Paper

Selectivity Control of Mask Material for XeF_2 Etching Using UV light Exposure

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A new technique to control selectivity of mask materials during XeF_2 etching was proposed. By exposing Si sample with SiO_2 and Si_3N_4 as mask materials to UV light of 981 mW/cm^2 during XeF_2 etching, the etching rate ratios of Si/SiO_2 and Si/Si_3N_4 were dramatically decreased from 11446 to 906.1 and from 488.2 to 29.3, respectively. This new technique allows us to remove the mask material selectively and change the mask pattern by UV light exposure during in-situ etching process without additional photolithography step and opens a new silicon micromachining process for 3-dimensional fabrication. The multi-step Si structure was successfully realized by this technique.

Keywords: XeF_2, 3-dimentuional microstructure, ultra violet light, selectivity

1 INTRODUCTION

Since there have been strong demands to realize three-dimensional microstructures for micro-sensors, micro-actuators and MEMS (Micro Electro Mechanical System) devices, various technologies have been developed including Si wet isotropic etching, wet anisotropic etching, dry isotropic etching and dry anisotropic etching (deep RIE). However, in conventional bulk micromachining, various limitations have been existing to fabricate the microstructure. Especially, a photolithography step to form etching mask pattern on a Si substrate with deep etched pattern is challenging problem and this step often limits the fabrication of 3-D microstructure. Because once etching process is performed, subsequent photolithography process is difficult in presence of deep etched pattern. Furthermore, if it is possible to change mask pattern locally during etching process, it will become very powerful technique for 3-D microstructure fabrication. In order to minimize the limitation, various fabrication techniques have been developed, for instance, multi-level surface micromachining [1], combination of ICP-RIE and XeF_2 etching [2,3] and DMP (Delay Masking Process) [4]. However, process cost of these techniques is expensive due to many processing steps.

We propose the new technique to control an etching rate of mask material locally and to change mask pattern during etching without photolithography. We noticed XeF_2 dry isotropic etching as base technique and UV light exposure to control the etching rate of mask material and to change mask pattern. XeF_2 etching has great selectivity to most of the material used for MEMS devices such as aluminum, silicon dioxide (SiO_2) and silicon nitride (Si_3N_4). It has a high etching rate and reaction probabilities at room temperature and requires no external energy sources to etching Si [5,6]. Therefore XeF_2 etching process will be expected to play an important role for the Si micromachining. In this paper, we present the first experimental results about effect of UV light exposure on the etching rate of mask materials and preliminary result about fabrication of 3-D microstructure using this technique.

2 ETCHING APPARATUS AND ETCHING SEQUENCE

Figure 1 shows a schematic diagram of the developed etching apparatus. The etching apparatus consists of a XeF_2 source chamber, an etching chamber, an expansion chamber and two vacuum pumps, a rotary pump and a mechanical booster pump. The etching chamber and the expansion chamber have diaphragm pressure gauges. The expansion chamber that located between the source chamber and the etching chamber is used to charge the amount of XeF_2 gas source that will be used for pulse etching. The amount of the charged XeF_2 gas to the expansion chamber is measured precisely as the pressure and then injected into the etching chamber.

Figure 2 shows the change of pressure in the expansion

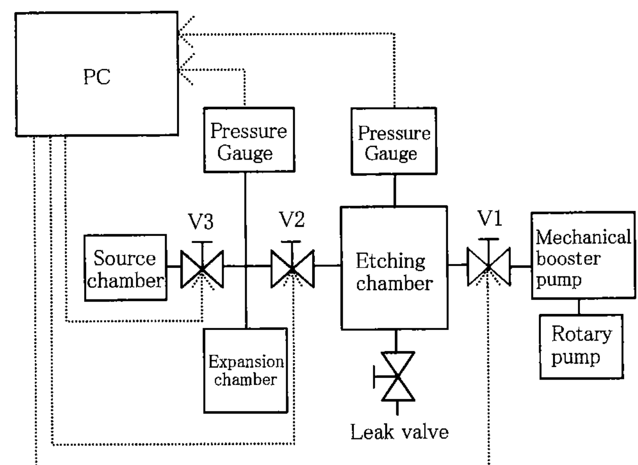

Figure 1. A diagram of the developed etching apparatus.

