Using Electron Cyclotron Resonance (ECR) Source to Etch Polyimide Molds For Fabrication Of Electroplated Microstructures

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Abstract

Dry etching of polyimide with an electron cyclotron resonance (ECR) source and Ni electroplating were applied to fabricate laterally driven resonant microsensors. With the ECR source, the generation of reactive species and the self-induced dc bias voltage can be independently controlled to provide fast polyimide etch rate (0.91 μm/min) and high selectivity (3150:1) over Ti etch mask. The etch anisotropy was found to improve at higher rf power and lower pressure. Compared to conventional reactive ion etching, etching with ECR source can typically provide 10x faster etch rate and 6x higher selectivity. Resonant elements in polyimide that are 32 μm high and 1 μm wide have been fabricated by etching in an O_2 plasma generated using the ECR source. In addition, high aspect ratio microstructures in Ni were formed by electroplating through the polyimide mold.

I. Introduction

Resonant-based microsensors and microactuators have the advantages of high sensitivity, linear response, and better design flexibility [1-3]. In order to increase the sensitivity of these sensors, the interdigitated resonant elements should be thick but the separation between elements should be small. This requires pattern transfer technology that is capable of fabricating high aspect ratio microstructures.

Electroplating of metal through polymeric molds has been developed to fabricate thick, high aspect ratio microelectromechanical devices [4-6]. The first major application of this technology was demonstrated by the LIthographie, Galvanoformung, Abformung (LIGA) process [4] in which high energy synchrotron X-ray was required to expose the thick polymethyl methacrylate (PMMA) resist. Although this technology is unsurpassed in its capability to fabricate thick high aspect ratio microstructures, it is limited because of the need for X-ray sources, facilities, and masks. To overcome this problem, deep UV lithography has been used to expose photosensitive polymers and create the required mold [5,6]. This is a very attractive technique because it is readily available; however, it has shortcomings in that the aspect ratio is limited to ~8. Dry etching of a polymeric mold using reactive ion etching (RIE) has also been demonstrated [7,8], and has the same shortcomings as deep UV due to the slow etch rate and low etch selectivity.

In this work, an electron cyclotron resonance (ECR) source is used to etch thick polyimide molds with small gaps between resonant elements to create high aspect ratio microstructures. Patterns in polyimide were etched in an O_2 plasma generated by the ECR source because it has many advantages over conventional RIE. With the combination of magnetic confinement and microwave power, the ECR source provides dissociation efficiency that is typically more than an order of magnitude higher than RIE [9,10]. The high efficiency allows high throughput since etching of deep microstructures up to 50 μm thick are needed [11]. With the magnetic confinement, plasma can be maintained at much lower pressure with the ECR source. This reduces scattering of reactive species and promotes vertical profiles and smooth surface morphology. The reduced scattering at low pressure is crucial for high aspect ratio structures since even a slight divergence of the reactive ions can cause substantial degradation in etch profile. In addition, the plasma system has a temperature controlled stage that can be cooled down to -130°C. This helps to maintain vertical etch profile by suppressing the spontaneous chemical reactions [12]. The independent control of the ion energy by a rf-powered stage and the ion flux by the microwave power provides the flexibility needed to optimize the etching with high etch rate (by high ion flux) and high etch selectivity to the mask (by low ion energy). High etch selectivity is important since a thin etch mask has to hold up throughout the etching of the deep structures.

Using the ECR source, resonant elements that were 32 μm thick with 1 μm gap have been fabricated in polyimide. The etch conditions were optimized to provide fast etching with high selectivity, vertical profile, and smooth morphology. By electroplating Ni through the polyimide molds, resonant accelerometers were formed with aspect ratio of 11:1.

II. Experimental

A. Plasma System with the ECR Source

The plasma etching system with an ECR source and a rf powered electrode has been previously described [10-12]. Microwave power at 2.45 GHz is coupled into the ECR cavity by a tunable input probe and a sliding short. Twelve permenant magnets are spaced evenly around the quartz disk to provide magnetic field at 875 G for the ECR excitation. The sample stage is connected to a rf power supply at 13.56 MHz. A self induced dc bias voltage ($|V_{dc}|$) is developed and it controls the ion energy.

