NE 455L/471 Nano Electronics MEMS Lab Report

University of Waterloo
4B Nanotechnology Engineering
Group 7

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Design and Fabrication of MEMS Devices

Introduction and Objective

The objective of this laboratory is to fabricate and test the two different MEMS devices that were designed in NE 454L last year. The entire laboratory was split into three periods. In the first two periods, a number of fabrication steps were performed in the clean room to create the patterns and structures desired. The last period enabled us to test the fabricated devices using a test regiment designed by us. The test regiment consisted of applying a reasonable range of inputs such as voltage, current, etc. and measuring device performance by recording output such as resistance, capacitance, etc. The motion of mechanical components was also visually examined using a microscope. Our design consisted of 3 different device designs with at least 4 replicas of each device: a) single cantilever, b) double cantilever, and c) thermal actuator. The fabrication results and analysis of these designs will be explained in this lab report.

First Device Results and Analysis (Single Cantilever)

The first device fabricated was a simple electrostatic cantilever that would swing upon the application of voltage. The lab report for NE 454L describes this device in detail. But the overall picture is as follows: A DC bias is applied to a chromium pad results in the accumulation of charge on one side of a capacitor that is made using an air gap and a silicon nitride (SiN) in between as the dielectric layer. This accumulation of charge generates an electric field causing the cantilever to bend downward towards the chromium pad. This bending motion will decrease the distance between the chromium pad and the cantilever which will be reflected by a change in capacitance. The design of this device is shown in Figure 1.

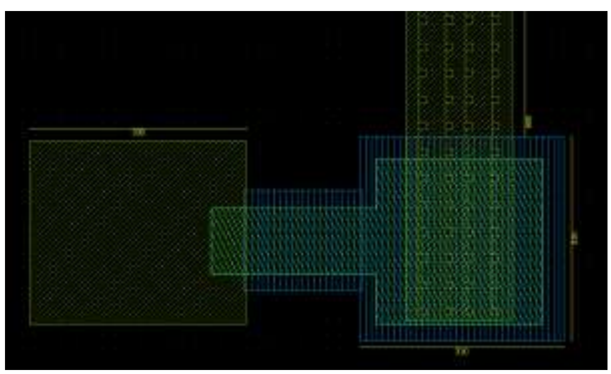

Figure 1 Design of Device 1 using Layout

The measured capacitance between the cantilever and the Cr gives us an idea of the distance, ie. the gap between the two using the equation $C=\varepsilon_r\varepsilon_o A/d$. The original capacitance with no bending was calculated to be $C=\varepsilon_r\varepsilon_o A/d$ = 1*8.854E-12 F/m*(152E-6 m *1E-6 m)/20E-6 m = **6.73E-17 F**. We used a capacitance meter to measure the capacitance between the cantilever and the Cr pad. Unfortunately, none of the 6 cantilever devices fabricated and tested (3 large, 2 medium, and 1 small) showed any signs of movement or change in capacitance upon application of voltages ranging from 0.1 V all the way up to 30 V. We did observe a capacitance reading on the nanofarad range when no voltage was applied and also rapid fluctuations in capacitance when light was shone on the wafer implying all the connections were good and that the capacitor works without any short circuiting. The only explanation for no observed change in capacitance is that the cantilever is being inhibited from moving somehow. We noticed a simple downward curling of the aluminum cantilever due to residual stress applied by the aluminum. In one sense, this is a good sign since it means that lift-off of the sacrificial photoresist layer was successful implying the cantilevers were in fact suspended in mid-air. We were also able to confirm this successful lift-off by visually observing the cantilever test structures designed by the lab instructor on the bottom-right corner of the wafer. Despite a successful lift-off, there is still the possibility that all 6 cantilevers were bent too far downwards due to the residual stresses applied by the weight of the aluminum layer causing them to touch and rest entirely on the substrate. This would imply that the capacitors weren't suspended in mid-air explaining the lack of motion and capacitance change upon application of voltage. But it doesn't explain the non-zero capacitance upon 0 voltage, but this could be due to a poorly calibrated capacitance-meter.