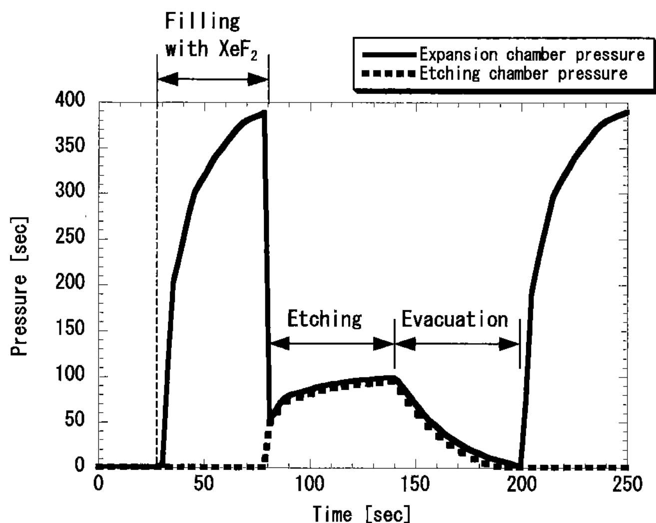

Figure 2. Change of pressure during etching sequence.

chamber and the etching chamber during one pulse etching. First, the expansion chamber is filled with the XeF_2 gas charged from the source chamber. Once the expansion chamber pressure reaches designated pressure, the charge of the expansion chamber and the evacuation of the etching chamber are stopped. Then XeF_2 gas in the expansion chamber is injected into the etching chamber and the etching begins. After waiting for certain duration time allowing the etching reaction, the etching chamber and the expansion chamber are evacuated.

The above mentioned pulse etching sequence is controlled by a computer using three important valves, V_1, V_2 and V_3 of the etching apparatus. The pulse etching involves following sequence: 1) V_3 is closed, V_1 and V_2 are opened. The etching chamber and the expansion chamber are evacuated. 2) V_2 is closed. 3) V_3 is opened and XeF_2 is sublimated into the expansion chamber until designated pressure is reached. 4) V_1 and V_3 are closed. 5) V_2 is opened and XeF_2 gas is injected into the etching chamber. After waiting for certain duration time allowing the etching reaction, the sequence is returned to 1). Since several hundred pulses are required for the MEMS fabrication, the etching sequence is automated with visual programing software HPVEE by Agilent Technologies.

An UV light source by Hamamatsu Photonics was combined with the pulse etching apparatus. Figure 3 shows a photograph of the etching apparatus with the UV light source. Through the window made of quartz glass placed on the top of the etching chamber, the UV light expose a sample surface. The UV light source contains mercury-vapor Xenon lamp and its wavelength ranges from 250 to 450 nm (Typ. 365 nm). UV light intensity was controlled from 0 to 981 mW/cm^2.

3 EXPERIMENTS

Characteristics of Si etching with XeF_2 and UV light

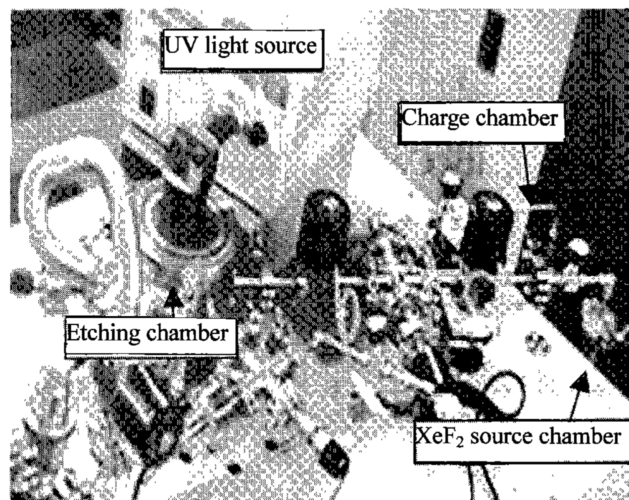

Figure 3. Etching apparatus with UV light source.

exposure were measured using a wagon wheel pattern formed on a (100) silicon wafer. Figure 4 schematically shows the wagon wheel pattern used to measure the Si etching rate. Al of 100 nm thickness deposited by vacuum evaporation was used as the etching mask layer. The etched depth of Si was measured by an optical microscope.

