Extended Abstracts of the 19th Conference on Solid State Devices and Materials, Tokyo, 1987, pp. 291-294

C-7-3

Maskless Ion Beam Assisted Etching of SiO_2

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Characteristics of ion beam assisted etching (IBAE) for SiO_2 have been investigated by bombarding 50 keV noble gas ion beams in XeF_2 atmosphere at a pressure ranging from a few mTorr to 65 mTorr to develop maskless ion beam assisted etching technique. The etched surface roughness and composition were measured by Dektak and Auger electron spectroscopy. A smooth, high-quality surface was formed. The etching rate is about 40 times large than that for physical ion beam etching. It was observed that the addition of H_2 gas in the etchant gas further increase the etching rate. The etching rate became 100 times higher than the etching rate for physical sputter etching when 30 % H_2 is introduced.

1. Introduction

The increasing density of components in integrated circuits and their smaller dimensions have demanded tighter tolerances in the pattern-defining processes. Maskless ion beam etching on semiconductor materials have been extensively investigated by using focused ion beam (FIB) over the past several years.[1-3]

In comparison to physical sputter etching, the ion beam assisted etching (IBAE) method seems to be more attractive for a number of advantages such as high etching rate, preferential etching with precise control and low damage for etched materials. Therefore, this method can be expected to find application in various device fabrication.

The work reported here is to focus on the characteristics of maskless ion beam assisted etching of SiO_2. The effects of various etching parameters such as ion species, ion dose, etchant gas pressure as well as the additive effect of H_2 gas have been investigated so as to find optimum condition for maskless etching. Auger analysis was performed to detect chemical composition of etched surface. The mechanism of enhancement of etching rate are discussed as well.

2. Experimental Procedures

Experimental set-up for ion beam assisted etching is shown in Figure 1.

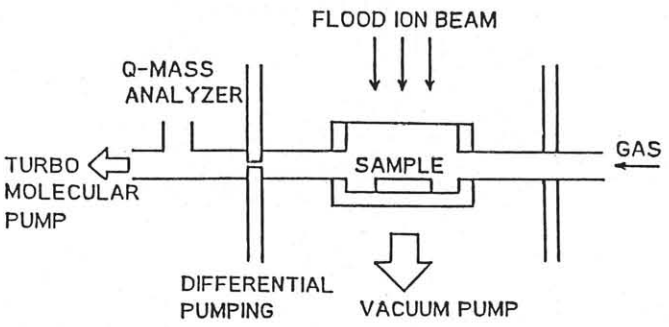


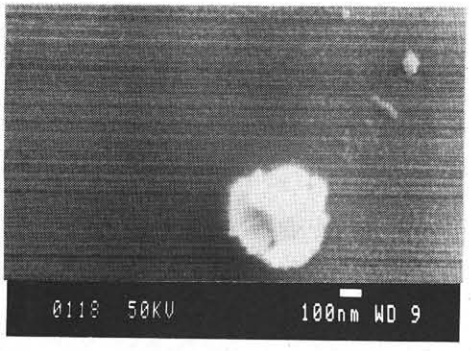
Fig. 1 Experimental set-up for ion beam assisted etching.

Thermal SiO_2 was mounted in an inner sub-chamber which was separated from the main chamber by a 0.2 mm thick plate with 0.8 mm aperture in diameter. The flow rate of XeF_2 gas to the sub-chamber was controlled by a

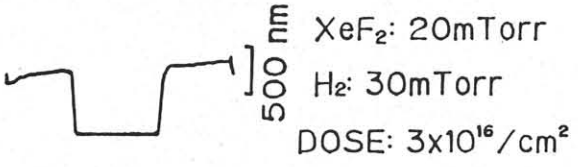
needle valve and the pressure inside the sample chamber was measured by a Pirani gauge attached to the sample chamber. The atmosphere inside was monitored by a quadruple mass spectrometer (QMS). Turbo molecular pump was employed to keep a base pressure of 10^{-6} Torr. With this arrangement, the gas could be introduced at the high gas pressure in the sample chamber, while keeping high vacuum pressure ($<10^{-5}$ Torr) outside. For the present experiment, 50 keV flood He^+, Ar^+ and Xe^+ were irradiated. The current density was about $2uA/cm^2$.

3. Results and Discussion

Figure 2 shows a Dektak tracing of the cross-section formed by 50 keV Ar^+ ion bombardment with XeF_2 ambient at the pressure of 30 mTorr, and the SEM photograph of the etched surface. In the SEM photograph, about 50 nm sized dust was observed to show the fine focusing. It is clear that a smooth, high-quality surface was formed by the present ion beam assisted etching.



