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Methodology for evaluating 2DEG carrier behavior in high-frequency bands in AlGaN/GaN HEMTs

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Abstract— **In this study, we analyzed the measurement results of the frequency dependence of the current collapse in AlGaN/GaN high-electron-mobility transistors and confirmed the gate voltage dependence and temperature dependence in the high frequency region. An oscillation phenomenon was confirmed in the frequency dependence of the drain current. It was suggested that the oscillation phenomenon is caused by electrons moving back and forth between the crystal defect and the two-dimensional electron gas (2DEG) following the frequency. In the high-frequency region (0.8 GHz to 5 GHz), we calculated the inflection point from the oscillation waveform of the drain current, and succeeded in separating the response performance owing to crystal defects that enable high-frequency response. As a method for evaluating 2DEG carrier behavior in high-frequency bands, area value evaluation of areas with frequency dependence was investigated. The area value increases as the temperature rises (22°C to 80°C); however, it is confirmed that the area tends to decrease at higher temperatures (100°C or higher). The calculation result of the area value is linked with 2DEG behavior in GaN crystal.**

Keywords— AlGaN/GaN HEMTs, Frequency dependence, oscillation waveform, 2DEG carrier behavior

I. INTRODUCTION

Gallium nitride (GaN), a wide-gap semiconductor is a promising material for high-power electronic devices owing to its high dielectric breakdown and high thermal conductivity [1,2]. Although there are other materials with wide bandgaps, such as silicon carbide (SiC), GaN can obtain a high-electron-mobility transistor (HEMT) structure by stacking aluminum gallium nitride (AlGaN) and GaN heteroepitaxial structures [3,4]. GaN spontaneously polarizes along the c axis. A two-dimensional electron gas (2DEG) is formed at the interface between the AlGaN and GaN layers, which are HEMT structures, owing to the piezoelectric polarization effect associated with lattice strain [5,6]. The technology for fabricating electronic devices with HEMT structures already exist for other material systems, and GaN-based HEMTs are being utilized [7,8]. However, the lamination structure of the AlGaN and GaN layers has a problem in that crystal defects are generated on the AlGaN layer side owing to the difference in lattice constant. The crystal defects in the AlGaN layer are formed by inheriting the point defects and edge dislocation created during the formation of the GaN layer [9]. This crystal defect traps electrons in the 2DEG layer and causes current collapse, which significantly reduces the drain current [10]. Several device structures have been proposed to suppress current collapse, and certain results have been obtained [11,12]. However, although these materials achieve a reduction in the current collapse phenomenon, their reduction in crystal defects and characteristics has not been discussed. Therefore, this study investigates the characteristics of crystal defects in relation to the current collapse phenomenon in AlGaN/GaN HEMTs. The frequency dependence of the drain current was observed before and after the current collapse phenomenon, and the electron capture process by the crystal defects was analyzed. By observing the behavior of these crystal defects, we confirmed the gate voltage dependence and temperature dependence of the drain current in the high frequency region. From these results, the energy transition until the carriers in the 2DEG were captured by crystal defects was confirmed. Therefore, we propose the transition of the energy acquired by the carriers in the 2DEG owing to the application of high frequency in the AlGaN/GaN HEMT and its analysis method.

II. EXPERIMENTAL METHOD

In our previous work [13], we established a method for measuring the frequency dependence of the current collapse. In this study, we analyzed the measurement results of the frequency dependence of the current collapse in AlGaN/GaN HEMTs and confirmed the gate voltage dependence and temperature dependence in the high-frequency region.

A. I–V characteristics measurement

Figure 1 shows a measurement block diagram of the changes in drain current with respect to the drain voltage (I–V characteristics). A gate voltage of -2.4 V was applied, and a drain voltage of 0 V to 7.0 V was applied in 0.1 V steps. In addition, the I–V characteristics were measured with a high frequency (10 GHz) applied through a vector network analyzer.

