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Electrical Properties of Metal-Insulator-Semiconductor Capacitors on Freestanding GaN Substrate

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1. Introduction

III-V nitrides' physical properties of high breakdown electric field and high electron saturation velocity make it useful for high-power electronic applications such as GaN-based field-effect transistors (FETs) or heterostructure FETs. Recently, several researchers have reported the introduction of AlGaN/GaN HFETs for switching power devices [1-3]. However, gate leakage current of these devices, which is mainly attributed to poor Schottky contact interface, is a pervasive problem. In order to reduce high leakage current, metal-insulator-semiconductor (MIS) structure has been proposed. Several gate insulators such as SiO_2, Ga_2O_3, and MgO have been used in GaN-based MIS structures on sapphire substrates [4-6]. However, interface state densities are still high order due to high density structural defect or dislocation in the vicinity between GaN and sapphire interface. Moreover, high quality insulators in these structures have not been achieved yet.

In this study, we investigated the electrical properties of three types of MIS capacitors using SiO_2, annealed SiO_2, and SiN_x deposited on freestanding GaN substrates with the aim of clarifying a desirable insulator for high-performance GaN electronic device.

2. Experiment

We fabricated three types of SiO_2, annealed SiO_2, and SiN_x MIS capacitors on freestanding GaN substrates. For comparison, we also prepared the same capacitors on Si substrates. The n-GaN epilayer was grown on 2-inch GaN substrate by metal organic chemical vapor deposition (MOCVD). This layer doped with Si was about 6μm and the electron concentration was 1×10^{16} cm^{-3}. The SiO_2 and SiN_x insulators were then deposited by low pressure CVD (LPCVD). The thicknesses were 90-100nm. In the case of annealed SiO_2, it was annealed by thermal annealing process at 900℃ for 20 minutes in nitrogen atmosphere. The front- and rear-face electrodes were formed using Al and Ti/Al metallization, respectively.

The high frequency C-V characteristics were measured using HP4284A LCR meter. The I-V characteristics were analyzed by Keithley model 236 source-measure unit. In addition, Time-dependent dielectric breakdown (TDDB) measurement was carried out to predict dielectric lifetime under constant current stress.

3. Results and Discussion

Figure 1 shows measured and ideal C-V curves at 300K, respectively. The measured C-V curves obtained from SiO_2 and SiN_x MIS capacitors are almost consistent with the ideal curves. Especially, the SiN_x MIS capacitor exhibits very steep slope of the C-V curve as shown in Fig.1. On the other hand, the measured result of annealed SiO_2 shows significantly gentler curve as compared to the ideal one. This result indicates that relatively high density of interface states is formed at annealed SiO_2/GaN interface.

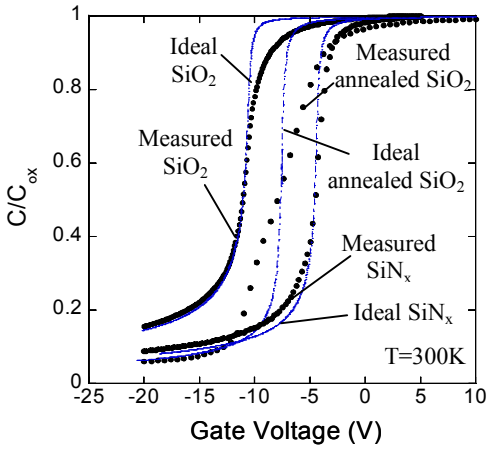

Fig.1 Typical C-V curves for the samples at 300K. Broken line is ideal C-V curve and dot symbol is measured one.

Based on the C-V data from the samples, we extracted the flatband voltage V_{fb}, fixed charge density Q_{ss}, and interface state density D_{it}. The obtained parameters are shown in Table 1. As can be seen in Table I, the SiN_x MIS capacitor shows comparatively low densities of fixed charge and interface state than as-grown and annealed SiO_2. The smallest flatband voltage shift is also in the SiN_x sample. These results suggest that the SiN_x MIS capacitor has good interface property at SiN_x/GaN. The as-deposited SiO_2 MIS capacitors using sapphire were reported to have high interface state densities of 4×10^{11} to 10^{12} $cm^{-2}eV^{-1}$

Table I several parameters obtained from C-V data

	SiO_2	Annealed SiO_2	SiN_x
V_{fb}(V)	-9.85	-6.02	-3.85
Q_{ss} (cm^{-2})	2.3×10^{12}	1.4×10^{12}	1.0×10^{12}
D_{it}($eV^{-1}cm^{-2}$)	1.0×10^{11}	9.2×10^{11}	1.2×10^{11}

[7,8]. The SiN_x/GaN samples without N_2-plasma treatment were also shown high D_{it} values of 3 to 9×10^{11} $cm^{-2}eV^{-1}$ [8,9]. Comparing with these results, the estimated D_{it} values from as-grown SiO_2 and SiN_x on freestanding GaN substrates are relatively low due to high crystalline quality of n-GaN epilayer/GaN substrate. That is, an improved insulator/GaN by using GaN substrate suggests making useful for the high-performance GaN electronic devices.

