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Invited

Pulse-Time Modulated Electron Cyclotron Resonance Plasma Discharge for Precise ULSI Patterning

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For future ULSI processes, high density plasma has serious problems for deep SiO_2 contact hole and minute poly-Si gate etchings, such as low selectivity, local side etching, and charge build-up damages. This is due to a high degree of dissociation and charge accumulation on the substrate involving higher electron energy and high density plasma. To settle these problems, this paper proposes a 10μsec pulse-time modulated plasma. It can achieve highly selective, highly anisotropic and charge-free etching by controlling reactive-radical generation and suppressing charge accumulation.

1. Introduction

Electron cyclotron resonance plasma (ECR), helicon wave plasma and inductive couple plasma etchings are known to have many advantages. These involve the generation of denser plasma at lower pressure, a higher ionization ratio, and more controllable ion energies than can be obtained in reactive ion etching (RIE). However, these plasma sources have shown to have serious problems for deep SiO_2 contact hole and minute polycrystalline silicon gate etchings, such as low selectivity[1)], local side etching ("notch")[2)] and charge build-up damages[3)] in submicron pattern fabrication of less than 0.25μm. This is due to a high degree of dissociation and charge accumulation on the substrate with higher energy electrons and higher plasma density. Namely, a trade-off still exists between anisotropy and selectivity, and a high etching rate and charge-free etching process even in these plasma etching technologies. Thus, a new method for accurately controlling the electron energy (electron temperature) is indispensable to break-through the limitation.

This paper proposes a short pulse-time modulated (TM) ECR plasma etching technique that enables a high rate, highly selective, highly anisotropic and charge-free etching using a pulsed discharge in the range of 10-20μsec.[1,4)]

2. Experimental

A schematic illustration of the ECR plasma etching system used in this study is shown in Fig. 1. The diameter of the plasma chamber is 260 mm, permitting substrates 6 inches in diameter to be handled. Three separated coils located around the periphery of this chamber generate flat and low-gradient magnetic field profiles for uniform and efficient microwave absorption in the ECR plasma.[5)]

A klystron source (NEC LD-7909, Nihon Koshuha) was used to generate microwaves. This source prevents oscillations of the introduced microwave frequencies and ripples in the generated microwaves, thus enabling stable microwaves to be introduced into the ECR plasma.[5)] The substrate holder was located near the ECR region, where a magnetic field strength of 875 G satisfies the resonance condition for microwaves of a 2.45 GHz frequency. In this study, the microwaves were accurately modulated from 10 to 100 μsec with a function generator and a pulse circuit. The pulse duration (pulse width) and period (interval) were changed from 10 to 100 μsec. Additionally, the response time for the microwave input was reduced to less than 2 μsec as a result of using the klystron source.

SiO_2 etching and polycrystalline silicon etching characteristics were investigated by altering the pulse width and the interval of the microwave in the pulsed ECR discharge. The etching gas was CHF_3 and Cl_2 and the flow rate was 30 sccm. The etching pressure was fixed at 2mTorr and 1 mTorr, respectively. The microwave power was 1 kW. A 400kHz radio frequency (RF) bias of 100 V was supplied to the substrate for deep SiO_2 etching. Moreover, charge build-up damages to thin gate oxides were observed by using threshold voltage (V_t) shifts in a single MOSFET and a floating gate MOSFET according to intentionally irradiating non-uniform O_2 plasma. The gate thickness was about 100 A, and the antenna ratio between Al pad and the active area was 7500 in the single MOSFET and 1 in the floating gate MOSFET.

3.Results and Discussion

A. Improvement of selectivity during SiO_2 etching

Generally, SiO_2 etching is performed using fluorocarbon gases in order to deposit a fluoropolymer on the underlying Si to attain a high ratio of SiO_2 etching selectivity to Si etching. In particular, the CF_2 radical has been reported as the main gas precursor for fluoropolymer deposition. However, high density plasma causes a low CF_2 radical density and a large amount of F atoms. This is because of the higher degree of dissociation with higher electron energy and higher electron density. To improve the etching selectivity, control of the CF_2 radicals and F atoms is needed.

