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Very High Reliability of Ultrathin Silicon Nitride Gate Dielectric Film for sub-100nm Generation

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Abstract

This paper focuses attention on electrical properties of ultra-thin silicon nitride (Si_3N_4) films directly grown on Si surfaces by microwave-excited high-density plasma system as an alternative gate dielectric. We demonstrated the electrical characteristics of the MNS capacitors with the Si_3N_4 films. The TDDB lifetime of the MNS capacitor is over 30,000 times larger compared with that of the MOS capacitor with the conventional dry oxide. Furthermore, the hysteresis of C-V curve measured at 400K can not be observed.

Introduction

The continued scaling of silicon oxide gate dielectrics to the fundamental limits governed by large gate leakage current requires the introduction of higher dielectric constant films, e.g. Si_3N_4. Furthermore, the higher reliability of gate dielectrics is required for sub-100nm technology nodes [1].

We have succeeded in forming the Si_3N_4 gate dielectric film by microwave-excited high-density plasma at a low temperature[2]. In the direct nitridation of silicon surface, Kr/NH_3 mixed gas was used. Due to the excellent interface characteristics, it is expected as an alternative gate dielectric. In recent research, we found that using Xe/NH_3 mixed gas and Xe plasma irradiation before nitridation can improve the reliability dramatically. The purpose of this paper is to investigate electrical properties of improved high reliability Si_3N_4 gate insulator.

Experimental

MNS capacitors were fabricated on Cz n-type (100) silicon substrate with a resistivity of $0.5\Omega\cdot$cm. The Si_3N_4 films were grown with the process pressure of 50mTorr using Kr/NH_3 or Xe/NH_3 mixed gas. Some samples have been treated by Xe plasma irradiation of 60sec before the direct nitridation. The microwave frequency is 2.45 GHz and the power was 5 W/cm^2. A TaNx metal gate electrode was formed by reactive sputtering at room temperature to eliminate gate depletion [3]. Subsequently patterning and wet etching of the gate electrode were performed for gate formation. Post metal annealing was carried out at 400°C in H_2/N_2=0.2/1.8 SLM for 30 minutes. The high-frequency (1MHz) C-V, J-V and constant voltage (Vg=+3.4V) TDDB characteristics have been investigated in this research.

Results and Discussion

Fig.1 shows the 50 % TDDB lifetime of the gate dielectric films as a function of the applied gate voltage. The lifetime of MNS capacitor with Kr/NH_3 nitridation is 800 times larger than that of MOS capacitor. In our research, it is known that the process pressure of 50mTorr is suitable for the direct nitridation. However, the low pressure is important factor of the higher electron temperature, as shown in Fig.2. Fig.3 shows the scattering cross section as the function of electron temperature [4]. From the figure, it is possible to reduce the electron temperature in the plasma by using the Xe gas instead of the Kr gas, which we used to form Si_3N_4 films until now. As the results, the electrical properties and the reliability have been improved drastically due to the lower damage in the Si_3N_4 growth period. Fig.4 shows the weibull plots of constant voltage (Vg=+3.4 V) TDDB measurement for the MNS capacitors with the Si_3N_4 film grown by the Kr/NH_3 (EOT=1.9 nm), the Xe/NH_3 (EOT=1.9 nm) and the Xe/NH_3 after Xe plasma irradiation (EOT=1.9 nm). The TDDB lifetime of the Si_3N_4 film grown by Xe/NH_3 after Xe plasma irradiation is 40 times larger than that grown by Kr/NH_3. This means that the lifetime of the Si_3N_4 film formed by Xe/NH_3 is 30,000 times larger than that of conventional oxide. Fig.5 shows the J-V curves of MNS capacitors. The leakage current of Si_3N_4 grown by Xe/NH_3 after Xe plasma irradiation is reduced to 1/9 of that formed by Kr/NH_3 at gate bias of 1 V. In Fig.6, a 20mV hysteresis exists in High frequency (1 MHz) C-V curve of Si_3N_4 film formed by Kr/NH_3 at a raised temperature of 400K. Fig.7 shows that there is no hysteresis existing at the Si_3N_4 film grown by Xe based direct nitridation. Fig.8 shows the AFM photos of Si substrate with or without 1hour Xe plasma irradiation before direct nitridation. The roughness of Si surface without Xe irradiation (Ref.) is 0.17 nm and that with Xe irradiation is 0.15 nm. The micro-roughness of the Si surface irradiated by the Xe plasma is the same as that of the initial surface. These results indicate that the Xe exited plasma is very effective for the Si_3N_4 film formation compare with Kr or Ar exited plasma.

