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Dynamic response of interface state charges in GaN MIS structures

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1. Introduction

An insulated-gate structure is very attractive for GaN-based high-efficiency power switching devices and high-power RF transistors. For realization of well-controlled and reliable insulated-gate structures, it is inevitable to achieve insulator-semiconductor (I-S) interfaces with a low density of electronic states. The capacitance-voltage (C-V) method is generally used to characterize the I-S interface states.

In case of GaN I-S structures, however, it is very difficult from room-temperature C-V characterization to obtain the properties of interface states located near midgap or deeper, because the wide-gap nature of GaN causes extremely large time constants for carrier emission from such deeper levels to the conduction or valence band at RT. Thus, the RT C-V method can only give the response from the states with a limited energy range close to the band edges. In addition, no information on the dynamic properties of the states such as charging/discharging response is obtained from a standard C-V technique.

The purpose of this study is to investigate the interface state densities near midgap and the dynamic response of electron emission from the states for the Al_2O_3/n-GaN structure.

2. I-S structure and measurement methods

Figure 2 schematically shows the Al_2O_3/n-GaN structure. We used an undoped GaN layer (n = 5 x 10^{16} cm^{-3}) grown on sapphire substrate by metal organic chemical vapor deposition (MOCVD). The Al_2O_3 layer with a thickness of 15 nm was deposited on GaN at 300 ^oC by atomic layer deposition using TMA and water vapor as sources. A ring shaped ohmic contact (Ti/Al/Ti/Au) was formed through photolithography and wet etching, followed by the anneal at 800^oC for 2 min in the N_2 atmosphere. Then, a circular Al/Au gate contact with a diameter of 200μm was fabricated on the Al_2O_3 film.

The static C-V measurements were performed in

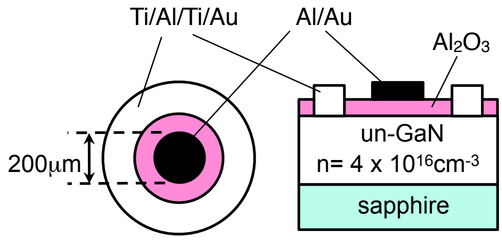

Fig.1 Al_2O_3/n-GaN structure

vacuum at temperatures from RT to 300^oC. The measurement frequency and the bias-sweeping rate were 1 MHz and 20 mV/s, respectively. For the capacitance transient measurement, we firstly set the bias voltage under the accumulation condition, and then switched it to the negative bias in the depletion range.

3. Results and discussion

Figure 2 (a) shows the C-V curves obtained at RT and 300^oC. At RT, we observed a relatively good C-V behavior with a small hysteresis, which is close to the calculated one. However, the pronounced change in the C-V result was obtained at 300^oC. We found the decrease in the C-V slope and a significant hysteresis behavior, indicating the contribution of the interface states at deeper energies at higher temperatures.

By comparing the experimental C-V data with the calculated ones, we estimated the distribution of

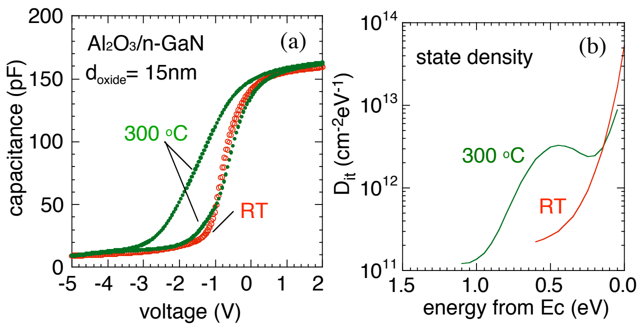

Fig.2 (a) Experimental C-V curves at RT and 300 ^oC.
(b) Interface state density distribution estimated from the C-V data.

interface state densities. The result is shown in **Fig.2 (b)**. An apparently low density was calculated from the data taken at RT. This may arise from an extremely slow response of the states at the deeper energies. The state densities calculated from the 300 °C data showed lower values near the conduction band edge than those from RT data. Since the electron emission rate at the states near the conduction band edge is very high at 300 °C, such shallow levels could act as empty states in the static C-V measurement. On the other hand, the 300 °C data provided higher densities for the deeper states, as shown in Fig. 2 (b), indicating that the electron emission rates at the deeper levels became close to the C-V sweeping rate.