Figure 2 shows an SEM image of one of our largest cantilevers. It is hard to tell from the SEM image if the cantilever is suspended in mid-air or not. It was also hard to tell this from the optical microscope due to blinding along the z-axis.

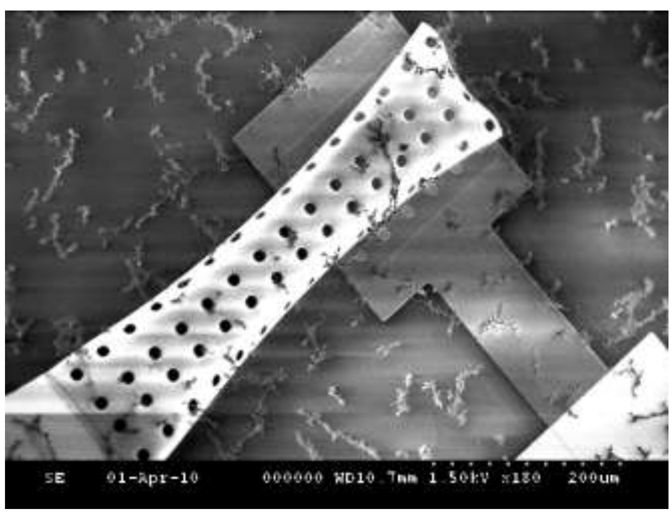

Figure 2 SEM Image of a Large Cantilever

We attribute the failure of this device to bad modelling during the design stage. We had used COMSOL multiphysics to do the modelling, but this model was too idealistic and did not incorporate any of the non-idealities introduced by the manual fabrication process. The COMSOL model forgot to take into account the loss of capacitance due to the presence of release holes. These release holes take away at least a third of our surface area. Furthermore, an overetch of the Al layer caused some of the release holes to widen a bit. Also, the model used predicted a capacitance change of 9.5E-2 pF upon application of 0.7 volts to the Cr pad. This capacitance (95 femtofarads) is too small to be detectable on the equipment provided.

Taking into account the release holes and the downwards bent cantilever due to residual stresses (Figure 3) into our model, two factors that reduce the overall surface area of the cantilever, will significantly decrease the 0-voltage capacitance. To compensate for these effects, we would need to increase the dimensions of the cantilever, and also increase the thickness of the photoresist layer to suspend the cantilever much higher from the bottom of the wafer.

