# Behavior of Crystal Defects at Low Temperature in AlGaN/GaN HEMTs

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***Abstract*— In this study, the current–voltage (IV) and Radio Frequency (RF) characteristics were measured in a low-temperature environment, and the transient response waveform was analyzed by the simplified Isothermal Capacitance Transient Spectroscopy (ICTS) method. According to the measurement results of the IV characteristics, the current value decreased rapidly as the temperature decreased, and the linear region could not be confirmed. From the RF characteristics, it was confirmed that the gain varies with temperature in the high-frequency band. Furthermore, the results suggested that substantial structural changes occurred in the device under low-temperature environments. In addition, it was confirmed by simple ICTS analysis that the capture cross-section and crystal defect concentration increased with decreasing temperature. At room temperature, the thermal energy imparted to the crystal layer induces phonon scattering at crystal lattice points. This implies that the process of trapping electrons in crystal defects is suppressed. In a high-frequency region, carriers trapped in crystal defects are released and the crystal defects become conspicuous. As a result, an increase in the capacitance component of crystal defects was confirmed, and it is thought that both the capture cross-section and the crystal defect concentration increased compared to those at room temperature.**

***Keywords*— *AlGaN/GaN HEMTs, frequency dependence, ICTS, phonon scattering***

## I. INTRODUCTION

Currently, the use of renewable energy is essential to curb environmental destruction caused by rapid global warming [1,2]. The utilization of renewable energy represented by sunlight requires highly efficient power semiconductor devices that can operate at high voltages and are compact and lightweight [3,4]. The rapid progress in the development of semiconductor devices has mainly been due to changes in the materials used. SiC and GaN are promising materials for power semiconductor device development [5.6]. GaN has a higher electron saturation velocity than SiC [7]. For this reason, GaN devices are superior to SiC devices in terms of low ON resistance and switching performance required for next-generation power conversion devices [8]. However, GaN is more difficult to crystallize than SiC. In particular, a heteroepitaxial structure is required for constructing high-electron-mobility transistors (HEMT) and implementing high-efficiency high-speed Fieed Effect Transistor (FET) [9,10]. Currently, the disparity in lattice constant between AlGaN and GaN results in the generation of strain stress near the interface, leading to a substantial amount of crystal defects within the AlGaN layer. As a consequence, this phenomenon contributes to the occurrence of current collapse during the FET operation [11]. Several methods, such as low-temperature CVD, have been investigated to suppress crystal defects in AlGaN layers and have shown some success [12]. However, the current situation is that it is difficult to completely remove crystal defects. Therefore, in this study, we focused on the characteristics of the crystal defects rather than their suppression of crystal defects. The AlGaN/GaN HEMT was placed in a low-temperature environment, and the IV and high-frequency characteristics were observed while gradually cooling to confirm the changes in the transport characteristics of the two-electron gas. Subsequently, the transient response characteristics of crystal defects were evaluated using simplified isothermal capacitance transient spectroscopy (ICTS) method [13]. As a result, although the activation energy of crystal defects does not depend on temperature, the temperature dependence of the crystal defect concentration and capture cross-section was confirmed. These results confirmed that the observed crystal defects tended to increase as the temperature decreased. This suggests that the external thermal energy promotes phonon scattering at the crystal lattice points and suppresses the trapping of electrons in the crystal defects.

## II. EXPERIMENTAL METHOD

In this study, a low-temperature environment was created using liquid nitrogen, and the temperature dependence of AlGaN/GaN HEMTs at low temperatures was measured for RF characteristics, current–voltage (I-V) characteristics, and transient response waveforms.

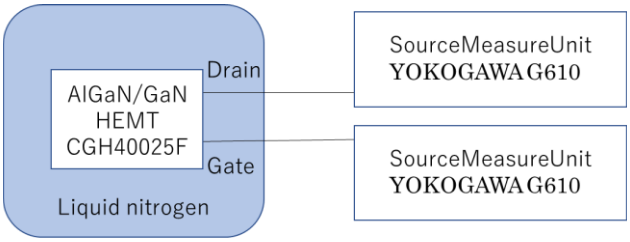

Fig.1. The experimental system used to measure IV characteristics at low temperatures.