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. As shown in **Fig. 3 (a)**, first, the bias voltage of +1 V was applied to the sample for 10s, which enabled the states filled with electrons. Then, we switched the bias to -4V, and measured the capacitance transient from 1 to 1000 s with a time interval of 1 s.

Figure 3 (b) shows the capacitance responses in the temperatures from RT to 300 °C. We observed a very slow response at RT. At 100 and 200 °C, the faster responses and larger magnitudes of capacitance change appeared. A further faster response with a small amplitude was found at 300 °C. Thus, we can obtain different dynamic responses at high temperatures.

According to the electron emission from the interface states, the depletion width decreased, leading to the time-dependent capacitance increase, as shown in **Fig. 4 (a)**. Then, we can estimate an average density of interface state contributing to the capacitance transient at the given temperatures, using the following equation.

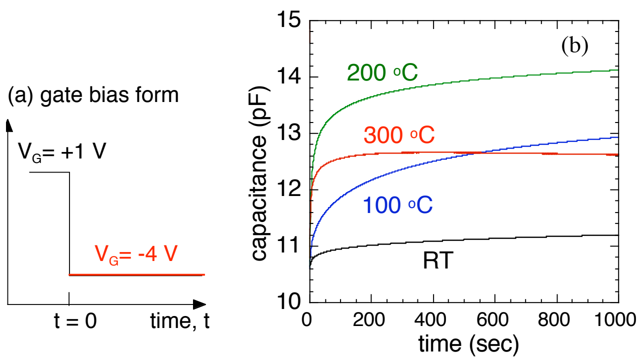

Fig.3 (a) The gate bias form for the capacitance transient measurement. (b) The measured capacitance transients at various temperatures

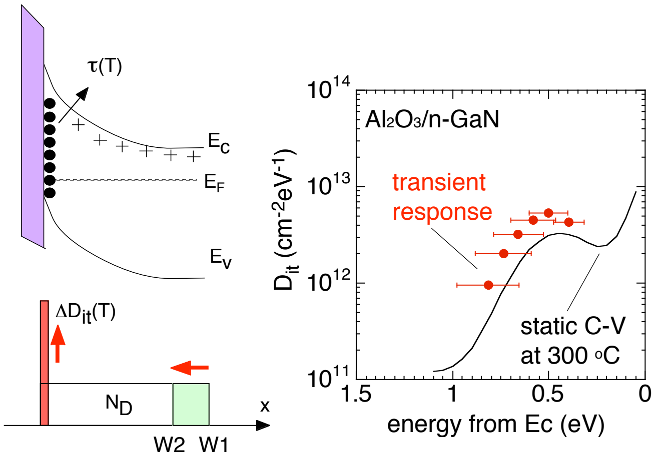

Fig.4 (a) Band diagram and charge distribution.
(b) Interface state densities obtained from the C-V data and the capacitance transients.

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

Here, W_1 and W_2 are the depletion widths at t= t_1 and t_2, respectively. Next, we estimated the energy range of the interface states which dominantly emit electrons in the measurement time window (from 1 to 1000 s), according to the following equation based on the Schockley-Read-Hall statistics.

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

where τ is the time constant for electron emission, v_{TH} is the thermal velocity, σ_n is the capture cross section.

The state density distribution obtained from the capacitance transient is compared with that from the C-V data at 300 °C in **Fig. 4 (b)**. If we assumed the capture cross section of the interface states to be 1 x 10^{-20} cm^2, a reasonably good agreement was obtained between those distributions. The lager values for the transient method probably arise from the longer integration time than the C-V method. Using a combination of the static and transient C-V measurements, thus, it is possible to estimate the capture cross section of the interface states, which is very important for understanding the dynamic charging/ discharging properties of interface states.