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Formation of Ge Oxide Film by Neutral Beam Post Oxidation using Al Metal Film

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Abstract

A damage-free and low-temperature neutral beam post-oxidation using an Al metal film was used to obtain a high-quality Germanium (Ge) oxide film. After deposition of a 1-nm-thick Al film on a Ge substrate, simultaneous oxidation of Al and Ge was carried out at 300°C, and a Ge oxide film with around 30% Ge dioxide content was achieved by controlling the acceleration power of the neutral oxygen beam. We also confirmed that the fabricated $AlO_x/GeO_x/Ge$ structure shows a low interface state density of less than 1×10^{11} cm^{-2} eV^{-1}.

1. Introduction

Ge complementary metal-oxide-semiconductor (CMOS) transistor is one of the most promising transistors due to its much higher bulk mobility for both electrons and holes than those in silicon (Si). However, their mobility readily deteriorates because of the instability of the Ge-oxide (GeO_x)/Ge interface [1]. To suppress the degradation of the interface with thin Ge oxide, post-oxidation of Ge has been proposed. Takagi et al. formed an alumina (Al_2O_3)/GeO_x/Ge structure using electron cyclotron resonance plasma post-oxidation [2–4]. This is an advanced oxidation technique because Ge oxide film can be prevented from exposure of ambient environment.

In previous study, we reported an Al_2O_3/GeO_2/Ge gate stack structure with low equivalent oxide thickness (EOT) and low interface state density (D_{it}) by using neutral oxygen beam [5,6]. Our oxidation process has great advantages for semiconductor oxidation such as elimination of UV photons, prevention of charge-up, and low-temperature process, that is, the Ge oxidation can be performed without serious damages. Recently, Watanabe et al. realized an Al oxide (AlO_x)/GeO_x/Ge structure by deposition of an aluminum (Al) metal film on a Ge substrate and post-deposition oxidation at 550°C [7]. Using this process, an AlO_x layer on a clean Ge surface can be obtained. In this study, we performed a neutral beam post-oxidation process to form thin Al- and Ge-oxide film and investigated the effect of beam energy of neutral oxygen beam on the characteristics of Ge gate stacks.

2. Experimental

Fig. 1 shows a generation system of neutral oxygen beam. This system consisted of a plasma chamber and an oxidation chamber separated by a Si aperture electrode with numerous holes and a high aspect ratio (1 mm in diameter and 10 mm in length). The Si aperture can effectively neutralize oxygen ions (charged particles) by collision with the sidewall of the aperture and also eliminate UV photons. As a result, only the neutral oxygen particles arrive at the sample surface. Details of this system have been described elsewhere [8].

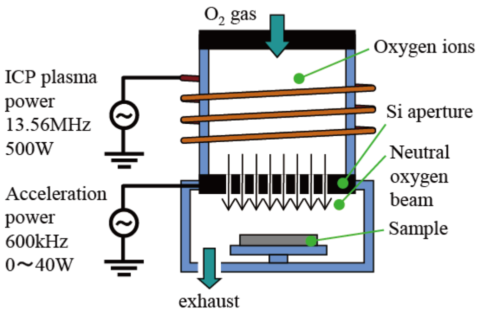

Fig. 1 Neutral beam apparatus.

Fig. 2 shows the fabrication procedure for the AlO_x/GeO_x/Ge structure and a Ge MOS capacitor. After removal of Ge native oxide using DHF solution, Al metal film was deposited by electron beam (EB) evaporation (R-DEC, RDEB-1206K) at RT. After ambient exposure for sample transfer, post-oxidation of the Al/Ge samples was carried out at 300°C using a neutral oxygen beam. The oxygen plasma was generated using the ICP source with

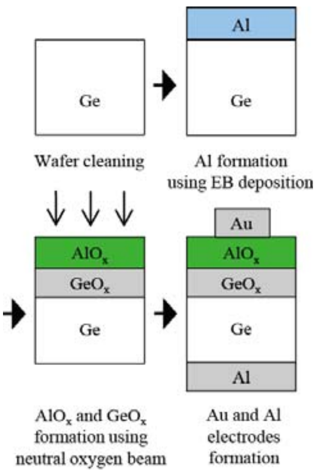

Fig. 2 Process flow for sample preparation.

source power of 500 W, and the beam acceleration power, which was applied to the Si aperture electrode, was also changed in the range 0 – 40 W to control the energy of the neutral oxygen particles. To evaluate the chemical structure of GeO_x and the composition ratio of GeO_2 and Ge suboxide, XPS measurement was performed. To investigate electrical characteristics and interface quality, we also fabricated an Au/AlO_x/GeO_x/Ge/Al MOS capacitor and performed *C*–*V* measurement and low-temperature conductance method (Keithley, 4200-SCS).