### A. Measurement Method of I-V Characteristics of AlGaN/ GaN HEMTs at Low Temperature

Fig. 1 shows the experimental system used to measure the I–V characteristics at low temperatures. A DC voltage of −2.5 V was applied to the gate electrode, and a voltage of 0 to 7.0 V was applied to the drain electrode in increments of 100 mV to obtain IV characteristics.

### B. Measurement Method of Frequency Dependence of AlGaN/GaN HEMTs at Low Temperature

Fig. 2 shows the experimental setup for measuring the frequency dependence of the AlGaN/GaN HEMTs at low temperatures. A voltage of −2.5 V was applied to the gate electrode and 3.0 V to the drain electrode, and frequencies of 10 MHz to 10 GH were given by a vector network analyzer. The waveform of the RF characteristic was obtained from the S-parameter, which is the measurement result.

### C. Crystal Defect Evaluation by Simplified ICTS Method

Upon establishing a low-temperature environment, the transient response waveform was measured using a sampling oscilloscope. By analyzing the transient response waveform, crystal defect evaluation of the AlGaN/GaN HEMT at low temperatures was performed. This was achieved by deriving the activation energies from the plots.

Fig. 3 demonstrates the experimental setup for measuring the transient response waveforms at low temperatures. The drain voltage was set to 0 V using a source measure unit, and a 0 2.0 V pulse wave was applied to the gate electrode. As shown in Fig. 3, the pulse wave applied to the gate electrode is transmitted to the sampling oscilloscope through the bias tee. The transient response waveform was obtained using 256 samples.

## III. RESULTS AND DISCUSSIONS

### A. The I-V Characteristics of AlGaN/ GaN HEMTs at Low Temperature

Fig. 4 shows the measurement results for the I-V characteristics. As the measurement temperature decreased, the current decreased; at 195 K, a linear region could not be confirmed. At extremely low temperatures, the electrons forming the 2DEG were frozen, and the electron transport characteristics from the source electrode to the drain electrode could not be confirmed.

### B. The Frequency Dependence of AlGaN/GaN HEMTs at Low Temperature

Fig. 5 shows the frequency dependence of the power gain obtained from the measured RF characteristics. The environmental temperature was set to five values from 299 K to 77 K, and the frequency dependence was confirmed. In the

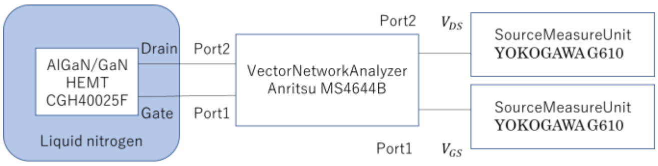

Fig. 2. The experimental setup for measuring frequency dependance of AlGaN/GaN HEMTs at low temperatures.

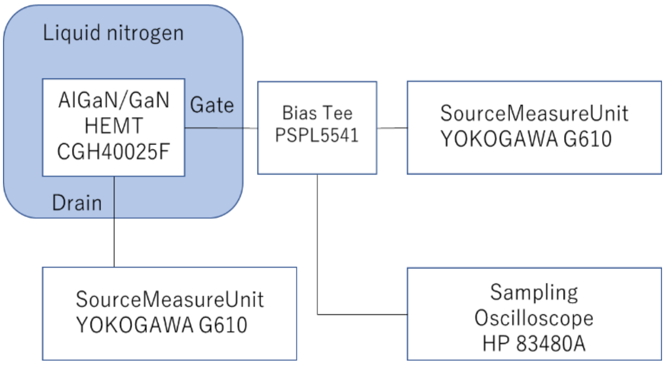

Fig. 3. The experimental setup for measuring transient response waveforms at low temperatures.

