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Trap characterization of in-situ metal-organic chemical vapor deposition grown AlN/AlGaN/GaN metal-insulator-semiconductor heterostructures by frequency dependent conductance technique

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Frequency dependent conductance measurements were employed to study the trapping effects of in-situ metal-organic chemical vapor deposition grown AlN/AlGaN/GaN metal-insulator-semiconductor heterostructures (MISHs). Conventional fitting method could not be used to explain the experimental parallel conductance ($G_p/\omega$) results. Alternatively, experimental $G_p/\omega$ values were resolved into two fitting curves for gate voltages ($-1.2$ to $-1.8$ V) near the threshold voltage ($V_{th}$) by a fitting model. In the low frequency region ($\leq 50$ kHz), the $G_p/\omega$ values can be fitted into a single curve. On the other hand, in the high frequency region, two fitting curves were necessary. The results using this model explicitly yielded two types of traps existing in the AlN/AlGaN/GaN MISHs, one due to the insulating AlN layer and the other caused by the AlGaN barrier layer. © 2011 American Institute of Physics. [doi:10.1063/1.3614556]

GaN based high-electron-mobility transistors (HEMTs) grown on silicon are attractive due to its low cost, high power, and high frequency applications attributed to their large band gap and high breakdown field. However, the gate leakage, reliability, and low breakdown voltage are the issues that limit these devices for their commercial application in high power and high frequency areas. To suppress the gate leakage and to improve breakdown voltage and a larger gate voltage swing, a variety of gate insulators have been investigated over connected to a probe station.

The frequency dependent conductance measurements were performed between the frequency range of 1 kHz to 5 MHz to evaluate the trap state time ($\tau_T$) and trap state density ($D_T$). Conductance technique for the measurement of trap states in MIS capacitors is generally accepted as the most accurate technique in existence. A device threshold voltage ($V_{th}$) of $-1.7$ V was observed for these MIS-diodes from capacitance-voltage (C-V) measurements. Traps due to the insulator and barrier layers in a MIS structure can be explicitly studied by selectively chosen voltages near the $V_{th}$.

The equivalent parallel conductance ($G_p/\omega$) values are calculated according to the expression

$$\frac{G_p}{\omega} = \frac{\omega G_m C_b}{G_m + \omega^2 (C_b - C_m)^2},$$

where $C_b$ is the barrier capacitance, $G_m$ and $C_m$ are the conductance and capacitance measured at different frequencies.

The AlN/AlGaN/GaN MISHs were grown using Taiyo Nippon Sanso, SR 4000 MOCVD system. The MISHs consists of (from the top) 2 nm $i$-AlN insulating layer, 25 nm $i$-$\text{Al}_{0.26}\text{Ga}_{0.74}$N layer, 1 nm $\text{AlN}$ spacer interface layer, 1 $\mu$m $\text{AlGaN}$ layer, 1.25 $\mu$m super lattice structure (SLS), and AlGaN/AlN buffer layer grown over 4 inch p-type Si substrate. The device fabrication started with mesa isolation using BCl$_3$ plasma based reactive ion etching. The devices were passivated using electron beam evaporated 100 nm SiO$_2$. Ohmic contacts were performed using conventional photolithography followed by metallization of Ti/Al/Ni/Au (15/80/12/40 nm). The Ohmic contacts were annealed at 850 °C using infra-red lamp annealing for 30 s in N$_2$ ambient. Finally, gate metals Pd/Ti/Au (40/20/60 nm) were deposited. Circular shaped MIS-diodes of area $7.07 \times 10^{-4}$ cm$^2$ were used for the conductance measurements. Figure 1 shows the cross sectional view of MOCVD grown AlN/AlGaN/GaN MIS-diode. Electrical characterizations on these MIS-diodes were carried out using Agilent B1505 power device analyzer/curve tracer set up connected to a probe station.

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and gate bias, respectively. The $G_{p}/\omega$ as a function of radial frequency ($\omega$) is given by the equation

$$\frac{G_{p}}{\omega} = \frac{qD_{T}}{2\omega \tau_{T}} \ln[1 + (\omega \tau_{T})^2].$$

(2)

The $D_{T}$ and $\tau_{T}$ are parameters that are extracted by fitting the experimental $G_{p}/\omega$ values. The $G_{p}/\omega$ values were plotted against $\omega$ for selected gate voltages ($V_g$) near the vicinity of $V_{th}$. The $G_{p}/\omega$ plot for MOCVD grown AlN/AlGaN/GaN MIS-diode at $V_g = -1.2$, -1.6, and -1.8 V are shown in Figs. 2 to 4. By selecting a range of voltages which do not significantly deplete the GaN layer, the effect of traps in the channel layer could be eliminated.12

Conventional curve fitting method could not explain the experimental $G_{p}/\omega$ dispersions of AlN based MIS-diodes. Alternatively, the experimental $G_{p}/\omega$ values were resolved into two fitting curves for all $V_g$ near $V_{th}$ using a curve fitting model. In the low frequency region ($\omega \leq 50$ kHz) indicated as region 1 in Figs. 2 to 4, the experimental $G_{p}/\omega$ values can be fitted into a single $G_{p}/\omega$ curve. On the other hand, in the high frequency region indicated as region 2, two $G_{p}/\omega$ curves were necessary to fit the experimental $G_{p}/\omega$ values. Similar fitting results were observed even at higher $V_g$ (as shown in Figs. 3 and 4), while the peak position in region 1 moved largely toward low frequency with an increasing $\tau_{T}$ value. This shows the $V_g$ dependency on $\tau_{T}$ for the AlN insulated MIS-diode. The fitting model clearly indicates the existence of two types of trap states and their correlation, as evident from the cross over point between regions 1 and 2, respectively. At this moment, we speculate that the $G_{p}/\omega$ dispersions at the cross over point can be due to the smooth AlN/AlGaN interface caused by *in-situ* deposition of the insulator. This behavior is quite unique from the previous reports on conductance analyses of ex-situ grown Al$_2$O$_3$ as gate insulator for AlGaN/GaN MIS-Hs,4,13 which showed conventional $G_{p}/\omega$ curve in the high frequency region for $V_g$ near the vicinity of $V_{th}$.

