) + i_n(f))|^2 + |a_2(f)v_n(f)|^2 + |a_3(f)i_{if}(f)|^2 \right) df}
$$

(A.13)

The bandpass filter can be implemented electronically using a standard filter that provides a selective bandwidth. Among the several options exist to implement a lock-in amplifier provides a very narrow bandwidth and a simple method to demodulate the signal. The selectivity of the bandpass filter allows to further reduce the noise. The SNR is the figure that ultimately determines the performance of the system.

A.2. Noise Simulations

The goal of this section is to simulate the noise contribution of each stage in order to predict the minimum detectable signal (MDS). In order to achieve this task, we simulated the noise of the photodetector and transresistance, using Matlab (Matlab Corporation, USA). Table 3.1 summarizes all the physical values used for the system. Figure A.3 illustrates the noise sources for each stage.
Figure A.3: Block diagram of the IHOS including different noise source. Modulation is performed prior to photodetection. Noise is added in the photodiode and amplifier stages.

First, we introduced noise sources of the photodiodes, and noise sources of the amplifier, as shown in Figure A.4. In this case, we plotted the current and voltage noise densities in the same graph in order to show the spectral distribution of each type of noise. The total input current noise is depicted in red; the feedback noise is depicted in green. Moreover, a simple method to estimate this figure in the lower spectrum can performed by measuring the output voltage at the output of the transresistance amplifier, without any input and in dark conditions, and subsequently dividing this figure by the gain of the amplifier.

The next step involved simulating the transfer functions of the amplifier: $a_1(f)$, $a_2(f)$, and $a_3(f)$, illustrated in Figure A.5. Furthermore, the frequency response of the amplifier is dictated by the cut-off frequency of the feedback network.

In order to graphically compute the noise, first we plot in a log-log graph the voltage-square and current-square densities of the noise mechanism. Thereafter, we plot the product of each transfer function squared by its input-square noise contribution. The resulting graphs are
illustrated in Figure A.6. In order to calculate the total noise contribution, it is necessary add the spectral densities at the output of the transresistance amplifier, shown as a blue trace.

Finally, in order to estimate the noise magnitude it is necessary to integrate the total of the square voltage spectral density over the desired frequency range. A simple method to estimate the magnitude of the noise at the output of the amplifier is based on multiplying the noise equivalent bandwidth (NEB) by the magnitude of the voltage density at each frequency. The minimum detectable signal (MDS) per system bandwidth can be estimated by the dividing the output noise by the gain of the amplifier. Figure A.7 shows the MDS as a function of frequency and NEB.

**Figure A.4:** Total current noise density at the input of the amplifier (red), and current noise density due to the feedback resistor (green).
Figure A.5: Transfer function for each noise generator. Green, red, and cyan correspond to the transfer functions of \( a_1(f) \), \( a_2(f) \), and \( a_3(f) \), respectively.

Figure A.6: Output voltage noise density at the output of the amplifier. Blue is the total.
Figure A.7: Noise signal as a function of bandpass filter quality factor. Green is 10, Light Blue is 20, Red is 25, Blue is 50, and Yellow is 100.
Table A.1: Values of the photodiode, amplifier, and bandpass filter used for simulation.

<table>
<thead>
<tr>
<th>Stages</th>
<th>Physical Variables</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photodiode</td>
<td>Active Area ($A$)</td>
<td>$8 \text{ mm}^2$</td>
</tr>
<tr>
<td></td>
<td>Operating Voltage ($V_d$)</td>
<td>$-1 \text{ V}$</td>
</tr>
<tr>
<td></td>
<td>Saturation Current ($I_{sat}$)</td>
<td>$10^{-11} \text{ A}$</td>
</tr>
<tr>
<td></td>
<td>Quantum Efficiency ($\eta$)</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Parallel Resistance ($r_d$)</td>
<td>$10 \text{ G}\Omega$</td>
</tr>
<tr>
<td>Amplifier</td>
<td>Capacitance ($C_d$)</td>
<td>$10^{-9} \text{ F}$</td>
</tr>
<tr>
<td></td>
<td>Input Impedance ($R_{in}$)</td>
<td>$100 \text{ M}\Omega$</td>
</tr>
<tr>
<td></td>
<td>Input Capacitance ($C_d$)</td>
<td>$10^{-12} \text{ F}$</td>
</tr>
<tr>
<td></td>
<td>Feedback Resistor ($R_f$)</td>
<td>$15 \text{ k}\Omega$</td>
</tr>
<tr>
<td></td>
<td>Feedback Capacitance ($C_d$)</td>
<td>$10^{-9} \text{ F}$</td>
</tr>
<tr>
<td></td>
<td>Open loop Gain ($R_f$)</td>
<td>$15 \text{ kV/A}$</td>
</tr>
<tr>
<td></td>
<td>Gain Product Bandwidth ($\omega_H$)</td>
<td>$10 \text{ MHz}$</td>
</tr>
<tr>
<td></td>
<td>Amplifier Input Noise ($e_n$)</td>
<td>$10 \frac{pV}{\sqrt{Hz}}$ pV</td>
</tr>
<tr>
<td></td>
<td>Amplifier Input Noise ($i_n$)</td>
<td>$0.5 \frac{pA}{\sqrt{Hz}}$</td>
</tr>
</tbody>
</table>
## Appendix II: Fabrication Notes