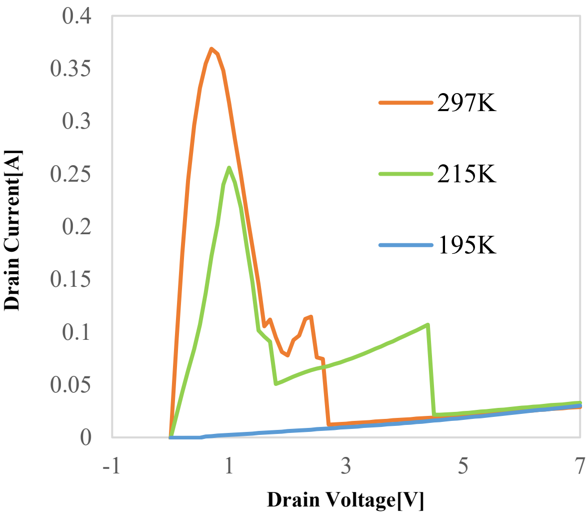

Fig. 4. The measurement results of IV characteristics.

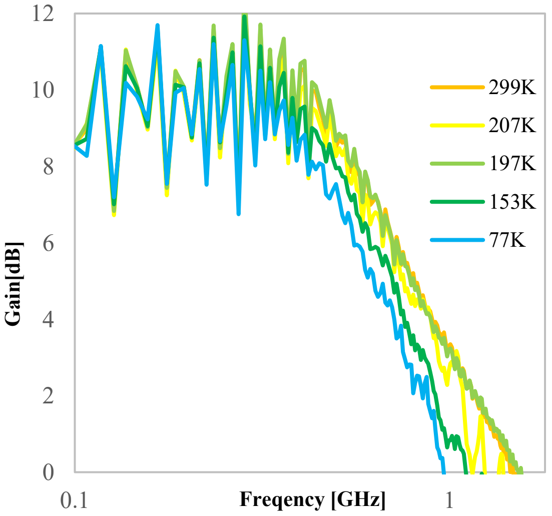

Fig. 5. The frequency dependence of the power gain obtained from the measured RF characteristics.

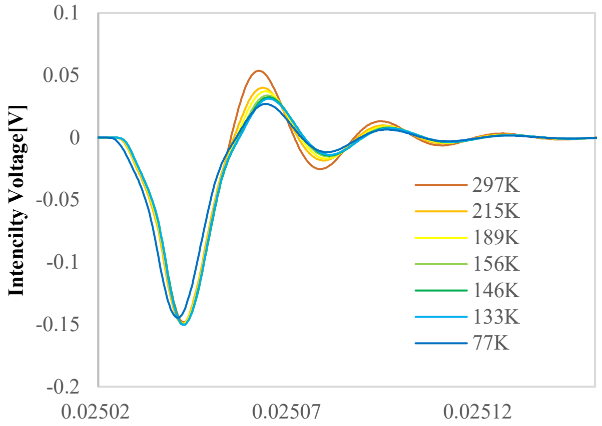

Fig. 6. The transient response waveform obtained from the sampling oscilloscope.

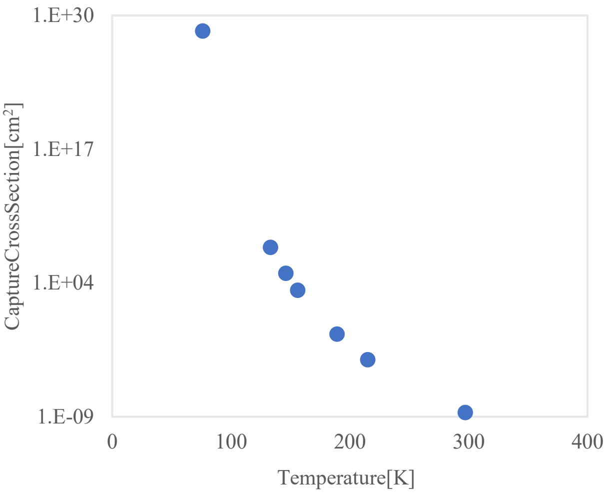

Fig. 8. The temperature dependence of the capture cross section obtained from the transient response waveform.