B. Frequency dependence of drain current

The AlGaN/GaN HEMT, the subject of this experiment, has a field-plate structure in the gate electrode part. With this structure, current collapse is suppressed when a high

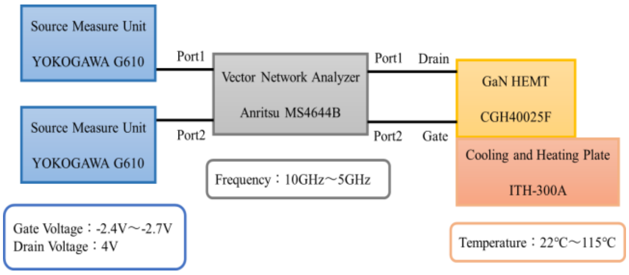

Fig. 1. Measurement block diagram of IV characteristics

frequency exceedining the time constant of crystal defects is applied to the gate electrode. [14] By measuring the drain current value when changing the frequency of the vector network analyzer, the waveform of the frequency dependence of the current collapse was obtained. Therefore, the frequency dependence of the current collapse can be obtained by sweeping from the low frequency at which the crystal defect can respond to the gate electrode to the high frequency at which the crystal defect cannot respond under the voltage condition that causes current collapse. The drain voltage was set to 4 V (current collapse area), and the drain current value was measured when the frequency was changed from 10 MHz to 5 GHz (every 2 MHz from 10 MHz to 1 GHz and every 20 MHz from 1 GHz to 5 GHz). At this time, the measurement was performed with the gate voltage condition from -2.4 V to -2.7 V (every 0.1 V). In addition, we measured the temperature under six conditions of 22°C, 40°C, 60°C, 80°C, 100°C, and 115°C for each gate voltage condition, and obtained 24 current collapse frequency-dependent waveforms.

III. Results And Discussions

A. Current-Voltage (I–V) characteristics

Figure 2 shows the measurement results of the I–V characteristics. The blue line is the measurement result when a DC gate voltage is applied, and the orange line is the I–V characteristics measured when 10 GHz is applied to the gate electrode. It was confirmed that the current collapse was suppressed when the I–V characteristics were measured at a frequency of 10 GHz applied to the device. The response time constant of the crystal defects that cause current to collapse is significantly smaller than 10 GHz. Therefore, electrons are not captured by crystal defects, and the current collapse is suppressed.

B. Frequency dependence of drain current

Figure 3 shows the measurement results of the frequency dependence of drain current. The result was a gate voltage of -2.4 V and a frequency sweep from 10 MHz to 5 GHz on the gate electrode. A frequency dependence is confirmed, in which the drain current value also increases while oscillating as the frequency increases. There were six series of environmental temperature changes from 22 °C to 115 °C. In the high-frequency region, the oscillation of the drain current value converged regardless of the environmental temperature change. In addition, it is confirmed that the drain current value decreases as the temperature increases in the high-frequency region. Temperature dependence was not confirmed in the low-frequency region. The oscillation phenomenon shown in Figure 3 is caused by electrons moving back and forth between the crystal defect and the 2DEG following the frequency. A decrease in the drain current indicates electron trapping to crystal defects, and an

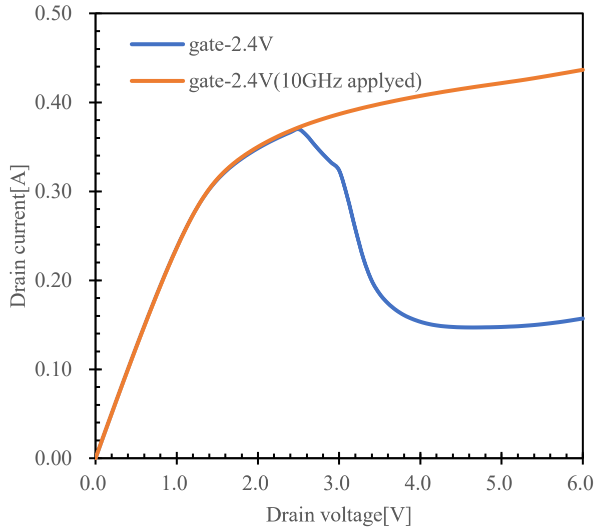

Fig.2. Measurement results of IV characteristics. The blue line: DC gate voltage
The orange line: 10 GHz applied

