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Anisotropic etching of n^+ polycrystalline silicon with high selectivity using a chlorine and nitrogen plasma in an ultraclean electron cyclotron resonance etcher

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Heavily phosphorus-doped polycrystalline silicon films (n^+ poly-Si) were etched in a pure chlorine plasma using an ultraclean electron cyclotron resonance etcher. Compared against undoped polycrystalline etching, horizontal etch rates were too high to allow anisotropic etching of n^+ poly-Si. With the addition of more than about 10% N_2, highly anisotropic etches of n^+ poly-Si can be obtained simultaneously with selectivities as high as 160 to SiO_2 in a 4 mTorr plasma. These results are significant to lower submicron fabrication. X-ray photoelectron spectroscopy studies show that Si—N bonds are formed on the n^+ poly-Si surface during etching and it is proposed that this layer protects the sidewall against Cl radicals in a N_2/Cl_2 plasma. The suppression of SiO_2 etching by O_2 addition to a N_2/Cl_2 plasma has also been demonstrated.

An anisotropic dry etch of n^+ polycrystalline silicon (n^+ poly-Si) with high selectivity is very important for gate electrode formation in ultralarge scale integration (ULSI) fabrication. It is well known that the anisotropic dry etching is realized by ion-assisted reactions with a suppression of radical reactions which lead to isotropic etching.[1] To suppress the radical reaction, etching at temperatures as low as -110 to -130 °C with time modulation has been proposed.[2] Practically speaking, wafer temperature control is very difficult to achieve in this type of system. To form sidewall protective films which scarcely react with the radicals, a gas chopping method[3] in which the N_2 and the SF_6 plasmas are alternately produced has also been proposed. Sidewall protective films are not normally formed in a N_2/SF_6 plasma. However, the reported selectivity of Si to SiO_2 in such a system is only about 10. In our previous work,[4,5] it has been found that an induction period exists for SiO_2 etching and that during this induction period, infinite selective Si to SiO_2 etching can be achieved in an ultraclean chlorine electron cyclotron resonance (ECR) plasma. Under this infinite selective etching condition, anisotropic etching of undoped polycrystalline silicon patterns has been realized, but such results have not yet been demonstrated for n^+ poly-Si patterns.[4,5]

In the present work, n^+ poly-Si etching has been investigated in a pure chlorine plasma using an ultraclean ECR etcher. It has been found that horizontal etch rates are too high to allow anisotropic etching, although the selectivity of n^+ poly-Si to SiO_2 etching is very high. With N_2 addition to Cl_2, both highly anisotropic and highly selective etching of n^+ poly-Si is achieved. Moreover, sidewall protection against Cl radical attack is discussed based on x-ray photoelectron spectroscopy (XPS) evaluations. The suppression of SiO_2 etching by O_2 addition to a N_2/Cl_2 plasma is also discussed.

An ultraclean ECR plasma apparatus[4,5] is used to obtain high selectivity. Precise amounts of high-purity chlorine and nitrogen are supplied by mass flow controllers and premixed before introducing them to the plasma chamber. The reactor pressure is measured with an MKS Baratron gauge. Microwave power used to generate the plasma is usually set at 700 W. By an electrostatic adhesive force, wafers are held strongly to the suscepter which is cooled by water to suppress a temperature increase of the wafers due to the plasma exposure.[6] The samples etched were 450-nm-thick phosphorus-doped n^+ poly-Si of about 20 $\Omega/\square$ and undoped poly-Si formed on thermally oxidized Si wafers. Thermally grown SiO_2 was used as a mask, since organic resist degrades the selectivity to the underlying SiO_2 because of carbon contamination. The vertical etch rate of poly-Si was determined by etched thickness measured by a Tencor Alpha Step 200 and etching time measurements. The horizontal rate was evaluated from cross-sectional scanning electron microscope (SEM) measurements. Thermally grown SiO_2 on Si was etched separately and the etch thickness was measured by an automatic ellipsometer. The etched surface of n^+ poly-Si was analyzed by XPS.

