Integrating MEMS Electro-Static Driven Micro-Probe and Laser Doppler Vibrometer for Non-Contact Vibration Mode SPM System Design

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Abstract

This research integrated a MEMS electrostatic driven micro-probe and a laser Doppler vibrometer for non-contact vibration mode scanning probe microscope system design. The microprobe tip was placed in perpendicular to the sample surface, and the built-in capacitor on the microprobe was excited to vibrate by a sinusoidal drive voltage to generate Coulomb electrostatic force. The applied frequency is right at the structure natural resonant frequency of the microprobe. Then let the sample carried by a Z-stage move up. When the sample gets closer to the microprobe, the Van Der Waal’s force between the sample and microprobe would become larger, and the microprobe vibration amplitude would be reduced, and which can be determined by a laser Doppler vibrometer. Since the probe vibration amplitude is proportion to the distance between the probe tip and the sample surface. Thus one can detect the sample surface profile, by moving the probe tip at a constant height, and using a laser Doppler vibrometer to obtain the topography with the amplitudes of microprobe vibration history. The accuracy of the proposed system is about 10 nanometers with a gauge meter.

Key Words: Microprobe, Non-Contact Vibration Mode, Scanning Probe Microscope

1. Introduction

Micro-Electro-Mechanical-System applies the also called Micro System Technology in Europe. The Nobel Prize winner, Prof. Feymann addressed that there’s plenty of room at the bottom in 1959 at American Physics Annual Conference [1], which was the first micro machine concept proposed. Up to right now the MEMS is from academic into industry and yielding many products with great potential, which integrates multi-domain knowledge into a cross-filed technology such as electronics, optics, electricity, mechanics, material, physics, and chemistry. In general, the microprobes are carried out by semiconductor process, the principle is to the measure the forces of atomic, Coulomb electrostatic and magnetic systems, or for scanning surface profilers with atomic and nanometer levels. In previous literatures, many kinds of microprobes were fabricated on the fields of demands [2–4].

In this research the microprobe is the key component made by MEMS technology on the silicon surface. Some thin film layers such as silicon nitride, silicon dioxide and metal are deposited on the surface to build a pair of released parallel plates as a capacitor structure for electrostatic force driver. The operation principle of the microprobe is firstly by placing the microprobe tip in perpendicular to the sample surface, and using signal generator to deliver a sinusoidal drive voltage, then the microprobe would vibrate due to the Coulomb electrostatic force generated by the electrodes on the micro-probe [5–11].
working frequency is right at the longitudinal bending mode natural resonant frequency of the microprobe. Thus this structure is a newly design. In this research, the microprobe was calibrated by a piezo-stage as well as a standard gauge meter. The accuracy of the proposed system is about 10 nanometers. The organization of this paper is as follows: the first section is introduction. The second one is principle of design and operation. The stress and strain analyses are in Section 3. The next are microprobe fabrication result and discussion. Section 5 is the system design and integration. The last part is the conclusion.

2. Operation Principle and Design

The principle of operation as shown in Figure 1 is firstly by using signal generator to deliver a sinusoidal drive voltage. The cantilever beam connected to the bottom electrode of the microprobe capacitor would vibrate due to the electrostatic force generated by the electrodes of the microprobe. The working frequency is the longitudinal bending mode natural resonant frequency of the microprobe. Then let the microprobe (carried by a piezo-stage) moving down, when the sample got closer to the microprobe tip, then the vibration amplitude of the microprobe would be decreased, because the Van Der Waal’s force between the sample and microprobe would become larger. Thus one can detect the surface profile of a sample, by moving and holding the tip at a constant height, then the probe vibration amplitude is proportion to the surface profile that can be determined by a laser Doppler vibrometer (SIOS SP-S 120/500), and the topography can be obtained by recording the amplitude of vibration history. In this paper, the microprobe was calibrated by a piezo-stage as well as a standard gauge meter. The result can verify the operation principles of the proposed microprobe and non-contact mode SPM system.

The electrostatic microprobe structure was developed by MEMS fabrication technology as shown in Figure 2. The cantilever and the micro-probe are shown in part a. Part b is the built-in capacitor of electrostatic structure to drive the cantilever and the microprobe tip. The mirror on the top surface of the cantilever as shown in part c is applied to reflect the laser beam for probe vibration amplitude and surface profile determination. The fabrication processes are as follows:

1. By oxidation process to build a layer of SiO$_2$ (10 $\mu$m) on each side of wafer (with thickness 450 $\mu$m) in $<100>$. Then using Mask #1 and the photolithography process to reserve the photo resist at the left side, and then etch the right hand side SiO$_2$.

