MICRO CANTILEVER BEAM FABRICATION AND CHARACTERIZATION

CHẾ TẠO VÀ KIỂM TRA ĐẶC ĐIỂM CỦA THANH MỀM CÔNG XÔN Ở KÍCH THƯỚT MICRO

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Abstract - Cantilever beam has become a ubiquitous structure which is utilized in many microelectromechanical systems (MEMs). For instance, piezoelectric cantilever beams are mounted into pressure sensors produced by Memscap or widely used in MEMs generators harvesting energy from vibration. In this paper, cantilever beams are designed and fabricated on silicon wafers. L-Edit software is used to design two masks for light exposure step. Fabrication process including photolithography, copper thermal evaporation, and etching is done to achieve the designed cantilever beams. The thickness of each layer is measured after each step to investigate the height of the cantilevers to the substrate. All lab work and accomplished results, in this report, will be represented in detail.

Key words - Cantilever beam; photolithography; MEMS.

Tóm tắt – Thanh mềm công xôn đã trở thành một cấu trúc phổ biến được sử dụng trong nhiều hệ thống vi cơ điện tử (MEM). Ví dụ, thanh công xôn áp điện được gắn vào cảm biến áp suất do Memscap sản xuất hoặc được sử dụng rộng rãi trong máy phát điện MEMs, nhằm thu năng lượng từ rung động. Trong bài báo này, thanh công xôn được thiết kế và chế tạo trên các tấm silicon. Phần mềm L-Edit dùng để thiết kế hai mặt nạ cho bước phơi sáng. Quá trình chế tạo bao gồm quang khắc, bay hơi nhiệt đồng và khắc được thực hiện để đạt được các thanh công xôn như thiết kế. Độ dày của mỗi lớp được đo sau mỗi bước để khảo sát chiều cao của công xôn so với nền. Tất cả các công việc trong phòng thí nghiệm và kết quả đã đạt được, sẽ được trình bày chi tiết trong báo cáo này.

Từ khóa – Thanh công xon; quang khắc; MEMS

1. Introduction

Microfabrication is a general term which is used to refer to microelectronic fabrication, MEMS fabrication, integrated circuit technology, etc… It is actually series of processes that apply various technologies in order to make micro devices. The cantilever beam is mostly used in many kinds of MEMS devices, such as micro sensors and actuators. For instance, piezoelectric cantilever beams are mounted into pressure sensors produced by Menscap or widely used in MEMs generators harvesting energy from vibration. This lab work concentrates on the practical aspect of three of these technologies - photolithography, physical vapor deposition (PVD) and etching. Its objective is to make a collection of copper cantilever beams on a silicon substrate using surface micromachining technique. Two masks will be used in photolithography process. The first one is to make a sacrificial layer (of photoresist) for the beams on the substrate which is then covered by a copper layer using PVD method. The copper-covered wafer is later coated by a second photoresist layer using spin coating. The second mask is used to transfer the beam patterns to the wafer. After developing the top layer and wet etching of copper, the exposed photoresist layer on the top and the bottom sacrificial layer will be removed by either wet etching or dry etching technique. The thickness of each layer is measured after each step to investigate the height of the cantilevers to the substrate as well as to see whether the beams are released and stiction occurs.

As shown in Figure 1, there are three main processes used to fabricate the copper beams. The first one is photolithography. Photolithography is one of the most important procedures in microfabrication technology. It uses light to transfer a given pattern from a mask onto a silicon wafer covered by chemical photoresist. It includes six minor steps which are wafer preparation, photoresist coating, pre baking, alignment and exposure, developing, photoresist striping. In this lab work, positive tone of photoresist will be used for the lithography process.

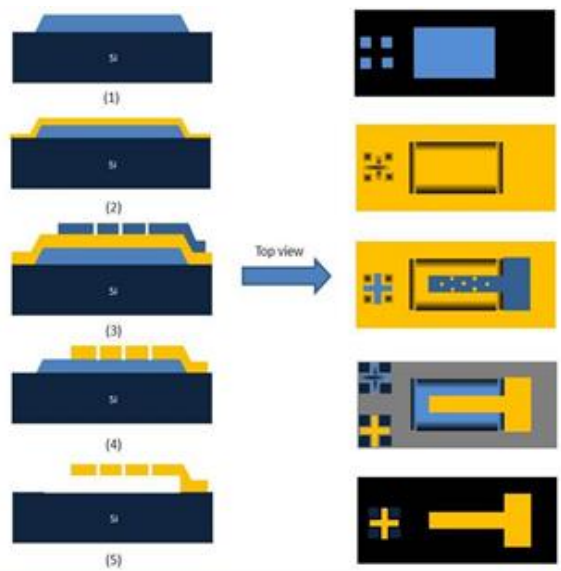


Figure 1. *Microfabicated processes of copper cantilever beams*

2. Fabrication Process

2.1. Mask Design

L-edit is used to design the mask. Due to the large space on the wafer (diameter= 4 inch), we have designed several groups of cantilever beams with different shapes and sizes. The details of the mask we've been using are shown in Figure 2 and 3. One layer is used for patterning the beam, while the second one will elevate the beam from the substrate.

