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Electrical properties of crystalline γ-Al_2O_3 films using conductive-AFM and MISFETs with Aluminum gates

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1.Introduction

For future LSI applications, it has been proposed to replace the traditional SiO_2 with the high-k materials such as Al_2O_3, ZrO_2, HfO_2, Si_3N_4 and Y_2O_3 for gate dielectrics. In our laboratory, crystalline γ-Al_2O_3 films have been studied and grown on Si substrate successfully using a hybrid source MBE [1]. It has a number of applications in Si devices such as quantum well devices and silicon-on-insulator technology [2]. The electrical properties of the γ-Al_2O_3 have been reported [3], which describes no SiO_2 interface layer between Si and Al_2O_3, high breakdown field comparable with SiO_2, and low leakage current compared with other insulators. Therefore, crystalline γ-Al_2O_3 films were expected as an attractive candidate for high-k materials. However, evaluations of crystalline γ-Al_2O_3 films might be not enough for several applications. Because crystalline films usually have crystal defects or grain boundaries, which may have a bad influence on the characteristics.

In this report, we evaluated the influence of crystal defects or grain boundaries by comparison of breakdown voltage among conductive AFM's cantilevers and MIS structures that has several electrode sizes. Furthermore, we fabricated n-channel MISFETs with Aluminum gates using the crystalline film as gate dielectrics and confirmed good characteristics.

2.Experiments

Ultrathin crystalline γ-Al_2O_3 films with the thickness of 3nm were grown on Si(100) substrates in multichamber MBE system. Si substrates were cleaned with a modified RCA cleaning process. To obtain γ-Al_2O_3 film with smooth surface, a prelayer was formed on the Si substrate. The prelayer was fabricated with 1-nm-thick SiO_2 and 1-nm -thick Al deposited at room temperature and then annealed at 800℃ for 30min, which results in a 1-nm-thick γ-Al_2O_3 layer. The prelayer formation is described in detail [4,5]. To obtain our expected γ-Al_2O_3 thickness, the deposition of the crystalline γ-Al_2O_3 was performed in a hybrid source MBE chamber with an Al K-cell as aluminum source and N_2O gas as oxygen source at 750℃, at a pressure of 3.2×10^{-2} Pa. The fabricated γ-Al_2O_3 films were characterized by AFM, ellipsometer, and in-situ XPS and RHEED.

For I-V measurements, 3-nm-thick γ-Al_2O_3 films were grown on Si(100). After growth of the films, we prepared MIS structures that consist of conductive cantilever electrode having 50-70 nm diameter or evaporated Al electrodes having several sizes of 2.5×10^{-5}, 1×10^{-4}, 4×10^{-4} , 2.5×10^{-3}, and 1.0×10^{-2} cm^2 as top electrodes, and Al was evaporated for back ohmic contact.

For n-channel MISFETs fabrication, non-self aligned process was used. The devices were fabricated on p-Si(100) substrate, 1-3 Ω·cm. The Source and drain region were implanted with the phosphorous. The activation annealing was carried out at 1000℃ for 20 min. 4.5-nm-thick γ-Al_2O_3 films were grown by the above mentioned method. To improve the electrical properties, the samples were annealed in a N2 environment at 600℃ for 30min [2]. Al was evaporated for the gate, source and drain electrodes. The devices have 50, 20, 10 and 5 μm as gate length and 100 and 200 μm as gate width, and MIS capacitances with electrode size 3.42×10^{-4} cm^2 were fabricated at the same time.

3.Results and Discussion

Figure 1 and 2 show the current density vs electric field characteristic with different electrode sizes and the electric field vs electrode size characteristic of the sample with 3-nm-thick γ-Al_2O_3 on n-Si(100), respectively. Measurement using AFM slightly tended to show higher breakdown voltage than those with Al electrodes. Except that, no remarkable difference was observed. It means that defects like pinholes into γ-Al_2O_3 layer are not present. High breakdown voltage (10 MV/cm) comparable with SiO_2 one was confirmed as well as low leakage current (10^{-6} A/cm^2) for all electrode sizes under this electric field, which is very low when compared with other insulator material. This trend was also confirmed 3nm thick γ-Al_2O_3 on Si(111) for several application.

Fig. 3 shows the typical C-V characteristics of MIS capacitance fabricated with Al_2O_3-MISFET process. The C_{max} was about 5.0×10^{-10} F with area size 3.42×10^{-4} cm^2.

Therefore, capacitance equivalent thickness (CET) was estimated about 2.4 nm. The fixed charges density was estimated about 1×10^{13} cm^{-2} from comparison with theoretical C-V curve considered only the effect of work function difference. Figure 4 and 5 show typical MOSFET characteristics using 4.5-nm-thick crystalline γ-Al_2O_3 films as gate dielectrics with W/L =100/10. The threshold voltage was estimated 0.60 V. The subthreshold slope was estimated 65 mV/decade.

