16.3 A Self-Resonant MEMS-based Electrostatic Field Sensor with 4V/m/√Hz Sensitivity

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Strong interest exists in applying MEMS to the area of metrology, particularly for use in non-contact measurement of electric fields [1]. Non-contact electric-field sensors are used in photocopiers, power line monitoring, proximity sensing and geophysical measurements. Applying MEMS technology will help lower the cost, size, and power impact of taking these measurements. In addition, the sensing principles behind this technique can be applied to non-contact voltage sensing and precision electrometers.

Previous MEMS electric-field-sensor designs have been implemented with some success, but do not meet established industry requirements [2]. In xerography applications, for example, the noise floor of the sensor must be roughly 10V/m/√Hz, and the linearity of the sensor must allow for 100V/m absolute accuracy over a typical range of ±200kV/m. Maintaining this level of resolution allows for accurate feedback correction of the potentials within the system. The previous designs fall at least an order-of-magnitude short of these requirements.

We have addressed the shortcomings of previous MEMS-based electric-field sensors by creating a self-resonant sensor using synchronous-detection-based interface electronics. The sensor architecture has three major blocks: a MEMS shutter, a sense interface, and a self-resonant circuit that feeds back to the MEMS shutter (Fig. 16.3.1). The sensing principle of the MEMS device is similar to existing architectures, namely vibratory rate gyroscopes. A grounded silicon shutter cuts through electric-field lines coupling to the underlying sensing plates (Figures 16.3.2 and 16.3.3). The amount of charge induced on the plate is a function of shutter displacement and the strength of the electric field. The design of the sensor and circuit maximizes the charge induced by insuring maximum shutter displacement, while minimizing the parasitic capacitances and other detrimental error sources.

The resonant MEMS sensor was designed for maximum sensitivity to electric fields. As shown in Fig. 16.3.4, the MEMS sensor is fabricated as a single polysilicon structure with an array of shutters that overlap with underlying differential sensing plates. These polysilicon plates are biased through high impedances to a ground reference. At each end of the MEMS structure, a series of interleaved fingers are included to provide velocity sensing and force excitation of the shutter. The MEMS sensor is tethered to the substrate with four springs, through which it is also grounded. Shutter displacement is maximized by using a high-Q (65 in air at 1 atm.) sensor, and by driving the sensor at its resonant frequency. To ensure the shutter was driven at resonance, we developed a self-resonant oscillator using the MEMS structure's velocity sensing and force excitation fingers coupled with a supporting electronic feedback loop. The effects of drift and offset in the sense-amplifier electronics were suppressed by choosing the MEMS structure's nominal resonant frequency to be 12kHz, ensuring that it was beyond the 1/f corner of the interface preamps. This frequency also provides for mechanical robustness to shock and vibration. Fully-differential sensing and force drives are used to suppress feed-through into the sensing circuitry.

The electronics for the electric-field sensor support low-noise operation by ensuring the shutter operates at resonance and enabling synchronous demodulation of the signal. The interface circuitry consists of two blocks: the velocity pick-off/force feedback loop, which drives the shutter at resonance, and the sensing chain. The self-resonance loop maximizes the displacement of the shutter for a given supply voltage. The principle of the oscillation-loop dynamics is well established, and is described in reference [3]. The sensing chain's noise performance was achieved using synchronous-demodulation techniques and high-impedance biasing of the sensor plates. The charge fluctuations induced on the sense plates can be compromised by low-impedance biasing of the node. We addressed this issue by using parallel diodes across the charge amplifier's feedback capacitor to set the quiescent point of the sense plates. This technique established a stable bias point for the sensor without undermining the noise performance or gain stability at the shutter's resonant frequency. The output of the charge amplifier is synchronously demodulated using the phase reference provided by the self-resonance feedback loop. The output of the demodulator is subsequently low-pass filtered.

