# MEMS LUBRICATING AIR BUBBLE ARRAY

**Jack Yu and Debbie G. Jones**

Department of Mechanical Engineering
University of California, Berkeley
5109 Etcheverry Hall
Berkeley, California 94720

## ABSTRACT

Single atomic monolayer (SAM) technology will be used to design an air bubble array for the lubrication of MEMS devices with sliding and rotating parts. Patterning a matrix of hydrophobic patches on a hydrophilic substrate will result in an array of air bubbles formed by the repulsive behavior of water molecules with the hydrophobic surfaces. The performance of the air bubble array will be determined by using a serpentine spring force gauge to measure the static friction required to pull a hydrophilic shuttle across the patterned substrate. Force calculations for air bubbles under hydrostatic pressure and a uniaxial compressive load show that the air bubbles will be able to withstand the external forces acting upon it.

## INTRODUCTON

In MEMS devices with sliding and rotating parts, friction forces are the limiting factor to the successful performance of the device [1]. Previous work investigating the friction forces in micromotors suggests that hydrophobic lubricants are ideal for MEMS lubrication [1]. Alongside friction, adhesion is a common problem, especially in the fabrication process of various MEMS devices. Subjecting a structure to an aqueous rinse and dry cycle can form strong capillary forces that cause the collapse of beams and plates [1]. The application of a self-assembled monolayer (SAM) is a popular technique for creating hydrophobic surfaces that repel water to prevent adhesion [1,3-5]. There have also been recent studies on using SAM technology for fluid directing and fluidic self-assembly by patterning hydrophobic-hydrophilic surfaces [6,7].

This report investigates the use of SAM technology to design an air bubble array for the lubrication of MEMS devices with sliding and rotating parts. Patterning a matrix of hydrophobic patches on a hydrophilic substrate will result in an array of air bubbles formed by the repulsive behavior of water molecules with the hydrophobic surfaces (see Figure 1). If a hydrophilic mate piece is placed on top of the patterned substrate, the air bubbles will provide a buffer between the surfaces as long as the bubbles remain intact. Force calculations for a bubble under hydrostatic pressure and a uniaxial compressive load are in the Expected Results section.

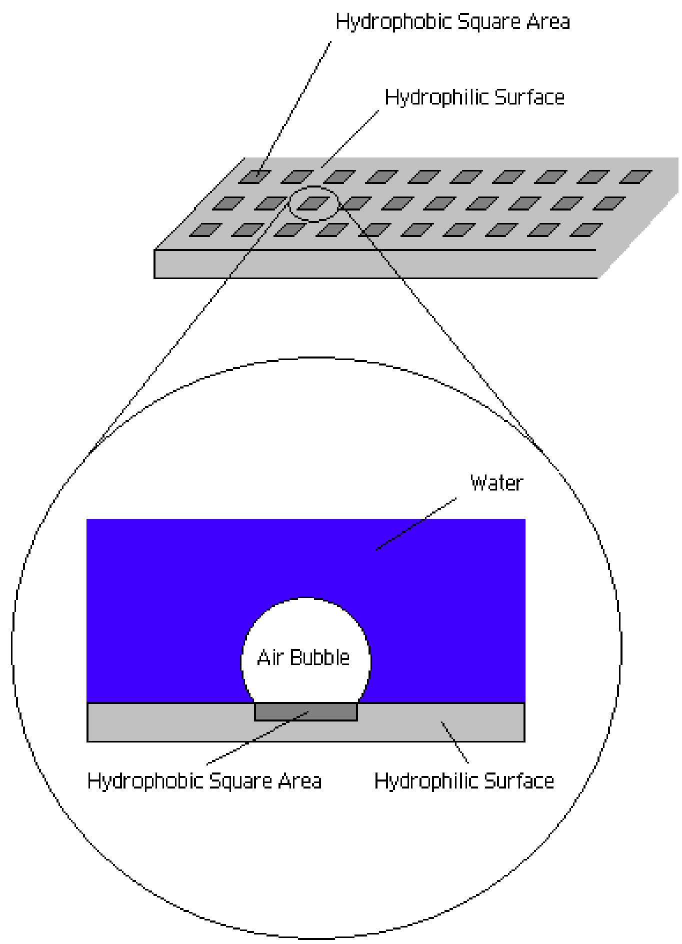


**Figure 1**: *Schematic of hydrophobic-hydrophilic patterned substrate with resulting air bubble formation.*

The performance of the air bubble array will be determined by using a serpentine spring force gauge to measure the static friction required to pull a hydrophilic shuttle across the patterned substrate. Test structures will be fabricated with various patch sizes and array dimensions for specified shuttle dimensions.

