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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/ω) results. Alternatively, experimental G_p/ω 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/ω 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 used for AlGaN/GaN MIS-HEMTs.[1–4] However, these insulators are deposited *ex-situ*, which can introduce additional growth and process related defects on these devices. Moreover, the interface formed between the insulator and semiconductor surface critically remains the deciding factor of a good insulator. On the other hand, metal-organic chemical vapor deposition (MOCVD) grown thin AlN insulating layer would be advantageous over existing *ex-situ* deposited insulators for its reduced AlN/AlGaN lattice mismatch, high dielectric constant, and large band gap. High temperature growth can facilitate the formation of single crystalline AlN layer over AlGaN/GaN heterostructure. On the other hand, for better device performance, lower gate leakage and to prevent tensile strain-induced cracking of AlN layer, low temperature growth is preferred for AlN based MIS-HEMTs.[5,6] Therefore, it is worthwhile to study the behavior of trap states existing in such AlN/AlGaN/GaN MISHs. Till date, there is lack of adequate information about the trap characterization of *in-situ* MOCVD grown AlN/AlGaN/GaN MISHs on silicon using a more sensitive technique, for potential application of AlN insulating layer in MIS devices. Ultra thin AlN layers grown on GaN have also been of great interest recently for a number of applications.[7,8] In this Letter, we report detailed frequency dependent conductance analyses of trapping effects of MOCVD grown AlN/AlGaN/GaN MISHs with thin AlN insulating layer.

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*-$Al_{0.26}Ga_{0.74}N$ layer, 1 nm AlN spacer interface layer, 1 μm *i*-GaN layer, 1.25 μm 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 patterns 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 7.07×10^{-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.

Frequency dependent conductance measurements were performed between the frequency range of 1 kHz to 5 MHz to evaluate the trap state time (τ_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.[9–12] 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/ω) values are calculated according to the expression

$$\frac{Gp}{\omega} = \frac{\omega G_m C_b^2}{G_m^2 + \omega^2 (C_b - C_m)^2}, \qquad (1)$$

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

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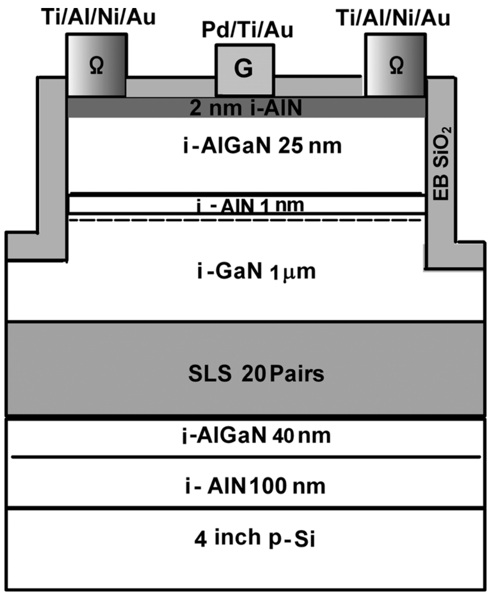

FIG. 1. Cross sectional view of *in-situ* MOCVD grown AlN/AlGaN/GaN MIS diode.

and gate bias, respectively. The G_p/ω as a function of radial frequency (ω) is given by the equation

$$\frac{Gp}{\omega} = \frac{qD_T}{2\omega\tau_T} \times \ln[1 + (\omega\tau_T)^2]. \quad (2)$$

The D_T and τ_T are parameters that are extracted by fitting the experimental Gp/ω values. The G_p/ω-ω values were plotted against ω for selected gate voltages (V_g) near the vicinity of V_{th}. The G_p/ω-ω 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/ω dispersions of AlN based MIS-diodes. Alternatively, the experimental G_p/ω values were resolved into two fitting curves for all V_g near V_{th} using a curve fitting model. In the low frequency region ($\leq$50 kHz) indicated as region ① in Figs. 2 to 4, the experimental G_p/ω values can be fitted into a single G_p/ω curve. On the other hand, in the high frequency region indicated as region ②, two G_p/ω curves were

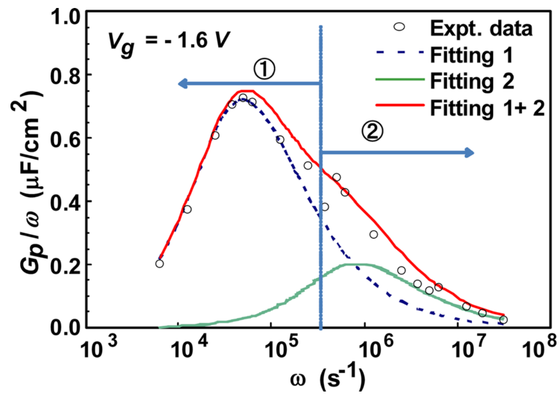

FIG. 3. (Color online) Frequency dependent parallel conductance as a function of radial frequency of *in-situ* MOCVD grown AlN/AlGaN/GaN MIS-diode at $V_g = -1.6$ V.

necessary to fit the experimental G_p/ω 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 τ_T value. This shows the V_g dependency on τ_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/ω 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_2O_3 as gate insulator for AlGaN/GaN MISHs,[4,13] which showed conventional Gp/ω curve in the high frequency region for V_g near the vicinity of V_{th}.

