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Low-Leakage-Current Ultra-thin SiO_2 Film by Low-Temperature Neutral Beam Oxidation

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1. Introduction

The scaling down of MOSFET require less than 1.5nm ultra-thin gate dielectric film [1]. In this range, it is difficult to use SiO_2, conventional dielectric material, because of too much leakage current. To settle these problems, high-k materials, such as HfO_2, ZrO_2, have been studied as new gate dielectric material [2]. But it is also important to fabricate extremely thin SiO_2 underlayer between high-k film and Si substrate [3] and to improve the electric characteristics. At the same time, high quality-thin SiO_2 films need to be fabricated at lower-temperature for the replacement gate process.

To realize these requirements, we propose formation of ultrathin SiO_2 film by oxygen neutral beam at low temperature (300 ºC) [4]. In this new method, low energy (<10eV) oxygen neutral beam was irradiated to Si substrate, and the substrate was atomically oxidized without any radiation damages even in the low temperature. It is expected that low energy oxygen neutral beam can accomplish low temperature, high quality and ultra-thin (less than 1nm) SiO_2 formation for future devices.

In this study, we investigated the SiO_2 film characteristics, such as chemical bonding state, roughness at interface between SiO_2 and Si, depth profile of O, Si and C and electric characteristics in the film formed by neural beam oxidation (NBO). We clarified that low temperature NBO film could realize lower leakage current than that in the thermal SiO_2 film.

2. Experimental

SiO_2 films are formed using our developed neutral beam source as shown in Fig. 1. This equipment consists of an inductively coupled plasma (ICP) source, an upper graphite electrode, a bottom silicon electrode, and a process chamber. The bottom silicon electrode has many apertures. Oxygen ions generated in O_2 plasma are neutralized by passing through the apertures. Then, low energy (less than 10 eV) oxygen neutral beams are irradiated to silicon substrate in the process chamber. Since the bombardment of neutral particles with kinetic energy activates Si surface, the oxidation reaction is enhanced even at low temperature.

The samples were p-type Si (100) wafers. Native oxide was removed by immersing the wafers in 0.5% HF. After that, SiO_2 film was formed using neutral beam equipment at a pressure of 0.14 Pa. The wafer was located on the heated stage, and surface temperature of wafer was fixed at 300 ºC.

Chemical bonding state of the NBO film was analyzed by using the X-ray photoelectron spectroscopy (XPS) and compared with that of thermally grown SiO_2 film. Cross-sectional high-resolution transmission electron microscope (HR-TEM) image of the NBO film was observed. In addition, roughness of interface between the SiO_2 film and Si substrate was measured by the grazing incidence X-ray reflectively (GIXR). Depth profile of Si, C, and O in the NBO film was also compared with that of thermally grown SiO_2 film by the secondary ion mass spectrometry (SIMS).

To measure electric characteristics of NBO film and thermally grown SiO_2 film, an Al electrode was deposited on these films and it was annealed at 450 ºC in H_2 for 30 min. C-V and I-V characteristics were measured and the leakage current as a function of equivalent oxide thickness (EOT) was derived.

3. Results and discussion

Figure 2 shows XPS spectra in Si2p region of the NBO film and thermally grown SiO_2 film. Since the chemical shift of oxide peak strongly depends on the thickness, the film thickness was fixed at 4 nm in both cases. The NBO film was concluded to have the same chemical bonding state as thermally grown SiO_2 film because of the identical value of the chemical shift.

Figure 3 shows a cross-sectional TEM image of the NBO film (4nm thick). The interface between SiO_2 and Si had no crystalline defects of Si and was very flat. Additionally, measurement of roughness for SiO_2/Si interface using GIXR also confirmed that the interface roughness was less than 0.2 nm.

Figures 4(a) and (b) show the depth profile of Si, O, and C in the NBO film (2nm thick) and thermally grown SiO_2 film (4nm thick), respectively. It is clear that the NBO film has uniform composition of Si and O in depth as well as thermally grown SiO_2 film.

Figure 5 shows relationship of equivalent oxide thickness (EOT) and the leakage current in the NBO film

(2nm thick) and thermally grown SiO_2 film (4nm thick). The NBO film realized lower leakage current, as compared with the thermally grown SiO_2 film. We found that the NBO could form higher quality and lower leakage current SiO_2 film even at low temperature. It is considered to be due to eliminating inner-stresses (inner-strains) and defects in the ultra-thin SiO_2 film formed by NBO at lower temperature.

