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DC AND RF CHARACTERISTICS FLUCTUATION OF INALAS/INGAAS HEMTS ACCORDING TO THE OPERATING TEMPERATURE VARIATION

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ABSTRACT: InAlAs/InGaAs high electron mobility transistors (HEMTs) are a type of field effect transistor that can achieve extremely high high-frequency gain owing to quantum effects operating in the channel layer. HEMTs are important components for devices that involve millimeter waves and high-speed optical transmission systems. However, InAlAs/InGaAs HEMTs have a frequency dispersion that depends on carrier recombination within the device. This is an InGaAs-specific phenomenon, which degrades the device's high-frequency gain performance. In this study, we investigated the direct current (DC) and radio frequency (RF) characteristics of InAlAs/InGaAs HEMTs by varying the operating temperature from liquid nitrogen temperature to 125 °C. The DC characteristics showed an increase of the device transconductance (*Gm*) at low temperature. Reducing the operating temperature from 125 °C to liquid nitrogen temperature increased G_m to 60 mS. High-frequency gain was also confirmed in the RF characteristics. The current gain cutoff frequency was 50.2 GHz at room temperature, and 66.8 GHz at liquid nitrogen temperature, representing an increase of 33.1%. Analyzing the high-frequency characteristics showed that the high-frequency gain increase at low temperature was related to the temperature dependence of the parasitic capacitance.

Keywords: HEMT, Current gain cutoff frequency, parasitic capacitance, Liquid nitrogen temperature

1. INTRODUCTION

Since their release, the communication speed of mobile communication devices has continued to increase. Nippon Telegraph and Telephone Company first realized the car phone for mobile communications in 1979. The maximum reception speed at this point was 0.3 kbps [1]. The advanced mobile phone system, later developed in North America, improved the maximum reception speed to 10 kbps. Mobile communications technology has continued to evolve, achieving even greater maximum reception speeds. In March 2016, a proposal for an LTE-Advanced Pro network was announced, representing a new general-purpose wireless technology that offers ultra-high-speed mobile communication of more than 10 Gbps. In only 37 years, the maximum reception speed has increased from kbps to Gbps [2]. However, further increases in communication speed are still in demand. For these purposes, it is necessary to understand the physical phenomena inside electronic devices used for high-speed communications.

We have been studying the physical properties of a phenomenon expressed in high electron mobility transistors (HEMTs) of the kind used in ultra-high-speed field effect transistors (FETs) [3-5]. Our previous research on inhibitors of carrier transport led us to propose fusing a high-speed device with a photo-responsive device [6].

However, the active layers of many semiconductor devices reach temperatures in excess of 100 °C when operating. This heat is generated when carriers pass through the active layer and collide with the crystal lattice. Lattice vibrations reduce the transport properties of carriers passing through the active layer. These thermal characteristics can be considered in terms of the electronic circuit performance, i.e., the temperature change can be considered from the response characteristics of the device. Previous studies have revealed changes in the performance of electronic devices at low temperature; however, there are no reported cases investigating the performance under cryogenic temperatures.

In this paper, we investigated how changing the device operating temperature affected the electronic properties of InAlAs/InGaAs HEMTs. The operating temperature was varied from liquid nitrogen temperature (−196 °C) to 125 °C. We confirmed changes in the radio frequency (RF) characteristics of the HEMTs operating over this temperature range. The direct current (DC) characteristics showed that the transconductance (*Gm*) increased with decreasing temperature. When the operating temperature was reduced from 125 °C to liquid nitrogen temperature, *Gm* almost doubled to 60 mS. The current gain cutoff frequency (*Ft*) was measured to be 50.2 GHz at room temperature; however, it increased to 66.8 GHz at liquid nitrogen temperature, indicating an improvement of 33.1%. By analyzing the high-frequency characteristics of the devices, we showed that the increase in the high-frequency gain at low temperatures was related to the temperature dependence of the parasitic capacitance.