Si samples covered by Si_3N_4, SiO_2 and Al without mask patterning were used to measure the etching rate of these materials with XeF_2 and UV exposure. LPCVD Si_3N_4, thermal SiO_2 and vacuum evaporated Al with thickness of 100 nm were used. The etched depths of Si_3N_4 and SiO_2 were measured by an ellipsometer.

The UV light intensity used for experiments ranged from 0 to 981 mW/cm^2. The etching experiments were carried out with XeF_2 charge pressure of 390 Pa. The etching chamber pressure increased from 50 to 100 Pa due to the formation of SiF_4 gas during the etching when the charge pressure of 390 Pa was used.

4 RESULTS AND DISCUSSION

A dependency of etched depth of Si on the UV light intensity is shown in Fig.5. The pulse duration of 60 seconds and the pulse number of 5 were used. The etched depth of Si gradually increased with increasing the UV light

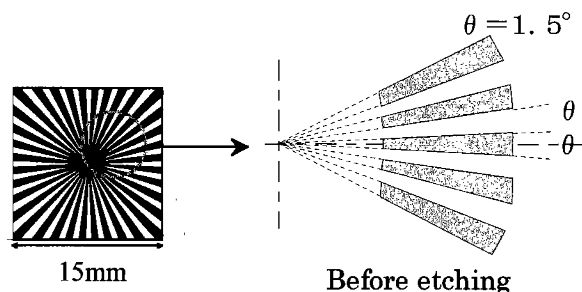

Figure 4. Wagon wheel pattern used for measurement of Si etched rate. Al was used as mask material.

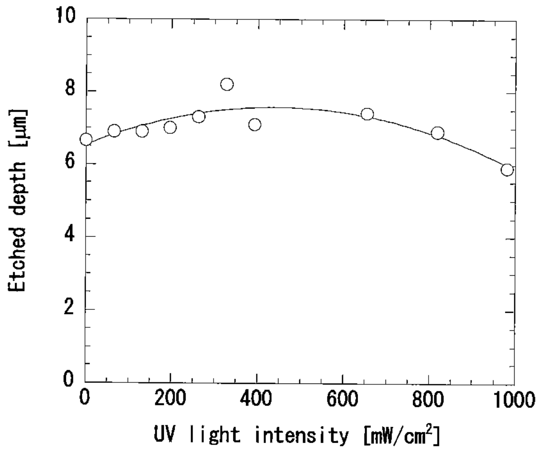

Figure 5. Dependency of the etched depth of Si on UV light intensity. The charge pressure of 390 Pa, the pulse duration of 60 seconds and the pulse number of 5 were used.

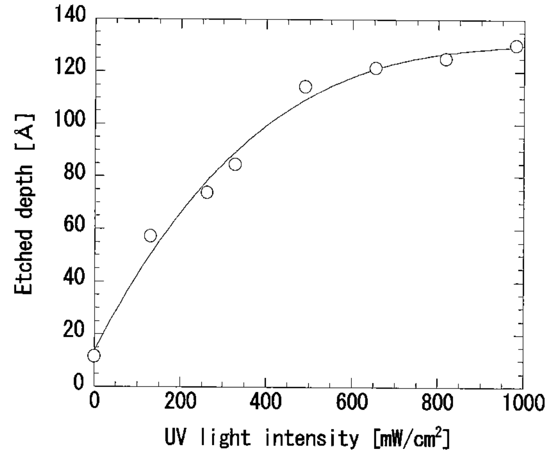

Figure 7. Dependency of the etched depth of SiO_2 on UV light intensity. The charge pressure of 390 Pa, the pulse duration of 60 seconds and the pulse number of 10 were used.

