Oscillating MEMS: the dazzling dynamics of microelectromechanical systems

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Abstract

This report discusses experimentation with designing and producing silicon-based MEMS devices for the purpose of testing specific features of liquid helium. Several designs of devices, which have a range of gap sizes and spring constants, have been investigated. This will allow for variety of data in the final experiment. The devices were designed in Tanner EDA's layout program, L-Edit. Then, the designs were sent to the commercial company Multi-User MEMS Processes (MUMPS) for fabrication. Between six and eight devices were "printed" on a chip. When the chips arrived at our lab, they underwent a manual assembly line that included dicing, releasing, and wire bonding. Last, each device was tested for maximum voltage to be withstood and for its peak resonant frequency. In the following sections I will describe in depth the meaning behind the basic design and variations, the fabrication process that took place at PolyMUMPS, how we prepared the devices, and how we tested them.

Introduction

University of Florida Physics professors Yoonseok Lee and Ho Bun Chan, who specialize in cryogenics and microelectromechanical systems (MEMS) respectively, have been collaborating resources to run experiments on ^{3}He. A team from each lab has been preparing the tools, which include a probe that withstands the millikelvin temperature regime and a selection of functioning MEMS devices. The six-foot probe, primarily steal and copper, will cradle a MEMS chip in an annealed silver cell that helps to draw heat away from the device. The design allows room for a vacuum-forming pump and for the necessary electrical connections to run to the device. Miguel Gonzalez and Jaymin Javari are designing and building the probe with the guidance of Dr. Lee. Ho Bun Chan has been directing Konstantinos Ninios and me to prepare MEMS devices designed especially for the helium project. The name MEMS provides a general, useful description of the machinery encompassed by this category of technology. MEMS suggests that such systems have dimensions in the range of microns, involve electricity, and contain moving parts [1]. Though the umbrella of MEMS now covers larger ground, including systems that involve other forms of energy, the devices employed by this experiment hold true to their name. Each microscopic device converts electrical energy to mechanical energy: a voltage source charges up parallel plates attached at their corners by springs. Alternating current causes the two plates to attract and relax. At a unique voltage a given device will go into resonance. This information is fundamental to the ultimate aim of the project. By submerging activated devices into the liquefied isotope helium 3, the researchers hope to discover the temperature at which a thin layer of liquid becomes superfluid. At this temperature, the liquid will lose all its viscosity, and the device will resonate as freely as if in vacuum. This report will concentrate on the preparation of MEMS, providing details on how the devices are designed, constructed, and tested.

Design

The basic structure of each device consists of two silicon square plates about 200 microns on a side separated by a gap of 2 microns high. Holding the plates together at each corner is a spring that bears resemblance to a mechanical frog leg (see Fig. 1.) The bottom polysilicon plate is attached to a ground of electrically resistant silicon nitride that isolates the device from the substrate. Each device requires three electrical connections. Figure 2 shows electrodes running to the bottom plate, and Figure 3 shows the bonding pads that connect to the electrodes. Referring to this image, the bonding pad at the bottom wraps around to the sides of the lower plate, which is separated from the center portion. The center of the bottom plate is connected to the bonding pad at the upper left, and the top plate is connected through the top right bonding pad through the corresponding spring. A direct current can be applied to the sides of the bottom plate. This current will excite the top plate to move downwards. When I apply an alternating current between the top and central bottom plate, a capacitance bridge can measure the changing capacitance. The simple relationship (where C is capacitance, A is area per plate, d is separation, and ϵ the permittivity of space)

$$C = \epsilon \mathrm{A}/d \tag{1}$$

easily transforms the capacitance to distance, informing me about how far the plate travels. The top plate can travel about one third of the total gap distance to the bottom plate before it snaps down and “sticks” to the bottom plate. When too much voltage is applied and the plates snap together, a thin glass needle must be maneuvered between the plates. By lifting up from underneath the top plate, I can restore the device to its original condition. Unfortunately, it is also possible to destroy the device (see Fig. 3 for an approaching needle.)