2. EXPERIMENTAL METHOD

Target Device and Experimental Setup

A schematic of the HEMT device structure used for these experiments is shown in Fig. 1.1. The carrier supplying InAlAs layer was silicon δ-doped to provide a high transconductance and a high degree of threshold-voltage uniformity. The epitaxial layers used in the experiment were grown on an Fe-doped semi-insulating InP substrate using metal-organic chemical vapor deposition. These layers comprised of an undoped InAlAs layer, an undoped InGaAs channel layer, an Si δ-doped layer, and an undoped InAlAs insulator layer. Heavily doped n-InAlAs/InGaAs capping layers were grown to lower the source and drain contact resistances. The electrode metals for the gate, source, and drain were non-alloyed.

A semiconductor parameter analyzer was used to measure the DC characteristics and a network analyzer with a frequency range of 1–20 GHz was used to measure the S parameters (HP8510B). The temperature of the sample device was controlled between −40 and 125 °C using a device holder with a Peltier element (VICS ITH-700). The operating temperature of the sample devices was monitored using a thermocouple placed directly under the device. Sample devices were placed directly in a liquid nitrogen environment for experiments conducted at liquid nitrogen temperatures (−196 °C). The temperature of the sample device was confirmed to be −196 °C using the thermocouple, and the DC and RF characteristics were measured. All the measuring systems were performed within a microwave system.

3. EXPERIMENTAL RESULTS

Figure 2.1 shows typical drain current and voltage characteristics (I–V characteristics) of an HEMT at room temperature. The HEMT used in this experiment showed a high *Gm* of up to 30 mS at V_{gs} = −0.6–0 V and V_{ds} = 1.5 V. The temperature dependence of the *Gm* maxima are shown in Figure 2.2. Although the *Gm* values were low at high temperature, *Gm* gradually increased at lower temperatures. This phenomenon can be attributed to suppressed phonon scattering by the lattice vibrations of the crystal at lower temperatures.

The frequency dependence of the current gain is shown in Figure 2.3. Frequency measurements were performed in the range of 1–20 GHz. Representative examples of the frequency characteristics at 125 °C,

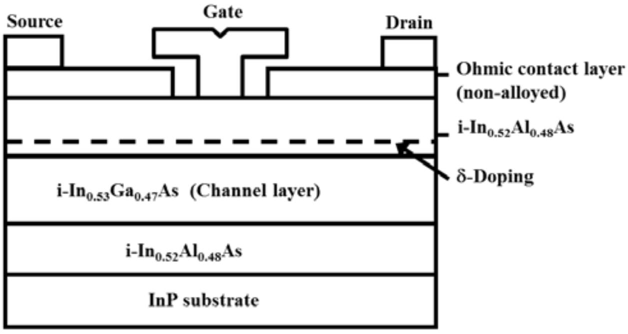

Figure 1.1 Schematic cross section of the HEMTs

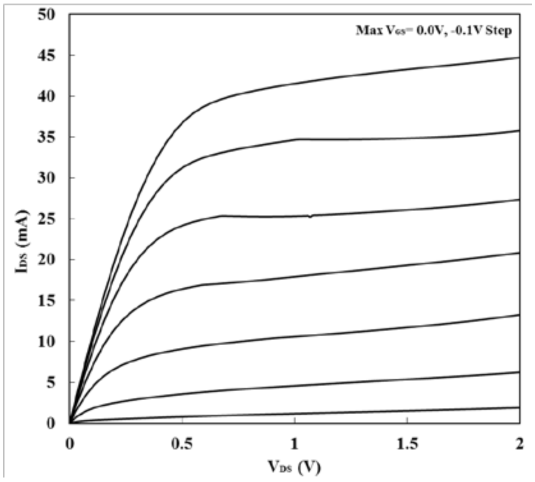

Figure 2.1 Typical drain current and voltage characteristics of HEMT.