The density of the CF_2 radicals and F atoms was controlled by altering the pulse width in the TM-ECR plasma. Figure 2 shows the dependence of the CF_2 relative radical density and F/CF_2 density ratio on the pulse width. The pulse interval was fixed at 10 μsec for all conditions. When the pulse width was 10μsec, a larger amount of CF_2 radicals was generated. By increasing the pulse width, the density of F atoms increased despite the decrease in CF_2 radicals. Figure 3 shows the electron temperature and electron density in the pulsed discharge and the continuous discharge. The electron temperature and the plasma density reached a steady state within the first 10 μ sec discharge. At the interval, the electron temperature drastically decreases, corresponding to the microwave power. Therefore, the dissociation processes are progressed at the microwave duration and not at the interval. In other words, although the low energy reaction $CHF_3 \rightarrow CF_2 + HF$, progresses during the first 10 μ sec of discharge, the other high-energy dissociations, $CHF_3 \rightarrow CHF_2 + F$, $CHF_3 \rightarrow CF_3 + H$, and $CF_2 \rightarrow CF + F$, are not expedited at the beginning of the discharge. Moreover, in a continuous discharge, CF_2 radicals decreased further and F atoms increased, because of the long dissociation processes. Namely, it is suggested that the polymerization and the SiO_2 etching selectivity to underlying Si are improved using an initial discharge of 10 μ sec. The SiO_2 etching selectivity and the etching rate as function of the pulse width for a constant 10 μ sec interval of the CHF_3 pulsed discharge are shown in Fig.4. The SiO_2 etching rate was kept almost the same as in the case of continuous discharge. This indicates that the plasma density was maintained, and the ion density and ion energies were kept in a pulsed discharge of 10-20 μ sec with applied RF biases, as shown in Fig.3. Additionally, the pulsed plasma can drastically improve the SiO_2 etching selectivity to underlying Si from 10 to 40, even in high-density, low-pressure ECR plasma. The pulsed discharge suppresses the F atom concentration and generates a large amount of CF_2 radicals in the fluorocarbon plasma. Therefore, it achieves a higher deposition rate and a low fluorine polymer, which causes a low sputtering yield to ion bombardment, because of high crosslinking of the deposited polymer in comparison with the continuous discharge.

B. Suppression of "notch" profiles during poly-Si etching

At lower ion energies, high density plasma also causes another serious problem, such as unusual notches, to appear at a narrow space pattern during phosphorus-doped polycrystalline silicon etching. A number of reports explained that this is because of the distorted trajectories of ions by local electric fields with a large amount of separated charges on the resist mask and the gate oxide, especially in patterns whose space is less than 0.5 μm. The charges are caused by differences between ion motions and electron motions in the ion sheath.

Figure 5 shows the notch depth and ion current density as a function of microwave power in the ECR plasma. Local side etching strongly depends on the microwave power, i.e., it is caused by a large amount of charges in the generation of high density plasma. When the power is less than 500 W, the notch can be eliminated even at 100 % over-etching in the ECR plasma. The plasma density (ion current density) is 40% of that resulting from a 1 kW discharge. It is supposed that the notch is prevented in a lower density plasma. The phosphorus doped polycrystalline silicon etching rate and etching selectivity, however, is rapidly reduced to 1500 A/min and 50 at the condition. It is very difficult to simultaneously attain a high etching rate and highly selective notch-free etching with a conventional plasma discharge.

Figure 6 shows the notch depth at the n^+ poly-Si as a function of over-etching time in the pulsed discharge (10 μ sec/10 μ sec) and the continuous discharge. The pulsed plasma prevents the notch, even at 200% over-etching with high etch rates. This suggests that the modulated plasma reduces the amount of surface charges on the substrate. Namely, the separated charges in the 10 μ sec discharge plasma are decreased as a result of a lower sheath potential and a lower electron temperature in the after-glow plasma, as shown in Fig.7. Therefore, a significant local electric field for distorted ion trajectories is not generated in the pulsed plasma.

