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Temperature-Dependent Interface-State Response in an Al_2O_3/n-GaN Structure

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With a combination of the static capacitance-voltage (C-V) and the capacitance transient (C-t) methods, the interface-state response in an Al_2O_3/n-GaN structure was investigated at temperatures ranging from 23 to 300 ^oC. We observed pronounced degradation of the static C-V curves measured at high temperatures, arising from the enhancement of charging/discharging rates of interface states at deeper energies within the bandgap of GaN. Faster responses with larger magnitudes also appeared in the time-dependent capacitance at high temperatures. From a simple analysis of the C-t results, we estimated the capture cross section of the states to be on the order of 10^{-19} cm^2.

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An insulated-gate structure is very attractive for GaN-based high-efficiency power switching devices and high-power transistors operating at high frequency [1-3]. For realization of well-controlled and reliable insulated-gate structure, it is necessary to achieve an insulator-semiconductor (I-S) interface with a low density of electronic states [1, 4, 5]. To characterize the properties of interface states, a static capacitance-voltage (C-V) method is generally used.

In the case of GaN I-S structures, however, it is difficult, from the room-temperature (RT) C-V method, to gain information on the interface states located near midgap or deeper, because the wide-gap nature of GaN makes the time constant for carrier emission from deeper states extremely large at RT. In this case, as schematically shown in **Fig. 1**, the charging state remains almost unchanged while the gate bias is swept in the C-V measurements even if the interface states have high densities. Thus, it should be pointed out that the RT C-V method only provides the response of the states with a limited energy range near the conduction band minimum or the valence band maximum. At higher temperatures, on the other hand, the deeper interface states can produce larger amounts of charges, particularly under bias conditions for depletion. Since high-power operation significantly increases the channel temperature in the GaN-based transistors [6-8], such interface charges may impede

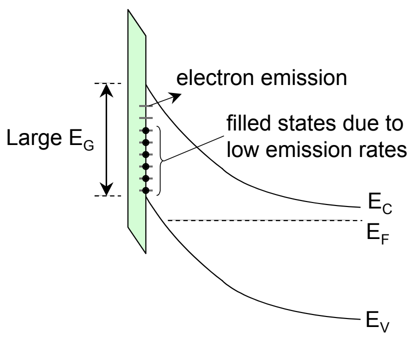

Fig. 1 (Color online) Band diagram of an insulator-GaN interface under depletion conditions. At RT, the charging state remains almost unchanged while the gate bias is swept in the C-V measurements even if the interface states have high densities.

the gate control and the operation stability. In addition, the dynamic trapping/emitting behavior of the interface states often causes operation lag and switching loss in high-power field-effect transistors (FETs) or high-electron mobility transistors (HEMTs). However, no information on the dynamic properties of the states is obtained from a static C-V technique at RT.

In this study, we investigated the temperature-dependent interface-state response in an Al_2O_3/n-GaN structure by a combination of static C-V and capacitance transient methods at high temperatures. Al_2O_3 has often been applied to the insulated-gate AlGaN/GaN HEMTs [2, 9-11], although the properties of Al_2O_3/GaN or Al_2O_3/AlGaN interfaces are not yet well understood.

We used an undoped GaN layer (n = 5 x 10^{16} cm^{-3}) grown on a sapphire substrate by metal organic chemical vapor deposition (MOCVD). We commissioned an institute outside the university to deposit the Al_2O_3 layer with a thickness of 15 nm on GaN at 300 °C by atomic layer deposition using trimethyl-aluminum (TMA) and water vapor as precursors. No surface treatment was applied to the GaN surface before the deposition process. A ring-shaped ohmic contact (Ti/Al/Ti/Au) was formed through photolithography and wet etching, followed by an anneal process at 800°C for 2 min in N_2 atmosphere. Then a circular Al/Au gate contact with a diameter of 200 μm was fabricated on the Al_2O_3 film.

The static C-V and time-dependent capacitance (C-t) measurements were carried out at temperatures from RT to 300°C using an HP 4192A impedance analyzer. The measurement frequency was 1 MHz. A cyclic ramp-bias was applied to the samples from the forward to reverse directions. The ramp rate in the static C-V measurements was 100 mV/s. For the C-t measurements, we first set the bias voltage under accumulation condition, and then switched it to a negative bias in the depletion range.

Figure 2 (a) shows the C-V curves obtained at RT and 300°C. At RT, we observed relatively good C-V behavior with a small hysteresis, which is close to the calculated curve without assuming interface states (solid line). The voltage shift in the C-V curve with respect to the calculated one corresponds to the density of a positive fixed charge of 6 x 10^{11} cm^{-2} in the Al_2O_3 layer. In contrast to the RT result, a pronounced change was observed in the C-V result measured at 300°C. We found significant hysteresis and a decrease in the C-V slope (stretch-out) as shown in Fig. 2 (a), indicating the contribution of the interface charges at deeper energies at higher temperatures. Matocha et al. [12] and Bae et al.[13] reported similar degradation in C-V characteristics at high temperatures for SiO_2/n-GaN structures.