When working with more than one layer, creating alignment marks was necessary in the mask design to connect the anchors and correspond to beam arms.

2.1.1. Design requirement

Length of beam: 50-100 µm.

Width of beam: 20-50 µm

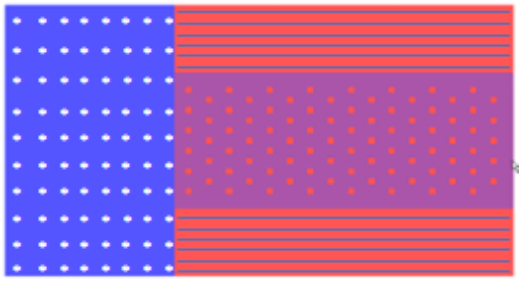


Figure 2. *Example of mass design for 100x40 µm beam*

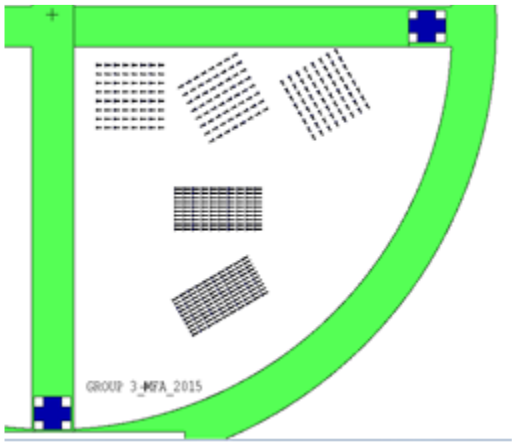


Figure 3. *Mask design in L-edit software*

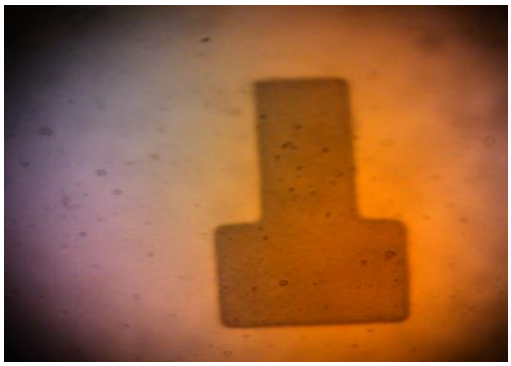


Figure 4. *Mask design of normal beam under TEM microscope*

2.1.2. Design of mask

- Design of structure*:*

Based on this requirement: the etching holes are designed with 2-dimension 2×2 µm and 3×3 µm. One problem arises with this is the resolution of the printing company cannot reach the design smaller than 10 µm. Therefore, even though there are many holes designed onto the mask, but no holes located on the beam when we do photolithography.

In our design, to reduce the effect of residual stress after fabrication, beside the normal straight mass Figure 4, design with a degree of angle such as Figure 5 is also demonstrated.

It is required 2 masks for the design of cantilever beam: one deal with the photoresist (PR) scarified layer (the horizontal line in Figure 2) and other is deal with copper beam design (the dotted line one in Figure 2). The holes are designed on the second mask will enable us to etch the sacrificial layer beneath the beam.

Based on the real experiment, besides the holes problem there is another problem arises with the mask design. The problem is that we should design the dimension of scarified layer is larger than the dimension of the beam as the reason of bad alignment between the first and second mask with make the cooper layer stick to the substrate (Figure 5 and 6).

Figure 5. *Mask design to reduce residual stress under microscope*

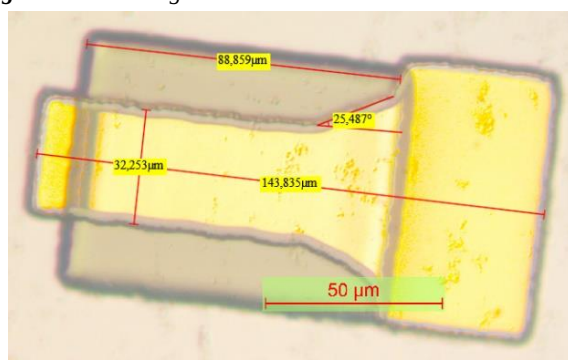


Figure 6. *The cooper layer of beam sticks to the substrate due to not good alignment*

- Design of alignment

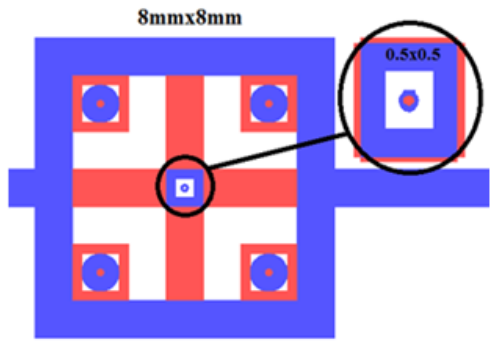


Figure 7. *Alignment design*

Problem arises in this design is the smallest feature of alignment marker is out of the reach of the microscope (see Figure 7). Then, it is hard to use this marker for alignment.