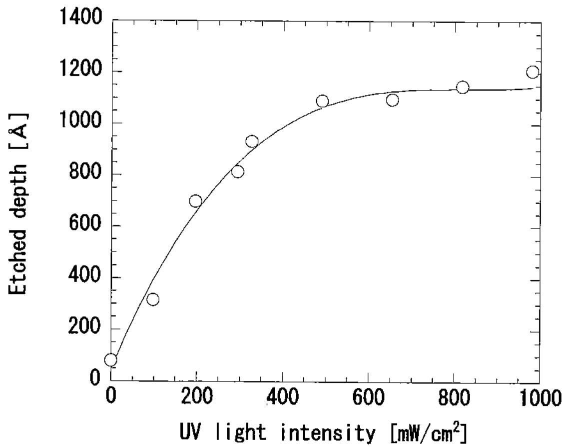

Figure 6. Dependency of the etched depth of Si_3N_4 on UV light intensity. The charge pressure of 390 Pa, the pulse duration of 60 seconds and the pulse number of 3 were used.

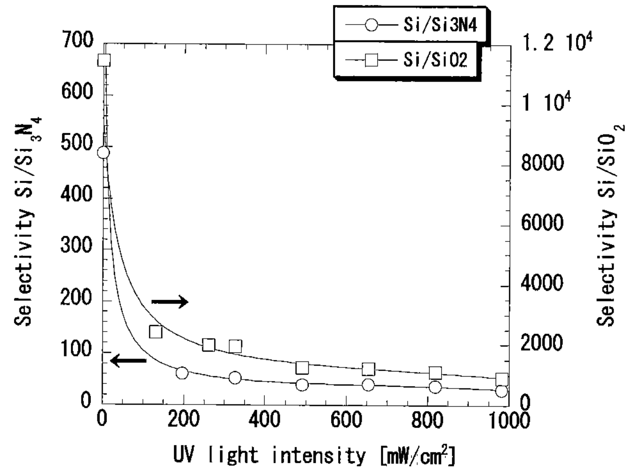

Figure 8. Dependencies of selectivities of Si_3N_4 and SiO_2 to Si on UV light intensity.

intensity, then it gradually decreased with increasing the UV light intensity. The etched depth of Si was 6.7 μm at the UV light intensity of 0 mW/cm^2, the maximum depth was 8.2 μm at 393 mW/cm^2, the minimum depth of 5.9 μm at 981 mW/cm^2. Figure 6 and 7 shows the dependensies of etched depth of Si_3N_4 and SiO_2 on the UV light intensity, respectively. The pulse duration of 60 seconds and the pulse number of 3 were used at Si_3N_4 etching. The pulse duration of 60 seconds and the pulse number of 10 were used at SiO_2 etching. The etched depths of Si_3N_4 and SiO_2 increased with increasing the UV light intensity from 0 to 981 mW/cm^2. The etched depth of Si_3N_4 and SiO_2 were increased from 81.6Å to 1208.8Å and from 11.6Å to 130.2 Å, respectively. The higher increasing rate is observed in the UV light intensity from 0 to 491 mW/cm^2. The maximum ratio in the etched depths of Si_3N_4 and SiO_2 were 14.8 and 11.2 times with UV exposure of 981 mW/cm^2, respectively. There was no measurable etching of Al with the UV light intensity from 0 to 981 mW/cm^2. Therefore Al can be used as excellent mask material for XeF_2 etching with UV exposure.

Etching selectivities of Si_3N_4 and SiO_2 to Si were calculated by dividing an etching rate of Si by etching rates of Si_3N_4 and SiO_2, respectively. The etching rate was calculated by dividing the etched depth by the number of pulses. As shown in Fig.7, by exposing UV light of 981 mW/cm^2, the etching selectivities of Si_3N_4 and SiO_2 to Si were dramatically decreased from 488.2 to 29.3 and from 11446 to 906.1, respectively. The maximum ratio in the selectivities of Si_3N_4 and SiO_2 to Si were 16.7 and 12.6 times with UV exposure of 981 mW/cm^2, respectively. From these results, it was confirmed that the selectivities of Si_3N_4 and SiO_2 to Si can be controlled by the UV light