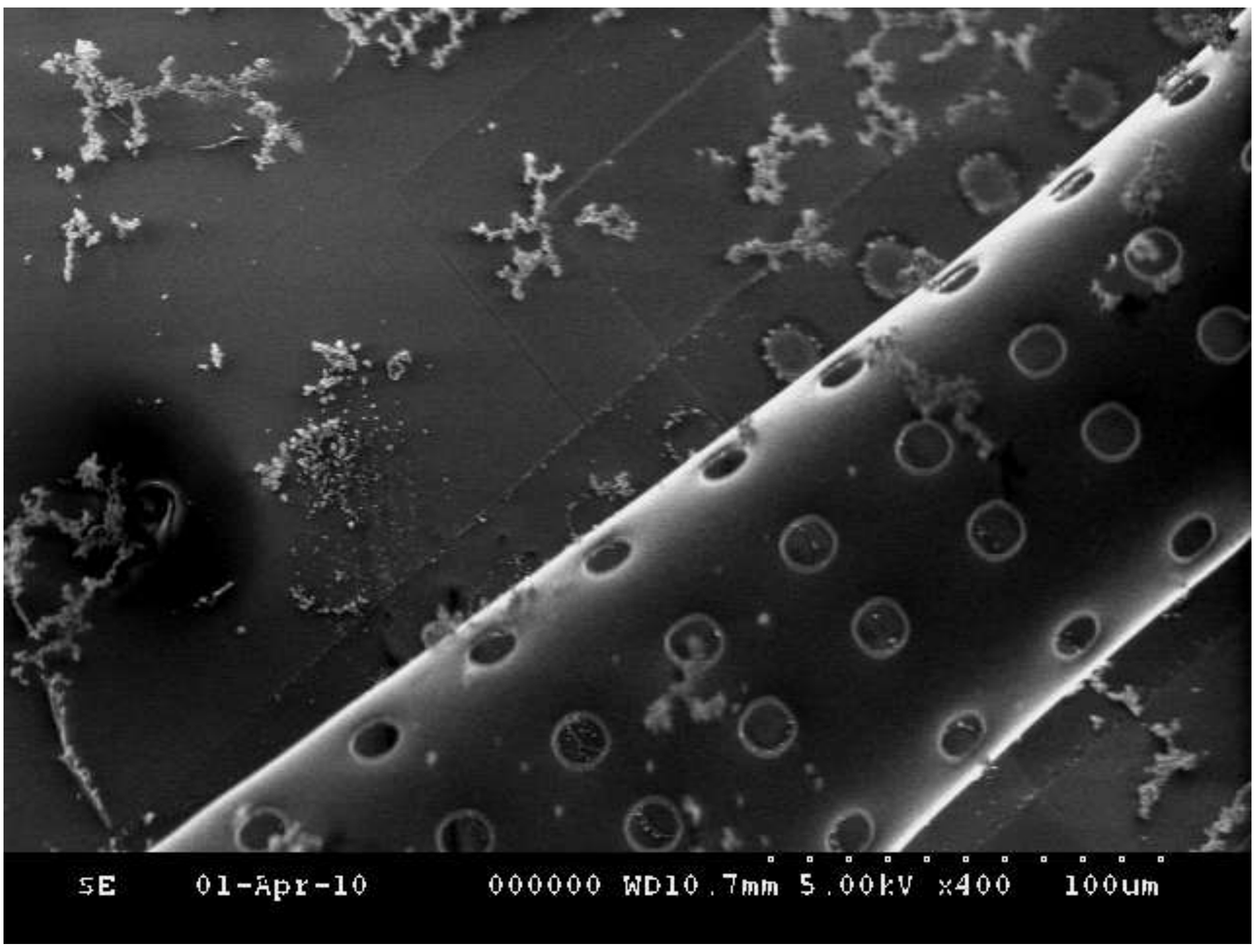

Figure 3 Bending of Cantilever and Decrease of Effective Surface Area

The SEM image above in Figure 3 also shows random bits of dust which we stipulate to be residue from burning away the photoresist. An EDX analysis in Figure 4 confirms that these “dust” artefacts aren’t metallic, and therefore some sort of organic residue from one of the fabrication steps.

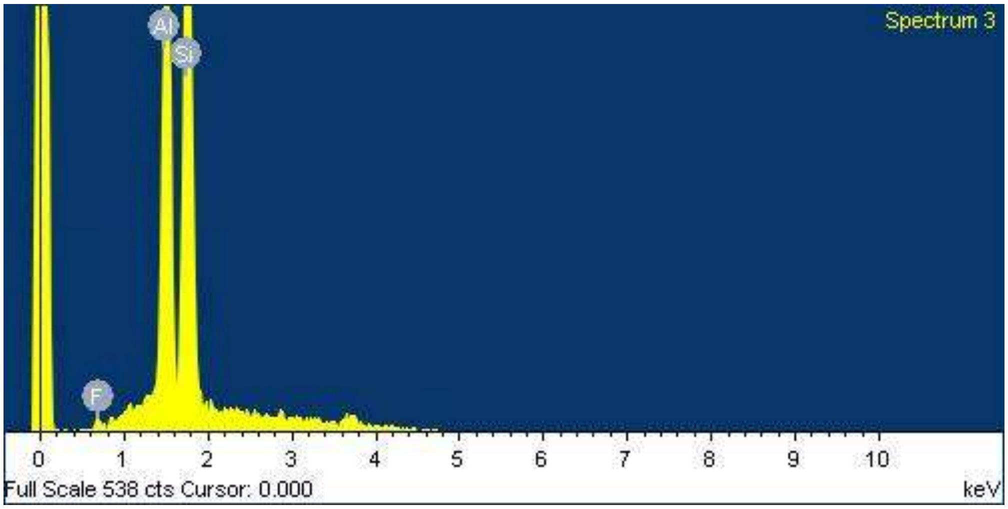

Figure 4 EDX Spectrum of the "Dust" Surrounding the Cantilever

The EDX was able to give us compositional information on these "dust" particles in Table 1.