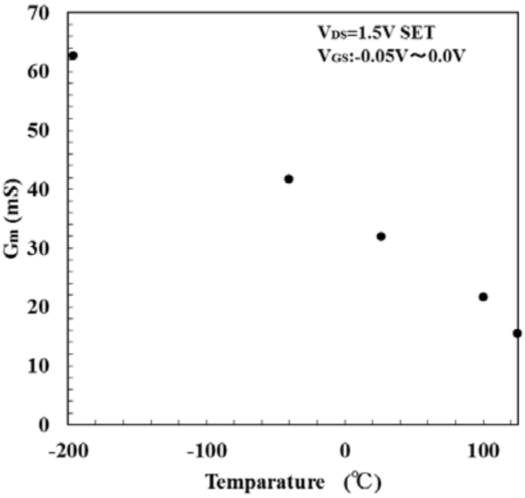

Figure 2.2 Temperature dependence of the transconductance (G_m) maximum values

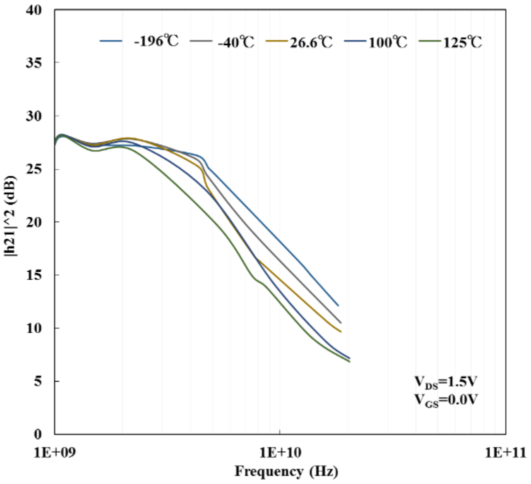

Figure 2.3 Frequency dependence of the current gain.

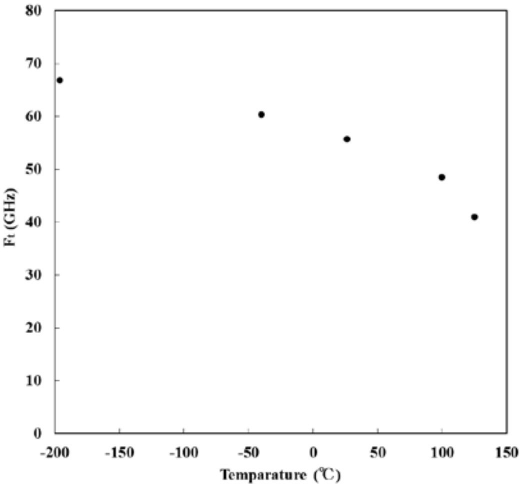

Figure 2.4 Temperature dependence of the current gain cutoff frequency f_t.gain cutoff frequency values

room temperature, −40 °C, and −196 ° C are shown in Fig. 2.3. Up to 10 GHz, the devices showed a stable gain of approximately 17 dBm at all temperatures; however, the gain dropped to −20 dB/decade above 10 GHz. Figure 2.4 shows the temperature dependence of the current gain cutoff frequency, f_t. At room temperature and −196 °C, the values of f_t were 50.2 and 66.8 GHz, respectively. This represents a 33.1% improvement in the cutoff frequency at low temperature.

4. DISCUSSION

As shown in Figures 2.2 and 2.4, the DC and RF characteristics improved at low temperature. In particular, the bandwidth increase contributed strongly to the high-frequency gain improvement. Considering that f_t is proportional to G_m in the theoretical formula for the current gain cutoff frequency [7], we may expect G_m to also increase at low temperature. This HEMT may be treated using the small-signal circuit model. Based on this model, G_m is strongly dependent on parasitic components [8]. High-frequency gain was calculated from the S parameter measured using the network analyzer. It is possible to convert S parameters to Y parameters, which allows calculation of the frequency response characteristics of the gate–source capacitance C_{gd} and gate–source capacitance C_{gs}. Figures 3.1 and 3.2 show the frequency response characteristics of C_{gs} and C_{gd}, respectively. The parasitic capacitance component showed large fluctuations with frequency for both C_{gs} and C_{gd}. This fluctuation may be attributed to small changes of the *S* parameters; however, here we consider only changes with temperature. At −196 °C, C_{gs} decreased considerably, and C_{gs} showed a slight reduction. However, C_{gd} was unchanged even at low temperature. Considering the factors that affect the parasitic capacitance of a FET, C_{gs} is most strongly affected by charging time and dominates the time constant of the carriers passing through the channel layer. However, C_{gd} represents the capacitance when carriers move rapidly through the gate, and does not strongly depend on temperature.