By comparing the experimental C-V data with the calculated values, we determined the distributions of interface state densities [1]. The result is shown in Fig. 2 (b). Except for the distribution near the conduction band, an apparently low density was obtained from the data measured at RT. In spite of the fact that the "true" density distribution is independent of temperature, the 200 °C data yielded higher densities for the deeper states. The 300 °C data showed additional higher densities. This indicates that the electron emission rates at deeper levels were enhanced at higher temperatures and that their charging/discharging behavior follows the voltage sweep in the C-V measurements. In this regard, the high-temperature data are close to the "true" density distribution near the midgap.

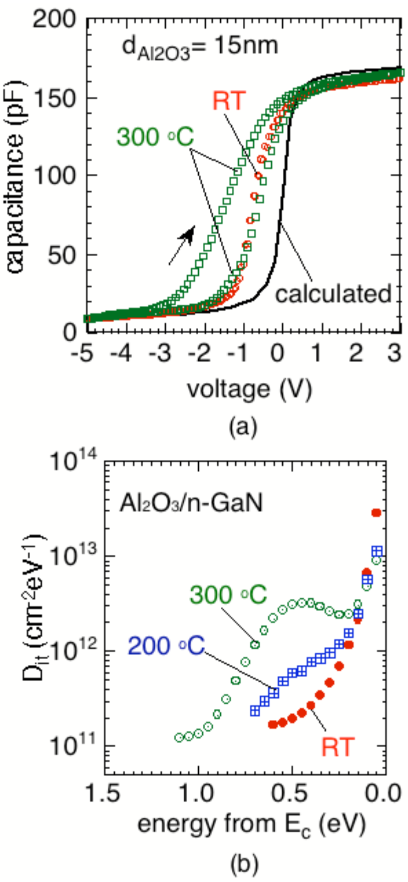

Fig. 2 (Color online) (a) C-V curves obtained at RT and 300°C and (b) distributions of interface state densities calculated by comparing experimental C-V data with calculated values.

Bae et al. [13] also pointed out that the interface state charge at deeper energies appeared at high temperatures, leading to the degradation of C-V behavior.

To obtain better insight into the dynamic properties of the interface state charges, we measured the capacitance transient of the Al_2O_3/n-GaN structure at various temperatures. First, a bias voltage of +1 V was applied to the sample for 10 s, which enabled the states to be filled with electrons. Then we switched the bias to -4 V, and measured the capacitance transient from 1 to 1000 s with a time interval of 1 s. **Figure 3** shows the capacitance change (ΔC) in the temperature range from RT to 300 ^{o}C. We observed a very slow response at RT. At 100 and 200 ^{o}C, faster responses and larger magnitudes of capacitance change appeared. An additional faster response with a small amplitude was found at 300 ^{o}C, probably associated with the lower density distribution of the interface states toward the midgap, as shown in Fig. 2 (b). Thus, we can obtain different dynamic responses of the semiconductor potential at various temperatures. No linear relationship between log (ΔC) and time was observed for all the temperatures, indicating that the capacitance transients were not governed by discrete deep levels in the GaN bulk, but dominantly caused by electron emission with continuous time constants from the interface states distributed continuously in the energygap. These results indicate that the operation performance of insulated-gate-type transistors could be affected by complicated responses of interface state charges, particularly in high-power and high-temperature operations.

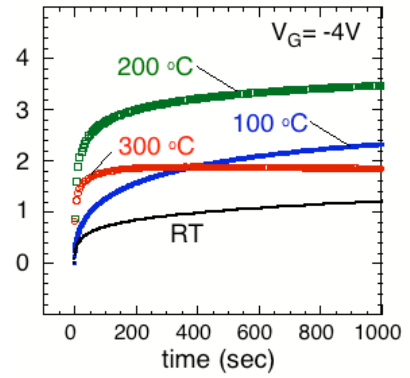

Fig. 3 (Color online) Capacitance change (ΔC) of the Al_2O_3/n-GaN structure in the temperature range from RT to 300 ^{o}C. First, the bias voltage of +1 V was applied to the sample for 10 s. Then, we switched the bias to -4 V, and measured the capacitance transient with a time interval of 1 s.

