1. Introduction

Ultrathin plasma Si oxynitride (SiON) films have been identified as leading candidates to replace conventional SiO₂ gate dielectrics in future ultra large-scale integrated circuits [1,2]. However, controlling the concentration and location of nitrogen in ultrathin SiON film through plasma processing is much more difficult, and serious problems still remain, such as the high interface state density caused by nitrogen penetrating the SiO₂-Si interface. Also, it is well known that shallow nitrogen profile in SiON film is required to improve the negative bias temperature instability (NBTI) lifetime for MOS FET [3,4]. To overcome these, we investigated a pulse-time-modulated (TM) N₂ neutral beam injection. Based on results, we have found that the location of nitrogen could be dramatically shifted to the surface of SiO₂ film by controlling the periodic N₂ injection time in TM N₂ plasma. The drastic improvement in the NBTI lifetime was confirmed.

In this paper, we report the controlling concentration and location of nitrogen in SiON film by using TM plasma, and the improvement in the NBTI lifetime due to shallow nitrogen profile of fabricated specimen.

2. Experimental

Specimens were fabricated using the N₂ neutral beam apparatus [5], and schematic of that is shown in Fig. 1 (a). The process chamber was separated from the inductively coupled plasma chamber by the bottom carbon plate. The bottom carbon plate has many apertures to extract neutral beams from the N₂ plasma in the process chamber. To clarify the main ion species in N₂ plasma, we investigated the QMS spectra shown in Fig. 1 (b). It can be seen that the main ion specie is N₂⁺. Hence, most accelerated N₂⁺ ions are converted into N₂ neutral beams by charge-transfer collisions with gas molecules and aperture sidewalls while passing through the bottom plate.

Fig. 2 shows a schematic of TM N₂ neutral beam generation. The energetic N₂ neutral beam during pulse-on time and the lower energy N₂ neutral beam during pulse-off time are periodically extracted from the carbon aperture to the specimen surface. In this experiment, a positive DC bias of +10 V was applied to the top carbon plate to produce lower energy neutral beams of around 10 eV.

For the investigation of fabricated SiON thin films, we have measured the nitrogen concentration and its depth profile by using secondly ion mass spectrometry. Also,
MOS FET devices were made on SiON films, and NBTI lifetime were measured with low voltage gate biasing.

3. Results and Discussion

A. Basic Mechanism for SiO₂ Top Surface Nitridation

The dependence of surface nitrogen concentration and peak location in a 2 nm SiO₂ film on injection energies of continuous (CW) N₂ neutral beam were evaluated to understand the basic mechanism for SiO₂ top surface nitridation (Fig. 3). The beam flux was fixed at about 1 mA/cm² (as an equilibrium of the ion current). When the beam energy is less than 2.8 eV, N₂ cannot be injected into SiO₂ films. This suggests that energy higher than 2.8 eV is needed to inject N₂ into SiO₂ films.

Based on this, we assessed the effect of TM N₂ neutral beam injection when forming an SiON film. Fig. 4 shows the time dependence of the beam energy distribution for TM N₂ neutral beam. In the pulsed N₂ neutral beam, a higher energy N₂ beam of more than 10 eV (pulse-on) and a lower energy N₂ beam of less than 2 eV (pulse-off) are periodically bombarded onto specimen. As a result, N₂ neutral beam can be injected into the SiO₂ film only during the pulse-on time.

We then measured the evolution of the surface nitrogen concentration in SiO₂ films exposed to the TM N₂ neutral beams. The peak location of the nitrogen concentration drastically shifted to the surface of the SiO₂ film when the time for periodic beam injection (pulse-on time) was decreased to 10 µsec (duty ratio: 16 %) and then the nitrogen peak concentration decreased slightly to about 90% of value for the CW neutral beam injection (Fig. 5). This suggests that a diffusion of injected N₂ into the SiO₂ film can be suppressed by periodically inserting 50 µsec of pulse-off time. That is, the injected N₂ diffuses into the SiO₂ film with a time constant of a few tens of µsec because of surface activation (an increase in surface temperature) caused by N₂ neutral beam bombardment.

B. Nitrogen Profile Control using Productive TM Plasma Source

Based on the above basic results, we investigated the N₂ profile control and the ultra shallow incorporation of N into thin SiO₂ film of 2 nm thick was actually investigated using TM N₂ plasma in the productive plasma source (inductively coupled plasma). To optimize the nitrogen depth profile in a thin SiO₂ film, the dependence of the N₂ peak location and peak concentration in a thin SiO₂ film on the ion density and the total process time was tested using TM (duty ratio: 20 %) and CW plasmas with the same ion energy. At the

![Diagram](image1.png)

Fig. 2 A schematic illustration of TM N₂ neutral beam generation. The energetic N₂ neutral beam during pulse-on time and the lower energy N₂ neutral beam during pulse-off time were periodically extracted from the carbon aperture to the substrate surface.

![Diagram](image2.png)

Fig. 3 The dependence of N₂ injection depth in a 2-nm SiO₂ film on N₂ Neutral beam energy. When the beam energy was less than 2.8 eV, N₂ is not injected into SiO₂ films.

![Diagram](image3.png)

Fig. 4 The time dependence of TM N₂ neutral beam energy distribution. In the pulsed N₂ neutral beam, a higher energy N₂ beam of more than 10 eV and a lower energy N₂ beam of less than 2 eV were periodically bombarded onto SiO₂ films.
same N₂ peak concentration of 8-9 % in the SiON film, the N₂ peak location drastically shifted to the front of the SiO₂ film when the periodic beam injection time was decreased to 10 µsec (Duty ratio: 16 %), whereas the N₂ peak concentration decreased slightly to about 90 %, compared with that under the CW N₂ neutral beam injection.

C. Drastic Improvement of NBTI Lifetime in CMOS at Low Voltage Operations

To investigate the improvement of NBTI lifetime, measurement devices with various EOT were produced with a standard 90 nm CMOS process flow. A base oxide of 1.6 nm was thermally grown prior to TM and CW plasma nitridation. NBTI lifetime measurements of TM plasma (duty ratio: 20 %, 50 %) and CW plasma devices with the same N₂ peak concentration of 9 % were compared when a 5% reduction of I_ds occurred (Fig. 7). TM N₂ plasma devices have drastically lower degradation on all devices with various EOT. The estimated lifetime at operating conditions (stress \(V_s = -2.3\) V, monitor \(V_g = -0.7\) V at \(105^\circ C\), respectively. Estimated lifetime is 200 % longer for TM than for CW N₂ plasma nitridation.

4. Conclusions

Our periodic nitridation could precisely control the N₂ diffusion in a SiO₂ film during plasma nitridation processes. The nitrogen peak location drastically shifts to the surface of the SiO₂ film while maintaining the concentration. As a result, the interface state density caused by nitrogen penetrating the SiO₂-Si interface was drastically reduced and then 200 % improved NBTI lifetime can be
accomplished.

References


