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Charge-Free and Dopant Dependence-Free Etching Processes Using Non-Maxwellian Electron Energy Distributions in Ultra-High-Frequency Plasma

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1.Introductions

High-density plasmas, such as electron cyclotron resonance (ECR) plasmas and inductive coupled plasmas (ICP), have been used in etching processes to fabricate ultralarge-scale integrated circuits (ULSIs) because they efficiently provide the radicals and ions required for the etching process. When the pattern size becomes smaller than 0.25 μm, however, these plasmas can have serious problems with respect to high-energy electrons in the patterning of the minute gate and Al electrodes. During Al electrode patterning, the topography-dependent charging that occurs in a dense antenna structure is a major concern for the reliability of the MOS devices. It is mainly due to surface electron charging in the narrow space patterns. The problems are enhanced in the higher energy electrons of high density plasma. Additionally, for dual gate patterning, the high degree of gas dissociation causes a large dopant dependence of poly-Si etching rate in low ion energy processes, because the chemical reaction is enhanced by generating a large amount of active radicals due to the higher energy electrons in these Cl_2 plasmas. To solve these problems, we have recently proposed the use of ultrahigh-frequency (UHF) power for plasma production. The low-mean-electron-energy (~2 eV, non-maxwellian electron energy distribution function) and high-electron-density (~10^{11} cm^{-3}) plasmas for large-scale and precise etching processes can be simultaneously produced with excellent uniformity (±5 % within a 30 cm diameter) by applying ultrahigh-frequency (UHF: 500 MHz) power to the plasma through a spokewise antenna.

In this paper, we report for the first time on the effects of non-maxewllian electron energy distributions for the doped poly-Si etching characteristics and the reduction of topography-dependent charging damage during Al patterning in UHF plasma.

2.Experiments

The reactor used in this study consisted of a plasma source (either UHF spoked antenna or ICP one-turn loop antenna) and a 40 cm i.d. anodized aluminum chamber, as shown in Fig.1 . To investigate the gas dissociation state, the main gas, Cl_2, was combined with a 5% rare gas mixture of Xe. The total gas flow was 50 sccm at a pressure of 3.5 mTorr. Optical emission from the Cl_2 at 3050 Å was attributed to ground state Cl_2. The absolute Cl_2 number densities were evaluated by using rare gas actinometry, using the $2p_5$ level of Xe. The Cl_2 number densities (n_{Cl_2}) were normalized with the plasma off ($n_{Cl2}{}^0$) and the degree of gas dissociation (%, $Cl_2 \rightarrow Cl$) was calculated from $100(1-n_{Cl_2}/n_{Cl_2}{}^0)$. Pure Cl_2 gas was used to investigate the poly-Si etching characteristics and the charging damages in the ICP and the UHF plasma. The substrate RF bias (600 kHz) was 50 V and 100 V (peak-to-peak voltage) for the poly-Si and Al etching, respectively. The NMOSFET has an edge-intensive metal antenna with several spaces to investigate the topography dependent charging, as shown in Fig.2. The gate length was 0.35 μ m. The gate oxide thickness was 4.5 nm.

3.Results and Discussions

There was a lower degree of gas dissociation in the UHF (30%) *vs.* the ICP plasma (70%), even when the electron densities ($1 \times 10^{11} cm^{-3}$) and ion current density (6 mA/cm^2) were nearly equal in the two plasmas, they were 3.5 mTorr and 1000 W. In the UHF plasma, the main neutral etching species is Cl_2, and the most likely ion is Cl_2^+. However, in the ICP, Cl is the predominant neutral and therefore Cl^+ will increase and perhaps become the dominant ion. These results can be explained by the differences in the electron energy distribution functions (EEDF) in these two plasmas (Fig.3). In the UHF plasma, a low degree of dissociation can be obtained at the same electron density, because of the smaller amount of high-energy electrons, more than 5 eV (non-Maxwellian EEDF). In the ICP, however, the number of high energy electrons is larger and results in the high degree of dissociation (Maxwellian EEDF). Under the equivalent conditions at 3.5 mTorr, the dependence of the poly-Si on the dopant in the Cl_2 ICP and UHF plasma was investigated, as shown in Fig. 4. Since the positive ion current densities were the same in the two plasmas at 1 kW and 3.5 mTorr (6 mA/cm^2), the ion energies at the wafer were the same for both plasma sources. However, the dependence of the etching rate on the dopant was much different for these plasma sources. The low degree of dissociation in the UHF plasma can completely suppress the dependence of the etching rate on the dopant even at a low ion energy of 50 eV, whereas the high degree of dissociation in the ICP causes a strong dependence of etching rate on the dopant. This is attributed to a more aggressive reaction by the Cl atoms, compared with the Cl_2 molecules during the poly-Si etching. We found that the dissociation state strongly influences the dependence of poly-Si etching rate on the dopant and that UHF plasma can pattern N^+ and P^+ poly-Si at the same time using just Cl_2 feed gas. Then, the selectivity of N^+ and P^+ poly-Si etchings to underlying SiO_2 etching was more than 100, at the same time.