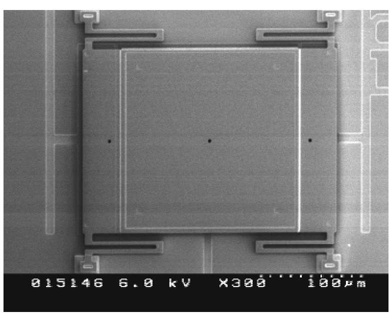

Fig. 1. Device from above.

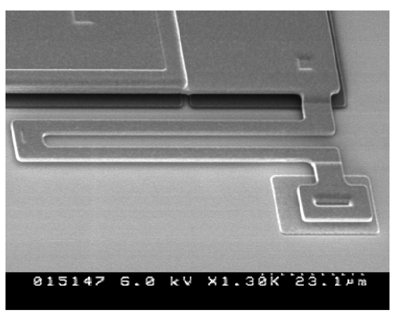

Fig.2. Detail of spring.

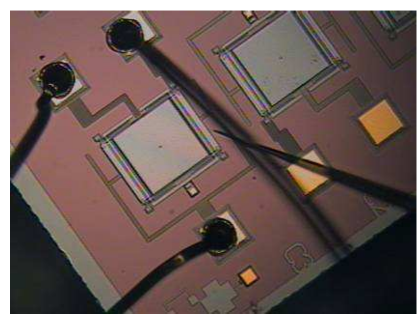

Fig.3. Device, wire bonds, and thin glass needle.

Variations

The two primary variations in the designs occur in the height of the gap between the plates and in the stiffness of the springs. Three polysilicon layers are required to form the two plates. The height of the middle layer, attached to either the bottom or top, determines the size of the gap. There are three gap sizes: 0.75 microns, 1.25 microns, and 2 microns. In addition to the distance between the plates, the spring constant can be altered. The stiffness is related to the length of the spring. Shorter springs require more voltage to move the top plate. We have made devices which range from twice as stiff to five hundred times as stiff as the original system. Other variations involve subtle differences in the materials layered. We designed the devices and the layout of the devices on the chips, and then shipped the layouts to PolyMUMPS, the branch that fabricates triple-layer polysilicon micromachines [2]. PolyMUMPS uses a layering and etching process to form the individual devices. Figure 4 shows a 16 square map of chips, and Figure 5 shows a detail of the chip from the second row and first column. Four grounding pads can be counted along the edges of this chip.

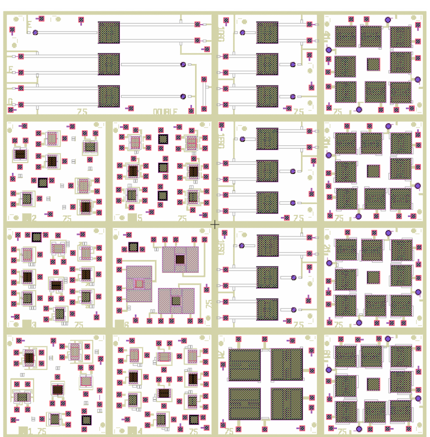

Fig.4. Design of 15 chips (the one at the top is doubled).

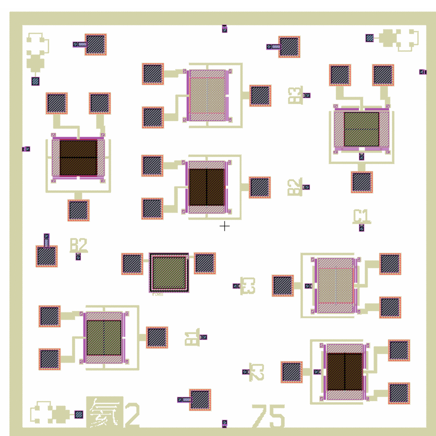

Fig.5. Detail from layout.

