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Low Temperature Microwave Plasma Etching

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New low-temperature microwave plasma etching is reported on this paper. Etch rates, side etch widths and selectivities as a function of the wafer temperature are measured in the temperature region of -150 ~ +30 ℃ for Si, WSi_2 and W. Highly selective anisotropic etching at a high rate, which implies dry etching without tradeoff is found to be possible without changing the discharge parameters. However, this etching is only achieved at reduced temperatures. The results indicate that the reaction probability and the vapor pressure of the reaction products are the main factors for side etching reduction at the low-temperatures.

1. INTRODUCTION

Tradeoffs between anisotropy and selectivity and between anisotropy and the etch rate have long been thought to be unavoidable in dry etching. Since side etch reduction is fundamental for continued design improvement, it became necessary for recent VLSI processing to sacrifice the selectivity and etch rate. However, a sophisticated masking structure and long processing time were required, resulting in poor reproducibility and yield. Thus, it is essential for anisotropy, selectivity and the etch rate to be satisfactory at the same time to eliminate these issues.

The effects of the wafer temperature on the above three etching factors have been neglected for a long time. This is because temperature measurement is not easy and many researchers concentrated on optimizing other parameters, except in recent work.[1-7] Keaton and Hess showed the temperature evolution of Al and its oxide etch rate and pointed out the importance of temperature control for highly reproducible etching.[2] Hussla et al. and Nakamura et al. discussed wafer heating during etching using fluoroptic temperature measurement.[3-4] Good thermal contact was attained and was used for Al profile control. In addition, Namatsu et al. reported the effect of the electrode temperature on low-pressure resist etching improved the anisotropy.[5]

All these experiments, however, used a water-based cooling system. Hence, the results did not conclusively prove that dry etching was achieved without tradeoffs. Bensaoula et al. obtained more conclusive results with tungsten by using an ion-beam-assisted etching system.[6] However, they still had to conclude that low-temperature etching is difficult because of input power from plasma.

In the recent letter,[1] the present authors showed that wafer temperature control below 0 ℃ during dry etching can eliminate the tradeoff problem. Moreover, such control provides an excellent possibility of allowing device processing at the nanometer level. In this paper, a systematic study of the etch rate, side etching, and selectivity as a function of wafer temperature is reported.

2. EXPERIMENTAL

Low-temperature microwave plasma etching was carried out in the temperature range of -150 ~ +30 ℃ using the specially equipped temperature control system shown in Fig. 1.

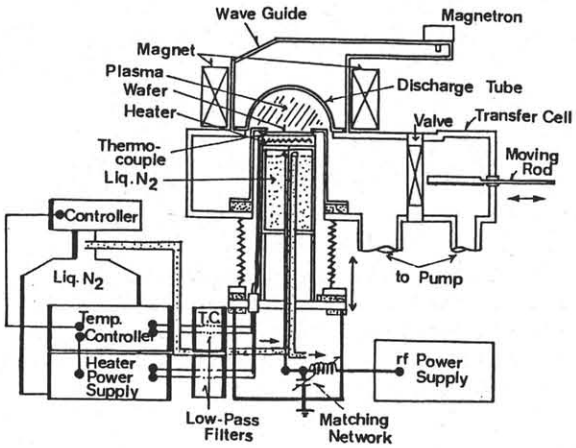

Fig. 1 Low-temperature microwave plasma etching system with new temperature controlled electrode

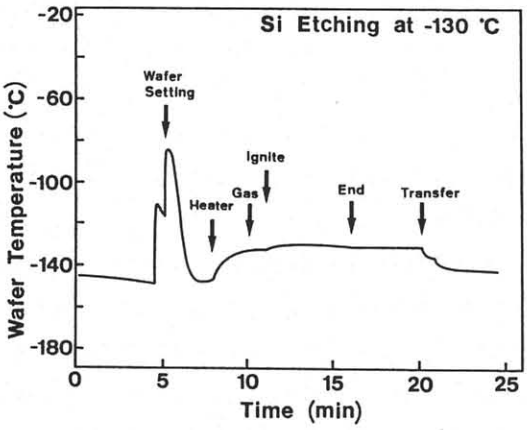

Fig. 2 Temperature profile measured as a function of the etching time

The central technical issue of the new etching regards the wafer temperature control in the above temperature range. For this purpose, a wafer was clamped to an electrode cooled with liquid nitrogen. Then the back of the wafer was cooled with He gas. This He gas had been cooled in advance by the liquid nitrogen. To avoid wafer temperature fluctuations, the cooling power was adjusted to compensate for the heat input from the plasma. Thus, it was possible to maintain the wafer temperature at a constant value in the range of -150 ~ +30 ℃ during etching lasting 30 minutes or more. The wafer temperature distribution as a function of the etching sequence is presented in Fig. 2.