Chamber pressure is controlled by the throttle valve and gas flow rate is adjusted by the mass flow controller. O_2 is introduced into the base of the ECR source through an annular gas ring. A 1500 l/s turbomolecular pump is used to maintain low pressure during etching. The stage position can be adjusted from 8 to 27 cm below the ECR source. The temperature of stage can be varied from -130 to 400°C by a combination of resistive heating and liquid N_2 cooling. In order to provide good thermal conductivity, wafer is clamped down and He is flown at the backside of the wafer.

B. Device Fabrication

Electrostatic comb-drive accelerometers with Ni plated resonant elements were fabricated. Stress-compensated SiO_2/Si_3N_4/SiO_2 dielectric layers with thicknesses of 300/150/300 nm were deposited on (100) p-Si (ρ = 3-10 Ω-cm) by low pressure chemical vapor deposition. 2-μm-thick Al was evaporated on top of the dielectric films as the sacrificial layer so that the resonant elements can be released from the substrate after Ni plating. The anchor areas were defined by wet etching of Al. A plating base which consisted of Cr/Au/Cr (50/300/100 nm) was evaporated over the entire wafer. Polyimide (Dupont Pyralin® PI-2611) was then spun on the wafer and multiple coatings were used for thicker layer. The polyimide was cured at 380°C for 60 min. 200-nm-thick Ti was evaporated as the etch mask and patterned by RIE. Patterns in polyimide were etched in an O_2 plasma generated by the ECR source. After Ni was electroplated through the polyimide, the polymer was removed by a high pressure O_2

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plasma. Finally the sacrificial Al layer was removed by wet etching, leaving free standing resonant elements in Ni.

III. Results and Discussion

For the etching of thick polyimide with high aspect ratio features, it is important to have high etch rate and selectivity. Figure 1 shows a comparison of etch rate and selectivity (ratio of polyimide over Ti mask etch rate) between a conventional RIE process and etching with the ECR source. For RIE, as rf power was increased from 50 to 300 W, the etch rate increased from 38 to 147 nm/min, but selectivity decreased from 528 to 115. When polyimide was etched with the ECR source, the etch rate was more than 6x higher and was 908 nm/min at 300 W. The increased etch rate is due to the higher ion flux generated by the microwave power. In addition, selectivity was 3150:1 at 50 W, much higher than RIE. Since the ECR source can generate high ion density in the discharge, $|V_{dc}|$ is lower compared to RIE when the same rf power is applied. At 300 W rf power, $|V_{dc}|$ was 530 V for RIE and 284 V for etching with the ECR source. The reduced $|V_{dc}|$ provides a higher selectivity since the Ti etch mask is mainly removed by physical sputtering. The results shows that the ECR source has the advantages of achieving fast etch rate and high selectivity due to its high ion flux and low ion energy.

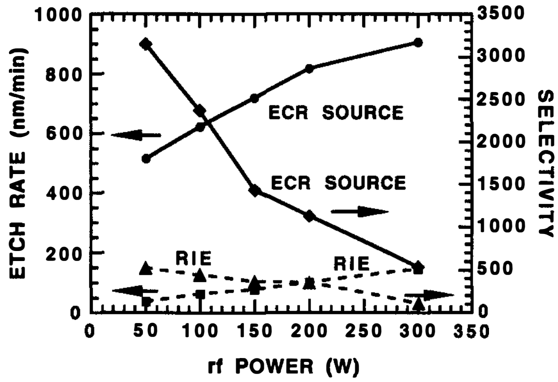


Fig. 1. Etch rate and etch selectivity comparisons between etching with an ECR source and RIE. For etching using the ECR source, microwave power was 750 W, rf power was 300 W, and O_2 flow rate was 20 sccm at 0.5 mTorr and 10 cm below the source. For RIE, the O_2 flow rate was 20 sccm and pressure was 3 mTorr.

The rf power not only controls the etch rate, it also has strong influence on the etch profile. The etch anisotropy was found to increase with rf power as shown in Fig. 2. At higher ion energy, the directionality of the ions has a weaker dependence on surface charge or field distribution across the wafer. The more directional ions impinging on the samples result in more vertical etch profile. The etch profile and surface morphology also depend on the pressure used during etching. More vertical etch profile and smoother surface morphology were obtained at lower pressure. This is related to the longer mean free path and reduced scattering at lower pressure. Since low pressure plasma down to 0.3 mTorr can be maintained with the ECR source, it is most suitable of generating vertical etch profile for high aspect ratio resonant elements.