Figure 1 shows the pressure dependence of vertical and horizontal etch rates as well as anisotropy and selectivity of the undoped poly-Si and n^+ poly-Si for the pure chlorine etching. Here, the anisotropy is defined as the vertical to horizontal etch rate, and the selectivity is defined as the etched thickness of undoped poly-Si and n^+ poly-Si to that of SiO_2. In Fig. 1 the horizontal etch rate of undoped poly-Si is low enough to give an anisotropic etch profile over the whole pressure range measured. The anisotropy is more than 12 even at pressures as high as 4 mTorr, where selectivity is also high. For n^+ poly-Si, the horizontal etch

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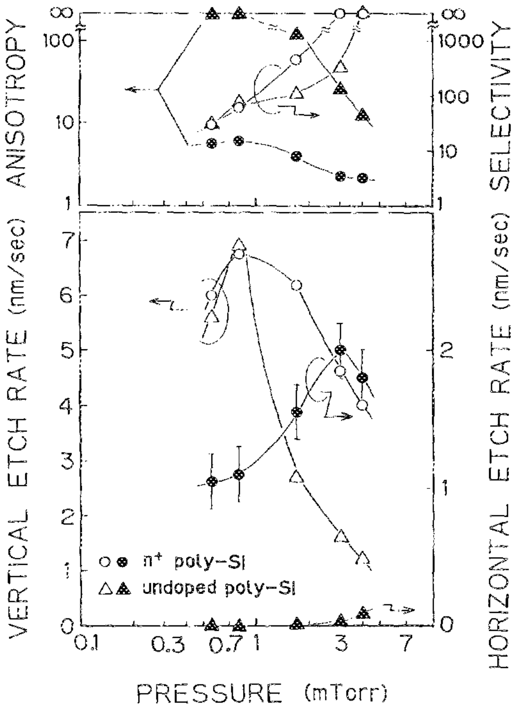

FIG. 1. Pressure dependence of vertical and horizontal etch rates as well as anisotropy and selectivity of the undoped poly-Si and n^+ poly-Si for the pure chlorine etching. Microwave power is 700 W.

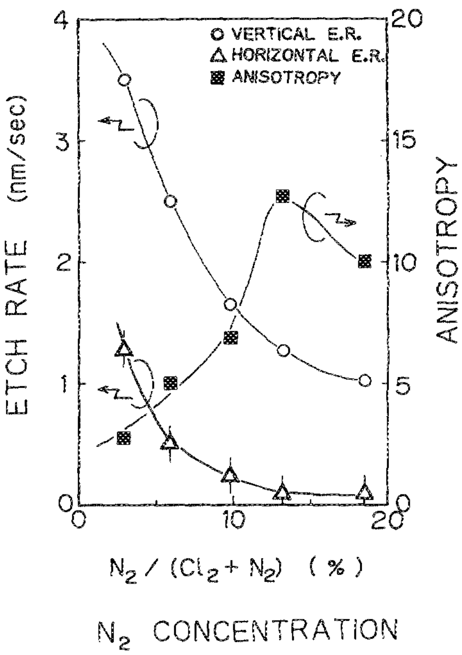

FIG. 2. Dependence of vertical and horizontal etch rate and anisotropy of n^+ poly-Si on added N_2 concentration. The pressure is 4 mTorr. Microwave power is 700 W.

rate is very high and the anisotropy is only 6, even at pressures as low as 0.57 mTorr. At high pressure, the anisotropy is as low as 2, although the selectivity is very high. From these results it is evident that the Cl radical attack on sidewalls is dominant in n^+ poly-Si etching at high pressure.

Figure 2 shows the effect of adding N_2 on the n^+ poly-Si etch rate at 4 mTorr. With increased N_2, the horizontal etch rate becomes very low and nearly constant within experimental errors when $N_2/(Cl_2 + N_2) \gtrsim 10\%$. Anisotropy is greatly improved by the N_2 addition to Cl_2 in spite of the decrease in the vertical etch rate. The selectivity was as high as 160 at 10% N_2 concentration, although the etched thickness of SiO_2 slightly increased and the induction period shortened with the N_2 addition.

From XPS studies of the n^+ poly-Si surface after etching with a N_2/Cl_2 plasma, it is found that the n^+ poly-Si surface has a nitrogen peak as well as chlorine and silicon peaks. The Si^{4+} peak appears at an energetically equivalent point to the peak of Si in Si_3N_4 films formed by low-pressure chemical vapor deposition. The nitrogen peak appears even when the ion shutter, which interrupts the direct incidence of ions, is closed. These results indicate that Si—N bonds are formed by the N radical both on the bottom and on the sidewall of n^+ poly-Si. Surface-bonded nitrogen would be effective in protecting sidewall etching in a N_2/Cl_2 plasma. In case of stopping N_2 addition, this nitride film is easily removed by the pure chlorine plasma with the shutter closed. Therefore, it is necessary that nitrogen should be added simultaneously to chlorine in order to protect the sidewall of n^+ poly-Si.