low-frequency band, the gain does not change with temperature, however, in the high-frequency band, the change in gain due to temperature can be confirmed. In particular, a remarkable change was confirmed from the point at which the gain started to decrease until the cutoff frequency was reached. This suggests a substantial structural change in the device at low temperatures. One of these factors is the temperature dependence of crystal defects at low temperatures. Thermal energy disappears from the crystal defects due to the lower temperature, and the energy required for activating the crystal defects becomes larger than that at room temperature. In addition, when crystal defects trap electrons, the energy required to emit electrons also increases. The change in activation energy usually varies only depending on the type and structure of crystal defects, but it is conceivable that temperature changes lead to similar phenomena.In other words, it can be inferred that the behavior of crystal defects in a low-temperature environment causes substantial structural changes.

### C. *Transient Response Waveform for Temperature Change*

Fig. 6 shows the transient response waveform obtained using a sampling oscilloscope. Fig. 7 shows an enlarged version of Peak2. Peak 1 of the waveforms was caused by the applied voltage; thus, Peak 2 was analyzed. When a pulse voltage is introduced to the AlGaN/GaN HEMT, a

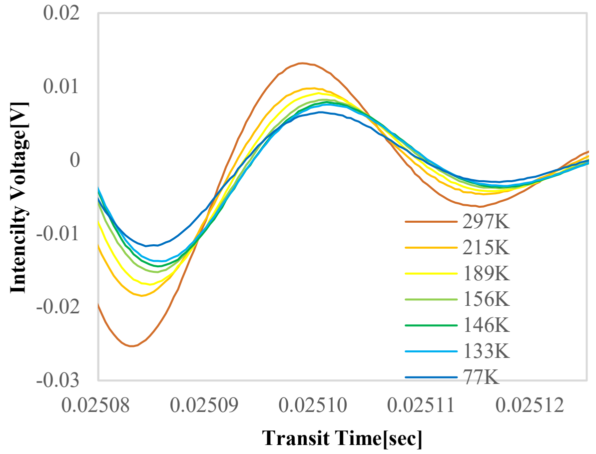

Fig. 7. An enlarged version of Peak2.

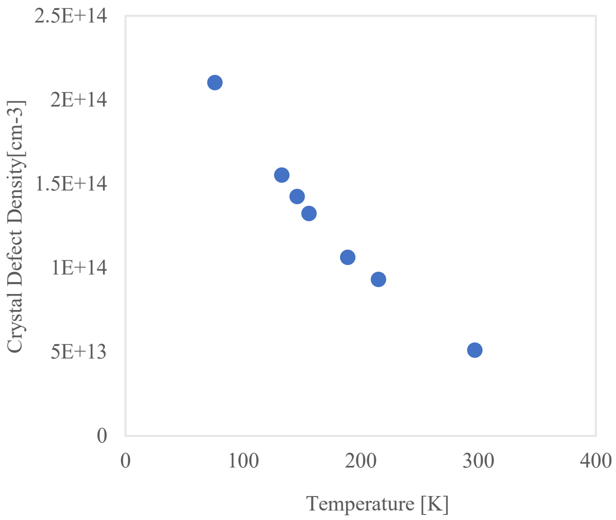

Fig. 9. The temperature dependence of crystal defect concentration.