We interpret that the main G_p/ω 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/ω 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/ω values. To validate this, conductance measurements were performed on reference AlGaN/GaN

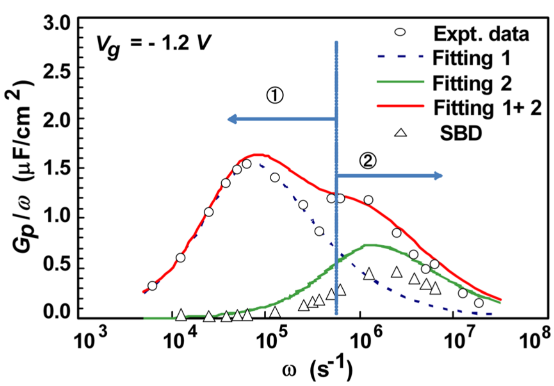

FIG. 2. (Color online) Frequency dependent parallel conductance as a function of radial frequency of MOCVD grown AlN/AlGaN/GaN MIS-diode at $V_g = -1.2$ V. The open triangles represent parallel conductance as a function of radial frequency for AlGaN/GaN SBD without the insulating AlN layer.

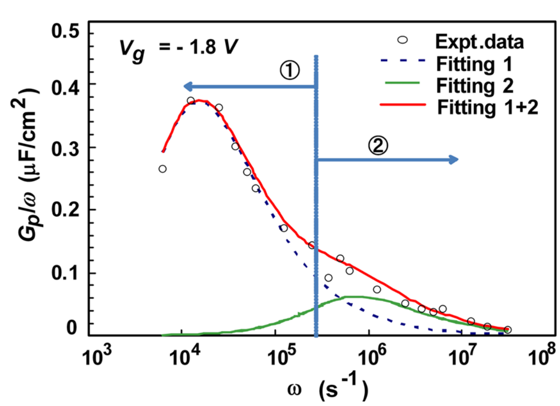

FIG. 4. (Color online) Frequency dependent parallel conductance as a function of radial frequency of *in-situ* MOCVD grown AlN/AlGaN/GaN MIS-diode at $V_g = -1.8$ V.

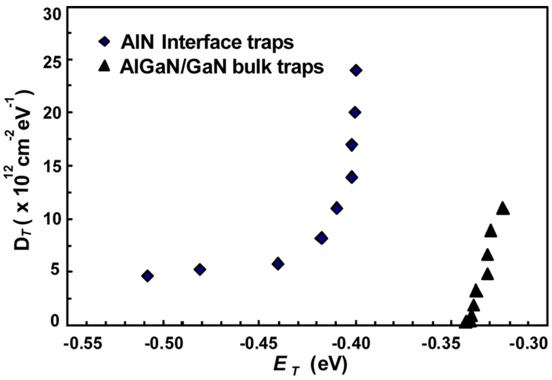

FIG. 5. (Color online) Trap state density as a function of trap state energy of *in-situ* MOCVD grown AlN/AlGaN/GaN MIS-diode due to AlN insulating and AlGaN barrier layers.

Schottky barrier diodes (SBD) with similar epilayers except without the AlN layer. The open triangles in Fig. 2 represent the G_p/ω values against ω for AlGaN/GaN SBD. The SBD showed a single G_p/ω peak in same frequency region, as of smaller G_p/ω 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/ω 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/ω 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 τ_T due to insulating AlN layer in MISHs was between 27 and 300 μs. On the other hand, the τ_T due to AlGaN barrier layer in the MISHs was in the range of 1–3 μs. The trap state energy level as a function of τ_T were extracted using the equation

$$E_T = kTln(\sigma_T N_c \upsilon_T)\tau_T. \quad (3)$$

where k is the Boltzman constant, T is the measurement temperature, σ_T is the capture cross section of the traps, N_c is the density of states in the conduction band, and υ_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 AlGaN barrier layer exhibited D_T of 1×10^{11} − 10×10^{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, resepectively.[15,16] 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 τ_T due to the AlN insulating layer was observed. On this basis, it might be expected that the E_T and therefore τ_T would increase with increasing Al concentration, leading to the observation of conductance dispersion at lower frequencies.[12] The D_{T-min} due to AlN and AlGaN barrier layer was 4×10^{12} and 1×10^{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_c-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.[6] 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-mins} of 4.5×10^{12} and 1×10^{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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