During the etching, it is possible to monitor the wafer temperature, which is very important for low-temperature etching. A very thin sheath-type thermocouple was used to measure the temperature of the 4" wafer. The top of the thermocouple was kept directly against the back of the wafer with a plate-type spring mechanism. Measurements were made several times at different locations to ensure accuracy. Wafer temperatures of the front and back surfaces were measured at the same time.

This result was seen in the good uniformity of the profile of a 4" Si wafer etched at -110 ℃ for 5 minutes. Further confirmation of good stability was obtained using fluoroptic fiber[3] in the temperature range of -150 ~ +30 ℃. Difference of the measured temperature for both the thermocouple and the fiber was found within 5 ℃ as shown in Fig. 2, when good thermal contact was achieved using the above mentioned mechanism.

Poly-Si, WSi_2, and W were etched. The discharge conditions were the same for each, i.e, the gas species, gas pressure, rf biasing power and flow rate were SF_6, 1.3 Pa, 30 Watts and 10 sccm, respectively. Crystalline Si was used to show the difference in etching with SF_6, CF_4, NF_3, Cl_2, and $CBrF_3$ gases. Additionally, bottom layer etching of a tri-layer resist was carried out to clarify the H_2O condensation effect on side etching at low temperatures.

3. RESULTS AND DISCUSSION

The etch rate and side etching width of crystalline Si etched in SF_6 gas are shown in Fig. 3 as a function of gas pressure and wafer temperature. The new axis for temperature indicates that the width of the Si side

etching goes down to zero below -110 ℃ without reducing the high etch rate of over 1.0 μm/min. The side etching of the resist decreases at this temperature range, too.

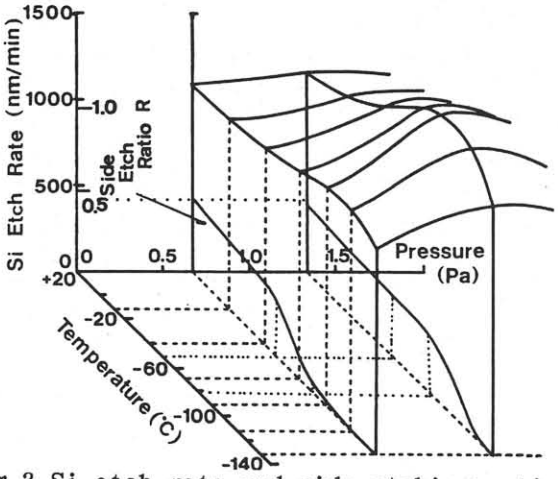

Fig. 3 Si etch rate and side etching ratio, R, as a function of gas pressure and temperature, where R is defined by the ratio of side etch width to etch depth

Eventually, the present technique provides an ultrafine pattern transfer. Furthermore, selectivity goes up to 20 in conjunction with a temperature reduction to -130 ℃. This high selectivity is attributable to a low biasing voltage of -15 V. Hence, low-temperature microwave plasma etching allows highly selective anisotropic Si etching at a high rate. Thus the tradeoffs are eliminated.

The bottom etch rates of Si for fluoride gases are shown in Fig. 4. The rates were found not to decrease at low temperature, except $CBrF_3$. Some film deposition is considered to take place for this gas at low temperature. The other results indicate that ion assisted reaction is dominant.

The side etching widths of n^+ poly-Si, WSi_2 and pure W films are shown in Fig. 5 as a function of the wafer temperature. No side etching was observed below -130, -60 and -20 ℃, respectively, under the same etching condition. The reaction of F atoms with the W started to decrease at +20 ℃. That of F with Si occurred at -60 ℃. Overall, the plots for the WSi_2 are somewhere between those of the others. These results indicate that, for side etching, the temperature dependence of the reaction probability has a major effect on the variation of the side etching width.