Etching of thick polyimide film requires a high etch selectivity between the polyimide and the etch mask. Among the different metal etch masks investigated, Ti was found to provide the highest selectivity as shown in Fig. 3. At 50 W rf power, the selectivity for Ti was 3150:1, followed by 790:1 for Cr and 570:1 for Al. Typically, metal mask is oxidized during polyimide etching in the O_2 plasma and it provides higher selectivity than SiO_2 mask. Compared to Cr and Al, Ti mask provides higher etch resistance because TiO_x has the lowest sputtering yield [13]. As rf power was increased from 50 to 300 W, the selectivity between polyimide and Ti mask decreased from 3150 to 536. Despite the lower selectivity at higher rf power, 300-nm-thick Ti mask can still hold up for the etching of 50 μm thick polyimide.

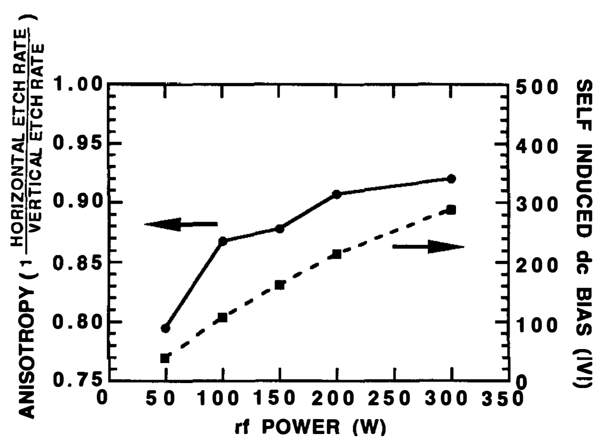


Fig. 2. Effects of rf power on polyimide etch anisotropy and self-induced dc bias. Oxygen was flown at 20 sccm with 750 W microwave power at 0.5 mTorr and 10 cm below the source.

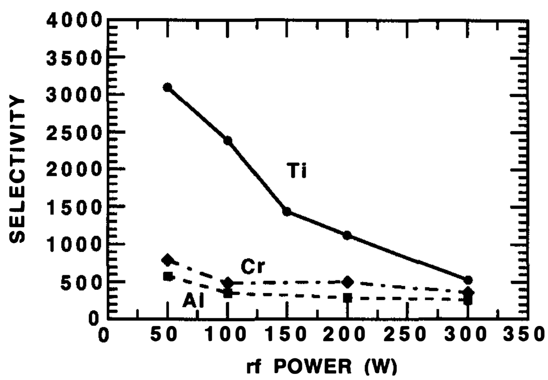


Fig. 3. Etch selectivity between polyimide and Ti, Cr, and Al masks in an O_2 plasma. Flow rate was 20 sccm at 0.5 mTorr with 750 W microwave power and 10 cm below the ECR source.

Since there are features with various sizes on the microsensors, it is important to study the influence of feature size on etch rate when thick polyimide is etched. Figure 4 shows the decreased polyimide etch rate with reduced spacing between elements. The polyimide was etched down to a depth of 24 μm. The etch rate was normalized to the etch rate of 30 μm wide spacing. Both rf power and pressure can change the feature size dependent etch rate. At 0.5 mTorr and 300 W rf power, the normalized etch rate varies from 0.91 to 1.0 for spacing ranging from 4 to 30 μm. When the rf power was reduced to 50 W, the normalized etch rate decreased significantly from 0.61 to 1.0 for the same range of spacing. The reduced etch rate for smaller features at lower rf power could be attributed to the less directional ions impinging on the samples. When the ion energy is lower, it is easier for the ions to be deflected by any perturbing electric field, resulting in lower ion flux at the bottom of high aspect ratio trenches. At higher pressure, the etch rate reduction for narrower spacing was more significant. The normalized etch rate for 4 μm spacing was 0.84 at 3 mTorr and 0.91 at 0.5 mTorr. The stronger dependence of etch rate on feature size is probably due to the additional scattering at higher pressure. The increased scattering makes it more difficult for the reactive radicals and the product species to enter or exit the high aspect ratio trenches [14]. Therefore, high rf power and low pressure are desirable to provide more directional reactive species to maintain constant etch rate.