(a)



(b)

Fig. 2 Scanning electron microscopy (a) and Dektak trace of SiO_2 surface etched by the ion beam assisted etching.

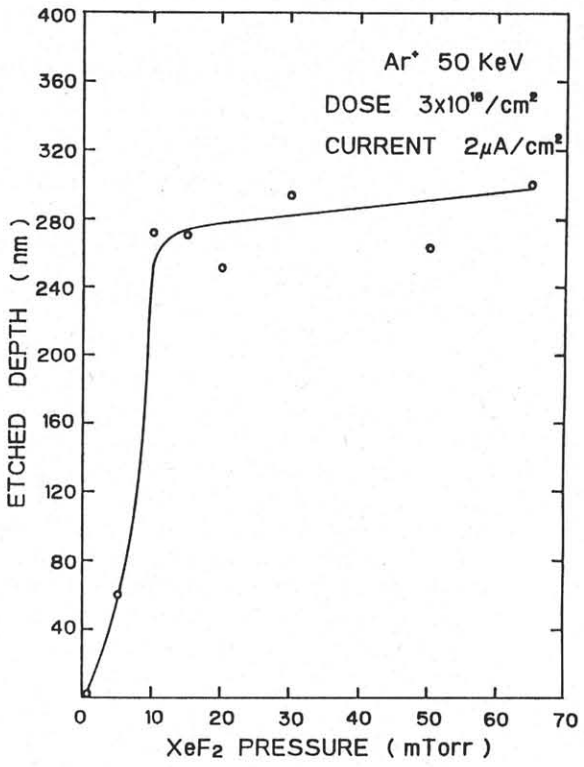


Fig. 3 Etched depth of SiO_2 filmasa function of XeF_2 pressure.

Figure 3 shows the etched depth as a function of XeF_2 gas pressure for 50 keV Ar^+ ion bombardment at the current density of $2uA/cm^2$. It was observed that the etching rate increased with increasing the XeF_2 gas pressure at a low pressure less than 10 mTorr and almost saturated with further increase of the XeF_2 introduction, which is qualitatively consistent with the mass balance model proposed by Barker et al [4] for a low-energy ion beam etching. Obviously, the etching rate is about 40 times larger than the etching rate for physical sputter etching as long as a gas pressure of more than 10 mTorr is introduced.

The fluctuation in gas pressure provides little influence on etching rate at saturated region. Therefore, the etched depth can be controlled by the other parameters such as ion dose. The etched depth was linearly dependent on the dose, i.e, the average etching rate was constant. These results suggest that the etched depth can be easily

controlled by ion dose, which is important for device fabrication.

The observed etching rate was 140 um/mA/cm^2. This value is 550 times larger than the value observed for an electron beam assisted etching using 1.5 keV electron beam[5] and XeF_2 gas. It can be expected that the etching rate should increase with in creasing the energy deposition rate by collisions. The energy deposition rate for 50 keV Ar and 1.5 keV electron beam in SiO_2 is 1.96×10^9 and 8.0×10^6 eV/cm/particle, respectively.[6,7] For 50 keV Ar, the energy deposition mainly occurs by nuclear collision and the electronic energy deposition rate is only 0.5 % of the total deposition rate.

The observed results suggest that nuclear collision is more effective to enhance the etching. The electronic collision induce transient excitation in electronic states of target and adsorbed atoms, while nuclear collision mainly induce persistent bond breaking or radiation damage. This may result in larger enhancement in the etching. Such enhanced etching due to radiation damage have often been observed for wet and dry etching of Si[8] or SiO_2[9].

Addition of H_2 further increased the etching rate. The etched depth are shown in Fig. 4 as a function of the mixing ratio for the etching using 50 keV Ar^+ at a dose of 2×10^{16}/cm^2, current density of 2uA/cm^2, and total etchant gas pressure of 30 mTorr. It is evident that the etching rate was significantly enhanced with increasing the partial pressure of hydrogen up to 30 %, at the value of which 3 times larger etching rate compared to that without hydrogen was observed.