Conclusion

We succeeded in improving the reliability of MNS devices by Xe based process due to the lower damage in the Si_3N_4 growth period. The TDDB lifetime of Si_3N_4 gate dielectric film formed by Xe based process is 40 times larger than that grown by Kr/NH_3 and 30,000 times larger than that formed by conventional oxide. Furthermore, Xe based process suppresses the hysteresis of C-V curve at the temperature of 400K. This Si_3N_4 film is sufficient ability for the gate insulator of 65 nm generation.

References

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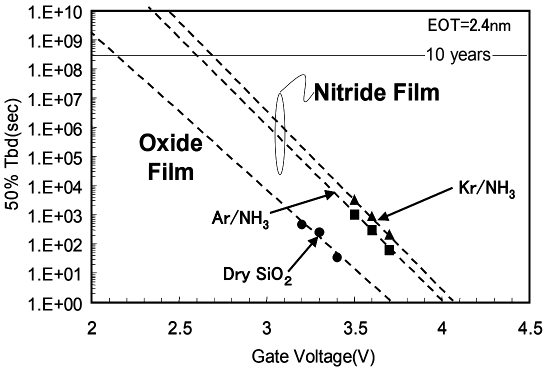

Fig.1 50 % lifetime of the gate insulators as a function of the applied gate voltage. The lifetime of Si_3N_4 is 800 times larger than that of SiO_2.

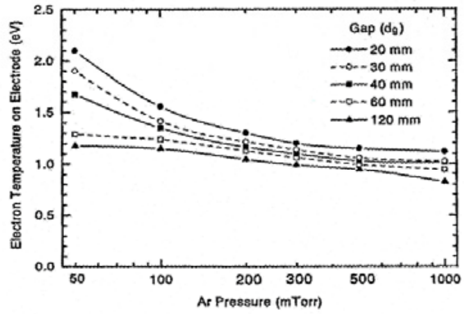

Fig.2 The electron temperature as a function of process pressure. The low pressure is important factor of the higher electron temperature.

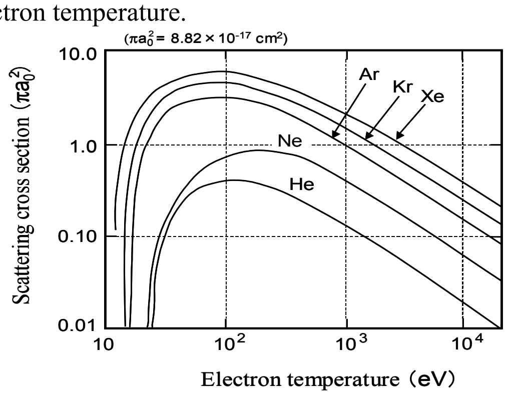

Fig.3 The scattering cross section as the function of electron temperature. It is possible to reduce the electron temperature in the plasma by using the Xe gas.