2. Remove proto resist, with the remaining SiO$_2$ as protection layer, put the wafer into KOH solution to remove silicon. Since the etching rate in $<100>$ is much larger than that in $<111>$, thus one can obtain a region with slant surface in Figure 3(a).

3. Remove SiO$_2$ layer, and deposit a Ni layer (3 $\mu$m) on the top surface. Using Mask #1 and photolith-

![Figure 1](image1.png)

**Figure 1.** The structure of the proposed system.

![Figure 2](image2.png)

**Figure 2.** The proposed system is with both electrostatic microprobe and laser Doppler vibrometer.

![Figure 3(a)](image3.png)

**Figure 3(a).** Result of step 2.
ography process to reserve photo resist at the left side, and then etch away the rest Ni layer. Finally, remove the photo resist.

(4) Deposit a layer of SiO$_2$. Using Mask #2 and photolithography process to reserve most of the photo resist except a small hole at the right side, and then etch the SiO$_2$ layer under the small hole as in Figure 3(b). Finally, remove the photo resist. The remaining SiO$_2$ region is to protect the underneath silicon.

(5) Using KOH solution to etch silicon region without SiO$_2$ protection, since the etching rate in $<100>$ is much larger than that in $<111>$, thus one can obtain a small V-groove region for Si$_3$N$_4$ (microprobe tip) deposition. Finally, remove SiO$_2$.

(6) Deposit a layer of Si$_3$N$_4$ (20 μm). Using Mask #3 and photolithography process to reserve photo resist at the regions of cantilever and microprobe, then etch the other SiO$_2$ layer to make main frame of cantilever and micro-probe. Finally, remove photo resist; the result is in Figure 3(c).

(7) Deposit a layer of Ni on the top side Si$_3$N$_4$ surface of the probe region. Using Mask #4 and the photolithography process to reserve the photo resist at the top side Si$_3$N$_4$ surface of probe region, then etching all other Ni layer away to make the mirror as shown in Figure 3(d). Finally, remove the photo resist.

(8) Deposit a thick layer of photo resist (with thickness 20 μm) on the top side surface. Using Mask #5 (negative type) and the photolithography process to remove the photo resist as a via hole through the SiO$_2$ layer as shown in Figure 3(d).

(9) Etch the Si$_3$N$_4$ layer under the via hole, and deposit a layer of Ni, then by using the lift off process to remove photo resist and Ni on which to make the interconnection to the bottom electrode.

(10) Deposit thick photo resist (30 μm) on top side surface. Using Mask #6 (negative type) and photolithography process to remove the left side photo resist. The result is as in Figure 3(e).

(11) Deposit a layer of copper (thickness 20 μm not thicker than the previous photo resist 30 μm), the copper is used as bottom electrode of electrostatic capacitor driver. Then by lift-off process one can remove the photo resist and the copper to make the
bottom electrode as in Figure 3(f).

(12) Deposit a layer of SiO$_2$ (thickness 30 μm) as well as a layer of photo resist (40 μm). Using Mask #6 (negative type) and the photolithography process to reserve the right side photo resist to make the upper electrode of the electrostatic capacitor as in Figure 3(g). Deposit a layer of copper (thickness 20 μm) on the top side surface. Then by using lift-off process to remove the photo resist and the copper on which to left the upper electrode. The result is as in Figure 3(g).

(13) Using Reactive Ion Etch (RIE) process to remove SiO$_2$ between the electrodes and left only one third for supporting the upper electrode. Using KOH solution to remove substrate silicon then one can obtain the microprobe structure as in Figure 2.

### 3. Stress and Strain Analyses

By using IntelliSuite software package this section is for the proposed microprobe stress and strain analyses to verify the design concept. Firstly, IntelliSuite 3D Builder module package is applied to set up the probe model, the side view, 3D model and the dimensions are as shown in Figures 4(a), (b) and (c), respectively.