<table>
<thead>
<tr>
<th>Experiment Name</th>
<th>Top Mask MEMS I – Definition – Dummy I</th>
<th>Start Date: 05-09-04</th>
<th>End Date: 19-09-04</th>
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</thead>
</table>

<table>
<thead>
<tr>
<th>Goal</th>
<th>Characterize front side photolithography and etching for optical MEMS modulator, using dummy (silicon wafers).</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Wafer</th>
<th>Silicon Wafer – Single side polished – 2 um thermal oxide – 550 µm</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Tool - Application</th>
<th>Process Step Name</th>
<th>Time – Other</th>
</tr>
</thead>
</table>

### Photo-lithography

<table>
<thead>
<tr>
<th>Tool – Application</th>
<th>Process Step Name</th>
<th>Time – Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin – 1 – RC8 – Karl Suss</td>
<td>HMDS 3000 RPM</td>
<td>40</td>
</tr>
<tr>
<td>Spin – 2 – RC8 – Karl Suss</td>
<td>1818s 3000 RPM</td>
<td>40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tool – Application</th>
<th>Process Step Name</th>
<th>Time – Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hotplate</td>
<td>Prebake</td>
<td>60 sec – 110 C</td>
</tr>
<tr>
<td>M16 – Karl Suss</td>
<td>Vac Contact</td>
<td>3</td>
</tr>
<tr>
<td>Developer</td>
<td>MIF 319</td>
<td>30</td>
</tr>
<tr>
<td>Hotplate</td>
<td>Hardbake</td>
<td>180</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tool – Application</th>
<th>Process Step Name</th>
<th>Time – Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nextral - RIE</td>
<td>RES- RIE</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tool – Application</th>
<th>Process Step Name</th>
<th>Time – Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nextral - RIE</td>
<td>SIO-RIE</td>
<td>180</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tool – Application</th>
<th>Process Step Name</th>
<th>Time – Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICP – DRIE</td>
<td>Noel_70</td>
<td>18 min – 62 cycles</td>
</tr>
</tbody>
</table>

### Images

- **Top View Optical Modulator**
- **Springs and Shutters**
- **Reinforcing beams for shutter and Transition Beams**
- **Spring Anti-stiction Stoppers**
### Observations /Remarks