The electric-field sensor was prototyped in the iMEMS3 process at Analog Devices, as shown in the SEM die micrograph in Fig. 16.3.5. The test included the MEMS electric field sensor, the velocity sensing interface for the self-oscillation loop, and the charge amplifiers for the sense chain. Co-integration of the MEMS sensor to the key interface electronics kept parasitic capacitance to a minimum. The test chip was packaged in a twenty-pin ceramic DIP, with an isolated lid providing a planar electrode for establishing electric fields. The MEMS sensor was mounted 0.5mm underneath the lid. The device was self-resonant at 11.4kHz, close to the target frequency of 12kHz. The sensitivity of the sensor was measured as 9.36V/V/m, within 5% of the design expectations. The noise floor was measured at 4.0V/m/√Hz, two orders of magnitude better than the current state-of-the-art MEMS device [2]. The linearity of the sensor was measured by applying a least-squares fit to the sensor output over a range of ±700kV/m. The maximum integral non-linearity was found to be 40V/m, an improvement by an order of magnitude over existing MEMS devices [2]. The data are summarized in Fig. 16.3.6 and a die micrograph is shown in Fig. 16.3.7.

The electric-field-sensor design described here represents a significant improvement in MEMS-based electric-field metrology. The key improvements are derived from a total system design that includes careful coordination of the MEMS sensor and interface circuitry. The performance achieved is now in the range of utility for xerographic machines, geophysical measurements, and proximity sensing. The design techniques described here can also be extended to improve the performance of non-contact voltmeters and electrometers.

References:
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[2] Riehl, Muller, Howe, Yasaitis, "Electrostatic Charge and Field Sensors Based on Micromechanical Resonators," *J. Microelectromechanical Systems*, vol 12, No 5, pp 577-589, Oct., 2003.
[3] Paik, Aina, Denison, Lundberg. "Feedback Control for a MEMS-Based High-Performance Operational Amplifier," *Proc. of the ACC, 2004*, pp. 380-385.

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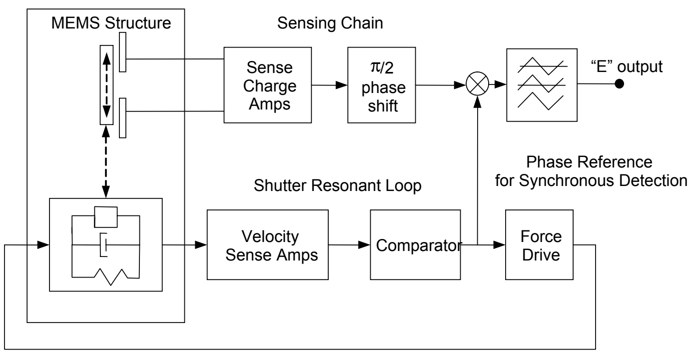

Figure 16.3.1: System architecture for the resonant MEMS E-field sensor.

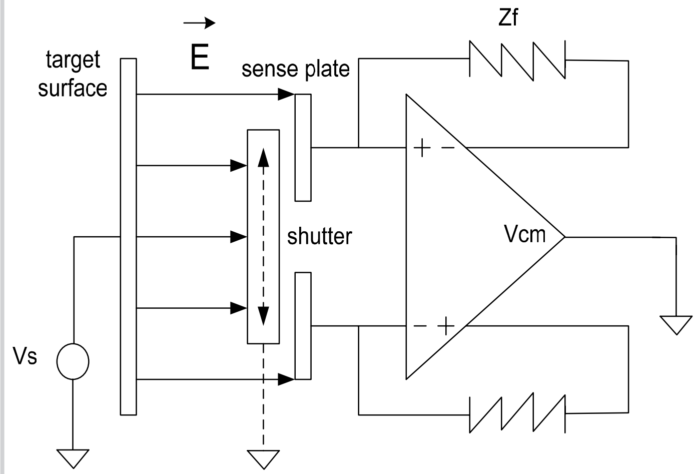

Figure 16.3.2: Sensing scheme for the E-field sensor.

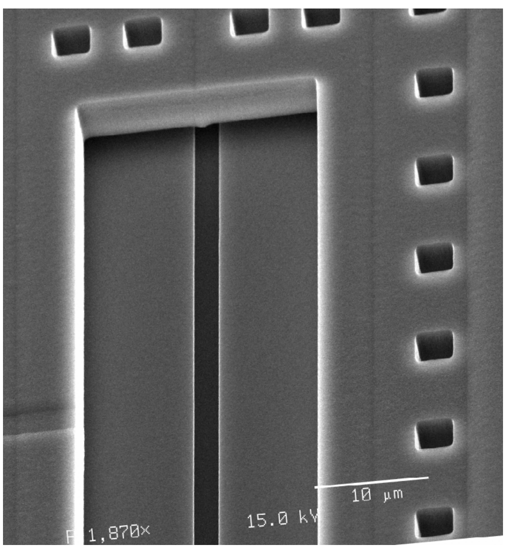

Figure 16.3.3: SEM view of shutter over differential sensing plates.

