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Neutral Beam Etching for Damage-free 50 nm Gate Electrode Patterning

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1. Introduction

The increased packing density of ultra large-scale-integrated circuits (ULSI) requires an ultra-thin dielectric film with a low leakage current and a high reliability in metal-oxide-silicon (MOS) devices. High-k films have been intensively investigated as a promising material to replace conventional SiO_2 gate dielectrics in future ULSI circuits. However, the high-k films are more fragile and defective in comparison with SiO_2. As a result, the process-induced damages become more serious problems, such as charge-build-damages, changes in film quality and generation of defects by the irradiation of charged particles (ions and electrons) and VUV photons during the plasma etching processes.

Furthermore, bending of the fine resist mask during the plasma etching is another important problem to degrade a critical dimension.

To overcome these problems, we developed a highly efficient neutral-beam etching system [1]. It is expected that neutral beam etching will be a promising candidate for damage-free high-k gate electrode patterning with the single-level resist process. In this paper, we report the characteristics of the poly-Si gate etching using SF_6 and Cl_2 gas chemistries.

2. Experimental

Our newly developed neutral-beam etching system is shown in Fig. 1. It consists of an inductively coupled plasma (ICP) and parallel carbon plates. The process chamber is separated from the plasma chamber by the bottom carbon plate, because carbon has the lowest sputtering yield under high-energy ion bombardment and does not contaminate semiconductor devices. There are many apertures in the bottom carbon plate to extract neutral beams from the plasma in the process chamber. In our experiment, the aperture open area was fixed at 50% within a 100-mm-in-diameter area of the bottom carbon plate to maintain the same discharge pressure in the ICP source. The apertures were 1 mm in diameter and 10 mm in length. In this experiment, a pulse-time-modulated plasma (on-time and off-time=50 μs / 50 μs) was used for generating a large amount of negative ions, because the negative ions were easily neutralized when passing through the aperture, as compared with positive ions. As a result, a high flux (more than 1mA/cm^2) and highly efficient (neutralization efficiency: 98%) neutral beams could be extracted from the pulsed plasma through the apertures. To control the neutral beam energy (10~100 eV), bias voltages were supplied to the top and bottom carbon plates. The top carbon plate bias was fixed at DC -100 V, and the bottom plate DC bias or RF (600 kHz) bias was changed. SF_6, Cl_2 and Cl_2/SF_6 mixture gas were used to evaluate poly-Si etching characteristics. Gas pressures were 0.5~1 Pa in the plasma chamber and 0.05~0.1 Pa in the process chamber. The patterned samples were 150 nm-thick non-doped poly-Si on 2 nm-thick SiON. The resist patterns were made by KrF lithography and were trimmed to 50 nm-width by plasma etching using HBr/O_2 gas chemistry.

3. Results and discussion

Poly-Si etching characteristics were investigated using neutral beams with pure SF_6 and pure Cl_2 gases by changing the beam energy. The etch rates coincide well with the values estimated by the Si atom chemical sputtering yield of F^+ and Cl^+ beams [2]. This result suggests that the poly-Si etching is caused only by energetic F and Cl atom beams without any influences of radicals from the plasma chamber in both cases. The radicals generated in the plasma chamber were almost consumed or recombined on the wall surface in the apertures of the bottom carbon plate.

Then, the etched profiles were shown in Fig. 2 and Fig. 3. In the case of the F atom beam, a large undercutting was observed with a high etching rate (60nm/min) and high etching selectivity (100~). The isotropic etching is considered to be due to a spontaneous reaction of energy-deficient F atoms generated by the collision of the low-energy F-atom beam with the surface. Conversely, in the case of the Cl neutral beam, anisotropic etching profiles could be obtained even by a low-energy Cl neutral beam as shown in Fig. 3, whereas the poly-Si etching rate was only 5nm/min at most. As a result, by just using pure SF_6 or pure Cl_2, it is very difficult to satisfy a high etching rate, high selectivity and highly anisotropic etching profile at the same time.

To overcome these problems, a Cl_2/SF_6 gas mixture was investigated. By adding a small amount of SF_6 into Cl_2, the anisotropic etching profile could be accomplished by maintaining the high etching rate (40nm/min), as shown in Fig. 4. To also achieve a high etching selectivity to underlying-SiO_2 (100~) at the same time, two-step etching was carried out with both a high-energy beam with SF_6/Cl_2 mixture gas for poly-Si etching and a low-energy beam with pure Cl_2 gas for over-etching. Generally, in the conventional plasma etching system, a fine pattern etching below 50 nm was very hard because the high-aspect-ratio resist patterns were bent during the etching processes. It is also a serious problem. Conversely, the neutral beam could perfectly eliminate the resist pattern bending.