4. Conclusions

It was shown that NBO could form high-quality SiO_2 film even at lower temperature (300 ºC) than thermal oxidation. By analyzing characteristics of the NBO film with XPS, HR-TEM, GIXR, and SIMS, we clarified that the NBO film had the same excellent property as the conventional thermally grown SiO_2 film.

In measurement of electric characteristic, lower leakage current was obtained for the NBO film than for the thermally grown SiO_2 film. Thus, NBO is a promising candidate for fabrication of future ultrathin (less than 1nm) SiO_2 film under high-k gate insulator films on Si substrate.

5.Reference

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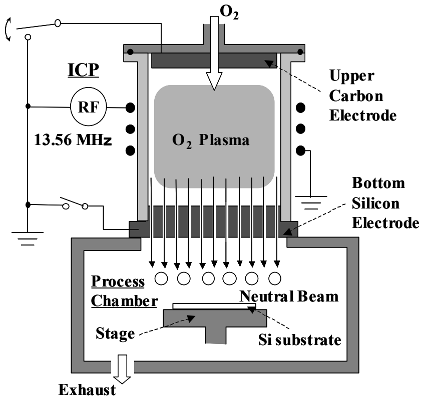

Fig.1 Neutral Beam Equipment

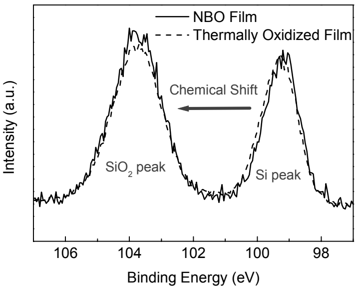

Fig.2 Si2p XPS spectra for the NBO film and thermally oxidized film

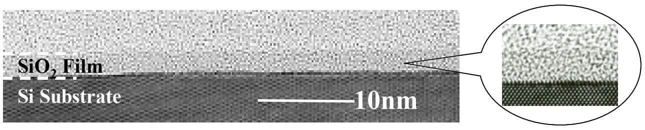

Fig. 3 Cross-sectional TEM images of the NBO film

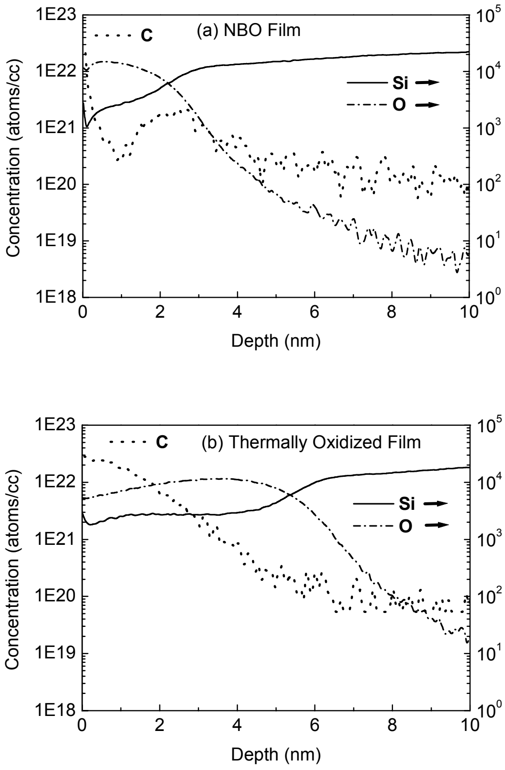

Fig. 4 (a) Depth profile of the NBO film (2nm) and (b) thermally oxidized film (4nm) measured by SIMS

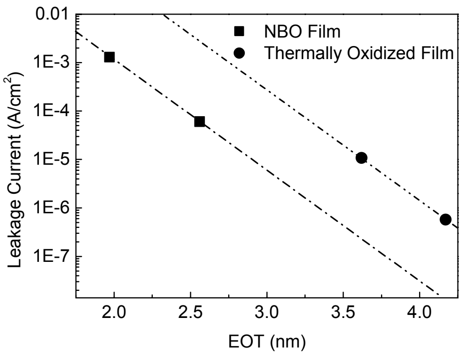

Fig. 5 Relationship of EOT and the leakage current in the NBO film and thermally oxidized film (J_g@V_{FB}-1V)