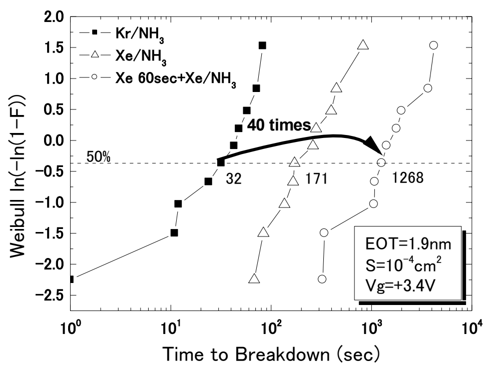

Fig.3 The weibull plots of constant voltage TDDB measurement for the MNS capacitors with Si_3N_4 films grown by Kr/NH_3, Xe/NH_3 and Xe/NH_3 with Xe plasma irradiation. The 50 % TDDB lifetime of Si_3N_4 formed by Xe/NH_3 with Xe irradiation is 40 times larger than that by Kr/NH_3.

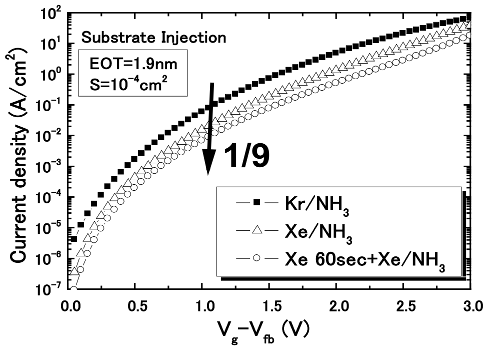

Fig.5 J-V curves of MNS capacitors. The leakage current of Si_3N_4 grown by Xe/NH_3 with Xe plasma irradiation is reduced to 1/9 of that grown by Kr/NH_3.

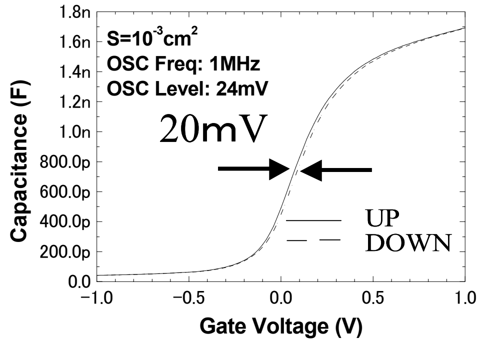

Fig.6 High-frequency C-V curve of MNS capacitor with Kr/NH_3 at 400K. The hysteresis value of 20 mV is observed.

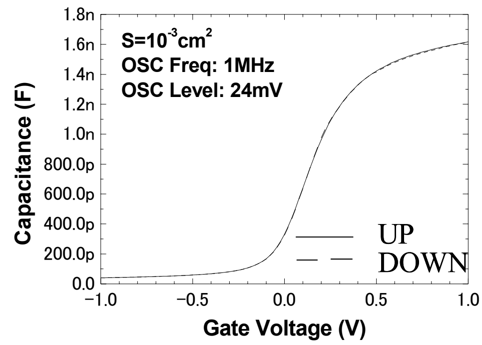

Fig.7 High-frequency C-V curve of MNS capacitor with Xe/NH_3 after Xe plasma irradiation at 400K. There is no hysteresis existing.

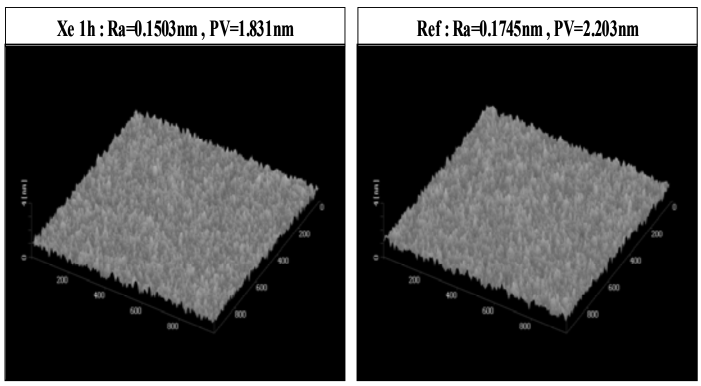

Fig.8 AFM photos. The roughness of Si surface without Xe irradiation (Ref.) is 0.17nm and that with Xe irradiation is 0.15nm. The increase of Si surface roughness has not been observed.