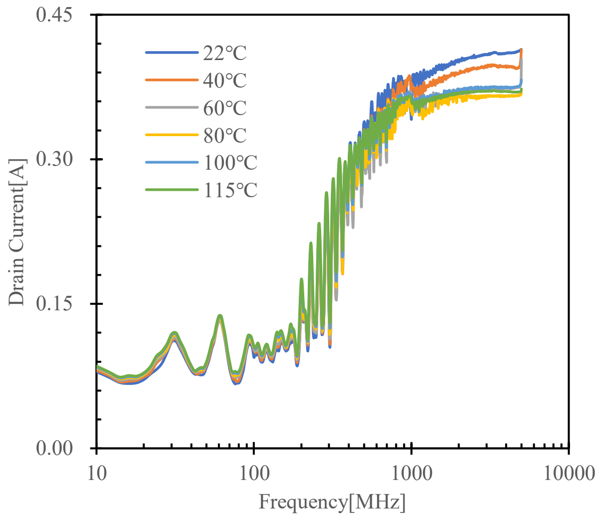

Fig. 3. Measurement results of the frequency dependence of the drain current.

increase in the drain current indicates electron release from crystal defects. As the frequency increases, the total number of electrons captured by crystal defects decreases, and the measured drain current increases.

In particular, in the high-frequency region exceeding 5 GHz, crystal defects cannot capture carriers, vibration almost disappears owing to frequency dependence, and current collapse is suppressed.

C. High-frequency responsive crystal defect

AlGaN/GaN HEMTs have been confirmed to have multiple crystal defects [14,15]. In the frequency dependence of Figure 3, multiple crystal defect responses are mixed in the low-frequency region. However, as the frequency increased, only the response of crystal defects with short time constants (which can handle high frequencies) was measured. Consequently, it is possible to separate only the response performance owing to crystal defects capable of high-frequency responses. The region was divided into two regions: 10 MHz to 1 GHz and 1 GHz to 5 GHz. Approximate straight lines were calculated for each region using the least-

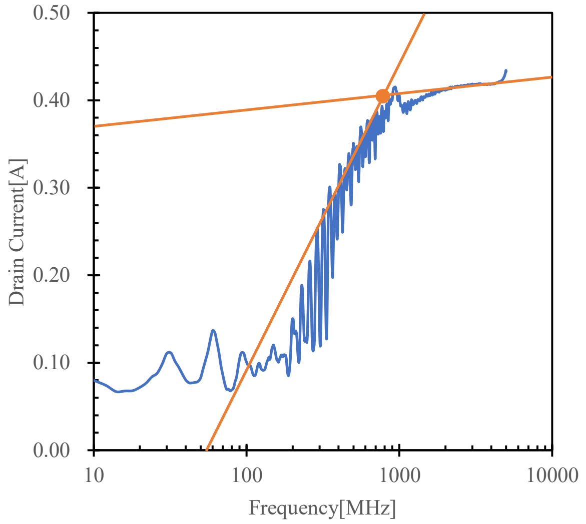

Fig. 4. Approximation lines and inflection points in the two regions at a gate voltage of -2.4Vat 22°C.

squares method in Python. The intersection point of the two straight lines was regarded as the inflection point of the response of multiple crystal defects, and the response of crystal defects capable of a high-frequency response. Figure 4 shows the approximation lines and inflection points in the two regions at a gate voltage of -2.4V and an environmental temperature of 22°C. The frequency dependence below the inflection point contains multiple crystal defect responses. Above the point of inflection, only the response of crystal defects that can handle high frequencies was considered. Figure 5 shows the temperature dependence of the inflection point positions (indicating the frequency). The gate voltage was changed from -2.4 V in -0.1 V steps. It can be confirmed that the value of the frequency at the inflection point tends to decrease with increasing temperature for each gate voltage.

Regarding the frequency response characteristics in the high-frequency region, the following can be considered. As the temperature increases, the phonon scattering at the crystal lattice points forming the AlGaN layer intensifies. The process of electron capture and release to crystal defects is inhibited owing to the enhanced electron thermal scattering factor. An increase in temperature leads to a decrease in the response time constant for crystal defects. Electron capture and release shift to the high-frequency side. Therefore, electron release from crystal defects is suppressed as the temperature rises in the high-frequency region. Consequently, the drain current is low in the high-frequency region. The vibrational phenomena that imply electron capture and release from the crystal defects shift to lower frequencies. Therefore, the inflection point of the frequency response characteristic also shifts to the low-frequency side.