In order to reveal the additive mechanism of H_2 gas, quadruple mass spectra of etchant atmosphere were measured. The observed spectra is shown in Figure 5. Before the introduction of H_2 gas, fluorine was the main

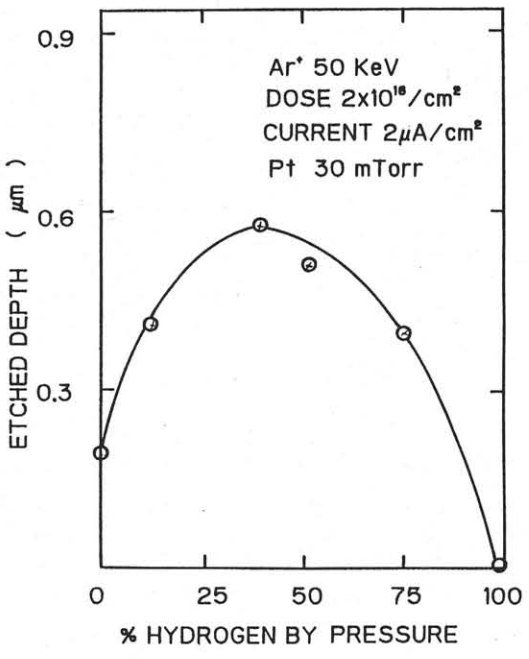


Fig. 4 Etcheddepthof SiO_2filmas a function of the mixing ratio of XeF_2/H_2.

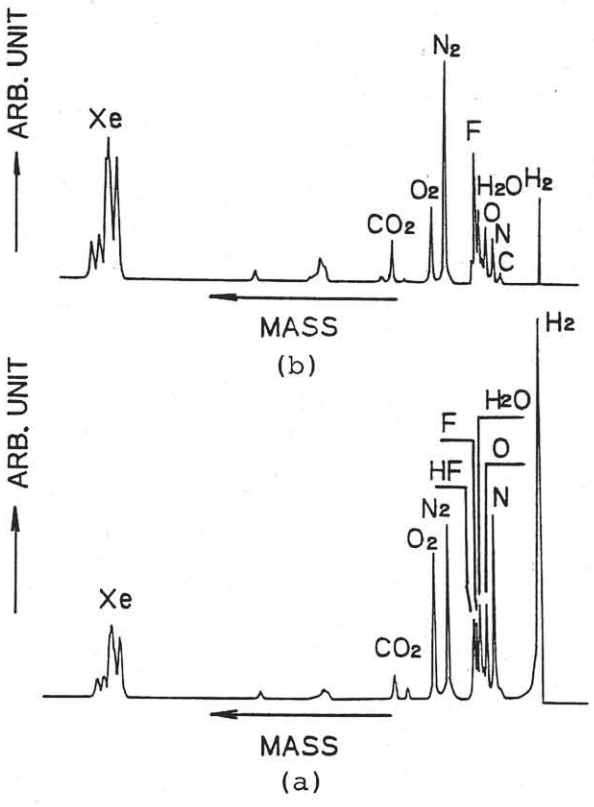


Fig. 5 Massspectraoftheetching atmosphere with (a) and without (b) adding of H_2.

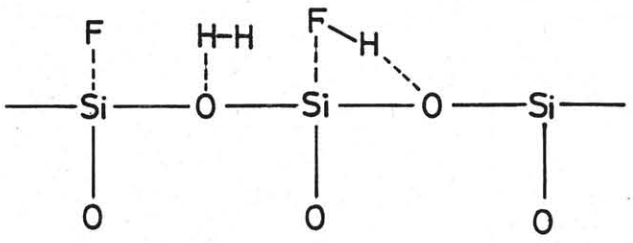


Fig. 6 Schematic diagram of the surface in H_2 and XeF_2 mixed gas atmosphere.

etchant as shown in Fig. 5 (a). After the introduction of H_2, it was observed that a considerable amount of HF was formed, as shown in Fig. 5(b). The existence of HF in the gas phase can be attributed to the high reactivity of XeF_2 to H_2.

It is likely that HF and H_2 are chemically absorbed on SiO_2 after the introduction of H_2 as shown in Fig. 6. The electron cloud between oxygen and silicon tends to move to the vicinity of oxygen and silicon respectively, due to the considerably high bond energy of H-O (110.6 kcal/mol) and Si-F (135 kcal/mol), while Si-O bond energy is 111 kcal/mol. Consequently, Si-O bonding is significantly weakened, and that makes it easy for incident ions to break Si-O bonding. Therefore, HF and H_2 gas presumably plays an important role in the enhancement of etching rate, though further details are unknown. Similar enhancement by the addition of hydrogen was also reported for the laser-induced etching of SiO_2 using a mixed gas of NF_3+H_2.[10]

From Auger analysis of etched surface, no fluorine residues were detected but a small carbon contamination was detected, which is probably a contamination at the surface which resulted from the residual gases in the chamber or a contamination in air when sample was taken out from the vacuum chamber.

4. Conclusion

A smooth, high-quality surface can formed by IBAE for SiO_2. The hydrogen adding provides influence on the etching rate enhancement with a maximum etching rate 100 times larger than that of physical sputter etching. This significant enhancement makes the ion beam assisted etching technique useful for maskless or resistless etching using focused or projection ion beam systems.

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