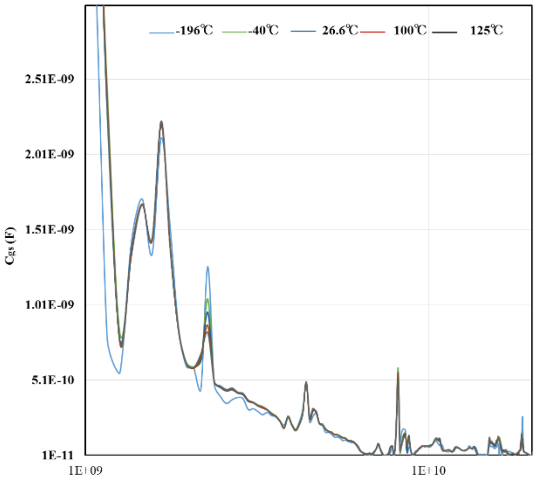

Figure 3.1 Frequency response characteristics of the gate–source capacitance C_{gs} values.

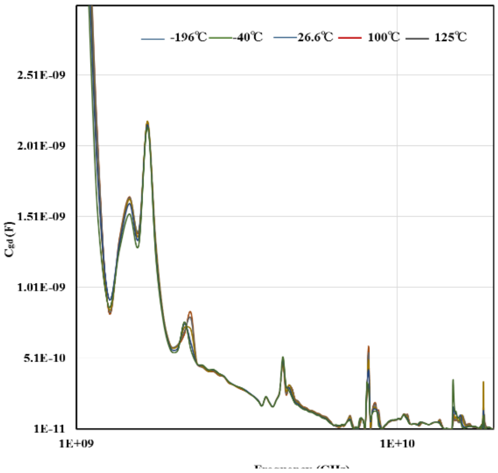

Figure 3.2 Frequency response characteristics of gate–drain capacitance C_{gd} values.

The temperature dependence of C_{gs} is caused by phonon energy reduction within the crystal layer itself. Thus, the improvement in high-frequency gain can be attributed to the shorter time constant.

5. CONCLUSION

We investigated the effects of operating temperature on the electronic properties of InAlAs/InGaAs HEMTs. The operating temperature was changed from liquid nitrogen temperature to 125 °C. We confirmed that the frequency characteristics of HEMTs varied with operating temperature. The DC characteristics showed an increase in *Gm* at low temperature. When the operating temperature was reduced from 125 °C to liquid nitrogen temperature, G_m increased to 60 mS. The values of F_t were 50.2 and 66.8 GHz at room and liquid nitrogen temperatures, respectively. This represents a 33.1% improvement at low temperature. Analyzing the high-frequency characteristics revealed that the cause of the high-frequency gain was related to the temperature dependence of the parasitic capacitance.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] A. Takahashi, et. J. Mag. Soc. Jpn., vol. 22, No. S2, 1998.

[2] Wang Hai, International Conference on Intelligence Science and Information Engineering (ISIE), pp.167-170, 2011.

[3] H.Taguchi, et.al., Physica status solidi (c) Vol. 5, No. 9, pp.2791-2796, 2008

[4] H.Taguchi, et.al., *Phisica stetus solidi (c)* Vol. 6, No. 6, PP.1386-1389, 2009.

[5] H.Taguchi, et.al. JAPANESE JOURNAL OF APPLIED PHYSICS, Vol. 49, No. 4, PP. 04DF03-07, 2010.

[6] H.Taguchi, et.al., Physica Status Solidi (c), Vol. 9, No. 2, pp.357-360, 2012.

[7] S. M. Sze,Smiconductor Device, John Welly & Sons, INC, 2nd Edition, pp-264

[8] H. Fukuda, et. Al., Solid State Electron, vol. 41, No. 10, pp-1599-1604, 199