C. Elimination of damage caused by charge build-up

The 10 μ sec pulsed plasma can also prevent thin gate oxides from being damaged by charge that accumulates during etching in a nonuniform plasma. The charge build-up damage was observed by using V_t shifts in a single MOSFET and a floating gate MOSFET according to the plasma irradiation. Figure.8 shows a V_t shift map for a single MOSFET in a 6 inch substrate according to the non-uniform O_2 plasma irradiation. With the pulsed plasma, no V_t shift was observed at all, whereas use of the continuous discharge caused V_t shifts of 45 mV with a large amount of charge on the gate electrode. The V_t shifts are considered to be due to degradation of the gate oxides by a large amount of charges on the gate electrode. 10 μ sec modulated plasma thus reduces the effects of charge accumulation on the substrate. Charges accumulate on the gate electrode as a result of nonuniform sheath potential distribution on the substrate. However, in the after-glow plasma, the charges are reduced by decreasing the sheath potential distribution on the substrate due to the lower sheath voltage. As a result, the amount of charges become smaller, as compared with the continuous discharge, as shown in Fig.9.

4. Conclusion

The pulse-time modulated ECR plasma proposed here makes it possible to realize highly anisotropic, highly selective, high-rate, notch-free and charge-free etching for SiO_2 contact hole and poly-Si gate exclusively using Cl_2 and CHF_3 gas. These etching characteristics are explained using the time dependence of the dissociation processes of reactive radicals and suppression of the amount of charge that accumulates on the substrate, attained employing a pulsed discharge in the range of 10 μ sec. This etching method is thus a very promising candidate for applications to 1 G bit and 4 G bit DRAMs.

Acknowledgements

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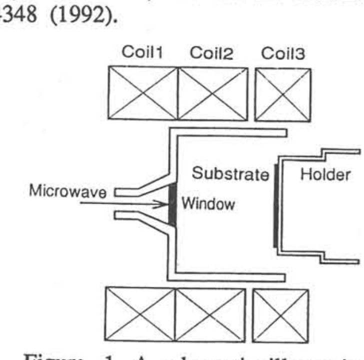

Figure. 1. A schematic illustration of the ECR plasma etching system. (Ref.5)

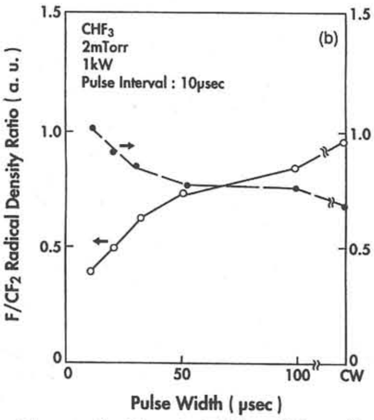

Figure. 2. Trends of the CF_2 radicals and F atoms in pulsed plasma.(Ref.1)

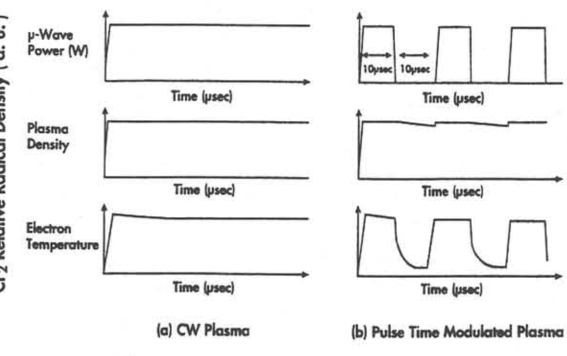

Figure. 3. Electron temperature and electron density in pulsed plasma and continuous discharge.