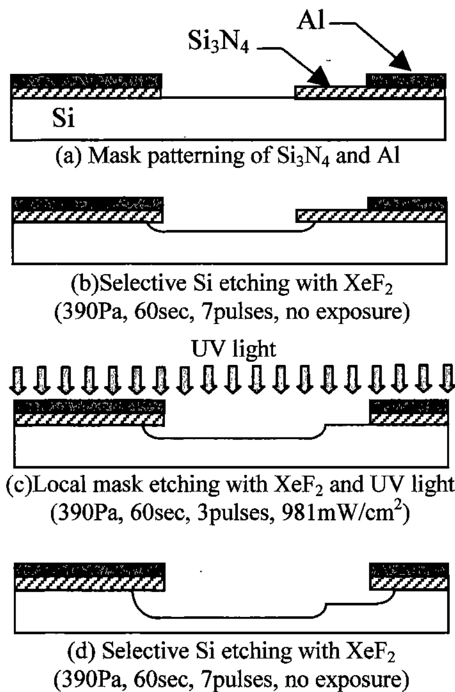

Figure 9. The process sequence and the experimental conditions. 100 nm-thick Si_3N_4 was used as the mask material.

exposure.

As a first step of the experiments, the 3-D microstructure was fabricated by using these etching characteristics. The process sequence shown in Fig. 9 was used. Al was used as the mask material for UV exposure. In step (a), 100 nm-thick LPCVD Si_3N_4 was patterned on a silicon substrate as the mask material, and 100 nm-thick Al deposited by vacuum evaporation was patterned on the Si_3N_4 mask as the mask material for UV exposure. In step (b), bulk Si was selectively etched by XeF_2 using the Si_3N_4 mask pattern. The etching in step (b) was carried out with 7 pulses (390 Pa, 60 sec). In step (c), the Si_3N_4 mask material was etched with XeF_2 and UV exposure by using the Al mask. The etching in step (c) was carried out with 3 pulses and the UV light intensity of 981 mW/cm^2 (390 Pa, 60 sec). In step (d), bulk Si was selectively etched by XeF_2 using the changed Si_3N_4 mask pattern. The etching in step (d) was carried out with 7 pulses (390 Pa, 60 sec). The profile of etched structure is shown in Fig.10. The Si_3N_4 mask protected the area A and B from XeF_2 etching, and the Al mask protected the area B from XeF_2 etching and UV exposure. The area C corresponds to the non-masked area. The area B corresponds to the masked area by Si_3N_4 that is exposed to UV exposure. The height at the area B and C were 14.8 μm and 20.0 μm, respectively. These dimensions can be controlled by UV intensity and number of pulses. From this experiment, it was confirmed that the Si_3N_4 mask material was locally removed and the multi-step Si structure was successfully fabricated.

This result encourages to develop a new process using spot UV light or patterned UV light as illustrated in Fig. 11. In

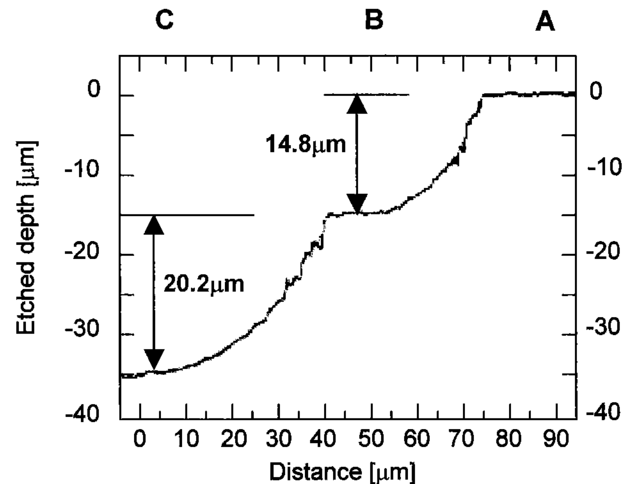

Figure 10. Fabricated profile measured by profile micrometer.

