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Current conduction in H_2O-grown ALD-Al_2O_3 films on Si substrates

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Abstract

Al_2O_3 is expected from power device engineer gate insulation of wide bandgap semiconductors (WBGSs) with alternative thermally SiO_2. In this study, O_3 treatment after atomic layer deposition (ALD) effectively reduces the negative-bias leakage current in Al-gated H_2O-grown ALD-Al_2O_3 films without much affecting the insulator semiconductor interface. Therefore, the O_3 treatment is a powerful tool for realizing high-performance, high-reliability gate insulation in non-Si MISFETs.

1. Introduction

WBGSs have recently been attracting attention from power device engineers as a substitute for Si because of their high blocking capability. A challenge of WBGSs metal-insulator-semiconductor field-effect transistors (MISFETs), such as those on GaN and diamond, is high-performance, high-reliability gate insulation, because the proven thermal SiO_2 is not available there. A promising solution to the challenge is Al_2O_3 films formed by ALD, due to their relatively wide bandgap (~7eV) [1], high dielectric constant (~9) [2], and high thermal stability [4]. The insulation characteristics of the ALD-Al_2O_3 films remarkably depend on ALD conditions, and O_3 as oxidant is found to be very effective in reducing the conduction current in Al_2O_3 films [5]. The O_3 growth, however, has a demerit of deteriorating the insulator/semiconductor interface and the semiconductor surface [6]. The purpose of this study is to develop a technology for reducing the current without damaging the interface or the semiconductor surface.

2. Experimental and Analysis

The samples in this study were MIS capacitors formed on (100) *p*-type 2-4 Ωcm Si substrates with a stack of Al_2O_3 (top) and SiO_2 (bottom) film as the gate insulator. This SiO_2 was chemically formed to a thickness of 1.2 nm by substrate cleaning, prior to ALD, using an ammonium hydroxide-hydrogen peroxide mixture. Al_2O_3 was then formed by ALD using H_2O oxidant at 450°C to a thickness of 32 nm and subjected to an in-situ annealing for 30 ~ 600 s in an O_2 environment (N_2 diluted) containing 150 g/Nm^3 O_3. For comparison, the samples that did not receive the O_3 annealing were also prepared. Subsequently, gate electrodes were formed by thermally evaporating Al through a shadow mask with openings of 200 μm square, hence completing the sample preparation.

The thicknesses of the SiO_2 and Al_2O_3 film were measured just after they were formed, using a spectroscopic ellipsometer. The current−voltage (*I*−*V*) characteristics of the MIS capacitors were measured at room temperature and analyzed using the space-charge-controlled field emission (SCC-FE) model [7], which assumed a sheet of dipoles at the Al_2O_3/SiO_2 interface and two sheets of charge in the Al_2O_3 films near the Al_2O_3/SiO_2 interface and near the Al gate.

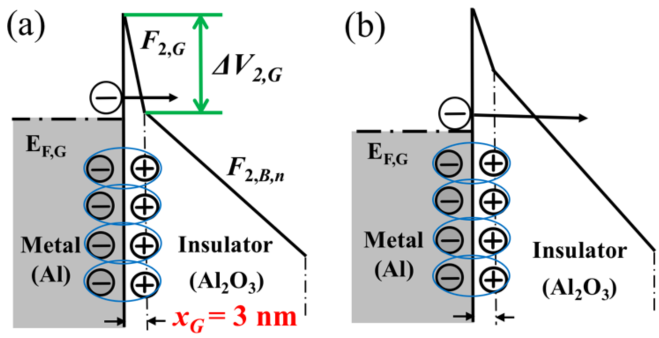

Fig. 2. Gate side energy band diagrams of ALD-Al_2O_3/SiO_2 MIS capacitors under (a) a high field and (b) a low field, based on the SCC-FE model. $\Delta V_{2,G}$ is the potential change caused by the sheet of dipoles located at the gate/Al_2O_3 interface. The best agreement between experimental and theoretical results was obtained by assuming the position x_G of the sheet of charge $Q_{2,G}$ to be 3 nm.

3.Results and Discussion

As shown by the symbols in Fig. 1, for negative bias, the current density of the Al-gated Al_2O_3/SiO_2 MIS capacitors remarkably decreases with O_3 treatment time to a minimum for treatments longer than 240s. By contrast, the *I*−*V* characteristics under positive bias only negligibly changed by the O_3 treatment (not shown). Given that electrons are injected from the gate and the substrate under negative and positive bias, respectively, the aforementioned results clearly reflect the fact that the O_3 treatment only modifies the surficial region of Al_2O_3, hence mostly affecting the energy band near the gate/Al_2O_3 interface, as schematically shown in Fig. 2.

The experimental results, shown in Fig. 1 (symbols), are excellently fitted by theoretical results (broken lines) that are calculated based on the SCC-FE model, assuming a potential change caused by the gate-side dipoles, as shown in Fig.3. The potential change for short O_3 treatments is relatively large, and, therefore, enhanced the current in the capacitors beyond the level that was expected from the work function of the gate electrode. It decreases with treatment time and gets minimal for treatments longer than 240 s in agreement with the *I*−*V* characteristics. This result indicates that the reaction between the gate (Al) and Al_2O_3 is effectively suppressed by the O_3 treatment. As shown in Fig.4, the O_3 treated samples (red filled circles) have a better SiO_2/Si interface than O_3–grown samples (open circles), as confirmed by the smaller flat-band voltage shift and by the absence of a hump of *C*−*V* characteristics, which is caused by many interface traps.