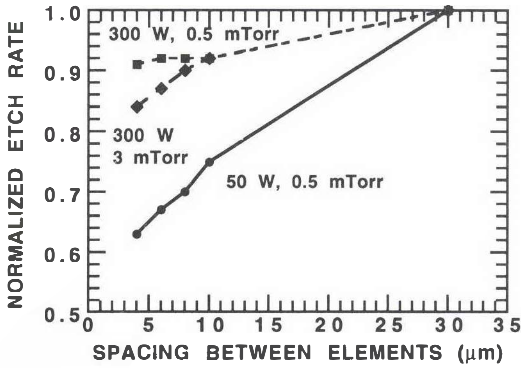


Fig. 4. Influence of feature size on polyimide etch rate. O_2 flow rate was 20 sccm and the source distance was 10 cm with microwave power at 750 W and rf power at 50 and 300 W.

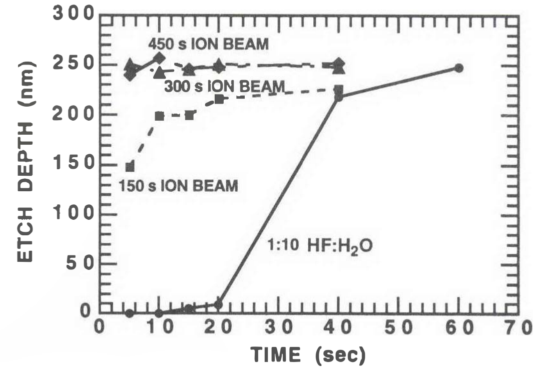


Fig. 5. The effects of Ar ion beam etching on oxidized Ti mask removal. The wet etch solution was $HF:H_2O$ = 1:10. The ion beam etching was carried out using 500 V Ar^+ with 1.2 mA/cm^2 at $1.5x10^{-4}$ Torr.

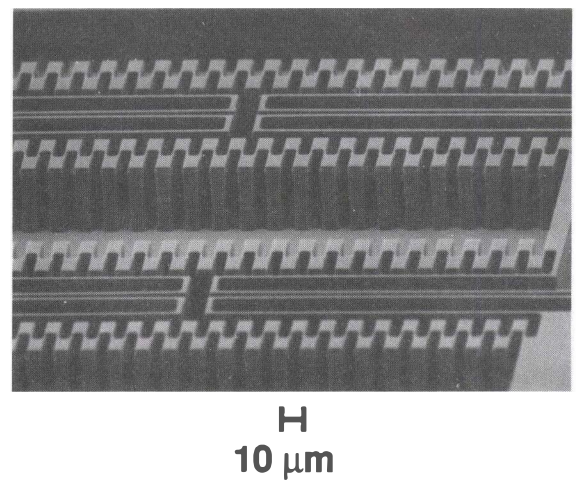
Since Ti etch mask was oxidized during etching of polyimide in the O_2 plasma, it cannot be efficiently removed by wet etching in HF. Ar ion beam etching (IBE) was applied to remove the oxide layer before Ni electroplating. The Ti etch mask was 250 nm thick and was oxidized in the O_2 plasma for 45 min, the time needed to etch 16 μm thick polyimide. Without oxidation, the Ti etch rate in 1:10 $HF:H_2O$ solution was found to be 47 nm/sec. As shown in Fig. 5, not much oxidized Ti was etched in the diluted HF solution after 20 s. Up to 60 s of etching was needed to remove all the Ti. The removal of the oxidized Ti etch mask is more controllable by IBE with Ar ions at 500 V and 1.2 mA/cm^2. The etch rate for the oxidized Ti was 10 nm/min. After removing the top 50 nm of oxidized Ti by 5 min of IBE in Ar, the rest of the etch mask can be completely removed in only 5 s by wet etching. The results indicate that IBE is very efficient in removing the TiO_x and the oxidized layer has a thickness of 25-50 nm.

Figure 6 shows the high aspect ratio (32:1) resonant elements in polyimide that were etched with the ECR source. The polyimide shown in Fig. 6(a) is 32 μm deep with 1 μm spacing between elements. Figure 6(b) shows the higher magnification of the resonant elements in polyimide. The surface is smooth without any residue and the etch profile is vertical. After electroplating Ni through the polyimide mold, accelerometers with interdigitated resonant elements were formed as shown in Fig. 7. The gap between the Ni elements is 1.3 μm and the Ni is 14 μm thick. With the small spacing, high sensitivity is expected for the accelerometer.

