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Microwave Plasma Etching of Silicon Dioxide for Half-Micron ULSIs

Kazuo NOJIRI, Eri IGUCHI, Koichiro KAWAMURA* and Kazuya KADOTA

Semiconductor Design & Development Center, Hitachi Ltd.
5-20-1,Josuihon-cho,Kodaira-shi,Tokyo 187,Japan
* Hitachi Microcomputer Engineering,Ltd.
5-22-1,Josuihon-cho,Kodaira-shi,Tokyo 187,Japan

A new SiO_2 etching technology for half-micron ULSIs has been developed using the microwave plasma etcher. The optimum conditions for SiO_2 etching are obtained, in terms of etch rate, geometrical controllability, and radiation damage by fully utilizing such advantages of the microwave plasma etcher, as independent control of ion energy and plasma density in low pressure regions. The condition for high selectivity is also found in the low pressure region with C_4F_8/CH_3F. The technology has been successfully applied to the formation of contact holes down to 0.4 μm with an aspect ratio of 6.

1. INTRODUCTION

As dimentions of semiconductor devices shrink to half-micron, dry etching technologies need to overcome some contradicting demands. Especially as for SiO_2 etching, it is required to etch small and deep contact holes at high rate without damage and side etching. However, these demands may not be satisfied with parallel plate type plasma etching or RIE which have been widely used for conventional VLSI fabrications. For example, in narrow-gap parallel plate plasma etching operated in the high pressure region (100 to 300Pa),etch rate is high and radiation damage is low, while the side etching in contact holes is caused by a large amount of inclined ions due to ion-molecule collisions. In RIE, with lower pressure (∿5Pa), a larger mean free path suppresses side etching. However, etch rate is lowered and radiation damage is induced to the Si surface by highly accelerated ions.

As an alternative and novel dry etching technology, the microwave plasma etching has been proposed[1-2]. The microwave plasma etching has the following advantageous features. (1)Low gas pressure operation (less than 1Pa) with high etch rate , (2)clean plasma source with no metal electrodes, and(3)controllability of ion energies without changing plasma density. In this paper, a newly developed SiO_2 etching technology for half-micron ULSIs using the microwave plasma etcher is described.

2. EXPERIMENTAL

The microwave plasma etching apparatus used in this work is shown in Fig.1. The microwave generated at 2.45GHz by a magnetron, is introduced into a discharge tube through a waveguide. Magnet coils are arranged around the periphery of the discharge tube to achieve an ECR condition. In this system, high density plasma is generated even in low pressure regions using ECR discharge. The RF power to control ion energies is supplied to the substrate. The frequency of the RF power was 400kHz. Etching gas mainly used in this study was C_4F_8. C_4F_8/CH_3F was also used to get higher selectivity.

Etch rates for thermally grown SiO_2 and Si substrate were studied as a function of

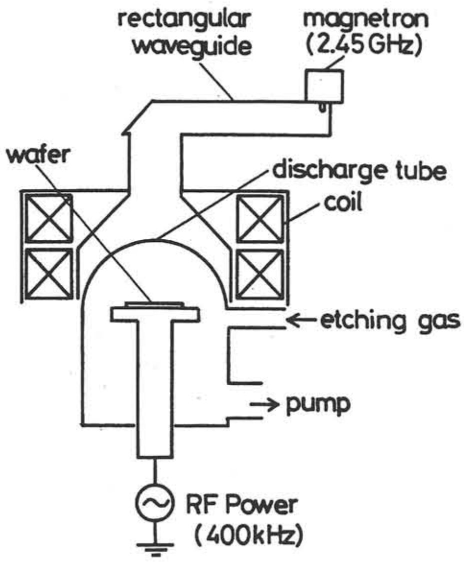

Fig.1. Schematic diagram of microwave plasma etching apparatus.