D. High frequency response analysis

The frequency dependence of the drain current (Figure 3) indicates that the oscillation phenomenon of the drain current is a current oscillation that occurs when crystal defects capture and release electrons. Consider the 0.8 GHz to 5 GHz band as the high-frequency region, we focus on the vibration phenomenon in that range. This area is on the high-frequency side from the inflection point shown in Figure 4.

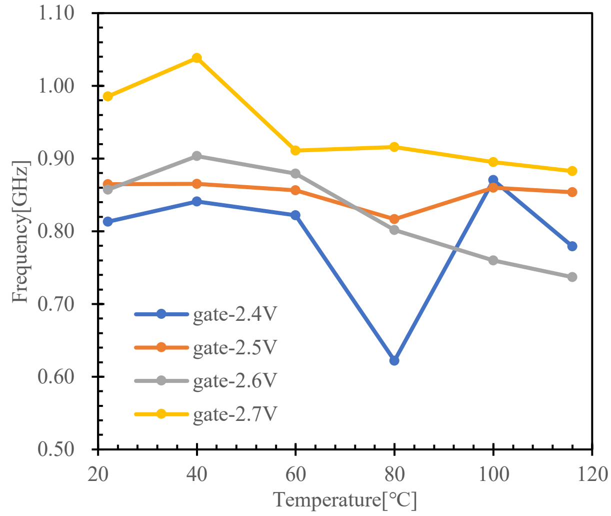

Fig. 5. Temperature dependence of the inflection point positions (Indicating of frequency).

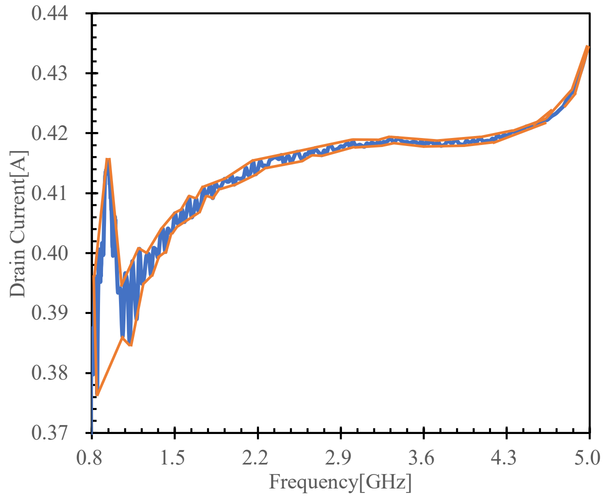

Fig. 6. Example of a plane constructed by connecting the upper and lower ends of vibration at the high frequency region.

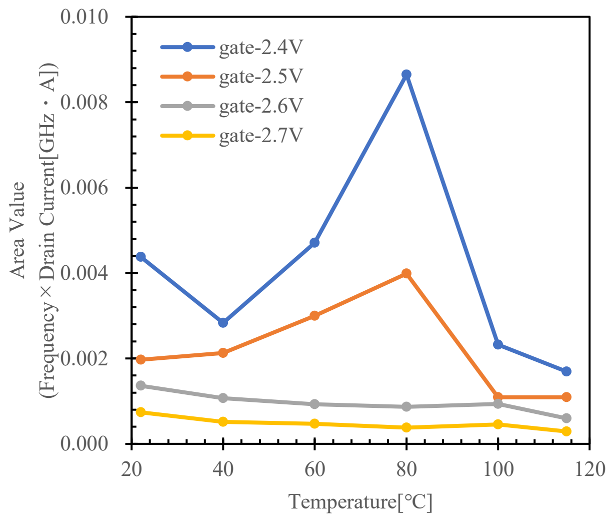

Fig. 7. Dependence of the area value on the gate voltage.

Figure 6 shows an example of a plane constructed by connecting the upper and lower ends of the vibration in the high-frequency region. The area of the region connected by the red line was calculated using Python. The area was calculated by the product of frequency and drain current value. Hereafter, this value defines as the area value. Figure 7 shows the dependence of the area on the gate voltage. It can be confirmed that the area tends to decrease as the gate voltage decreases. From the I–V characteristics, the number of carriers remaining in the 2DEG decreases as the gate voltage is lowered. It is believed that the area value decreased because the number of electrons moving between the crystal defects and 2DEG also decreased.