According to the electron emission from the interface states, the depletion width decreases, leading to an increase in capacitance over time, as shown in **Fig. 4**. Then we can estimate the charge density of interface states, $q\Delta D_{it,C\text{-}t}(T)$, that contributes to the capacitance transient at a given temperature, using a simple equation:

$$q\Delta D_{it,C-t}(T) = \int_{W2}^{W1} \frac{\varepsilon_{OX}}{d_{OX}} N_D \left(\frac{x}{\varepsilon_{GaN}} + \frac{d_{OX}}{\varepsilon_{OX}} \right) dx, \qquad (1)$$

where W_1 and W_2 are the depletion widths at t= t_1 and t_2, respectively, ε_{OX} and ε_{GaN} are the dielectric constants for Al_2O_3 and GaN, respectively, d_{OX} is the Al_2O_3 thickness, N_D is the donor density in GaN, and x is the depth from the GaN surface. W_1 and W_2 were directly calculated from the corresponding capacitances at t= t_1 and t_2. In addition, we can estimated the energy range of the interface states, $E_{rang}(T)$, which dominantly emit electrons within the measurement time window (from t=1 to 1000 s), according to the following equation based on the Schockley-Read-Hall statistics:

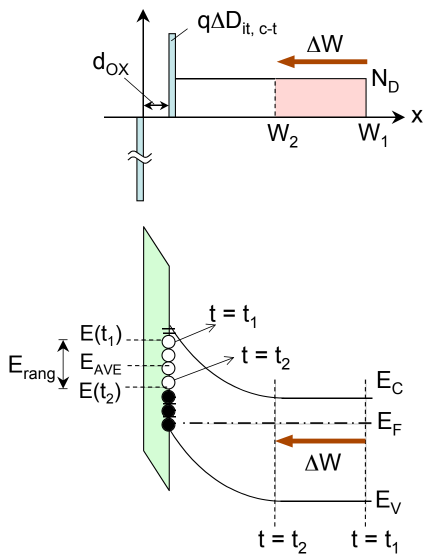

Fig. 4 (Color online) (a) Charge distribution change and (b) the corresponding electron emission from the interface states in the depletion region.

$$t(T,E) = \frac{1}{v_{TH}\sigma_n N_C}\exp\left(\frac{E_C - E}{kT}\right), \qquad (2)$$

where t(T, E) is the time constant of the interface state for electron emission, v_{TH} is the average thermal velocity of electron, σ_n is the capture cross section, N_C is the effective density in the conduction band, E_C is the energy at the conduction-band minimum, E is the interface state energy from E_C, k is the Boltzmann constant and T is the absolute temperature. When we assume the σ_n value, the energy range, $E_{rang}(T) = E(t_2) - E(t_1)$, corresponding to the measurement time range can be calculated, as shown in Fig.4 (b). Then we defined the interface state density as $D_{it,C\text{-}t} = \Delta D_{it,C\text{-}t}/E_{rang}$ at the average energy, $E_{AVE}= (E_2\text{-}E_1)/2$.

The interface state density distribution obtained from the static C-V data at 300 °C is compared with that from the transient capacitances using the analysis described, as shown in **Fig. 5**. If we assume a σ_n value of (3 ± 2) x 10^{-19} cm^2, a reasonably good agreement is obtained between those distributions. The slightly larger values obtained from the transient method probably arise from an integration time longer than in the static C-V method. The σ_n values ranging from 10^{-17} to 10^{-15} cm^2 have been reported for the interface states in the SiO_2/Si structures prepared by thermal oxidation of Si [14, 15]. Deuling et al. [14] also reported a weak temperature dependence of σ_n in the SiO_2/Si structures. On the other hand, no study has been performed on the capture cross section for the GaN I-S interface states. With regard to discrete deep levels in the GaN bulk materials, several groups reported the σ_n values in a very broad range from 10^{-23} to 10^{-14} cm^2 [16-18]. Using a combination of static and transient C-V measurements, it is therefore possible to estimate the capture cross section of the interface states, which is very important to understand the dynamic charging/discharging properties of interface states.

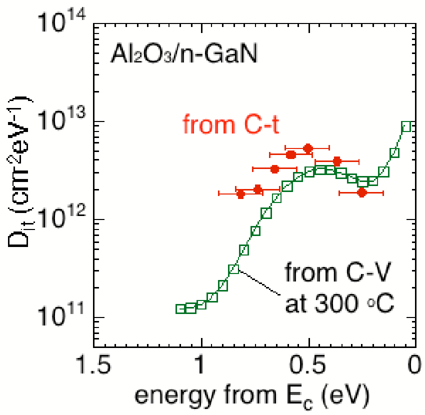

Fig. 5 (Color online) Interface state density distributions calculated from the C-V data at 300 °C and C-t data. When we assumed a σ_n value of (3 ± 2) x 10^{-19} cm^2, a reasonably good agreement was obtained between the two distributions.

In summary, we investigated the temperature dependence of interface-state response in an Al_2O_3/n-GaN structure by a combination of static C-V and capacitance transient methods. A pronounced degradation appeared in the static C-V curves measured at high temperatures, arising from the enhancement of charging/discharging rates of interface states at deeper energies. Faster responses with larger magnitudes were also observed in the time-dependent capacitance at high temperatures. From a simple analysis of the C-t result, we determined the interface state density distribution near the midgap, and estimated the capture cross section of the states, which is very important to understand the dynamic charging response from interface states.

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