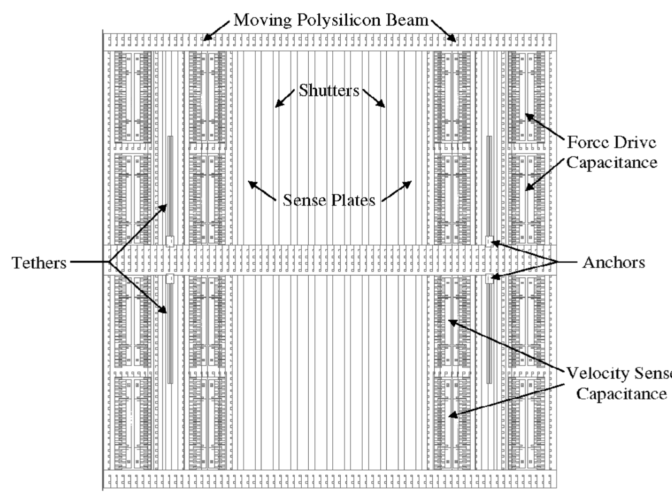

Figure 16.3.4: Architecture of the MEMS shutter.

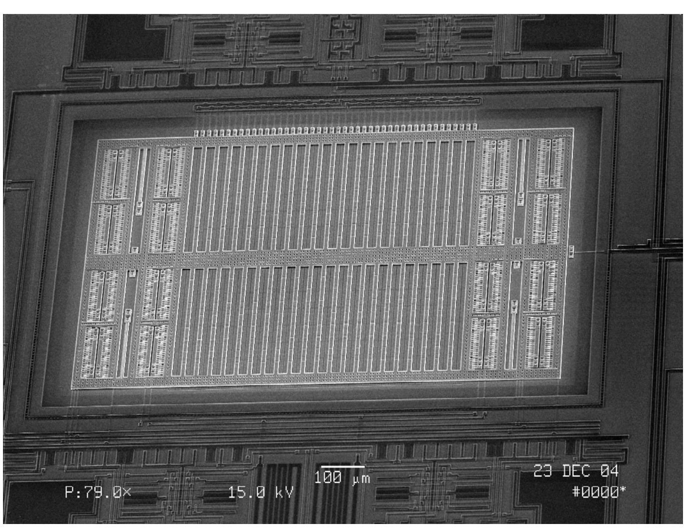

Figure 16.3.5: SEM of fabricated MEMS shutter with integrated interface circuitry.

Parameter	Riehl [2] EFM	Measured Results
Input-referred Noise	700 V/m/rtHz	4 V/m/rtHz
Measured Field Range	+/- 333 kV/m	+/- 700 kV/m
RMS Field Error	630 V/m	< 40 V/m

Figure 16.3.6: Summary of results.

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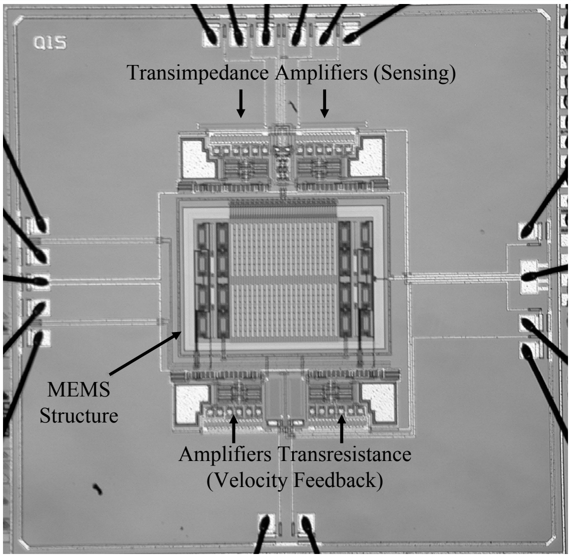

Figure 16.3.7: Die micrograph.