It is better to design the marker much smaller (50x50 µm) for alignment convenient. Our group with support from PhD student, have used the beam structure for this job.

2.2. Photolithography

The photolithography is done twice: Before and after of copper evaporation process for both mask 1 and mask 2.

In photolithography, a sequence of activities is needed for transferring pre-designed patterns, i.e. cantilever beams from two masks, onto the surface of a wafer. The procedure of photolithography follows different steps shown in Figure 8.

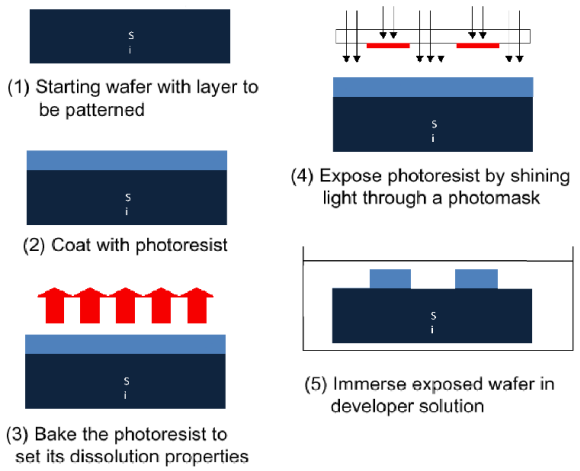


Figure 8. *Photolithography Steps [1], [2], [3]*

2.2.1. Surface Preparation

Before photoresist coating, wafer cleaning is utilized to remove atmospheric dust, smoke particles, small bacteria, photoresist or lint from wipers on the surface wafer. Some contaminants can be abolished with a chemical treatment using acetone $(CH_3)_2CO$, or isopropanol $(CH_2CHOHCH_2)$ while some stains are only cleaned by dry cleaning methods such as using nitrogen gas to blow out these dusts. After that, wafer baking is applied to reduce surface moisture, offer resist wetting properties, and therefore increase the adhesion of the resist to the substrate. In the practical lab work, we baked two wafers at 100ºC for 2 minutes on a hot plate (Figure 9).

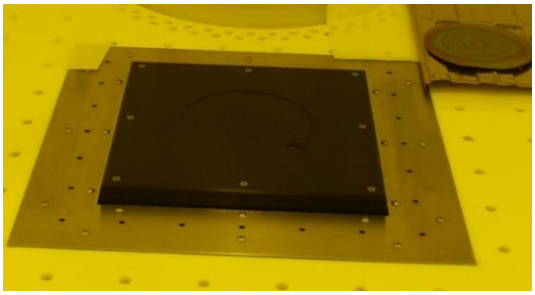
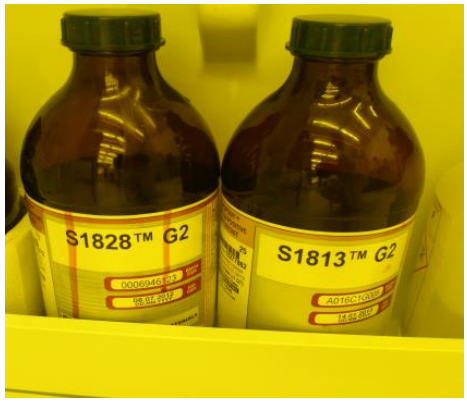


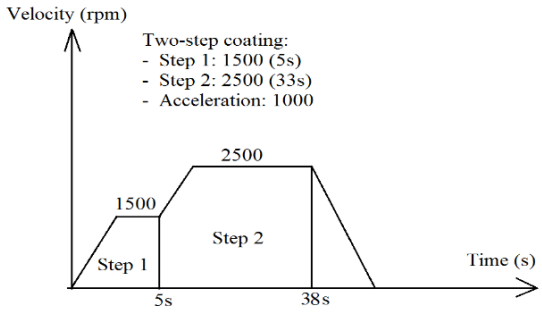
Figure 9. *Hot plate*

2.2.2. Spin Coating

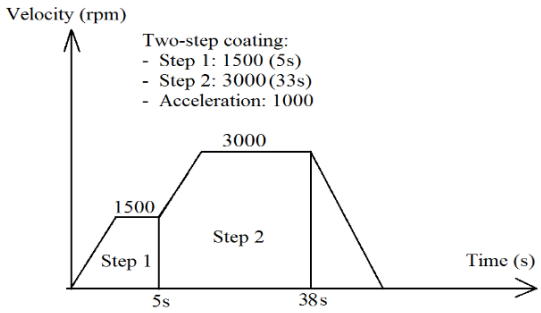
The wafers, after baked, are placed on a rotating chuck and held via vacuum suction. Photoresist is poured on the wafers surface and then spread out by using a coating spinner. Photoresist is a first imagable layer to register the patterns on the desired surface and also works as a sacrificial layer for surface micromachining in this lab. There are two types of photoresist used for two wafers including S1813 and S1828. Both of them are positive photoresists which belong to S1800 series photoresists. However, the 1828 photoresist is more viscous than 1813 one; therefore, the thickness of the former photoresist is larger than that of the latter. Expectedly, the developer for those photoresists is MF-319, a metal-ion-free developer family. Notably, the resist volume must be considered carefully because too much resists may cause non-distribution. Figure 10 shows velocity changes corresponding to different durations programmed for the spinner. Even though the same programming process is used for two wafers, photoresist thickness of two wafers is varied as a result of different photoresist used.