4.Summary

In this study we confirmed that the influence of crystal defects or grain boundaries in the electrical properties of γ-Al_2O_3 films were little. Furthermore, we fabricated crystalline γ-Al_2O_3 n-channel MOSFET with Aluminum gates and typical characteristics were confirmed. From these results, crystalline γ-Al_2O_3 is suitable for gate insulator in future.

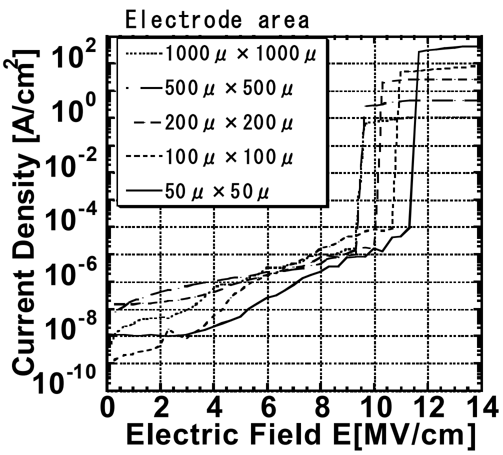

Figure 1. Electrode area dependence of current density – electric field characteristics of 3-nm-thick crystalline γ-Al_2O_3 deposited on n-Si(100)

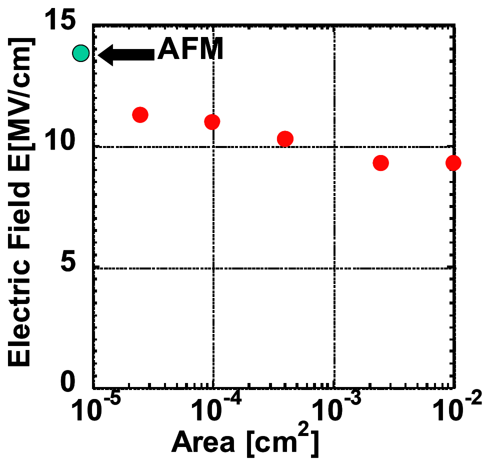

Figure 2. Relation of break down field - electrode area of 3-nm-thick crystalline γ-Al_2O_3 deposited on n-Si(100)

Acknowledgments

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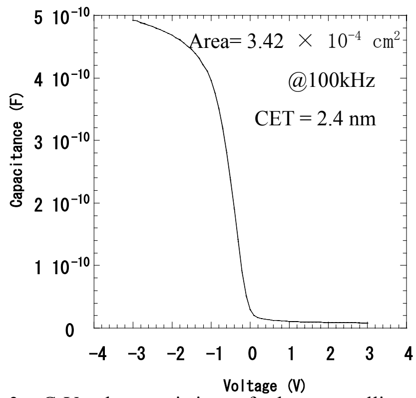

Figure 3. C-V characteristics of the crystalline γ-Al_2O_3 MIS capacitance fabricated with Al_2O_3 -MISFET

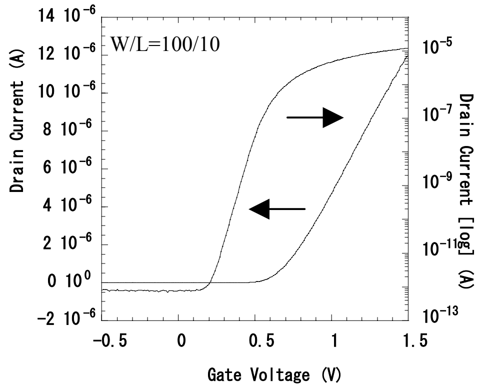

Figure 4. I_D-V_G characteristics at V_{DS} = 10 mV of the crystalline Al_2O_3-MISFET fabricated on p-Si(100)

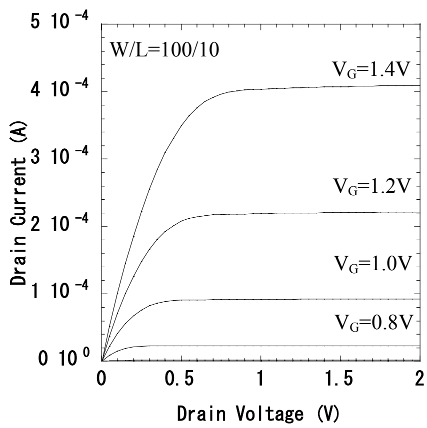

Figure 5. I_D-V_D characteristics at difference gate voltage of the crystalline Al_2O_3-MISFET fabricated on p-Si(100)