Table 1 Compositional Analysis using EDX

Element	Weight %	Atomic %
Fluorine (F)	0.61	0.89
Aluminum (Al)	35.28	36.10
Silicon (Si)	64.11	63.02
Totals	100.00	100.00

The other type of cantilever, the double cantilever, was tested in much the same way as the single cantilever was. These double cantilevers did not show any movement either. Due to time constraints, we were only able to test one of the 3 double cantilevers fabricated. The only difference was that the positive bias was applied to the metal connect underneath the SiN layer instead of to the cantilever directly to check if this made any difference. The same reasons for failure apply to the double cantilever as described for the single cantilever.

Second Device Results and Analysis (Thermal Actuator)

The design of this thermal actuator device and operation principles can be found in the Lab 6 prelab and also the NE 454L lab report submitted last year. Figure 5 shows the layout and design of our device on the Layout software program.

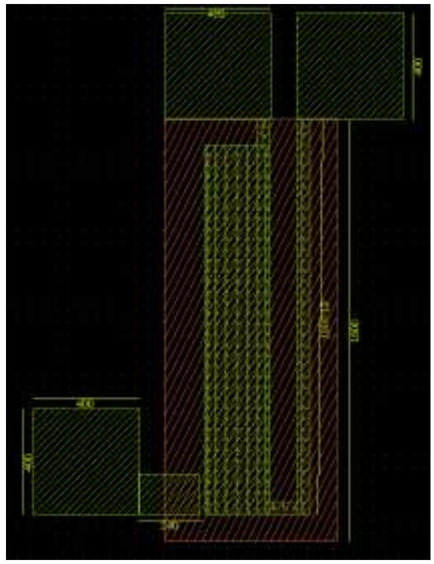

Figure 5 Layout and Design of the Thermal Actuator

We wanted to conduct two types of testing to the thermal actuator: AC and DC testing (see pre-lab for test plan). However, due to time restrictions, we were able to conduct only DC testing. AC testing would also have been significantly more challenging than simple DC testing.

The original plan was to apply a voltage and measure a current at the gate. Instead, we applied a DC current to the thin arm of our thermal actuators which caused the actuators to heat up, expand and actually move. This movement was observed visually through the optical microscope inside the probing station. We therefore conclude this device design and fabrication was successful.

The new plan was to measure the resistance across the actuator and the gate which was supposed to make our device work like a switch. We would know when the actuator makes contact with the gate since when this happens, the resistance value would drop noticeably since there is no longer an air gap between the two metals. However, only visual motion was observed; no resistance drop was observed presumably because the arms didn't move enough to actually touch the side gate before they cracked.

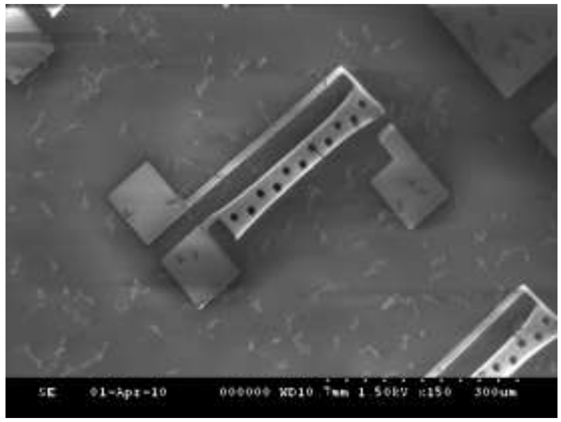

Figure 6 SEM Image of a Fabricated Thermal Actuator

The operation of the device as follows: Upon passing of current through the arms of the device, Joule heating will cause the arms to expand. However, the thinner arm will expand faster/more than the thicker arm resulting in non-uniform expansion and consequent bending of the arms in the direction of the thicker arm. This bending will hopefully be sufficient to cause the thicker arm to make contact with the side-gate seen above in Figure 6.