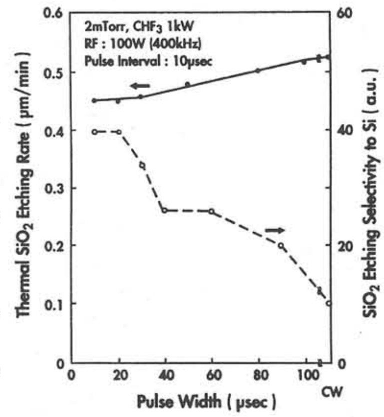

Figure. 4. SiO_2 etching selectivity and etching rate in pulsed plasma.(Ref.1)

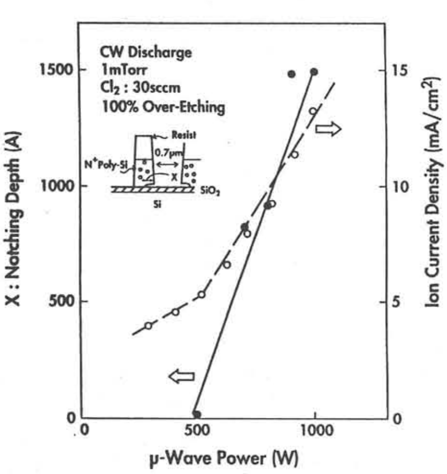

Figure. 5. Notch depth as a function of microwave power in continuous ECR plasma discharge.(Ref.4)

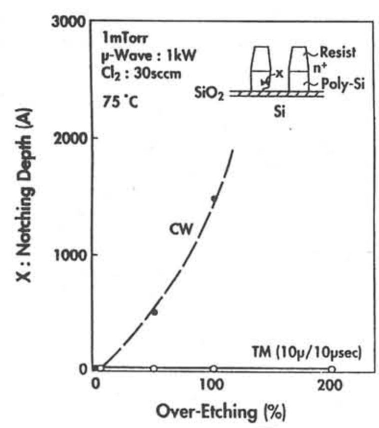

Figure. 6. Notch depth as a function of over-etching time during pulsed discharge and the continuous discharge. (Ref.4)

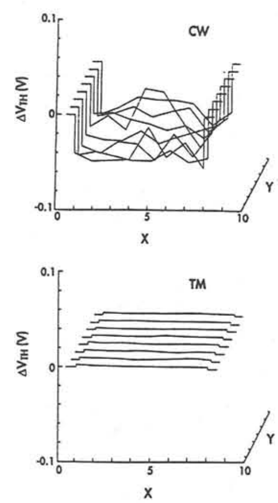

Figure. 8. Threshold voltage shift map for a single MOSFET in a 6 inch substrate according to the amount of O_2 plasma irradiated in a 10 μ sec pulsed plasma (TM) and continuous discharge (CW).

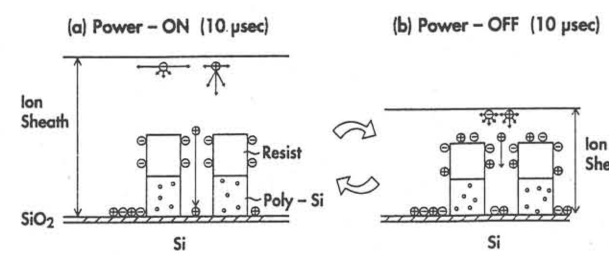

Figure. 7. Suppression mechanism of notch profile for pulsed plasma.

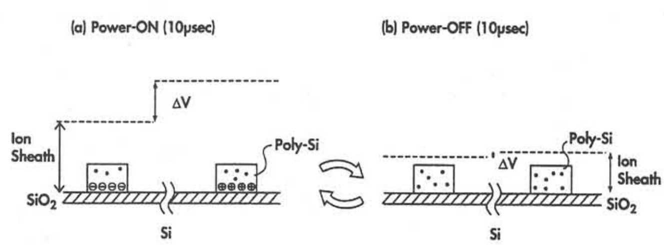

Figure. 9. Reduction mechanism of charge accumulation in pulsed plasma.