PolyMUMPS

At PolyMUMPS, the chips were formed by a layering and etching surface-micromachining process. The process begins by coating a silicon wafer with silicon nitride to keep future devices electrically isolated. The surface is then covered with the first thin layer of polysilicon, Poly0, and after that with a sheet of UV-sensitive photo resist. By exposing this layer to UV light and developing it, the photoresist is lithographically patterned into a mask for etching. According to the PolyMUMPS design handbook, “reactive ion etching (RIE) is used to remove the unwanted polysilicon. After etching, the photo resist is chemically stripped in a solvent bath” [3]. This etching process is used by PolyMUMPS repeatedly with other layers of material, including Poly1, Poly2, metals, and oxides. Metals form the bonding pads. To create the gap in our devices, a sacrificial layer of silicon oxide is patterned between the layers of polysilicon. We have PolyMUMPS return us the devices with this oxide layer intact. At our lab, we remove this layer with an acid bath. Once the layer is removed, the devices on the chip are very fragile. The basic etching process is illustrated bellow in figure six.

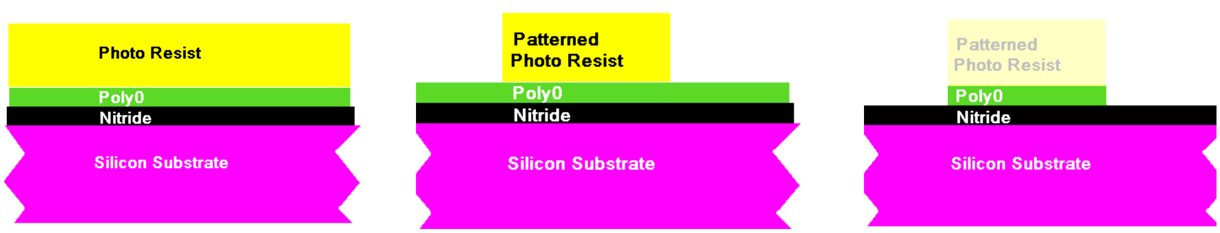

Fig. 6. Illustration of steps in etching process.

Releasing

Releasing refers to the process of removing the silicon oxide from in between the plates, thereby creating the gap that allows the plates to oscillate. Before we removed this silicon oxide layer in the lab, we first had to dice the chips. This broke a solid group of 16 chips into individual pieces. The chips were glued with photoresist to keep them steady during the dicing.

The photoresist sticks to the silicon and had to be cleaned before we released the chips. Photoresist was removed with consecutive soaks and rinses in acetone and isopropanol. After several minutes in each solution, the chips were picked up with tweezers and blown dry with an air gun. We had to be careful to hold the chips firmly, lest they fly around the chemical hood. Once they were dry, we prepared the chips for releasing, a brief but perilous task that involved the very toxic hydrofluoric acid. Hydrofluoric acid can eat through skin and dissolve the bone's calcium *unbeknownst* to the victim! This is highly problematic and has caused fatalities in the past. Therefore, the HF soaking process was taken seriously. One person wore protective gear while transferring the chips, and another person stood watch. After seven minutes the chips and tools were rinsed thoroughly in DI water.

To dry the chips at this point in the process was not as simple as using the air gun, as we had done after rinsing in isopropanol. Hydrofluoric acid had crawled through the sides and through tiny holes in the tops of devices, and had eaten away the silicon oxide layer. Now the devices had a real gap. Even small gusts of air could destroy the sensitive machinery. A critical point dryer carefully changed the medium surrounding the chips from liquid to gas. First, the chips were soaked in methanol. We placed the chips in a small metal cradle and then placed this cradle into the round cage of the critical point dryer, which we had also filled with methanol. The temperature and pressure were such that carbon dioxide would enter the chamber as liquid. Carbon dioxide liquid is mixed into the methanol in small stages. In stages we emptied some methanol, stirred in CO_2, emptied some of the new mixture, stirred in more CO_2, and so on for six or seven rounds. Once we were certain that the majority of the liquid was carbon dioxide, we slowly raised the temperature. The liquid gently transitioned to a gas, which phase change we watched happen through the dryer's window. The pressure was released. The devices were ready to be wire bonded.