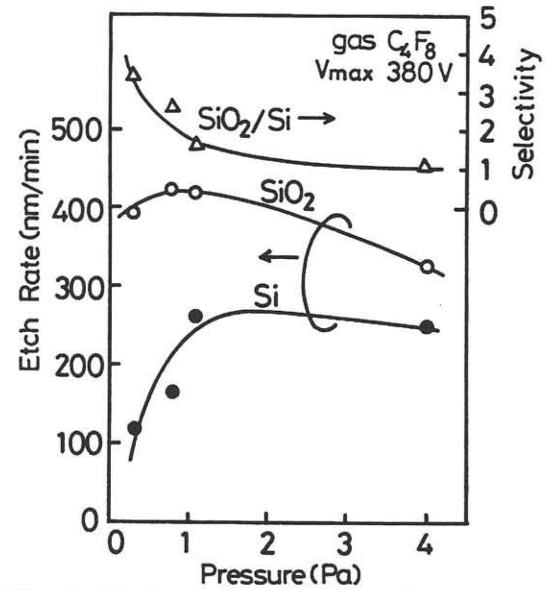

Fig.2. Etch rate and selectivity as a function of pressure.

pressure (0.3 to 4Pa), and maximum acceleration voltage Vmax (0 to 500V). Here, Vmax is defined as |Vdc|+Vpp/2, and can be controlled by the RF power. Microwave power was kept constant at 500W.

To evaluate the radiation damage induced to the Si surface during etching, the lifetime of minority carrier was measured as a function of Vmax. In this study, an optical lifetime measurement technique[3] was used. The measurement procedure has been reported in previous paper[3].

Moreover, etching characteristics for small contact holes with high aspect ratios were investigated. The samples were with 1.6 μm thick PSG films deposited on the Si substrates. On the PSG films, 1.7μm thick photoresist mask patterns (hole diameter ranging from 0.4 to 3.4μm) were formed using electron beam lithography and tri-level resist technique.

3. RESULTS AND DISCUSSION

In the microwave plasma etching, it is found that the Si etch rate is very high because of high concentration of fluorine radicals. Therefore, the selectivity to Si is low in spite of using C_4F_8, which was expected to have high selectivity[4]. Figure 2 shows the dependence of the SiO_2 and Si etch rate on gas pressure. The etch rate for Si is drastically reduced below 1Pa. This phenomenon is thought to be caused by the reduction of fluorine radicals in this pressure region. The etch rate for SiO_2, on the other hand, does not change in this region. Therefore, the selectivity can be improved below 1Pa. In the following experiments, 0.4Pa was chosen as a standard pressure.

The dependence of the etch rate and selectivity on Vmax is shown in Fig.3. Both SiO_2 and Si etch rates increase with Vmax, resulting in nearly constant selectivity. Adding 30% CH_3F to C_4F_8, the etch rate for Si is considerably reduced, leading to higher selectivity. Because the CH_3F addition reduces fluorine radicals by the reaction of fluorine and hydrogen to form HF, and enhances polymerization of fluorocarbon and hydrocarbon fragments on the Si surface. In this case, the selectivity increases with decreasing Vmax.

Radiation damage of the microwave plasma etching and RIE was evaluated by measuring the lifetime of minority carrier. In this experiment, Si substrates were exposed to

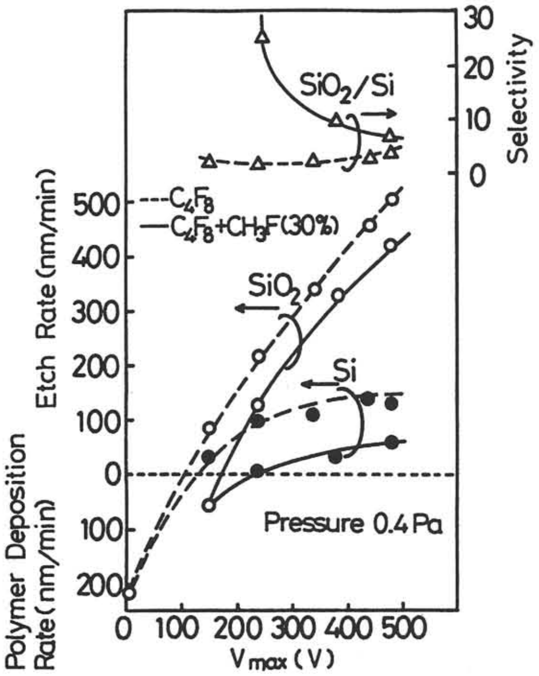

Fig.3. Etch rate and selectivity as a function of Vmax.