To clarify the damage-free etchings using a neutral beam, the plasma-induced-current in the SiO_2 film was detected using our developed on-wafer-monitoring, as shown in Fig. 5. In the SiO_2 film, the irradiation of ions and VUV photons generate hole-electron-pairs. The induced current corresponded to the generated charges in the SiO_2 film and to the interface state density between Si and the SiO_2 interface [3]. When the conventional plasma was irradiated to the on-wafer-monitoring, high-induced current was observed in the SiO_2 film due to energetic ions and VUV photons. Conversely, the currents were extremely small just under the irradiation of the neutral beam. These results suggest our newly developed neutral beam can accomplish damage-less etching processes while maintaining high performance etching characteristics.

3. Conclusions

Poly-Si gate etching characteristics in the neutral beam etching system were evaluated using SF_6 and Cl_2 gases. Though the etching reaction was caused only by fast halogen atom beams in both cases, there is a trade-off between the etched pattern profiles, etching rate and etching selectivity. By a combination of Cl_2 and SF_6 gases, a high-performance etching and extremely fine poly-Si gate electrode patterning below 50 nm-width could be successively obtained using a single-level resist process. In addition, it is clarified that damage-less etching processes can also be achieved in the neutral beam system.

References

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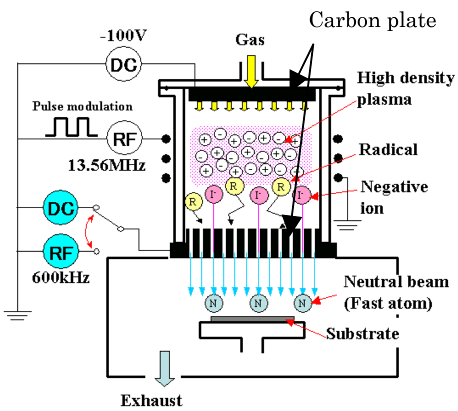

Fig. 1 Neutral beam etching system.

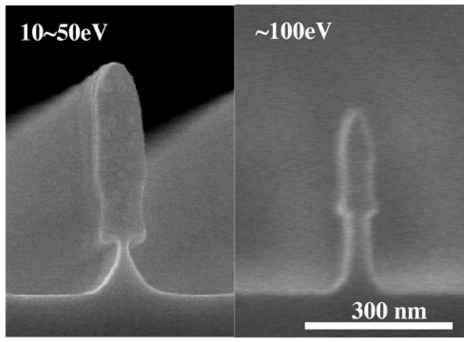

Fig. 2 Pattern profiles of poly-Si etched at different bias conditions in a pure SF_6 gas system.

Fig. 3 Pattern profiles of poly-Si etched in a pure Cl_2 gas system.

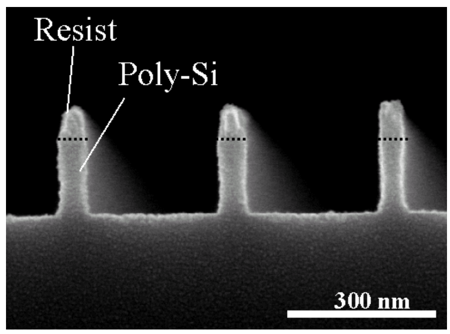

Fig. 4 Pattern profile of poly-Si etched at an optimum gas ratio in a Cl_2/SF_6 gas system.

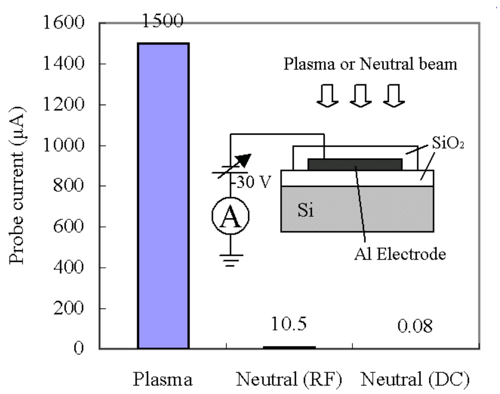

Fig. 5 Probe current of the on-wafer monitoring device irradiated by SF_6 plasma or neutral beam.