Figure 8 shows the temperature dependence of the area value. As a property of semiconductor materials, increasing the temperature inhibits the transport of carriers in the 2DEG owing to lattice scattering [16]. However, as the temperature increases, thermal carriers are added from the semiconductor crystal and the current value increases [17]. As shown in Figure 8, although the area value increases as the temperature increases (22°C to 80°C), it is confirmed that the area tends to decrease at higher temperatures (100°C or higher). The calculation result of the area value (Figures 7 and 8) is linked to the 2DEG behavior in the GaN crystal.

IV. Conclusions

In this study, we analyzed the measurement results of the frequency dependence of the current collapse in AlGaN/GaN HEMTs and confirmed the gate voltage dependence and temperature dependence in the high-frequency region. An oscillation phenomenon is observed in the frequency dependence of the drain current. It was suggested that the oscillation phenomenon is caused by electrons moving back and forth between the crystal defect, and the 2DEG following the frequency. In the high-frequency region (0.8 GHz to 5 GHz), we calculated the inflection point from the oscillation waveform of the drain current, and succeeded in separating the response performance owing to crystal defects that enable high-frequency response. As a method for evaluating 2DEG carrier behavior in high-frequency bands, the area value evaluation of areas with frequency dependence was investigated. As a property of semiconductor materials, increasing the temperature inhibits the transport of carriers in the 2DEG owing to lattice scattering. However, as the temperature increases, thermal carriers are added from the semiconductor crystal and the current value increases. The area value increases immediately as the temperature rises (22°C to 80°C), and it is confirmed that the area tends to decrease at higher temperatures (100°C or higher). The calculation result of the area value (Figures 7 and 8) is linked to the 2DEG behavior in the GaN crystal.

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References

[1] S. Warnock, A. Lemus, J. Joh, S. Krishnan, S. Pendharkar, and J. A. del Alamo, "Time-dependent dielectric breakdown in high-voltage GaN MIS-HEMTs: The role of temperature," IEEE Transactions on Electron Devices, vol. 64, no. 8, pp. 3132-3138, July 2017.

[2] Q. Zheng, C. Li, A. Rai, J. H. Leach, D. A. Broido, and D. G. Cahill, "Thermal conductivity of GaN, GaN 71, and SiC from 150 K to 850 K," Phys. Rev. Materials, vol. 3, pp. 014601, January 2019.

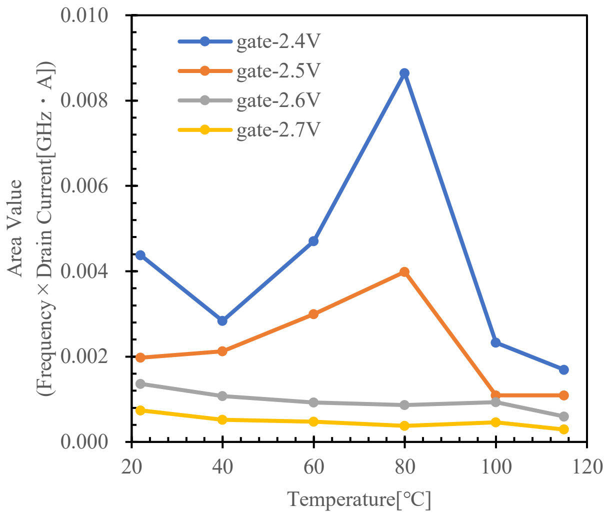

Fig. 8. Temperature dependence of the area value.

[3] T. Egawa, "Heteroepitaxial growth and power electronics using AlGaN/GaN HEMT on Si," 2012 International Electron Devices Meeting, San Francisco, CA, USA, pp. 27.1.1-27.1.4, March 2012.

[4] N.A. Torkhov, L.I. Babak, and A.A. Kokolov, "The influence of AlGaN/GaN heteroepitaxial structure fractal geometry on size effects in microwave characteristics of AlGaN/GaN HEMTs," Symmetry, vol. 11, no. 12, pp. 1495, December 2019.