We interpret that the main $G_{p}/\omega$ peak exhibited in the lower frequency region could be due to interface states existing in insulating AlN layer, which includes the traps at the AlN/AlGaN interface. The smaller $G_{p}/\omega$ peak observed relatively in the high frequency region corresponds to the bulk traps caused by the AlGaN barrier layer and AlGaN/GaN interface (hereinafter referred to as the AlGaN barrier layer). Further, the fitting curve $(1 + 2)$ of the proposed model represents the combined contribution of trap states due to the insulating AlN and AlGaN barrier layers, which agrees well with the experimental $G_{p}/\omega$ values. To validate this, conductance measurements were performed on reference AlGaN/GaN.
Schottky barrier diodes (SBD) with similar epilayers except without the AlN layer. The open triangles in Fig. 2 represent the $G_p/\omega$ values against $\omega$ for AlGaN/GaN SBD. The SBD showed a single $G_p/\omega$ peak in same frequency region, as of smaller $G_p/\omega$ peak exhibited in AlN/AlGaN/GaN MIS-diode (referred as fitting curve 2 in Figs. 2 to 4).

Furthermore, to extend the arguments based on this model, conductance analyses was performed on another in-situ MOCVD grown AlN/AlGaN/GaN MISHs with 5 nm AlN insulating layer. Interestingly, the experimental $G_p/\omega$ values were also resolved into two fitting curves, exactly in the same frequency ranges as obtained for AlN/AlGaN/GaN MISHs with 2 nm AlN as insulating layer. Two $G_p/\omega$ peaks in the AlN based MISHs could be the result of smooth interface between the in-situ grown AlN layer and the AlGaN barrier layer as observed from our experimental results and fitting model. In contrast, the conductance analyses of any of the AlGaN/GaN MISHs with ex-situ grown insulators could not be explicitly resolved into two trap states caused due to the insulator and barrier layers, respectively.

The trap parameters were also extracted for these AlN based MIS-diodes. The $\tau_T$ due to insulating AlN layer in MISHs was between 27 and 300 $\mu$s. On the other hand, the $\tau_T$ due to AlGaN barrier layer in the MISHs was in the range of 1–3 $\mu$s. The trap state energy level as a function of $\tau_T$ were extracted using the equation

$$E_T = kT \ln(\sigma_T N_c \tau_T).$$

where $k$ is the Boltzman constant, $T$ is the measurement temperature, $\sigma_T$ is the capture cross section of the traps, $N_c$ is the density of states in the conduction band, and $\tau_T$ is the average thermal velocity of the carriers. The values of the constants were considered according to Ref. 14.

The plot of trap state density as a function of its energy level is shown in Fig. 5. A $D_T$ of $4 \times 10^{12} - 20 \times 10^{12}$ cm$^{-2}$ eV$^{-1}$ due to the AlN insulating layer was located deeply at $E_T$ 0.4–0.52 eV. The AlN barrier layer exhibited $D_T$ of $1 \times 10^{11} - 10 \times 10^{12}$ cm$^{-2}$ eV$^{-1}$ distributed at shallow energy levels $E_T$ (0.32–0.34 eV). Recently, excess traps at energy levels of 0.22 and 0.38 eV below the conduction band were reported for HfAlO and AlO based AlGaN/GaN MISHs, respectively. In this present study, using thin AlN layer as the gate insulator, these traps are as deep as 0.52 eV. In general, the trap state density and its energy levels can vary with the insulator and the alloy composition of the AlGaN barrier layer due to change in band gap and band-edge energies in the MISHs. Thus, in the case of in-situ grown AlN/AlGaN/GaN MISHs, relatively deep traps with higher $\tau_T$ due to the AlN insulating layer was observed. On this basis, it might be expected that the $E_T$ and therefore $\tau_T$ would increase with increasing Al concentration, leading to the observation of conductance dispersion at lower frequencies. The $D_{T-min}$ due to AlN and AlGaN barrier layer was $4 \times 10^{12}$ and $1 \times 10^{11}$ cm$^{-2}$ eV$^{-1}$ located at energy levels of 0.52 and 0.34 eV, respectively. However, midgap interface state density cannot be located directly because the trap states located beyond $E_T$ -0.7 eV cannot sufficiently respond during C-V and conductance voltage (G-V) measurement time, limiting the $D_T$ characterization near the conduction band edge. Therefore, conductance measurements at higher temperatures and ultra violet irradiation are necessary to obtain the information of deeper trap states.

In summary, the experimental and the fitting results from extensive conductance studies on in-situ MOCVD grown AlN/AlGaN/GaN MISHs significantly shows the existence of two types of trap states and their correlation. We observe the conductance dispersions in the cross over region can be caused at the AlN/AlGaN interface due to in-situ deposition of AlN insulating layer compared to the other existing ex-situ grown insulators. $D_{T-min}$ of $4.5 \times 10^{12}$ and $1 \times 10^{11}$ cm$^{-2}$ eV$^{-1}$ at energy positions $E_T$ (0.52 and 0.33 eV) below the conduction band were observed corresponding to the trap states of AlN insulating and AlGaN barrier layers, respectively. Frequency dependent conductance analyses is a beneficial technique for the trap state characterization of AlN/AlGaN/GaN based MISHs.

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