plasma for 1 minute. Lifetime measurements were made after removing the 10nm thick surface layer of Si substrate using a down-stream etcher with CF_4/O_2 mixture gas, followed by oxidation in dry O_2 ambient. Figure 4 shows the dependence of the lifetime of minority carrier on Vmax. The lifetime is normalized to that of the control sample. As can be seen from Fig.4, the degradation of the lifetime measured in the microwave plasma etching sample is suppressed up to Vmax=300V.

From Fig.3, the SiO_2 etch rate and selectivity for the sample etched with C_4F_8/CH_3F are 250nm/min and 15 respectively, at a Vmax of 300V. These values are sufficient for practical use. Therefore,the microwave plasma etching can realize low damage and high rate etching for SiO_2 by utilizing the advantage of controlling the ion energy without changing plasma density. For RIE,etch rate was low (40nm/min),and the lifetime is reduced to 20% of that of the control sample (see Fig.4).

Figure 5 shows the dependence of PSG etch rate on the diameter of contact holes. The etch rates are normalized to that for the holes with 3.4µm diameter. In the plasma etching, the etch rate strongly depends on the hole size,and drastically decreases below a diameter of 1.0µm. The decrease in the etch rate is 40% at a diameter of 0.4µm (the aspect ratio is 6 including the mask thickness). It indicates that the plasma etching is not a practical answer to form the half-micron contact hole because of relatively steep dependence of the etch rate on the hole diameter. Even in RIE, 20% reduction in the etch rate is seen at a diameter of 0.4µm. The microwave plasma etching, on the other hand, shows a plateau in the etch rate characteristics down to a diameter of 0.4µm.

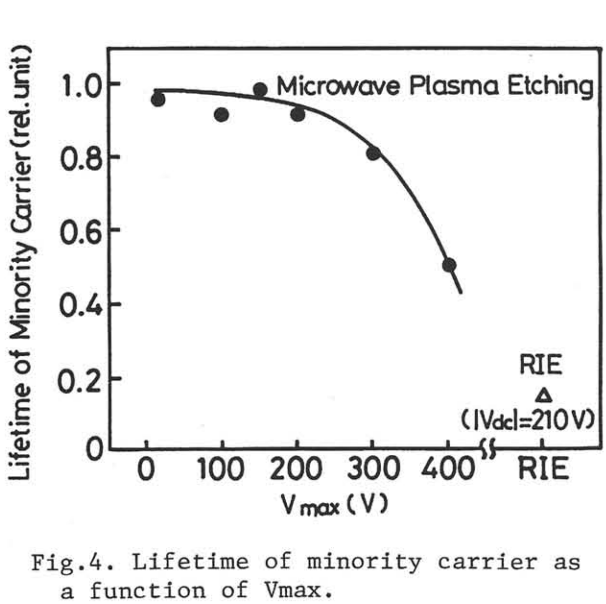

Fig.4. Lifetime of minority carrier as a function of Vmax.