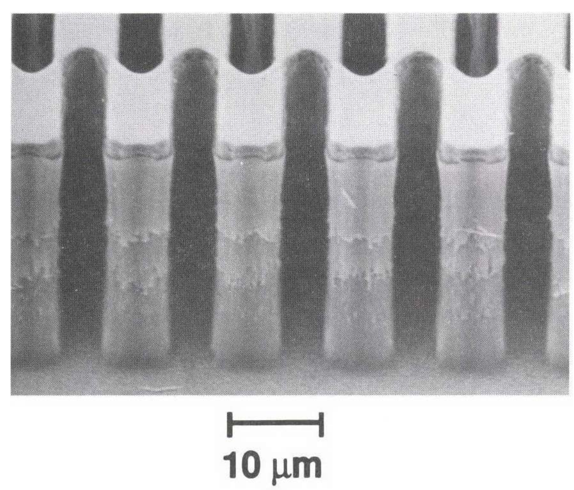
These results demonstrate that high aspect ratio resonant elements for microsensors can be fabricated by etching polyimide in an O_2 plasma generated using the ECR source. By optimizing the etch conditions, fast etch rate, high selectivity, vertical profile, and smooth surface morphology can be obtained.

IV. Conclusion

A plasma system with an ECR source was applied to etch high aspect ratio features in polyimide for the fabrication of electroplated Ni microsensors. Using the ECR source, polyimide was etched with fast etch rate, high selectivity, vertical etch profile, and smooth surface morphology. The high density and low energy ions generated by the ECR source provide polyimide etch rate of 0.91 μm/min and selectivity up to 3150. The low pressure plasma allows etching of polyimide with vertical profile and smooth surface. Ti was found to have the highest etch selectivity over polyimide in the O_2 plasma. After etching, the thickness of the oxidized Ti was <50 nm and it can be removed efficiently by Ar IBE. Microstructures that are 32 μm deep and 1 μm wide in polyimide have been fabricated. Electroplated Ni resonant elements that are 14 μm high with 1.3 μm spacing between elements have also been made. Plasma etching with an ECR source has been demonstrated to have the capability of generating high aspect ratio resonant elements with small spacing for highly sensitive microsensors.

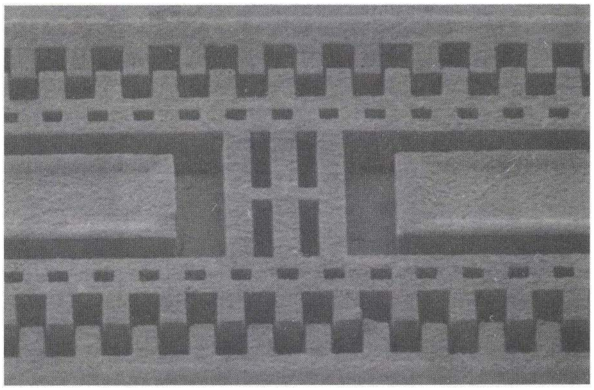


(a)



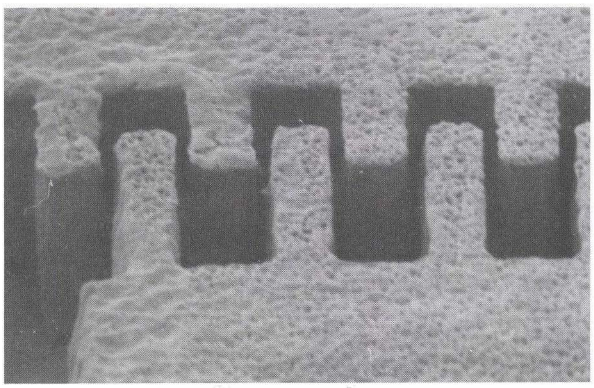
(b)

Fig. 6. High aspect ratio microstructures in polyimide. Etching was carried out with 750 W microwave power at 0.3 mTorr, 12.5 sccm O_2, -300 V, and 10 cm source distance. The polyimide etch depth was 32 μm with 1 μm spacing between resonant elements.



10 μm

(a)



10 μm

(b)

Fig. 7. Eletroplated Ni resonant elements with aspect ratio of 11:1. The Ni was plated with current density of 5 mA/cm^2 at 50°C.

Acknowledgments

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