- Front side photolith was easily defined; the pattern transfer to the oxide was also defined without any complications.
- The silicon etch profile was a non-issue, as the given verticality was acceptable.
- Before defining on DRIE, backside photolithography and pattern transfer were defined.
- Removing Photoresist is required. There are two options: NMP, heating it up to 50 C, or RIE oxygen. The former is more practical and faster, while it is ‘dirty’; the latter is efficient but slow. Yet, as there is a subsequent wet-process (development for backside), there is no need to keep the process dry up to that point.
- Front side definition on dummies provided some grass, black, and white silicon. Before ICP etch, it is better to clean the front side of the wafer (isopropanol and acetone).
- If there is some grass observed, one option is to run a short isotropic etch (SF6) to undercut the submicron pillars. A time of 20-45 seconds should be sufficient.
- In addition, it is important to finish up the ICP etch with the etch step.
- Using Optical Tool – delta-focus measured depth: 29 um
- Using Alpha-Stepper, measured depth:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Depth (um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center - Center</td>
<td>27.13</td>
</tr>
<tr>
<td>Center - Left</td>
<td>29.48</td>
</tr>
<tr>
<td>Center - Right</td>
<td>27.46</td>
</tr>
<tr>
<td>Center - Down</td>
<td>28.65</td>
</tr>
<tr>
<td>Center - Left - Top</td>
<td>29.13</td>
</tr>
<tr>
<td>Center - Right - Top</td>
<td>30.14</td>
</tr>
<tr>
<td><strong>Mean Value</strong></td>
<td><strong>28.665</strong></td>
</tr>
<tr>
<td>Experiment Name</td>
<td>Top Mask MEMS I – Definition – Dummy II</td>
</tr>
<tr>
<td>-----------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>Goal</td>
<td>Characterize backside photolithography and etching for optical MEMS modulator, using dummy (silicon wafers).</td>
</tr>
<tr>
<td>Wafer</td>
<td>Silicon Wafer – Single side polished – 2 µm thermal oxide – 550 µm</td>
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<td>Procedure</td>
<td>Tool - Application</td>
</tr>
<tr>
<td>Photo-</td>
<td>Spin – 1 – RC8 – Karl Suss</td>
</tr>
<tr>
<td>lithography</td>
<td>Spin – 2 – RC8 – Karl Suss</td>
</tr>
<tr>
<td></td>
<td>Hotplate</td>
</tr>
<tr>
<td></td>
<td>MI6 - Karl Suss</td>
</tr>
<tr>
<td></td>
<td>Developer</td>
</tr>
<tr>
<td></td>
<td>Hotplate</td>
</tr>
<tr>
<td>Photoresist</td>
<td>Nextral - RIE</td>
</tr>
<tr>
<td>Descum</td>
<td></td>
</tr>
<tr>
<td>Pattern</td>
<td>Nextral - RIE</td>
</tr>
<tr>
<td>Transfer</td>
<td></td>
</tr>
<tr>
<td>Silicon Etch</td>
<td>ICP – DRIE</td>
</tr>
<tr>
<td>Images</td>
<td>Backside shutter windows</td>
</tr>
<tr>
<td></td>
<td>Optical image of shutters</td>
</tr>
</tbody>
</table>
Observations /Remarks

- Backside was first defined using 4562; unfortunately it ran out so subsequent trials will be based on AZ5214E.

- Line widths were preserved (2.5 um wide), while some of the line-lengths (1 mm long) were not properly defined as straight lines were present, but rather curved lines.

- The photo-definition was kept, as it would still serve for the subsequent silicon definitions.

- The oxide etch was a non-issue, as the images revealed an acceptable pattern transfer.

- Before ICP etch, an outer ring of the wafers (about 8 mm) was cleaned of photoresist using a q-tip with isopropanol and acetone while the wafer was spun at 1,000 rpm. This step was necessary in order to prevent the wafer from sticking to the ICP ceramic chuck.

- Initially, about 100 um were etched down to the silicon. The etching into the silicon revealed that lines were properly transferred. Using the delta-focus optical microscope, the following etched depths were attained:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Depth (um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left – Center</td>
<td>105</td>
</tr>
<tr>
<td>Left – Down</td>
<td>104</td>
</tr>
<tr>
<td>Left – Top</td>
<td>107</td>
</tr>
<tr>
<td><strong>Mean Value</strong></td>
<td><strong>105.33</strong></td>
</tr>
</tbody>
</table>

- The floor seemed to be quite clear of particles or unwanted features. The photoresist mask proved to have resisted quite to the SF6 etching.
Using the Alpha-stepper the following depth measurements were taken:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Depth (um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left – Center</td>
<td>219</td>
</tr>
<tr>
<td>Left – Down</td>
<td>225</td>
</tr>
<tr>
<td>Left – Top</td>
<td>232</td>
</tr>
<tr>
<td>Right – Center</td>
<td>223</td>
</tr>
<tr>
<td>Right – Down</td>
<td>220</td>
</tr>
<tr>
<td>Right – Top</td>
<td>226</td>
</tr>
</tbody>
</table>

**Mean Value** 224.16

The bottom window width variation was measured with an optical microscope was about 70 um, see images. Therefore, if we assume a linear etch and the initial window was 97.5 um as defined by the photomask, the etch angle is 3.93 degrees.
פרק מס' 1: מבוא
1.1 רדיו גלי משולבת אופטית
1.2 תיאור
1.3 מטרות המחקר
1.4 הוראות
1.5 ארנגלים ואתגרי פיתוח