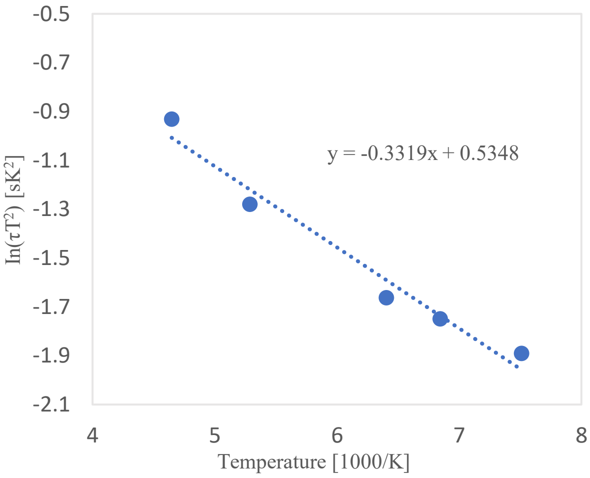

Fig. 10. The Arrhenius plot obtained from the analysis of the transient response waveform.

negative voltage is measured immediately after (-0.15V valley in figure 6).2DEG carriers are formed in the GaN layer by the pulse voltage ON. After that, when the pulse is turned off, the peak recovers positively, but some of the 2DEG carriers are trapped by crystal defects. A voltage difference is created by the trap, and it does not return to

0V. After a further period of time, electrons start to be emitted from crystal defects, electrons increase again in the GaN layer, and the voltage becomes negative. This is why peak 2 is generated. Therefore, by observing the temperature dependence of peak 2 as shown in figure 8, the temperature characteristics of crystal defects can be clarified.

### *D. Capture Cross-section and Crystal Defect Concentration*

Fig. 8 shows the temperature dependence of the capture cross-section obtained from the transient response waveform. Fig. 9 shows the temperature dependence of the crystal defect concentration. A simple ICTS method was used to measure the change in the capacitance component of the crystal defects [13]. The analytical results for the temperature dependence of the transient response suggest that the crystal defects increase with decreasing temperature. Lowering the temperature did not activate the existing crystal defects. The crystal defects that did not contribute to the current collapse phenomenon at approximately room temperature became apparent as the temperature decreased.

### *E. Evaluation of Activation Energy of Crystal Defects Using Arrhenius Plot*

Fig. 10 shows the Arrhenius plot obtained from the analysis of the transient response waveform. The slope of the nearly straight line obtained from this plot indicates the activation energy of the crystal defects used in the experiment [14]. The activation energy of the crystal defects obtained from the approximately straight line was 0.332 eV. This value is approximately equal to that reported in the literature [14].

## IV. CONCLUSIONS

In this study, the IV and RF characteristics were measured in a low-temperature environment, and the transient response waveform was analyzed using a simple ICTS method.

From the RF characteristics, it was confirmed that the gain varied with temperature in the high-frequency band. In addition, the results suggest that substantial structural changes occurred in the device in low-temperature environments. According to the measurement results of the IV characteristics, the current value decreased rapidly as the temperature decreased, and a linear region could not be confirmed. In addition, simple ICTS analysis confirmed that the capture cross section and crystal defect concentration increased with decreasing temperature. This result suggests that the thermal energy was imparted to the crystal layer. At room temperature, the thermal energy imparted to the crystal layer induces phonon scattering at the crystal lattice points, suggesting that electron trapping in the crystal defects is suppressed. The phonon scattering was suppressed as the temperature decreased. In the high-frequency region (fast time constant region), carriers trapped in the crystal defects are released, and the crystal defects become conspicuous. As a result, an increase in the capacitance component of the crystal defects was confirmed, and it is thought that both the capture cross-section and the crystal defect concentration increased compared to those at room temperature. This behavior of the crystal defects at low temperatures can be presumed to be the cause of the substantial structural changes in the device, as suggested by the RF characteristics. In addition, the activation energies obtained from the Arrhenius plots were in good agreement with the literature values, confirming the validity of the analysis in this experiment.

## ACKNOWLEDGMENT

The authors are grateful to the Chukyo University Research Found for financial assistance with this research.

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