(a)



a) Velocity diagram for photoresist S1813



b) Velocity diagram for photoresist S1828

(b)

Figure 10. *(a) Two types of photoresist using for wafer 1 and 2 (b) Velocity diagram for two-step coating*

In this process shown in Figure 10, the wafers are at first spun at slow speed to dispense photoresist everywhere on the wafer surface because of centrifugal forces. After that, the wafer speeds up 2500rpm or 3000rpm for 33 seconds. Higher spin ramping provides better coating

uniformity. The resist thickness determined using equation (1) depends on resist viscosity, spinner rotational speed, molecular weight, and solution concentration.

$$T = \frac{KC^{\beta}\eta^{\gamma}}{\omega^{\alpha}} \quad (1)$$

Where,

K = overall calibration constant;

C = Polymer concentration in g/100 ml solution;

η = Intrinsic viscosity;

ω = rotaion per minute (rpm);

α, β, γ are exponential factors.

2.2.3. Soft bake

The purposes of this step are to improve adhesion between photoresist and oxidized wafer, evaporate the coating solvent, densify the photoresist. The photoresist wafers were baked at 100ºC for 2 minutes on a hot plate. Practically, that the wafers can be stuck on the hot plate by pressing Vacuum button will increase baking efficiency.

2.2.4. Alignment

Mask-to-wafer alignment is to register patterns prior to light exposure. Normal alignment with a split-field microscope is applied for exposure systems which have at least two alignment marks. In order to straightforwardly align, the first mask with the wafer, a long rectangular parallel to the wafer flat should be designed on the mask surface. It took a lot of time for our group to do the alignment step since the wafers did not have good alignment marks.

2.2.5. Exposure

There are three methods of exposure including contact, proximity, and projection methods. In this lab project, we used the contact method which transfers the printed mask pattern on the photoresist layer with size and scale conservation. After exposed to UV lights, the wafers are transferred entirely almost all patterns due to the contact exposure advantages of small diffraction and fine resolution albeit our group's beam structure is very small. The time for UV light exposure is about 25s depended on the type of photoresist, mass patterns and photoresist thickness.

2.2.6. Development

Development transforms the latent resist image formed during exposure into a relief image that will serve as a sacrificial layer for copper thermal evaporation in next lab. Based on positive photoresist, 1828 and 1813, wet development with MF319 is used to remove the photoresist area exposed to UV light.

2.2.7. Hard bake

The purpose of hard bake is to remove the final 3-4% solvent and harden the photoresist and improve adhesion to the substrate. It takes typically 5 min on hot plate at 100ºC. Hard baking results curved convexes, instead of acute ones, at edges of photoresist surface shown in results section. In practice, this step is only applied for the photolithography before copper evaporation but not for one after that.

2.2.8. Inspection

This step is to measure the thickness of photoresist layers to check the performance of the previous steps. Inspection is done using Veeco Dektak 150 Profilometer. The good performance of whole photolithography may be determined based on many factors such as defects, particles, step height, critical dimension and so on.

2.3. Evaporation of Copper

In this process, we use the Minilab equipment to evaporate Cu on the photoresist using PVD method.

Principle of metallization using PVD:

Metallization is a process where a layer of metal is deposited on a substrate surface. In this process, the metal vapor that is generated and diffuses in vacuum condenses on the substrate to be coated. The vapor is generated in a thermal way where a high current passes through a coil, heats the metal and evaporates it, resulting a so-called evaporation method. However, the temperature of the coil should not be too high in avoiding vapor bubbles in the melted metal.

In order to have an optimum diffusion condition for vapor, low material losses and high quality of layers, the maximum operational pressure should be $4x10^{-4}$ mbar. The pressure at the beginning of evaporation must be lower as the pressure increases during vapor deposition due to outgassing from the material to be evaporated.

In the vacuum chamber, a crystal quartz is used as a sensor to measure the rate and thickness of the coated layer. These parameters are calculated based on Z-factor (Acoustic impedence), which is used to match the acoustic properties of the material being deposited to the ones of quartz material of the sensor.

$$\text{Z-factor} = \frac{Z_q}{Z_m} \quad (2)$$

Where,

Z_q: The acoustic impedance of the base quartz material of the sensor crystal;

Z_m: The acoustic impedance of the material being deposited.

