# Characterization and Fabrication of the NanoGate for Nanoscale Fluidic Research

James White, Graduate Research Assistant
Alex Slocum, Professor of Mechanical Engineering
Jeffrey Lang, Professor of Electrical Engineering

Massachusettes Institute of Technology
Cambridge, Massachusetts, 02139 USA
slocum@mit.edu

## Abstract

The NanoGate is a device that precisely meters the flow of tiny volumes of fluid. Precise control of the flow restriction is accomplished by deflecting a cantilevered plate that is anchored by a torsion spring, as shown in Figure 1. The opening is adjustable on a sub-nanometer scale using a piezoelectric actuator. Therefore, the Nanogate could act as a molecular filtering device or a high precision proportional valve. In addition, the Nanogate has been manufactured on both the micro and macro scale. The Nanogate is the first analytical instrument to allow nanometer-to-hundred nanometer sized gaps to be set by controlled actuation, thereby enabling studies of fluid flow never before possible.

## 1. INTRODUCTION

### A. Overview

The Nanogate is a micro-mechanical device that can accurately and repeatably control a nanometer-sized gap. The circular flexure structure is etched in silicon then selectively bonded to a Pyrex 7740 substrate. A piezoelectric ring actuator is positioned on top of the 150 μm-thick Nanogate diaphragm using pick-and-place assembly, then eutectically bonded to ensure electrical contact. The diameter of the Nanogate diaphragm is 7 mm. The overall die size is 10 mm. Surrounding packaging permits the inlet and outlet of gases or liquids, and fixtures the Nanogate relative to the optical interferometer used for position sensing.

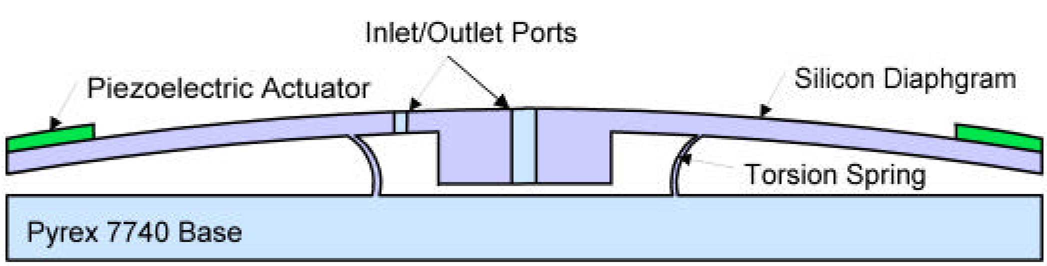


**Figure 1: Nanogate structure (deformed)**

### B. Gas Flow

Here, the NanoGate is being used to investigate fluid flow effects at extremely small length scales. Prior research at UCLA by Prof. C.M. Ho, for example, looked at gas flows in microchannels with a Knudsen number[1] of 0.058. In our estimation, the Nanogate will allow us to experimentally determine the properties of gas flows with a Knudsen number of 1 to 10, using an adjustable mechanism. Initially, the leak rate of helium through the Nanogate will be tested against a NIST calibrated leak using a conventional helium leak detector. This will provide experimental comparison to the well-understood theory of molecular gas flows, and determine the Nanogate's viability as an adjustable leak standard.

### C. Liquid Flow

A further experiment will be to investigate the properties of pressure driven liquid flows confined to a narrow gap. This area of fluid mechanics – "nanoscale fluidics" has not been widely studied, however several groups have conducted studies in this regime, using the surface force apparatus. These studies have shown an unexpected dependence between the confinement of the liquid, and variations in the bulk properties such as viscosity and density [3,4,5]. One hypothetical explanation for this change is shown graphically in Figure 2 below. As the size of the gap in which the fluid flows is reduced, short-range ordering—vitrification or crystallization occurs, increasing the viscosity of the liquid.