Then one can use the other software modules for mechanical and electrostatic performance analyses. The mask in GDS II or DXF format can be obtained by using the IntelliMask module. For mechanical performance analysis, Figure 5 shows the mask layout developed by IntelliMask module. Figure 6 shows the displacement of

![Figure 3(f). Result of step 11.](image)

![Figure 3(g). Result of step 12.](image)

![Figure 4(a). Side view of probe model.](image)

![Figure 4(b). 3D probe model.](image)

![Figure 4(c). 3D probe model (dimensions all in μm).](image)

![Figure 5. IntelliMask module is applied for mask layout.](image)
the bottom plate with 3 MPa load in the negative y-axis on the microprobe. Figure 7 shows the displacement of the bottom plate with 0.3 MPa load in the positive y-axis on the microprobe.

Then applying driving voltage to the electrodes, Figure 8 shows the bottom plate displacement. Figure 9 shows the resonant frequency analysis of the microprobe structure. It should be noted that in the simulation boundary conditions of upper plate and the left hand side of capacitor structure are fixed, and the probe longitudinal bending mode resonant frequency is 84962.7 Hz (Mode 1), which is the best condition for practical usage; because the applied voltage can be reduced under this condition, and the sensitivity of profile measurement can also be increased. Figure 10 shows the capacitance analysis with 10 volts applied to the electrodes of the microprobe structure.
4. Probe Fabrication and Discussion

Figure 11 shows the top views of mask #2 made by NDL (National Nano Device Lab) (left) and the result of V-groove (right) after silicon etching process of Step 5 in our MEMS Lab. Figure 12 shows the V-groove profile after Step 5. Figure 13 shows the near views of the canti-

![Figure 8. The bottom plate displacement with 30 volts applied to the microprobe electrodes.](image)

![Figure 9. Probe structure resonant frequency analyses.](image)

![Figure 10. The capacitance analysis with 10 volts applied to the microprobe electrodes.](image)

![Figure 11. The top views of mask #2 (left) and the result of V-groove (right) after silicon etching process of Step 5.](image)

![Figure 12. The profile of the V-groove after Step 5.](image)
lever (left) and the probe tip (right). It should be noted that the operation principle of this SPM system is non-contact mode, thus the radius of probe tip is not so critical. However, one can sharpen it to nanometers by laser ablation to increase the sensitivity.

5. Integrated SPM System Design

Figure 14 shows the structure of integrated SPM system, which includes electrostatic micro probe, laser Doppler vibrometer, XY-stages, piezo (Z)-stages, signal generator, PC, and with programming firmware for system operation.

The system operation principle is firstly by placing the microprobe tip in perpendicular to the sample surface, and using signal generator to deliver a sinusoidal drive voltage, and then the microprobe would vibrate due to the Coulomb electrostatic force generated by the electrodes on the microprobe. The practical working frequency is some what lower (10%) than the simulated one. This is due to the process deviations. Then let the sample carried by a Z-stage move up. When the sample gets closer to the microprobe tip, then the vibration amplitude of the microprobe tip would be reduced and which can be determined by a laser Doppler vibrometer, because the Van Der Waal’s force between the sample and micro-probe tip would become larger. Thus one can detect the surface profile of the sample, by moving and holding the tip at a constant height, and then the probe vibration amplitude is proportion to the surface profile that can be determined by a laser Doppler vibrometer (SIOS SP-S 120/500, the accuracy is 0.3 nm), and the topography can be obtained by recording the amplitude of vibration history. In this section the microprobe tip displacement and vibration amplitude was calibrated by a piezo-stage, the result is in Figure 15.

Then the measurement of a sample was made and compared with that obtained by a commercial surface profiler, the results are respectively shown in Figures 16 and 17, which can verify not only the concept and the re-
alization of the proposed microprobe, but also the operation principle of the non-contact mode SPM system. The accuracy of the proposed system is about 10 nanometers. The vibrometer time domain result for the surface profile measurement is shown in Figure 18.

6. Conclusion

This research proposed a non-contact mode SPM system design by integrating MEMS electrostatic micro-probe and laser Doppler interferometer to develop a high precision measurement system. In this paper we had shown the operation principle to detect the surface profile of the sample by moving and holding the micro-probe tip at a constant height, and the topography can be obtained by recording the amplitude of vibration history. In this research, we used a piezo-stage and a gauge meter to calibrate the micro-probe; the accuracy of the proposed system is about 10 nanometers with a gauge meter. Thus we had verified the structure and the operation principle of the proposed electrostatic driven microprobe as well as non-contact mode SPM system.

Figure 17. The surface profile of a gauge meter obtained by the proposed system.

Figure 18. The vibrometer time domain result for the surface profile measurement.
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