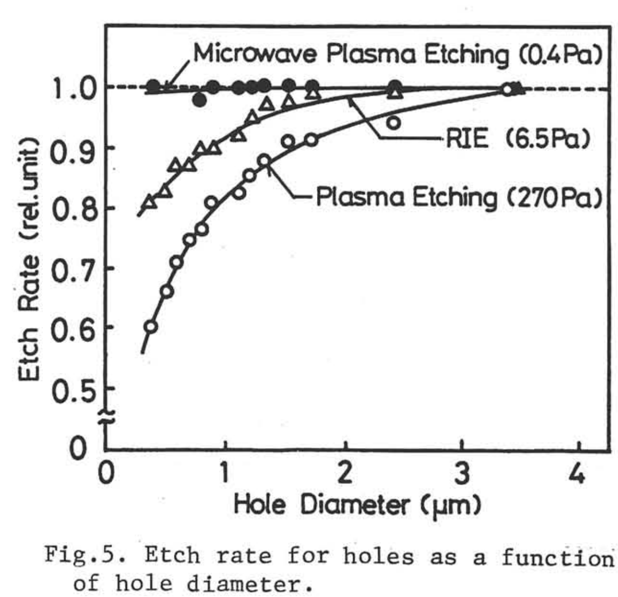

Fig.5. Etch rate for holes as a function of hole diameter.

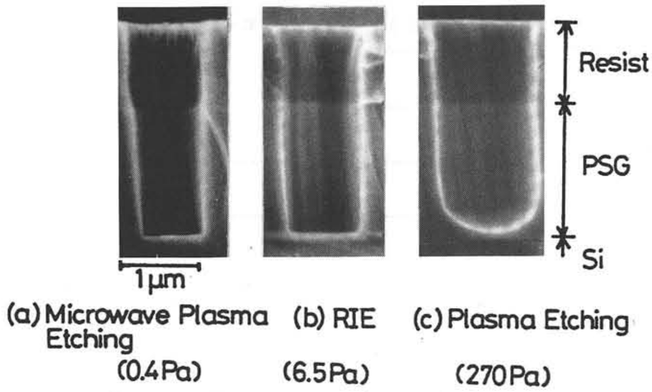

Fig.6. SEM cross-sectional profiles of holes with high aspect ratio.

Figure 6 shows SEM cross-sectional views of deep holes with high aspect ratio, comparing the microwave plasma etching, RIE and plasm etching, using the same mask. In the plasma etching, side etching occurs (CD loss is 0.25µm), and the bottom of the hole does not reach the Si substrate because of the reduction of the etch rate. In RIE, though CD loss(0.05µm) is less than that of the plasma etching, the sidewall is bowed. In the microwave plasma etching, on the other hand, the sidewall is straight and slightly tapered. The diameter in the bottom of the hole is 0.1µm smaller than that of the resist mask.

These phenomena are explained by the difference of the gas pressure in each etching technology. Gas pressures of the plasma etching, RIE and the microwave plasma etching are 270Pa, 6.5Pa and 0.4Pa, respectively. In the plasma etching, since the gas pressure is high, a large amount of ions are inclined by ion-molecule collisions. These ions hit the sidewall, resulting in side etching, The decrease in the etch rate for the small holes is explained in terms of the decrease in the total amount of ions reaching the hole bottom with the decrease in the solid angle. In RIE, since the gas pressure is lower than that of the plasma etching, the side etching and change in the etch rate are smaller than these of the plasma etching. The bowing in the side wall is thought to be caused by the ions scattered at the opposite sidewall. In the microwave plasma etching, since the ions are collimated due to low gas pressure, the directional etched profile is formed and also most of the incident ions reach the bottom of the hole, even at a diameter of 0.4µm, which leads to a slight decrease in the etch rate. The taper in the sidewall may be a result of polymer deposition on the sidewall.

4. CONCLUSION

A new SiO_2 etching technology for half-micron ULSIs has been developed using the microwave plasma etcher. The SiO_2 to Si selectivity ratio is found to be improved with a gas pressure less than 1Pa. Low damage and high rate etching for SiO_2 has been realized by controlling the ion energy without changing plasma density. Normally impinging ions collimated at lower gas pressure (0.4Pa) lead to directional etching of small and deep holes without side etching,and consequently the stable controllability of the etch rate to hole diameter variations is obtained. In this technology, 0.4µm contact holes with an aspect ratio of 6 are formed without a decrease in the etch rate. These results demonstrate that the microwave plasma etching of SiO_2 will be a major technology for half-micron ULSI production.

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