## DESIGN

*Air Bubble Array:*

A silicon substrate will be patterned with hyprophobic patches. Zhao *et al*. have demonstrated a technique for creating hydrophobic and hydrophilic regions in micro channels using a simple ultraviolet photopatterning process. A silicon substrate is cleaned with a methanol wash and made hydrophobic by growing a SAM on the surface. A photomask is deposited on the SAM-coated channel filled with a NaOH solution and patterned by exposing it to an ultraviolet light source. A final rinse with methanol reveals the hydrophobic-hydrophilic patterned substrate [6].

*MEMS Force Gauge:*

A serpentine spring force gauge designed by Richard Yeh (*University of California, Berkeley*) will be fabricated with a single mask process on an SOI wafer. The force gauge is composed of two springs with 12 beams of dimensions of 100µm x 2µm x 2µm, a vernier, and a pull ring. The pull ring will allow a probe tip to actuate the slider. The spring constant of the force gauge is estimated to be 0.4 N/m [8]. For the purposes of this investigation a shuttle (load) will be integrated into the force gauge for testing. The polysilicon structure will be defined with a deep-trench etch and released with an HF etch.

## TEST STRUCTURES

The performance of three air bubble arrays will be tested. Various regions of a hydrophilic silicon wafer will be patterned with arrays of hydrophobic patches. Table 1 shows the dimensions of various sizes of hydrophobic patches and array sizes that will be implemented for testing.

| *Test* | *Patch Size* | *Array Size* |
|---|---|---|
| 1 | 14µm x 600µm | 1 x 1 |
| 2 | 2µm x 2µm | 7 x 300 |
| 3 | 4µm x 4µm | 3 x 50 |

**Table 1**: *Table of patch and array sizes for test structures.*

Test 1 is for a single rectangular hydrophobic patch; one air void beneath the shuttle. Tests 2 and 3 are for square hydrophobic patches.

A hydrophilic shuttle with dimensions of 10µm x 600µm x 2µm will be integrated into the fabrication of the force gauge (Figure 2a). The force gauge will be placed on top of the patterned substrate and the whole system will be immersed in water to form the air bubble array beneath the shuttle. With a probe tip inserted in the pull ring of the force gauge the shuttle will be actuated as shown in Figure 2b. Measurements of the force needed to actuate the shuttle will be recorded. The same measurements will be repeated with an un-patterned silicon substrate for performance characterization.

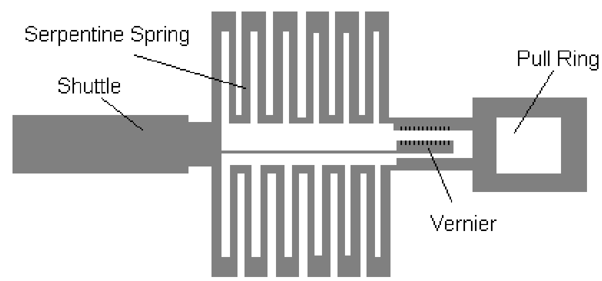


**Figure 2a:** *Schematic of serpentine force gauge with integrated hydrophilic shuttle.*

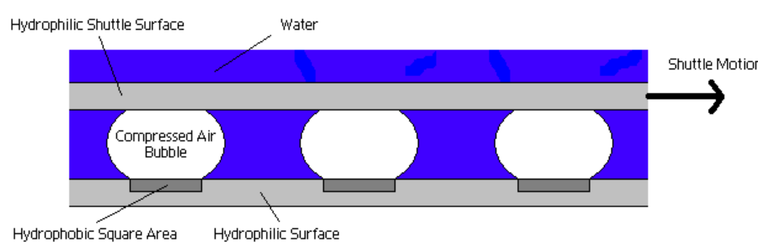


**Figure 2b:** *Schematic of hydrophilic polysilicon shuttle riding on air bubble array.*

## EXPECTED RESULTS

In the case of hydrostatic pressure and uniaxial compressive loading (i.e. the weight of the shuttle), an air bubble will be modeled as a cylinder with bowed load-bearing walls, as shown in Figures 3a and b.