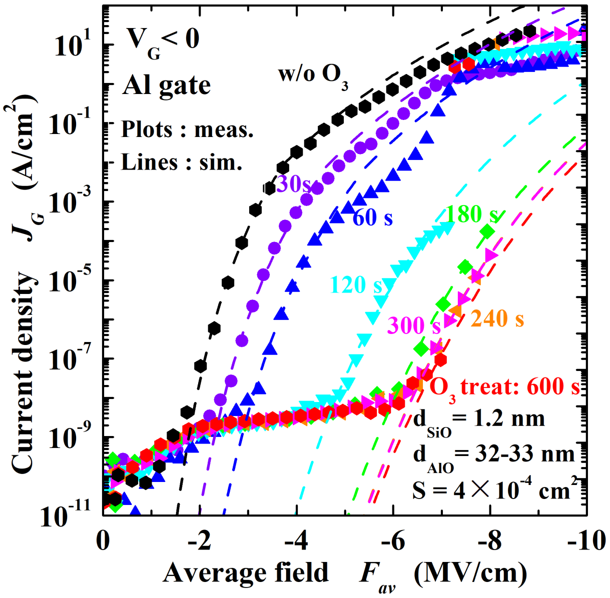

Fig. 1. *I*−*V* characteristics of Al-gated Al_2O_3/SiO_2 MIS capacitors under negative bias. The abscissa is the average field in the Al_2O_3 film. The symbols and lines represent experimental and simulated results, respectively, and the numbers attached to the symbols and lines represent O_3 treatment time in units of second.

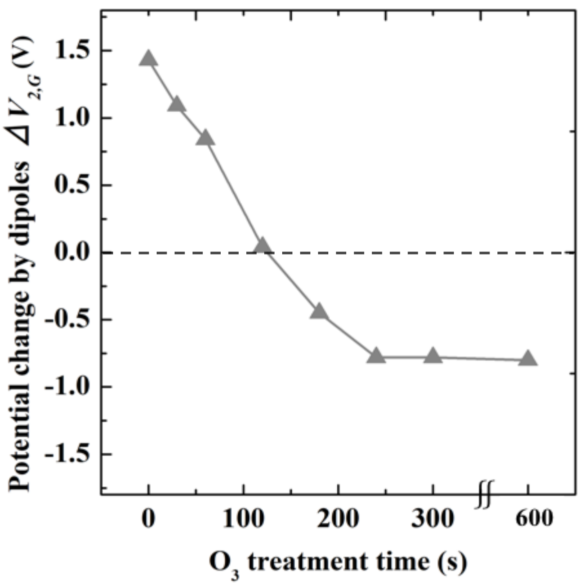

Fig. 3. Potential change caused by gate-side dipoles. The values in this figure are used in the simulations shown in Fig. 1.

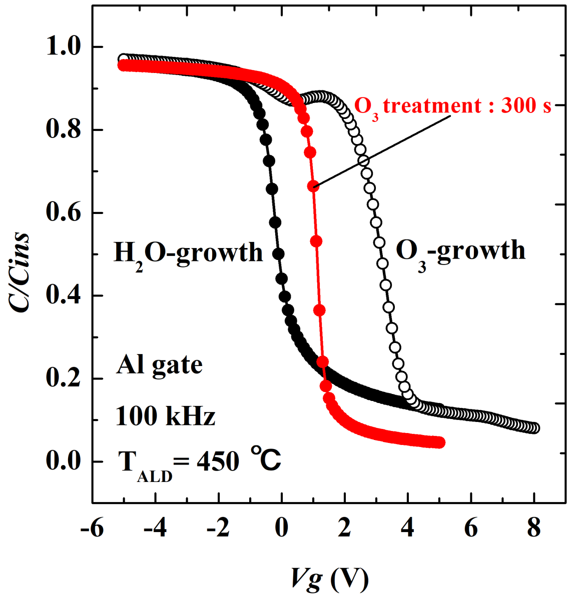

Fig. 4. *C*−*V* characteristics (100kHz) of Al-gated Al_2O_3/SiO_2 MIS capacitors.

4. Conclusion

O_3 treatment after ALD effectively reduces the negative-bias leakage current in Al-gated H_2O-grown ALD-Al_2O_3 films without much affecting the insulator/semiconductor interface. The SCC-FE analysis revealed that this current reduction was achieved by the reduction in gate-side dipoles as a consequence of suppressed reaction between the gate and Al_2O_3. Therefore, the O_3 treatment is a powerful tool for realizing high-performance, high-reliability gate insulation in non-Si MISFETs.

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References

[1] S. Canulescu, et al., Appl. Phys. Lett. **109**, 091902 (2016).

[2] A. Hiraiwa, T. Saito, D. Matsumura, and H. Kawarada, J. Appl. Phys. **117**, 215304 (2015).

[3] L. Zhang, H. C. Jiang, C. Liu, J. W. Dong, and P. Chow, J. Phys. **D 40**, 3707 (2007).

[4] A. Hiraiwa, D. Matsumura, and H. Kawarada, J. Appl. Phys. **119**, 064505 (2016).

[5] S. Okubo, et al., 15a-B9-2, The Japan Society of Applied Physics 2016 fall meeting.

[6] A. Hiraiwa, A. Daicho, S. Kurihara, Y. Yokoyama, and H. Kawarada, J. Appl. Phys. **112**, 124504 (2012).

[7] A. Hiraiwa, D. Matsumura, and H. Kawarada, J. Appl. Phys. **120**, 084504 (2016).