[5] W. E. Muhea, F. M. Yigletu, R. Cabré-Rodon, and B. Iñiguez, "Analytical Model for Schottky Barrier Height and Threshold Voltage of AlGaN/GaN HEMTs With Piezoelectric Effect," in IEEE Transactions on Electron Devices, vol. 65, no. 3, pp. 901-907, March 2018.

[6] K. Osipov, I. Ostermay, M. Bodduluri, F. Brunner, G. Tränkle, and J. Würfl, "Local 2DEG Density Control in Heterostructures of Piezoelectric Materials and Its Application in GaN HEMT Fabrication Technology," in IEEE Transactions on Electron Devices, vol. 65, no. 8, pp. 3176-3184, August 2018.

[7] T.J. Flack, B.N. Pushpakaran, and S.B. Bayne, "GaN technology for power electronic applications: a review," J Electron Mater, vol. 45, pp. 2673-2682, March 2016.

[8] A. C. Liu, P. T. Tu, C. Langpoklakpam, Y. W. Huang, Y.T. Chang, A. J. Tzou, L. H. Hsu, C. H. Lin, H. C. Kuo, and E. Y. Chang, "The evolution of manufacturing technology for GaN electronic devices." Micromachines, Vol. 12, No. 7, pp. 737, June 2021.

[9] Y. Yao, Y. Ishikawa, Y. Sugawara. "Observation of Threading Dislocations in Ammonothermal Gallium Nitride Single Crystal Using Synchrotron X-ray Topography". J. Electron. Mater. Vol. 47, pp. 5007–5012, April 2018.

[10] S. Yang, C. Zhou, S. Han, J. Wei, K. Sheng, and K. J. Chen, "Impact of Substrate Bias Polarity on Buffer-Related Current Collapse in AlGaN/GaN-on-Si Power Devices," in IEEE Transactions on Electron Devices, vol. 64, no. 12, pp. 5048-5056, Dec. 2017.

[11] T. Zhang, Y. Lv, R. Li, Y. Zhang, Y. Zhang, X. Li, J. Zhang, and Y. Hao, "Current-Collapse Suppression of High-Performance Lateral AlGaN/GaN Schottky Barrier Diodes by a Thick GaN Cap Layer," in IEEE Electron Device Letters, vol. 42, no. 4, pp. 477-480, April 2021.

[12] R. Ye, X. Cai, C. Du, H. Liu, Y. Zhang, X. Duan, and J. Zhu, "An Overview on Analyses and Suppression Methods of Trapping Effects in AlGaN/GaN HEMTs," in IEEE Access, vol. 10, pp. 21759-21773, December 2021.

[13] H. Taguchi, K. Akahori, T. Shimazu, and H. Tanabe, "Analysis of Drain Current Transient Response of Gate Pulse Voltage in AlGaN / GaN High Electron Mobility Transistors," Advances in Science, Technology and Engineering Systems Journal, vol. 3, no. 5, pp.216-219, August 2018.

[14] T. J. Anderson, M. J. Tadjer, J. K. Hite, J. D. Greenlee, A. D. Koehler, K. D. Hobart, and F. J. Kub, "Effect of Reduced Extended Defect Density in MOCVD Grown AlGaN/GaN HEMTs on Native GaN Substrates," in IEEE Electron Device Letters, vol. 37, no. 1, pp. 28-30, Jan. 2016.

[15] J. Bergsten, M. Thorsell, D. Adolph, J. T. Chen, O. Kordina, E. Ö. Sveinbjörnsson, and N. Rorsman, "Electron Trapping in Extended Defects in Microwave AlGaN/GaN HEMTs With Carbon-Doped Buffers," in IEEE Transactions on Electron Devices, vol. 65, no. 6, pp. 2446-2453, June 2018.

[16] L. Mitterhuber, R. Hammer, T. Dengg, and J. Spitaler. Mitterhuber, "Thermal characterization and modelling of AlGaN-GaN multilayer structures for HEMT applications," Energies vol.13, no.9, pp.2363, May 2020.

[17] B. Chatterjee, C. Dundar, T. E. Beechem, E. Heller, D. Kendig, H. Kim, N. Donmezer, and S. Choi, “Nanoscale electro-thermal interactions in AlGaN/GaN high electron mobility transistors,” J Appl Phys, vol. 127, no. 4, pp. 044502, January 2020.