פרק מס' 2: סקר ספרות
2.1 תיאור
2.2.1 ביולוגיים חיישנים
2.2.2 ביולוגיים חיישנים שלמים
2.2.3 פעולות עקרונות
2.2.4 הפיסיקו-ליזם של עיקלי אור צור "חיים אורגניזמים"
2.3.1 גילוי DC או של ביולוגיים נייחים בשילוב.CharField 2.3.2 עיבודים גורם גילויי "אור ממצאים"
2.3.3 עיבודים ייצור גילויי "אור חיים אורגניזמים"
2.3.4 עיבודים ייצור גילויי "אור מוצק מצב במשקיף שימוש יישור"
2.3.5 בזגין CCי CCD
2.3.6 בזגין רגיש אור "אור גאוניים חום ו" שיפור במ:create Basis
2.4.1 רימונים
2.4.2 מאמנים MOEMS
2.4.3 מאמנים משקף
2.4.4 מאמנים מעבר
2.5 תהליך ייצור h MOEMS
2.6 סכום
8.5 מדריך ייצור תואר "אורגניזמים".
8.6 יישומים.
8.7 מסקנות.
9 פד ס: מסקנות 9.1 מושג חדש.
MOEMS מסקנות 9.2.
9.2 מושג חדש 9.3 MOEMS.
9.4 תצאות ניסיון 9.5 שיפור הרגישות.
9.6 תחינים 9.7 יישומים נוספים.
10 פד ס: מרחב מיקום.
11 נספח מס: תשובת על.
12 נספח מס: תשובת ייצור.

En plus de l'hétérodynie optique, nous avons également développé une nouvelle méthode de traitement de l'interférence nulle, appelée Multiple Aspect Ratio Structural Integration in Single Crystal Silicon (MASIS). Cette méthode permet d'intégrer des structures à plusieurs aspects dans un seul cristal de silicium, ce qui augmente la flexibilité et la finesse de l'interface. En combinant cette nouvelle technique avec les MOEMS, nous avons pu développer un système d'interférence nulle de haute qualité, capable de fonctionner à des fréquences de 1 à 5 kHz et d'utiliser des tensions de fonctionnement de ±15 V ou ±3.5 V.

Les résultats obtenus avec cette nouvelle méthode ont démontré une amélioration significative de la qualité de l'interférence nulle, avec une diminution de l'interférence de 1/4 de sa valeur initiale. Ces résultats ont été obtenus à l'aide de mesures expérimentales et de simulation numériques.

בדרק, ו, לא תאורש אלא עם הפרך בחרה, הגבון בחובה, על תמר הרעש הגדור עיון תמר ההפרעה הנבהת.
ופורתו העתידית הלא רצוי בן המאמצון ומגעל גילי זרה.

עדו, ו, מציגה ניסיון אופטי ליבשת את "שרוש" מבנה פוטוןיות MOEMS לפלט אופטי גילי קוחה.

אופטימיות יכולות עזרה, גילי קוחה אופטיים של המו iphone בקר请联系-וי-ידישים של חוטים-ו-חדוועים של חוטים-שלמות.

בפרט. נמצארה זו, וחוסמו של השלום והחיים מחסומים, החסומים בנות ול.FullName

המהווה על "זרחי יעילת". עונש לכל נזק למגורר לאחר שאותה התפשטות האופטיים

כל זה ונקלא תערובת הנפה לש ריכוז הערעל וב себוב.

הירשים שושב מבחר יקנפ אחריה פוטוןיות ( selv-יהלום) לפלט אופטי גילי

פוקדים של רעיית שלג. גליל אופטי זכרון "י חותמת ויין." הניתן מישורוני או פוטונים שוקע פלטת חカラ

המהלך של החול חלום, והז любом הפרט. גליל זכרון ויין בתביעה פורמט药材.

במה החשובה ממנה, עבור כל 300-100 Putin שישים כדי ייסוד עם המקור, והיוורע החברות של

אלה כריך משולב המיון ב- תנאים האופטיים והחיים של MOEMS לפלט אופטי גילי

רעייתו. זז, והאמנויות של השדרה זו הנסככות על MOEMS ימלול לוחות בין שיווקים ברבד

הNavBar משולב ו- פטרוות ו- אופטיים, בן טור אופטי גליל או חלש מתרוער נוכים.
HETERODYNE DETECTION OF OPTICAL BIOREPORTERS
BASED ON MICRO-OPTO-ELECTRO-MECHANICAL-SYSTEMS (MOEMS) METHODS

גראל מ.אלפמן

תורם לשםตลת ההנאה"דוקטור לפילוסופיה"

הוגש לג(assign של האוניברסיטה תל-אביב

עבוודה זו נעשתה באוניברסיטה תל-אביב בפקולטה להנדסה

ברדרעת פרופ' יוסי שֶם

גיוס חפשיור.
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