Wire Bonding

Considerable time and energy had already been invested in the devices. Before proceeding to the wire bonding process, we checked each device under the optical microscope to make sure it was intact. Since it is possible for springs and top plates to break during the release, we checked them first. Each chip was glued to an individual ceramic package. These round packages have 20 gold pins available for electrical connections. The probe has a holder for round packages. Only three of the pins have been connected, and the rest have been grounded. So far, I have only been able to wire two or three devices on a chip to the package, but in the ideal case there would be four. For the devices to be wired appropriately for the fixed connections in the probe, they must be done in consecutive symmetry. If the sides, top plate, and bottom plate are wired in that order for one device, they must be done so for all devices on all chips. Figure 7 shows a schematic wiring diagram and Figure 8 shows a side-view. The wire bonder resembles a high tech sewing machine with a mobile capillary threaded with hair-like golden wire. The first of each bond compresses a soft golden ball to the bond pad of a device. Then we direct the capillary by way of an attached handle to one of the flat gold pin heads of the ceramic package. The second bond is a pressure bond, which clips off the wire with force. Often this second bond fails to stick and we are left to correct errors with jury-rigged last resorts.

If the wires drooped or took on strange shapes, we redirected them with fine tweezers. All of these processes were done underneath an optical microscope. A minor misdirection of the hand ruined my work on several occasions.

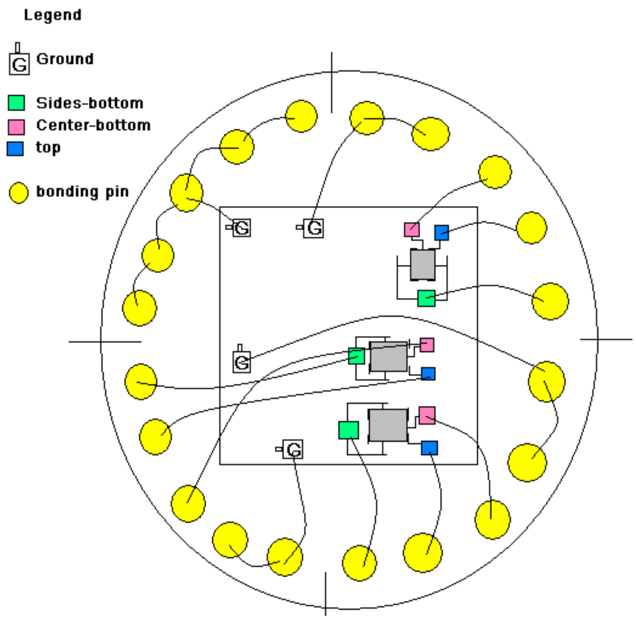

Fig. 7. Sample wiring diagram. Three devices are connected to the bonding package.

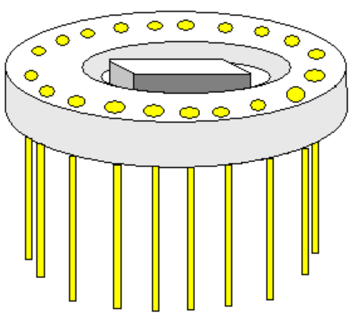

Fig. 8. Side view of a chip mounted to a bonding package.

Retrieving Data

A specially tailored holder with 20 sockets had already been prepared for the round packages. The holder has six available connections. Because any given device only requires three connections, we grounded three extraneous connections at the site of the holder. We then lined up the three consecutive pins that correspond to the wired device with the three available connections on the holder. We connected a capacitance bridge to the top plate and central bottom plate. We applied a small alternating voltage to these plates- 0.1 volts. We then applied a direct current to the sides of the bottom plate. As we increased the voltage along the sides of the bottom plate, the top plate drew in nearer to the base. As the separation decreased, the capacitance bridge showed an increase of capacitance. When the devices snapped down, the capacitance stopped increasing. Looking at a sample plot of capacitance vs. voltage (Figure 9), we see that the rate of change for the increasing capacitance rises as the device approaches snapping down. This reflects the inverse relationship between capacitance and distance. Table 1 provides information on a selection of devices, including the initial gap, the spring constant, and the snap-down voltage. All devices in a particular series (the A's for example) will have the same spring constant. The initial number in the case of 5B2 denotes a spring that is five times stiffer than that of the B2 device. The suffix numbers 1, 2, and 3 describe the initial gap between the plates. Once devices had been snapped down, the glass needle was carefully guided between the two plates to gently pry them apart. When this worked, the springs restored the device to its initial condition.