Figure 2 shows typical I-V characteristics for the samples deposited on GaN and Si substrates. From linear relation of $log\ (J/E^2)$ vs. $1/E$, Fowler-Nordheim tunneling current is dominant conduction mechanism in as-grown and annealed SiO_2. On the other hand, the SiN_x capacitor is governed by Poole-Frenkel emission current that shows the linear relation of $log\ (J/E)$ vs. $1/E^{1/2}$. The leakage currents

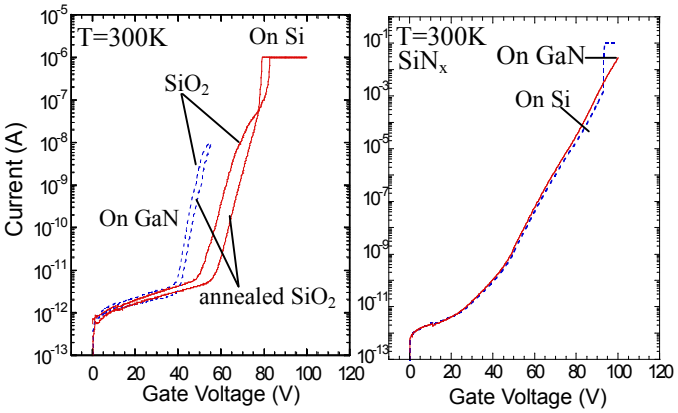

Fig.2 Typical I-V curves for the samples at 300K. Broken line is MIS samples on GaN and straight one is those on Si substrates.

of as-grown and annealed SiO_2 are changed according to GaN and Si epilayers under the same voltage as shown in Fig.2. However, the same I-V characteristics are obtained from two SiN_x MIS capacitors on GaN and Si layers, which imply that the leakage currents of the SiN_x are independent on epilayers. Therefore, we speculate that the introduction of SiN_x insulator for the GaN MIS structure enables to control the gate leakage current and realize high drive current.

Figure 4 shows TDDB characteristics under constant current stress at 300K. The dielectric breakdown time τ_{BD} is generally given by [10]

$$\tau_{BD} = A\exp(-\beta \cdot V_i),$$

where A is the constant, β is the voltage acceleration constant, and V_i is the voltage applied across insulator layer, respectively. From the slopes of logarithmic plots, as-grown and annealed SiO_2 MIS capacitors are predicted to be less than 10 years as the dielectric lifetime. However, the SiN_x capacitor has comparatively long TDDB lifetime for more than 20 years at high voltage of 55V. These results prove that the MIS capacitor using SiN_x insulator shows higher reliability as compared to as-grown and annealed SiO_2.

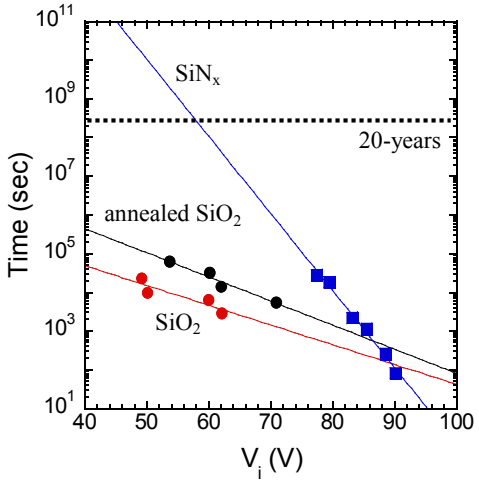

Fig.4 TDDB characteristics for the samples at 300K.

4. Conclusions

The electrical properties of SiO_2, annealed SiO_2, and SiN_x MIS capacitors on freestanding GaN substrates were investigated using C-V, I-V, and TDDB measurements. The SiN_x MIS capacitor showed lower flatband voltage, fixed charge and interface state densities than as-grown and annealed SiO_2. The same I-V characteristics were also shown in the SiN_x capacitors deposited on GaN and Si epilayers. These results indicate that the SiN_x MIS capacitor has good interface properties at SiN_x/GaN interface and enables to control of gate leakage current. In addition, the dielectric lifetime of the SiN_x is predicted to be more than 20 years at 55V, while those of as-grown and annealed SiO_2 are estimated to be less than 10 years. Therefore, we confirmed that the MIS capacitor using the SiN_x shows high reliability as well as good interface properties at insulator/GaN as compared to the SiO_2.

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