Materials and equipment:

- Two after-develop wafers with patterns of mask 1 on them.
- 5 mg of copper.
- A mini wolfram boat to hold copper.
- MiniLab vacuum deposition system.

The chamber used to evaporate cooper is shown in Figure 11.

The whole process can be described in 5 steps as following:

- Fixing the boat of copper in the vacuum chamber.
- Adjusting the position of the sensor so that it had the same height as the substrate for an accurate estimation of rate and thickness, or tooling=100% (the actual substrate deposition rate or thickness equals the one measured by the sensor)

- Using a strong vacuum pump to lower the pressure inside the closed chamber.

- When the pressure is decreased to 10^{-6} torrs, start the evaporating process.

- Waiting until the thickness of the metal layer increases to the one of interest.

Figure 11. *Vacuum chamber*

Stopping the machine and waiting until the pressure is high enough to open the chamber and the temperature is low enough so one can take the wafer out of it.

2.4. Wet Etching for Copper

The purpose of this process is etching away the copper on one side of the cantilever. We use the alkaline copper etching, the solution used for etching in our case is $Cu(NH_3)_4Cl_2$ [4], [5]

Chemical reaction equation:

$$2Cu^0 + 2Cu^{+2}(NH_3)_4Cl_2 \rightarrow 4Cu^{+1}(NH_3)_2Cl$$

$$4Cu^{+1}(NH_3)_2Cl + 4NH_3 + 4NH_4Cl + O_2 \rightarrow 4Cu + 2(NH_3)_4Cl_2 + 2H_2O \quad (3)$$

This process depends on the room temperature, and the etching rate is 2.48 µm/min-3.1µm/min.

- First we put the wafer 1 in the solution (the color is blue) for 10s, then put it in water to check. When we found that etching is not completely, we put it in the solution for 5s again. Wash the wafer then complete the first wafer etching for Cu. Use microscope to take pictures.

- The process of wafer 2 is same as the wafer 1, but the etching time is 20s.

2.5. Wet Etching for Photoresist

We cut the wafer to several pieces and choose some of them to try wet etching in order to make a detailed comparison between these fractions afterwards. The purpose of this process is to remove away the photoresist remain below the cantilever to help release the beam.

We firstly observed certain part of each segment under microscopy and measured the sizes of beams which get prepared for the following observation to check the beam is released or not with no etching holes on the beam at all. The solution for this wet etching is microposit remover 1165.The cantilever structure after wet etching is shown in the result.

2.6. Dry Etching for Copper

Dry etching refers to the removal of material, typically a masked pattern of semiconductor material, by exposing the material to a bombardment of ions (usually a plasma of reactive gases such as fluorocarbons, oxygen, chlorine, boron trichloride; sometimes with addition of nitrogen, argon, helium and other gases) [5] that dislodge portions of the material from the exposed surface [6]. Unlike with many (but not all, see isotropic etching) of the wet chemical etchants used in wet etching, the dry etching process typically etches directionally or anisotropically.

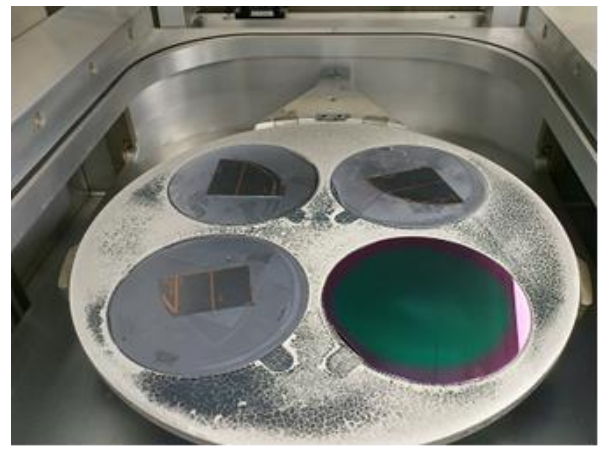


Figure 12. *Dry etching chamber*

In our work, structure of beams of both wafer 1 and wafer 2 is process with dry etching machine follow these steps:

Put the wafers into the left chamber as in Figure 12

- Supply N_2 into the chamber to clean the environment inside it.

- Pump the pressure to create high vacuum and balance the pressure between the left chamber and the right one.

- Wafer loading (the wafer will be moved from the left chamber to the right one).

- Set the dry etching parameters.

- Turn on the fed gases to bring them into the right chamber.

- Turn on the pressure and the RF power.

- Unload the wafer.

- Dry etching process finished, take the wafer out of the chamber.

3. Result

3.1. Photolithography for first mask

The purpose of this process is etching away the copper on one side of the cantilever. We use the alkaline copper etching, the solution used for etching in our case.