We also measured the resonance of the devices. For this process, we sealed a chip in a 3 millitorr vacuum and connected a device to the appropriate equipment. The top plate was grounded. The sides of the bottom plate were connected to an AC-DC coupler. The AC was connected to a function generator. Direct current was applied and increased to find the resonant frequency. The central portion of the bottom plate was connected to a pre-amplifier and was given 0.2 volts. The central bottom plate allowed us to measure the changing amplitude of the device. Figure 10 shows a schematic view of the electrical connections used to measure the resonance, and Figure 11 shows a plot of data for device A1. The peak amplitude for this device occurs at about 1.647 volts.

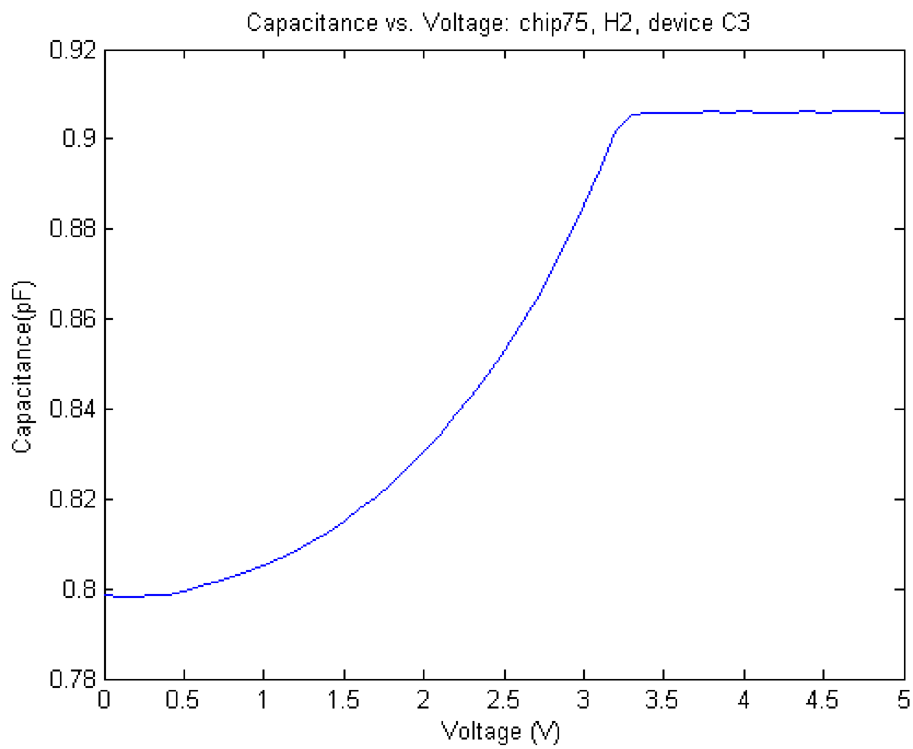

Fig. 9. Voltage vs. capacitance. The top plate snaps down at about 3.3 V. Since it stops traveling down, the capacitance reading stays the same even as voltage is increased.

Table I. Specific information about five devices.

Device	Initial Gap (µm)	Spring Constant (Kz)	Snap-Down Volt. (V)
A1	2	2.1226	7.35
A2	1.25	2.1226	6.5
A3	0.75	2.1226	6.67
C3	0.75	1.8714	3.3
5B2	1.25	10.232	10.89