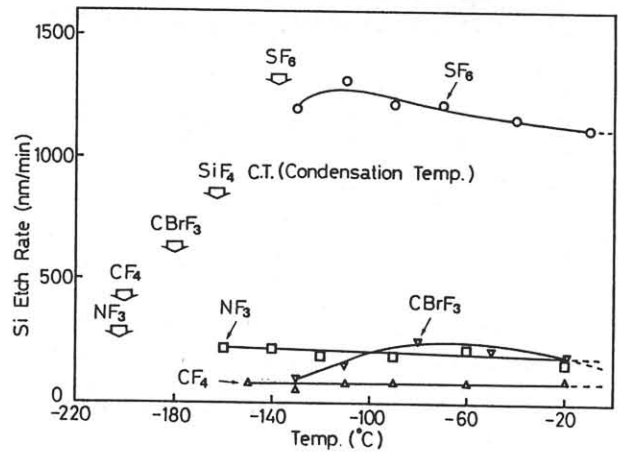

Fig. 4 Wafer temperature dependence of the bottom etch rates of Si for fluoride gases

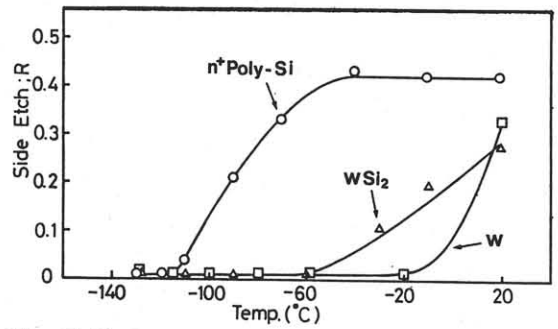

Fig. 5 Temperature dependence of the side etching ratio, R, of poly-Si, WSi_2 and W etched with the same SF_6

Figure 6 shows the temperature dependence of the resist etching rate and the side etching width in O_2 plasma. At -110 ℃, no side etching occurred, even at a high etch rate of 800nm/min. The reaction products of the resist were CO, CO_2, C_xH_y and H_2O. This H_2O is thought to reduce the side etching of the resist because of its low vapor pressure at low temperatures. The condensation phenomenon of H_2O was measured by adding it during discharge. The H plasma emission from the H_2O was monitored as a function of the

determining the rate for resist side etching, therefore, was concluded to be the vapor pressure of the reaction product.

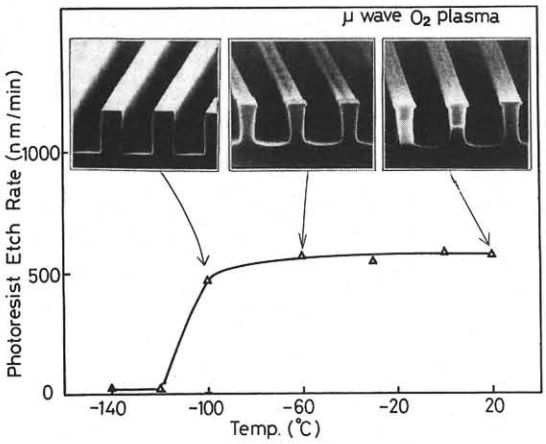

Fig. 6 Temperature dependence of the resist etch rate and the side etching ratio, R, with O_2 gas plasma

Using a reactive spot model[8], the results are discussed below to clarify the factors underlying the low-temperature dry etching. Concerning the bottom etch rate, very little temperature fluctuation is observed for silicon etching with fluoride gases. The two major factors of the etch rate are the spontaneous reaction and the ion assisted reaction. The spontaneous one is considered to have a temperature dependence. Hence, spontaneous etching including the damage layer etching, is not dominant. The models for ion assisted reaction are (1) the ion induced damage layer etching model[9], (2) the ion assisted evaporation model[10], and (3) the ion assisted reaction excitation model[11].

Among these models, the damage model predicts a spontaneous reaction and therefore is temperature dependent. The same is true for the evaporation model since the reaction of the radicals with the surface atoms takes place before ion bombardment.

On the other hand, the reaction occurs due to the ion bombardment for the last model. The reaction takes place under an excited condition caused by ion collision. Consequently, the probability does not depend on the wafer temperature. Therefore, with ion bombardment, the etch rate as a function of the wafer temperature should remain constant. The low-temperature etching indicates that the excitation model is appropriate for understanding the etch rate.

4. CONCLUSION

In conclusion, the reaction probability and the vapor pressure of the reaction product are the main factors for side etching reduction in low-temperature microwave plasma etching. Less depositing type gases provide high etch rate. Low biasing is essential to achieve high selectivity in low-temperature etching.

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