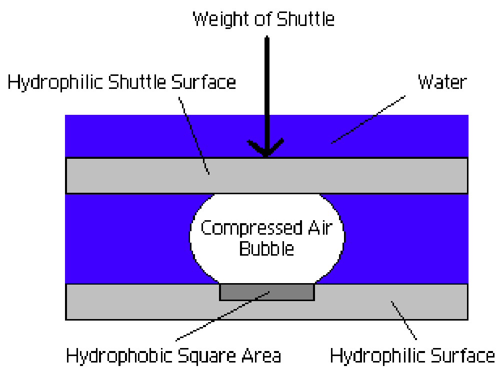


**Figure 3a**: *Theoretical model of air bubble subjected to hydrostatic pressure and uniaxial compressive loading.*

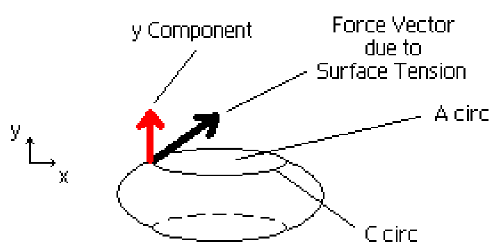


**Figure 3b**: *Model of force due to surface tension in an air bubble.*

An air bubble will remain intact if the force due to the supposed surface tension is not exceeded by the sum of the force due to net pressure and the compressive uniaxial force;

$$F_{ST} \geq F_{Pressure} + F_{Shuttle} \tag{1}$$

where $F_{ST}$ is the force due to surface tension, $F_{Pressure}$ is the force due to hydrostatic pressure, and $F_{Shuttle}$ is the weight of the polysilicon shuttle.

$$F_{ST} = \gamma C_{Circ} \tag{2}$$

where $\gamma$ is the surface tension of an air bubble and $C_{circ}$ is the circular perimeter of the cylinder as indicated in Figure 4.

$$F_{Pressure} = P_{Net} \cdot A_{Circ} \tag{3}$$

where $P_{Net}$ is the pressure difference across the air bubble and $A_{circ}$ is the circular area of the cylinder as indicated in Figure 4.

$$P_{Net} = \rho_{Water} g h \tag{4}$$

where $\rho_{Water}$ is the density of water, $g$ is gravity, and $h$ is the height of water in which the test structure is immersed.

$$F_{Shuttle} = \rho_{Poly} \cdot V_{Shuttle} \cdot g \tag{5}$$

where $\rho_{Poly}$ is the density of polysilicon and $V_{Shuttle}$ is the volume of the shuttle.

Equation 1 shows that increasing the circular perimeter of the cylinder will increase the force due to surface tension. This perimeter value may be increased by making the air bubble larger or by forming multiple air bubbles from an array of hydrophobic areas. Thus, the total circular perimeter from each air bubble in the array may be defined as

$$T_{Circ} = N \cdot C_{Circ} \tag{6}$$

where $N$ is the number of air bubbles, and $T_{Circ}$ may replace $C_{Circ}$ in Equation 2.

Table 2 summarizes the expected forces due to surface tension, hydrostatic pressure, and weight of shuttle for three test runs.

| *Test* | *$F_{ST}$ (μN)* | *$F_{Pressure}$ (μN)* | *$F_{Shuttle}$ (nN)* |
|---|---|---|---|
| 1 | 85.96 | 0.824 | 0.137 |
| 2 | 252.0 | 0.177 | 0.137 |
| 3 | 168.0 | 0.235 | 0.137 |

**Table 2**: *Table of expected results from test structures.*

## DISCUSSION

If the static frictional force is less when the contact surface is patterned with an array of hydrophobic patches than when the surface is unpatterned and hydrophilic, then the air bubbles formed on the hydrophobic patches most likely remained intact as predicted. If, however, the force is not less, then it is possible that the theoretical assumptions were incorrect, i.e. the air bubbles could not withstand the weight of the shuttle. A more thorough investigation of air bubble integrity would have involved examining the free energy of the surface, as well as the stiffening properties under uniaxial compression. It is also possible that the corners of the hydrophobic patches were stress inducers and led to air bubbles that were less stable than if they were completely spherical or even cylindrical as theorized. The shear force induced by the moving shuttle could have ruptured these less stable air bubbles.

## CONCLUSION

If the testing of the air bubble array is successful, implementing this technology in sliding and rotating MEMS devices could significantly reduce frictional forces detrimental to device performance. In addition to device refinement, this technology could also lead to development of new devices, such as a frictionless valve for fluid flow control in microfluidics.

## ACKNOWLEDGMENTS

The authors would like to thank Professor Kristopher Pister (*Department of Electrical Engineering*) for discussions about the investigation. Recognition should also be given Professor A. P. Pisano (*Department of Mechanical Engineering*) for his support and guidance.

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