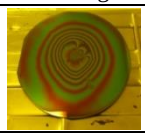
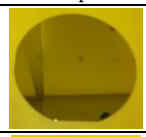
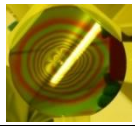
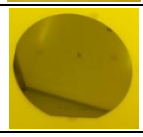
	Wafer after spin coating	Wafer after development
Wafer 1 (Photoresist 1813)		
Wafer 2 (Photoresist 1828)		

Figure 13. *Wafers after spin coating and development*

As we can see from Figure 13 and Figure 14 baking of phothoresist not only decrease its the thickness but also make a peak on the edge of the photoresist wall. The reason mainly because photoresist sink inside but on the side wall, due to exposure process with UV light, the photoresist is hardening.

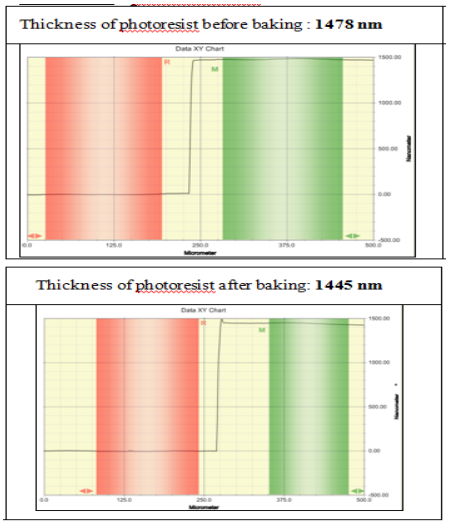


Figure 14. *Thickness of photoresist of wafer 1*

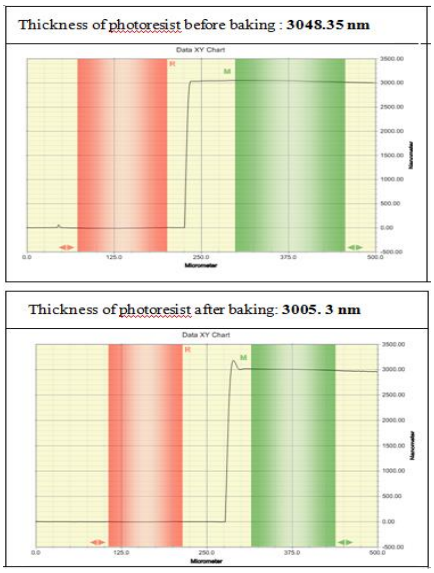


Figure 15. *Thickness of photoresist of wafer 2*

3.2. Cooper evaporation

The measurements of deposition rate and thickness of the copper layer are shown in the Figure 15 by using SEM microscope.

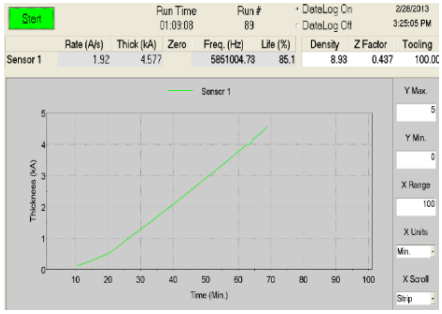


Figure 16. *Deposition rate and thickness of copper layer*

From the Figure 16 and 17, it can be observed that the thickness of cooper layer is almost linearly increasing and is around 460nm in final.

However, the actual thickness of this layer measured by the profilometer is about 310nm. It can be explained that the difference comes from the inaccuracy of the sensor using to estimate the thickness.

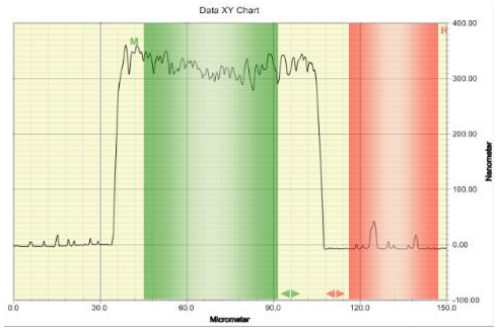


Figure 17. *Thickness of Cu layer measured by profilometer*

3.3. Photolithography with second mask

Wafers after coating photoresist are shown in Figure18. The thickness of photoresist layer on each wafer is illustrated in Figure 19 and Figure 20 respectively.

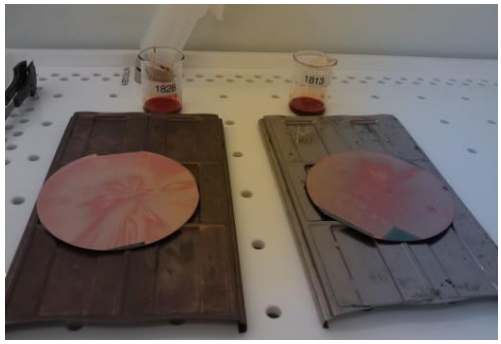


Figure 18. *Wafers after coating photoresist (wafer 1 on the right, wafer 2 on the left)*