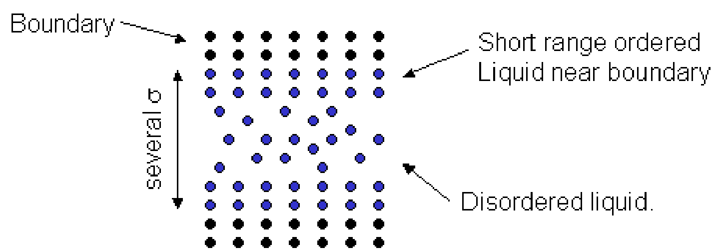


**Figure 2: Hypothesized non-continuum behavior of a liquid**

Furthermore, unexpected variations in "slip length" as a function of the liquid-air wetting angle have been observed [6]. Here, certain Newtonian fluids appear to be less viscous than expected at short length scales! The Nanogate will be used to quantitatively verify these results, which appear to violate the assumptions of a no-slip boundary condition, and a continuum liquid governed by Navier-Stokes' laws.

## 2. THEORY

### A. Gas Flow

It is well known that the Navier-Stokes equations governing gas flow do not adequately model flows at low pressures or at very small length scales. The Knudsen number (Kn = ?/L), gives a quantifiable indication of when a correction to Navier Stokes is required.

For example, at Knudsen numbers greater than 0.01, the no-slip boundary condition fails, and higher-level approximations to the flow boundary conditions are required. This is the slip-flow regime, and is of interest to MEMS microchannel designers. The conductance in this region is modeled by [1]:

---

[1] $Kn = \lambda/L$, where $\lambda$ is the mean free path of the molecules in a gas.

$$\frac{\dot{m}}{\Delta P} = \frac{H^3 w}{12\mu LRT}\bar{P} + \frac{H^3 w}{2\mu LRT}\frac{2-\sigma_m}{\sigma_m}K_o P_o \quad (1)$$

Here, $K_o$ is the Knudsen Number, and $\sigma_m$ is the transverse momentum accommodation coefficient (TMAC), a measure of the fraction of transverse momentum exchanged between the gas and the wall in a collision.

Beyond slip-flow is a transition flow region (Kn > 0.1), where high-order boundary conditions for Navier-Stokes equations are no longer valid, and Boltzmann transport equation begins to govern the flow. This is the region in which the Nanogate operates.

At very high Knudsen numbers (Kn > 1), the flow is governed by the Boltzmann transport equation. Various numerical techniques for calculating the flow in this regime have been demonstrated. However, limited experimental investigations have been performed, due to device constraints. In particular, experiments involving the flow of gases at atmospheric pressure, through nanometer-sized channels, are of interest in this case.

The Nanogate enables us to investigate these high Knudsen number flows with an adjustable mechanism. For example, for nitrogen at STP, the mean free path is approximately 90 nm. For a 10 nm slit, Kn = 9. For a slit 1000 nm high, Kn = 0.09. Therefore, the operating regime of the Nanogate ranges from molecular to slip-flow.

### B. Liquid Flow

Preliminary molecular dynamics (MD) simulations of liquid flow in a narrow channel predict some nonlinear dependence between channel size and viscosity. For very narrow channels, the viscosity of the liquid increases substantially. Tabulated below are the results of an MD simulation of liquid Argon at 100K with a fluid film thickness varying between 4 and 12 atoms, confined between a solid Xenon framework.

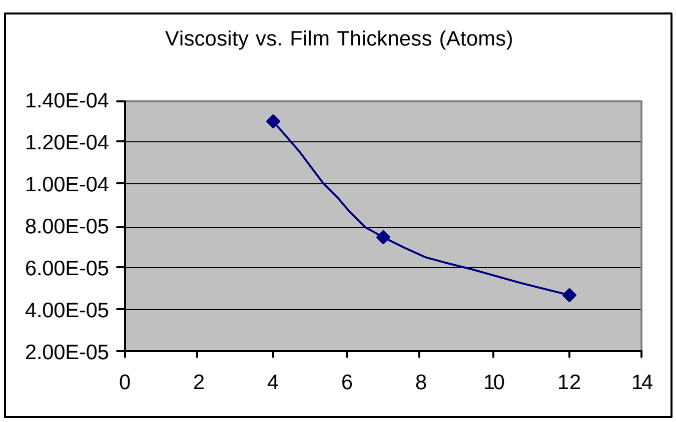


**Figure 3: Plot of viscosity as a function of film thickness**

Clearly, the viscosity increases substantially as the fluid film thickness decreases, although the calculated results are consistently less than the experimentally determined bulk value of 1.77 x $10^{-4}$ kg/m·s.