step (a), Si_3N_4 or SiO_2 is deposited and patterned on a silicon substrate as the mask material. In step (b), bulk Si is selectively etched by XeF_2 using the mask pattern. In step (c), by exposing the mask to UV light locally, only exposed areas of the mask material are locally etched with XeF_2. Therefore, it is possible to change the mask pattern during the etching process. In step (d), bulk Si is selectively etched by XeF_2 using the changed mask pattern. This process will enable us to eliminate the photolithography step for the second mask layer such as Al in Fig. 9 and expand the possibility of 3-D microstructure fabrication.

5 CONCLUSION

The new technique of bulk micromachining based on XeF_2 etching was proposed. By exposing UV light during XeF_2

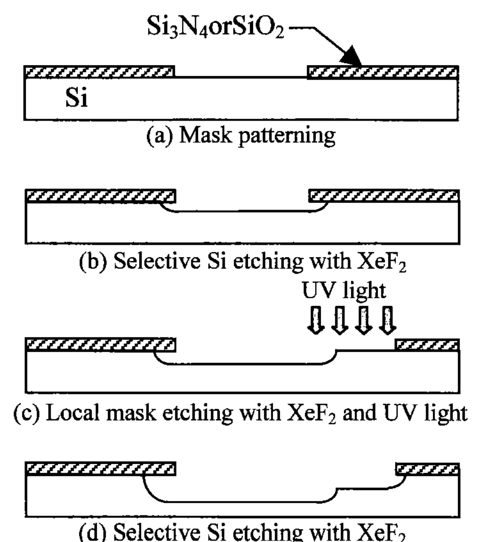

Figure 11. A process sequence for 3-D microstructure using XeF_2 etching with UV exposure.

etching, the etching rate of Si_3N_4 and SiO_2 used as mask can be increased. This enables us to modify the mask pattern during XeF_2 etching without photolithograpy. Consequently, the multi-step Si microstructure was successfully fabricated using this technique. This technique expands the possibility of 3-D micromachining and will allow us to fabricate more complex 3-D microstructure. The fabrication technique for in situ modification of mask pattern using spot UV light or patterned UV light is the next step of this research.

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REFERENCES

[1] A. A. Yasseen, J. Mitchell, T. Streit, D. A. Smith, M. Mehregany, "A Rotary electrostatic Micromotor 1 x 8 Optical Switch", Tech. Digest of IEEE Micro Electro Mechanical Systems (MEMS98), pp.116-120, 1998.

[2] J. J. Choi, R. Toda, K. Minami, M. Esashi, "Silicon Angular Resonance Gyroscope by Deep ICPRIE and XeF_2 Gas Etching", Tech. Digest of IEEE Micro Electro Mechanical Systems (MEMS98), pp.322-327, 1998.

[3] Risaku Toda, Kazuyuki Minami, and Masayoshi Esahi, "Thin Beam Bulk Micromachining Based on RIE and Xenon Difluoride Silicon Etching", Int. Conf. Solid-State Sensors and actuators, Transducers`97, Vol.1, No.2, pp.671-674, 1997.

[4] M. Mita, Y. Mita, H. Toshiyoshi and H. Fujita, "Delay-Masking Process for Silicon Three-Dimensional Bulk Structure", IEE Japan, Vol. 119-E, pp.310-311, 1999.

[5] H.F. Winter and J.W.Coburn, "The etching of silicon with XeF_2 vapor", Appl. Phys. Lett., Vol.34, No.1, pp.70-73, 1979.

[6] Patrick B.Chu, Jeffrey T.Chen, Richard Yeh, Gisela Lin, Jeff C.P. Huang, Brett A.Warneke, and Kristofer S.J.Pister, "Controlled Pulse-Etching with Xenon Difluoride", Int. Conf. Solid-State Sensors and actuators, Transducers`97, Vol.1, No.2, pp.665-668, 1997.

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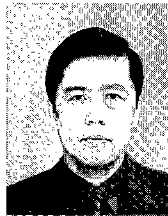

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