Additionally, we investigated the effectiveness of UHF plasma in reducing topography-dependent charging for Al patterning in MOS devices, as shown in Fig.5. The shift in the threshold voltages (V_{th}) of an antenna device from that of a device without an antenna indicates the amount of charging-induced oxide trapped charge. In the conventional ICP source, the V_{th} showed a dramatic positive increase at high antenna ratios of more than 1000. The V_{th} shift was larger when the antenna space was smaller. This result clearly indicates that the charging responsible for the V_{th} shift results from the topography-dependent charging. When the UHF plasma with the same electron density was used, the V_{th} shift became dramatically smaller. This result suggests that the topography-dependent charging during Al patterning is caused by the high energy electrons with energy of about 5 eV or more, and that the UHF plasma can suppress the charging damage to the gate oxide even with a high plasma density.

4.Conclusions

ICP and UHF plasma observed electron density of $10^{11}cm^{-3}$ at 3.5 mTorr, yet the UHF plasma was much less dissociated (30%) than the ICP (70%). This can be attributed to the differences in the electron energy distribution. When using the UHF plasma, the poly-Si etching rate does not depend on the dopant and there is no-topography-dependent charging with just Cl_2 gas, whereas when using the ICP there is etching rate dependence on the dopant and charging damage for the same conditions as those used for the UHF plasma etching. UHF plasma can produce ideal electron energy distributions for precise ULSI patterning.

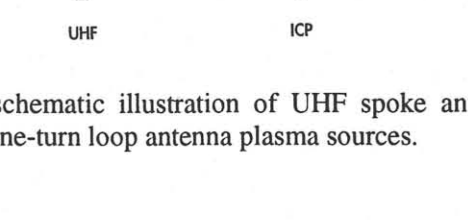

Fig.1 A schematic illustration of UHF spoke antenna and ICP one-turn loop antenna plasma sources.

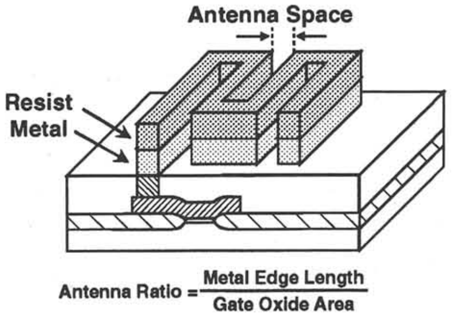

Fig.2 Antenna MOSFET with edge intensive metal antenna. Antenna space ranges from 0.4 µm to 3.0 µm.

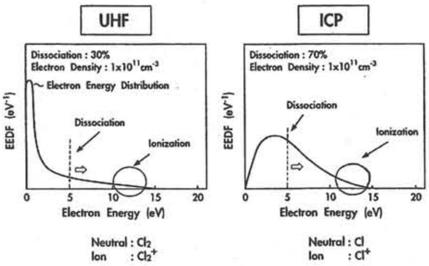

Fig.3 Electron energy distribution functions (EEDF) in UHF plasma and ICP. Dissociation and ionization is much different in these plasma sources because of different EEDF.

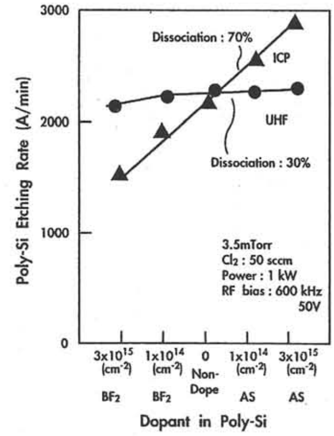

Fig.4 Dependence of the Poly-Si etching rate on the dopant in Cl_2 ICP and UHF plasma.

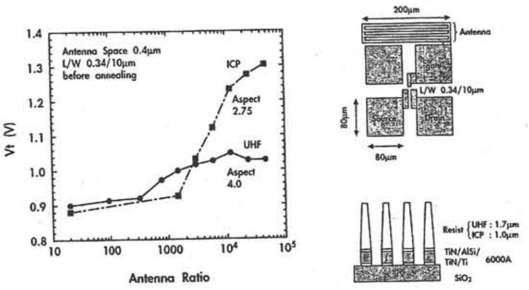

Fig.5 Threshold voltage of antenna MOSFETs as a function of the antenna ratio for UHF plasma and ICP .