## 3. DESIGN OF NANOGATE:

Initial Nanogate designs were ill-conceived since they relied heavily on conventional machining and polishing techniques, making the cost of the first functional prototype prohibitive. Further work applied microfabrication techniques to the manufacture of the Nanogate valve. This proved to be highly effective in producing larger quantities of Nanogate valves with greater consistency in the results. Furthermore, the integration of the actuator (and, ultimately, leak rate sensor and displacement feedback) gives a far more useful, compact and inexpensive device than previously available.

FEA modeling of the Nanogate structure confirmed that the mechanical transmission ratio will be 20:1, with a 2.5 micron maximum deflection of the center valve land.

## 4. FABRICATION PROCESS AND RESULTS

The Nanogate structure was etched on the STS DRIE machine at MIT's Microsystems Technology Laboratory. Two images of the bare silicon etched structure are shown below. The multiple valve lands in Figure 4 are anticipated to improve sealing and resistance to particulate contamination.

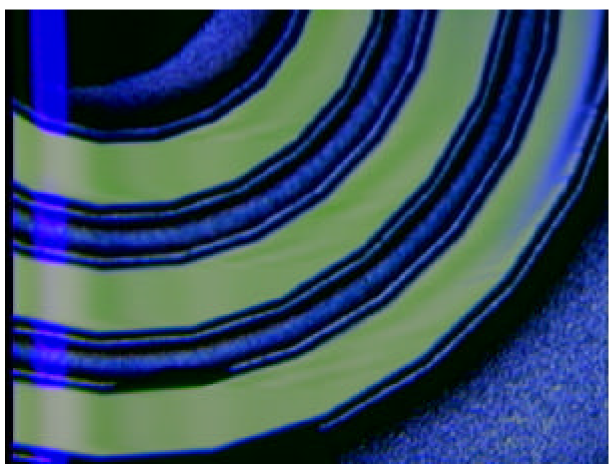

**Figure 4: Nanogate valve land with multiple rings**

The flexure attachment shown in Figure 5 is intended only for structural support during bonding, and for electrical grounding after the piezoelectric actuator has been mounted.

**Figure 5: Detail of flexure attachment**

Selective anodic bonding of the silicon diaphragm and the pyrex substrate has not been completed as of this writing.

## 5. CONCLUSIONS

Fabrication of a silicon micromachined Nanogate with piezoelectric actuation is well underway. Initial work with a macroscopic prototype confirmed that the Nanogate principle was viable, and that a Nanogate structure could seal effectively. Work is progressing rapidly towards testing and characterization of a micromachined Nanogate.

## 6. REFERENCES

1. E.B. Arkilic, "Measurement of the Mass Flow and Tangential Momentum Accomodation Coefficient in Silicon Micromachined Channels," MIT Ph.D Thesis, 1997.
2. Kittel, "Thermal Physics," McGraw-Hill, 2.ed, 1980.
3. D.Y.C. Chen and R.G. Horn, "The drainage of thin liquid films between solid surfaces," J. Chem. Phys., 83 (10), 15 Nov. 1985, p. 5311-5323.
4. Dhinojwala, A. and Granick, S., "Relaxation time of confined aqueous films under shear," J. Am. Chem. Soc., 1997, 119, 241-242.
5. Heuberger, M. et. al., "Density fluctuation under confinement: when is a fluid not a fluid?," Science. v. 292, May 4, 2001 p. 905-908.
6. Zhu, Y. and Granick, S. "Rate Dependant Slip of Newtonian Liquid at Smooth Surfaces," PRL v. 87 no. 9, 27 Aug. 2001.