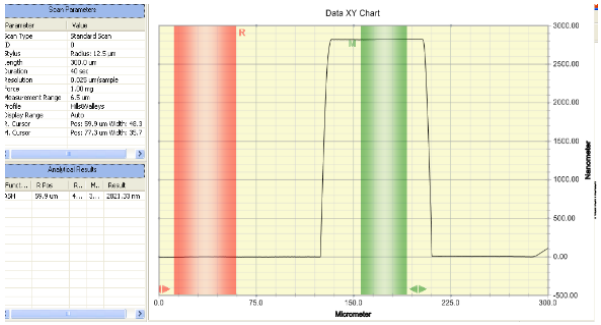


Figure 19. *Thickness of photoresist of wafer 1*

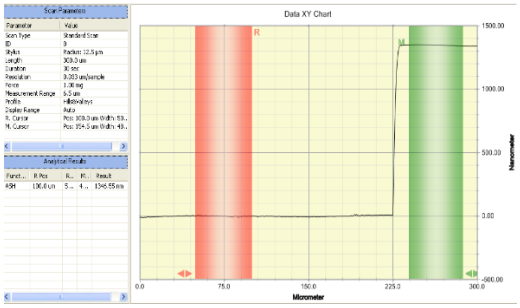


Figure 20. *Thickness of photoresist of wafer 2*

We measure the thickness of photoresist of two wafers and the result is shown in Table 1.

Table 1. *Thickness of photoresist*

Wafer	Thickness of photoresist/nm
Wafer 1 (1813)	1346
Wafer 2 (1828)	2821

After photolithography, we observe the structures under microscopy.

We can see from the Figure 21 and 22 that only a part of patterns is transferred completely onto the wafer surface on both wafers. There may be several reasons lead to this phenomenon [1], [2]:

3.3.1. The inaccurate alignment.

Since the size of alignment mask is too big to observe in the view of microscopy, we have to use a group of cantilevers on wafer as alignment, which finally turns out that the patterns on the wafer coincide with on the mask 2 partially instead of entirely.

3.3.2. Due to improper bake [7], [8]

Improper soft-bake will cause polymerized, less photo-sensitivity and affect adhesion and exposure, also improper hard-bake will cause the photoresist not filly polymerized, high photoresist etch rate, poor adhesion and so on. Therefore, we suppose the improper bake may response for the destroyed patterns.

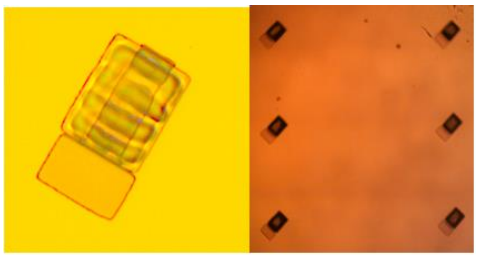


Figure 21. *Structures on wafer 1*

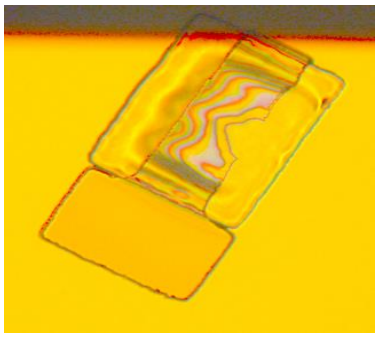


Figure 22. *Structures on wafer 2*

3.4. Etching for Copper

Before we start to do the etching for Cu, we take the picture (see Figure 23) that is the structure of wafer 1, we could not find holes in the beam. We also could not find holes in the structure of wafer 2.

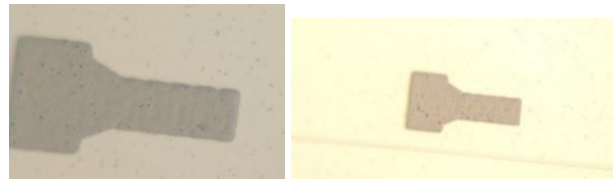


Figure 23. *Before etching for wafer1 and wafer2*

When we finish etching for Cu, we take the picture of wafer1 and do some measurement. It is shown in Figure 24.

We can clearly see the structure, but we could not see the holes. Because of our mask design for diameter of the hole is very small, and the microscope can't be observed. Under the copper, The shades of gray is the photoresist.The picture of wafer 2 is shown in Figure 24. The result is same as the wafer 1. In this lab, because of the time for etching we also get some structures which were broken.

3.5. Releasing photoresist

There is over-etch problem happening as shown in Figure 24. The structure of the beam is not straight but serrated on the sides, due to too long etching time.