The SiO_2 etch rate and the decrease of the induction period due to N_2 addition have been confirmed to be suppressed with O_2 addition. This result is shown in Fig. 3. It is found that the infinite selectivity is achieved during 10 min with an addition of 1.9% O_2 in 10% N_2 concentration.

Figure 4 (a) shows a SEM cross-sectional view of n^+ poly-Si patterns etched with the pure chlorine plasma. The etching profile is isotropic and a large undercut is introduced. The etched profile with the nitrogen-added chlorine plasma is shown in Fig. 4(b). Excellent anisotropic etching was observed along with high selectivity.

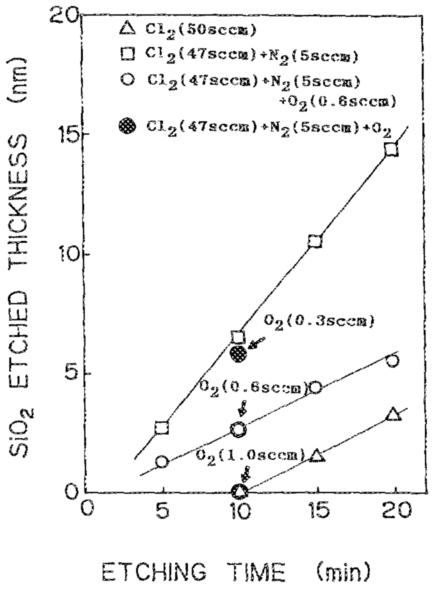

FIG. 3. Effect of O_2 addition on SiO_2 etching with the nitrogen added chlorine plasma. The pressure is 4 mTorr and microwave power is 700 W.

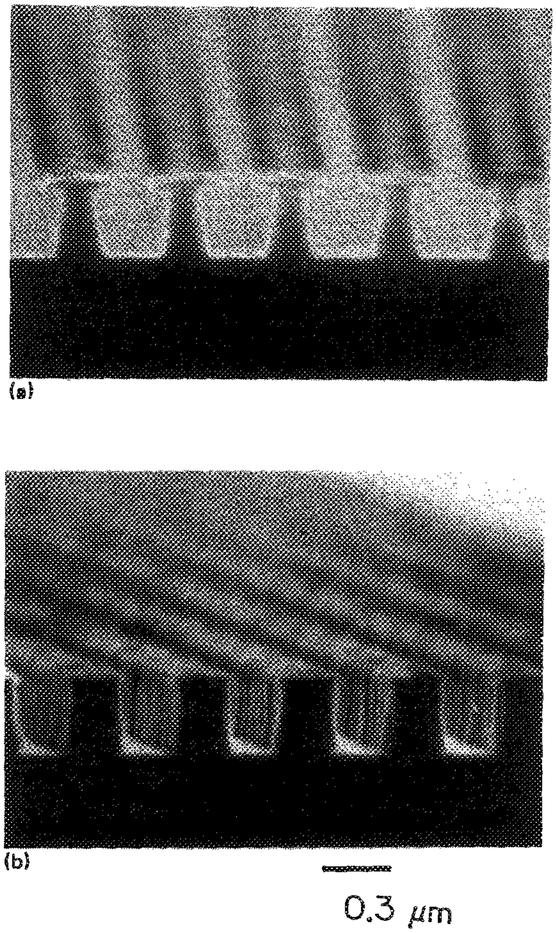

FIG. 4. (a) Isotropic etch profile of n^+ poly-Si etched with the chlorine plasma. The Cl_2 gas flow rate is 50 sccm, the pressure is 4 mTorr, and microwave power is 700 W. (b) Anisotropic etch profile of n^+ poly-Si etched with the nitrogen added chlorine plasma. The Cl_2 gas flow rate is 47 sccm, the N_2 gas flow rate is 5 sccm, the pressure is 4 mTorr, and the microwave power is 700 W.

In conclusion, highly anisotropic etching with excellent selectivity for n^+ poly-Si has been achieved with nitrogen addition to a chlorine plasma using an ultraclean ECR etcher. It has been found from XPS studies that the Si—N bond formation on n^+ poly-Si surface with the N_2 addition protects the sidewall etching against the Cl radical reaction. The suppression of SiO_2 etching by O_2 addition is also demonstrated.

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