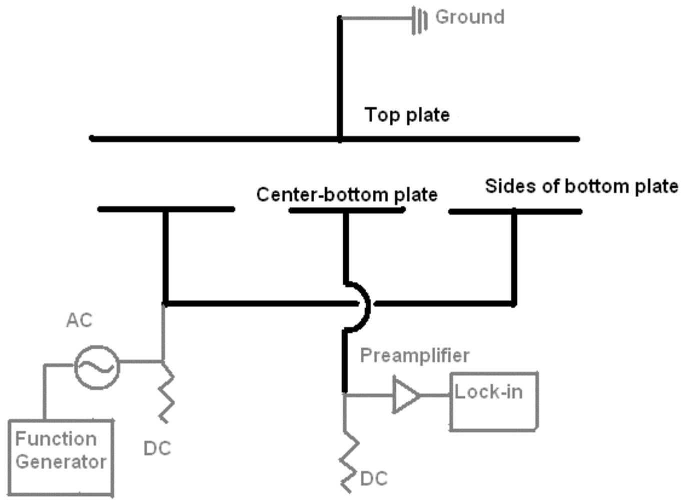

Fig. 10. Wiring scheme for measuring resonance. The device is shown in black and the equipment is shown in grey.

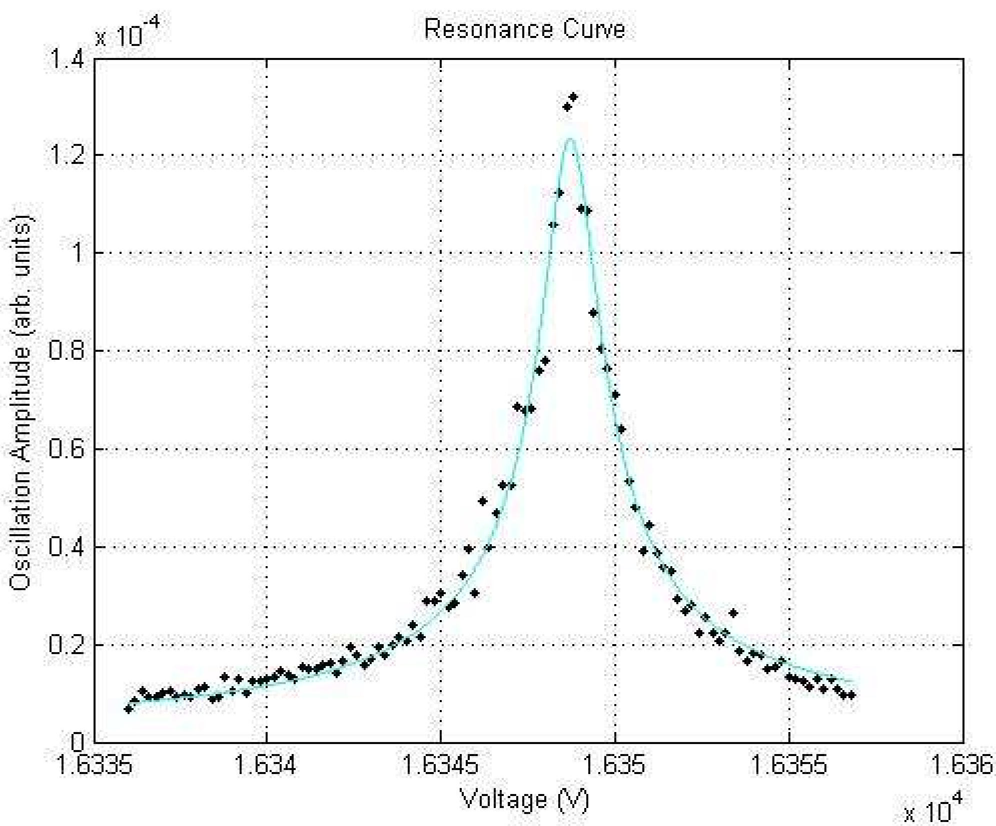

Fig. 11. Resonance curve for device A1.

Summary

Working with MEMS is an involved procedure that requires a great deal of hands on work even after fabrication. Preparing the devices takes time, and it is not uncommon to release a chip, wire the devices, and record the data only to break the devices while putting them away. Nevertheless, we continue to assemble the devices and record data in pursuit of the helium project. Once we have the snap-down voltage and resonant frequency for the devices in vacuum, we will be able to compare that data with data taken from devices in liquid helium.

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References

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[2] David Koester, Allen Cowen, Ramaswamy Mahadevan, Mark Stonefield, and Busbee Hardy, PolyMUMPS Design Handbook, 2 (2003).

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