## 7. ACKNOWLEDGEMENTS

This research was funded by an NSF award, number 9900792. James White acknowledges the generous support of the Hertz Foundation.

We would also like to thank the following people for their contributions: **Dr. Albert Lee and Patrick Abbott** at the National Institute of Standards and Testing in Gaithersburg, MD facilitated the high precision flow measurements.

**Alexander Henry Slocum**
**Professor of Mechanical Engineering**

**Education**

Ph.D. in Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, June, 1985, "Sensor System Design to Determine Position and Orientation of Articulated Structures"

**MIT Service** **13 years**

| Position | Beginning | End |
|---|---|---|
| Assistant Professor (CE) | Sept. 1985 | July 1989 |
| Assistant Professor (ME) | July 1991 | July 1992 |
| Associate Professor (ME) | July 1992 | July 1995 |
| Associate Professor (ME, tenured) | July 1995 | July 1998 |
| Professor | July 1998 | Never |

**Other Related Experience**

| Employer | Position | Beginning | End |
|---|---|---|---|
| NIST | Mechanical Engineer | June 1982 | Sept. 1986 |
| Cranfield Inst. Tech. | Visiting Professor | Oct. 1989 | Oct.1990 |

**Patents (58 granted total, more pending)**

1. A. Pfahnl, A. Slocum, J. Lienhard, "Heat-transfer enhancing features for semiconductor carriers and devices ",#6,036,023, Mar. 14, 2000
2. A. Slocum, L. Muller, "Integrated Prober, Handler, and Tester for Semiconductor Applications", 6,024, 526, Feb. 2000
3. A. Slocum, M. Chiu, "Interface Apparatus for Automatic test Equipment ", #6,104,202, August, 2000
4. A. Slocum, "System to Test Trays of Integrated Circuit Packages", #6,097,201, August 2000.
5. A. Slocum, "Linear motion carriage system and method with bearings preloaded by inclined linear motor with high attractive force", #6,150,740, Nov., 2000
6. M. Culpepper, A. Slocum, "Quasi-Kinematic Coupling and Method for Use in Assembling and Locating Mechanical Components and the Like", # 6,193,430, Feb. 2001
7. A. Slocum, K. Wasson, "Damped tool holder and method", #6,280,126, Aug, 2001

**Principal Publications for last five years**

1. *Marsh, E.R., Slocum, A.H., "An Integrated Approach to Structural Damping," Precision Eng., Vol. 18, Nos. 2/3, 1996, pp 103-109.
2. Schmiechen, P., Slocum, A.H., "Analysis of Kinematic Systems: a Generalized Approach", Precision Eng., Vol. 19, No. 1, July 1996, pp. 11-18.
3. Pfahnl, A. C., Lienhard V, J. H., Slocum, A.H., "Heat Transfer Enhancing Features for Handler Tray-Type Device Carriers", IEEE Transactions on Components, Packaging, and Manufacturing Technology Part C: Manufacturing, Vol. 21, No. 4, October 1998.
4. Kotilainen, M., Slocum, A. "Manufacturing of Cast Monolithic Hydrostatic Journal Bearings", Journal of the Int. Societies for Precision Engineering and Nanotechnology, Vol. 25 (2001), pp. 235-244.
5. Hale, L, Slocum, A, "Optimal design techniques for Kinematic Couplings", Journal of the International Societies for Precision Engineering and Nanotechnology, April 2001, vol. 24, number 2, pp. 114-127

**Honors & Awards**

1. SME 1993 Earl E. Walker Outstanding Young Manufacturing Engineer Award
2. SME 1997 SME Frederick W. Taylor Research Medal
3. Nine R&D 100 Awards -one of 100 best new technical products of the year (from 1994-1999)
4. Who's Who in America Science and Engineering
5. Martin Luther King Leadership Award (1999)
6. MacVicar Faculty Fellow (10 year fellowship for outstanding teaching)

7. Massachusetts 2000 Professor of the Year Award, Carnegie Foundation