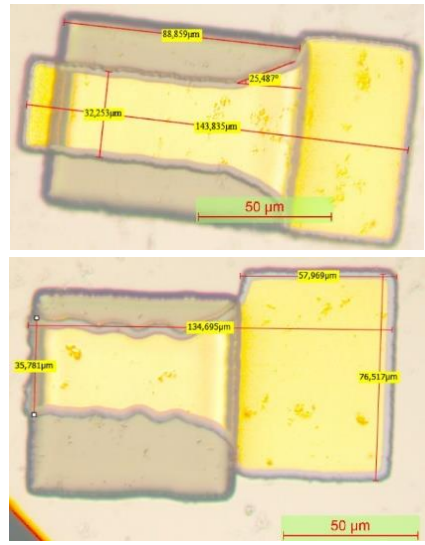


Figure 24. *After etching for wafer1 (1st picture) and wafer2 (2th picture)*

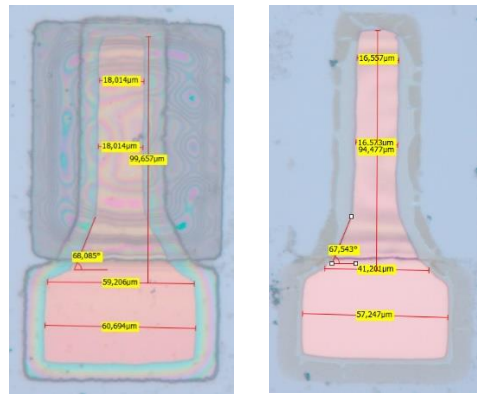


Figure 25. *Before and after photoresist etching for wafer1*

Table 2. *Thickness Measurement*

No	Thickness of beam Wafer 1			Thickness of beam Wafer 2		
	Before photoresist (nm)	After Photoresist (nm)	Cu	Before photoresist (nm)	After photoresist (nm)	Cu
1	1346	1149	680	2821	1149	334
2	1346	1149	680	2822	1148	334
3	1347	1149	680	2821	1149	336
4	1344	1149	680	2820	1150	336

Table 3. *Thickness Measurement*

No	Thickness of Cu Wafer 1		Thickness of Cu Wafer 2	
	Before Dry etch 25 min (nm)	After Dry etch 25 min (nm)	Before Dry etch 30 min (nm)	After Dry etch 30 min (nm)
1	680	610	334	321
2	680	610	334	321
3	682	610	336	322
4	679	610	336	322

After etching, the thickness of the beam is different (see Figure 26-28).

Wafer 1: 1813 after dry etch 25m

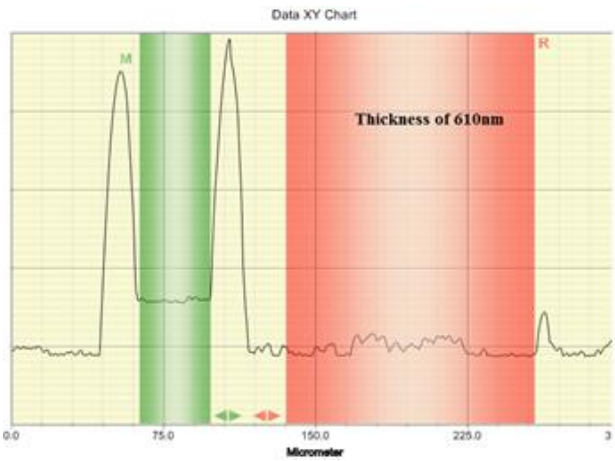


Figure 26. *Thickness of support after etch*

Wafer 2: 1828 after dry etch 30min

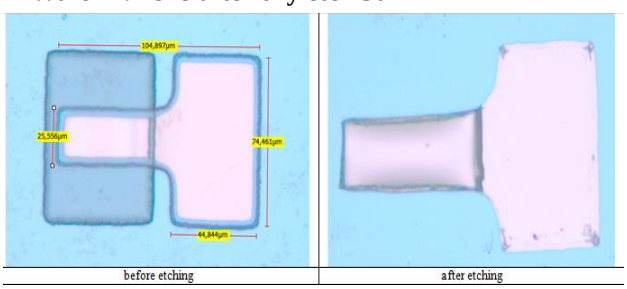


Figure 27. *Before and after photoresist etching for wafer2*

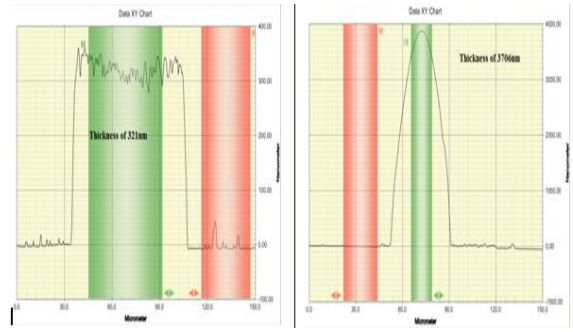


Figure 28. *Support thickness of cooper after 30min dry etching*

4. Conclusion

This paper has presented the fabrication process of piezoelectric cantilever beam for two wafers. Two masks are first designed using L-edit software. Photolithography steps such as photoresist coating, soft baking, UV light exposure, and development are in turns processed for these wafers. Two wafers are coated with different types of photoresist, i.e. S1813 and S1828. Copper evaporation using physical vapor deposition is then conducted to create a thin copper layer with the thickness approximately about 300nm for wafer 1 and 600nm for wafer 2. Further steps including photolithography for the second mask, copper wet and dry etching, and sacrificial layer removal are done to achieve cantilever beams. In this report, all fabrication steps and results demonstrate the understandings and accomplishments in cantilever beam microfabrication.

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