As seen in the first device, the COMSOL model which we used to verify our design did not take into account the release holes or the residual stresses from the lift-off. We also noted that the actuator did not actually make contact with the side gate since no drop in resistance was observed on the DMM. This makes sense since the resistance of air is on the order of 1E14 ohms which will not be registered on the DMM. However, at least bending of the arm was observed visually. All this implies the actuators were too far away from the gate, and so for next time, we would probably decrease the distance from 20 microns to say 10 or 15 microns.

The amount of current passed through the actuator was 1 ampere. This would cause a rapid shift of the arm towards the gate. Unfortunately, the current source used was not meant for such sensitive measurements, and turning off the source to allow the device to cool would cause a rapid downsurge of current resulting in the thin arm to snap into two as can be seen in the SEM images in Figure 7. This problem could be circumvented by not turning off the source completely but by just adjusting the maximum current setting to 0 A. Connecting the current source to a surge protector would also prevent rapid drops in current.

In total, 3 actuators were tested: 2 large-sized and 1 medium-sized. All 3 actuators showed bending before they broke-off as can be seen in Figure 7.

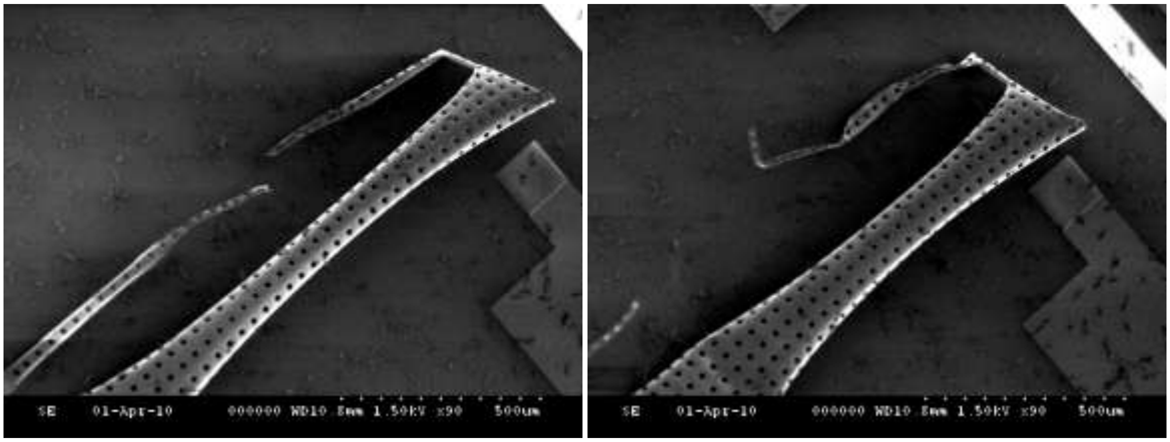

Figure 7 Damaged Thermal Actuators After Intrusive Testing

Conclusions

In conclusion, a lot was learned from our first MEMS fabrication and testing experiment. The primary lesson learned is that the fabrication process introduces numerous non-idealities into our devices that need to be incorporated into our COMSOL model during the verification phase in Lab 3. As such, just because the COMSOL model says our device will work doesn’t necessarily mean the device will actually work in practice. Especially when fabrication is being done manually by human beings, there can be several slight variations from procedures.

The second lesson learned was that the fabrication process is *extremely* sensitive to the timing and precision of the steps. The slightest mistake or deviation from procedure can cause device mal-functioning or complete failure. The third lesson learned is that debugging for reasons for device failure is a challenging task that requires a lot of insight and experience. Since there are so many steps in the fabrication process, it is hard to pin-point exactly which step caused the failure. Also, 1.5 hours was not sufficient to thoroughly perform failure analysis on all our devices. Perhaps 2 to 2.5 hours of access to the probing station would be adequate.

Overall, this laboratory was a phenomenal learning experience.