3. Results and Discussion

Fig. 3 shows Ge 3d XPS spectra of the 1-nm-thick Al film deposited on the Ge substrate after irradiation with the neutral oxygen beam at 300°C. Here, GeO_2 is associated with the Ge^{4+} oxidation state, and the peak levels of Ge^{1+}, Ge^{2+} and Ge^{3+} correspond to a mixture of Ge suboxide. From the result of peak fitting, it was confirmed that 22% GeO_2 is formed in the GeO_x film whereas no peaks corresponding to GeO_2 was appeared without neutral beam post-oxidation. This result also suggests the formation of a GeO_x layer under the AlO_x (Al) film using the neutral oxygen beam.

In Fig. 4, the GeO_2 content is plotted as a function of acceleration bias power, corresponding to beam energy. In this experiment, an Al film with the thickness of 1 nm was used for post-oxidation. It was observed that increase of beam energy in the range 0 – 30W resulted in increase of GeO_2 content in the GeO_x layer. However, although the GeO_2 content using 40 W was almost the same as that using 30 W, the GeO_x layer formed at 40 W was thicker than that formed at 30 W. These results suggest that there is an optimal beam energy for the neutral oxygen beam to form a thin Ge oxide with high GeO_2 content.

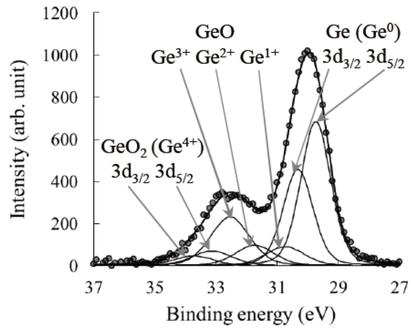

Fig. 3 XPS spectra of Ge 3d of Ge oxide film formed by neutral beam post-oxidation with an Al film.

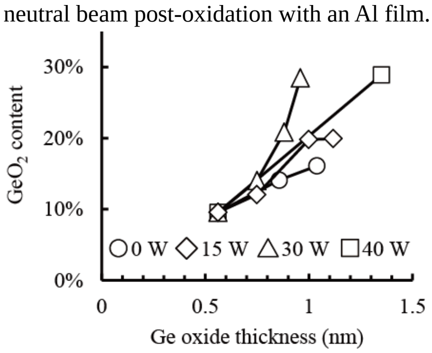

Fig. 4 GeO_2 content versus Ge oxide thickness as a function aperture bias power.

We fabricated Au/AlO_x/GeO_x/Ge/Al MOS capacitors with thin AlO_x (1.5 nm) and GeO_x (1.0 nm) films using neutral beam post-oxidation at 300°C, and the electrical characteristics were evaluated in terms of the *C*–*V*, as shown in Fig. 5. The EOT of this capacitor was 2.8 nm. Using this device structure, we also confirmed the D_{it} of less than 1×10^{11} $cm^{-2}eV^{-1}$ near a midgap, as shown in Fig. 6. This result indicates that a high-quality AlO_x/GeO_x/Ge interface was achieved using a simultaneous neutral beam post-oxidation process of Al and Ge at low temperature.

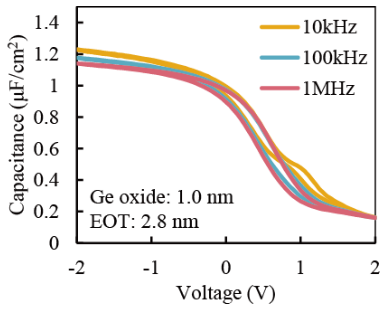

Fig. 5 *C-V* characteristic of AlO_x/GeO_x/Ge MOS capacitor.

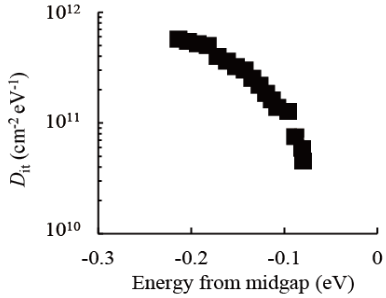

Fig. 6 Calculated D_{it} of AlO_x/GeO_x/Ge MOS capacitor.

4. Conclusions

We investigated Ge oxide thin films formed at a low temperature by combining neutral oxygen beam and post-oxidation using an Al film. This process enabled the formation of high-quality Ge oxide film with high GeO_2 content and a low D_{it} value. The results we obtained show the potential of neutral beam post-oxidation for forming high-quality GeO_2 thin films.

Acknowledgements

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References

[1] K. Kita et al., Jpn. J. Appl. Phys. **47**, 2349 (2008).
[2] R. Zhang et al., Appl. Phys. Lett. **98**, 112902 (2011).
[3] R. Zhang et al., Microelectron. Eng. **88**, 1533 (2011).
[4] R. Zhang et al., Appl. Phys. Lett. **102**, 081603 (2013).
[5] A. Wada et al., *Extended Abstracts of SSDM* (2012) 16.
[6] A. Wada et al., Appl. Phys. Lett. **100**, 213108 (2012).
[7] I. Hideshima et al., Current Applied Physics **12**, S75 (2012).
[8] S. Samukawa, Jpn. J. Appl. Phys. **45**, 2395 (2006).