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ИССЛЕДОВАНИЕ ТЕМПЕРАТУРНЫХ ХАРАКТЕРИСТИК УСТРОЙСТВ НА БАЗЕ GAN HEMT

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Анногтация. В настоящем документе рассматриваются переменные температурные характеристики устройств AlGaN/GaN HEMT. Дизайн конструкции устройства AlGaN/GaN HEMT и его основные характеристики при 300K были изучены с помощью программного обеспечения Silvaco simulator. В результате моделирования было установлено, что температура оказывает определенное влияние на передаточные характеристики, выходные характеристики и характеристики диапазонов энергопотребления, что влияет на рабочие характеристики устройства.

Ключевые слова: моделирование, материалы GaN, устройства GaN HEMT, температурные характеристики, Silvaco моделирование

STUDY ON TEMPERATURE CHARACTERISTICS OF GAN BASED HEMT DEVICES

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Abstract. In this paper, the variable temperature characteristics of AlGaN/GaN HEMT devices are discussed. The structure design of AlGaN/GaN HEMT device and its basic characteristics at 300K were studied by Silvaco simulation software. Through simulation, it is found that temperature has a certain influence on the transfer characteristics, output characteristics and energy band characteristics, which has an impact on the performance of the device.

Keywords: modeling, GaN materials, GaN HEMT devices, temperature characteristics, Silvaco simulation.

GaN is a new type of semiconductor material, which is at the forefront of global semiconductor research and is becoming a key material for microelectronics and opto-electronic devices. Compared with the first generation semiconductor materials (such as silicon), it has a larger band gap, higher mobility, better thermal stability, and can work at higher temperatures, and has obvious advantages in manufacturing high power density, high frequency, and high temperature devices. Compared with second-generation semiconductor materials, such as aluminum nitride, GaN has higher hardness and wider band gap, allowing higher power, frequency devices to be manufactured with higher efficiency and shorter wavelengths.

HEMT is the high electron mobility transistor, which has the advantages of high speed, high power and low noise, especially the electron mobility is very high, and can achieve high-speed and high-power amplification and switching operation. It is usually made of GaN or GaAs, high frequency characteristics and high temperature stability, widely used in communication, radar, satellite communication and other fields.

1.AlGaN/GaN HEMT device characteristics

1.1 Working principle of AlGaN/GaN HEMT device

AlGaN/GaN HEMTs work by controlling the gate voltage to adjust the width of the electron trap layer, thereby controlling the flow of current through it. This device has the advantages of high frequency, high power and high temperature, so it is widely used in the field of RF and power electronics.

Figure 1 shows the structure of the AlGaN/GaN HEMT device. The structure of AlGaN/GaN HEMT devices is usually composed of a substrate, GaN layer, AlGaN layer, and metal electrodes. The substrate is usually a silicon substrate or a sapphire substrate, which is used to provide mechanical support and thermal management of the device. GaN layers are typically GaN materials used to provide electron transport channels. The AlGaN layer is typically an AlGaN material used to form a gate structure that controls the concentration of electrons in the channel. Metal electrodes are used to provide electrode contact and current injection. A heterojunction is generated at the interface of AlGaN material and GaN material, and this heterojunction will form 2DEG, which is mainly near the GaN side.

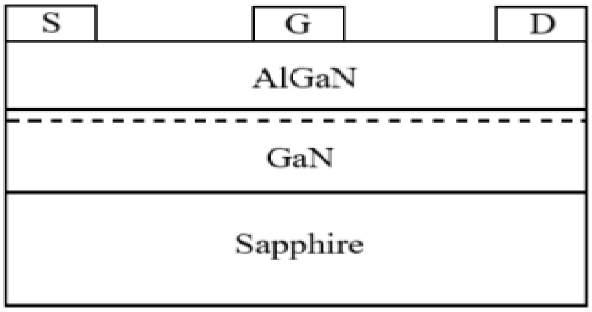

Figure 1- Structure diagram of AlGaN/GaN HEMT device

1.2 DC characteristics of AlGaN/GaN HEMT devices

The output characteristics, transfer characteristics and transconductance curve of the device in the DC characteristics:

(1) Saturated drain current

Saturated drain current refers to the drain current when the electrons in a two-dimensional electron gas reach saturation state at a given drain voltage. This parameter reflects the carrier concentration and electron mobility of two-dimensional electron gas. In general, the larger the saturated drain current, the higher the carrier concentration of the two-dimensional electron gas, the better the electron mobility.

(2) transconductance

The transconductance of a HEMT device is the gain between its output current and input voltage, usually expressed as the change in output current per unit voltage. The transconductance of HEMT devices is much larger than that of MOSFET devices, which is due to the high electron mobility, low carrier concentration, and large electric field strength of HEMT devices.

(3) Threshold voltage

The threshold voltage refers to the voltage required to form a conductive channel in an AlGaN/GaN HEMT device. Since the AlGaN layer in the AlGaN/GaN heterostructure can form an electron gas on the GaN surface, the threshold voltage is reduced. In general, AlGaN/GaN HEMT devices typically have lower threshold voltages than conventional GaN materials. In a transistor, the threshold voltage Vth refers to the situation where the reference value of the output signal begins to change when the voltage of the input disturbance signal reaches a certain level.

(4) Band gap width

The band gap width of a HEMT device refers to the band gap between the conduction band and the valence band of a HEMT device, also known as the band gap. Band gap width is an important parameter of HEMT devices, which determines the electrical performance and application range of the devices. Generally speaking, the larger the bandgap width, the better the electrical performance of the device, but the more difficult the preparation is.

2.Simulation of variable temperature characteristics of AlGaN/GaN HEMT devices

2.1 Device Structure

According to the basic structure knowledge of AlGaN/GaN HEMT device, the device structure is designed in the simulation software, and the specific structure is shown in Figure 2.

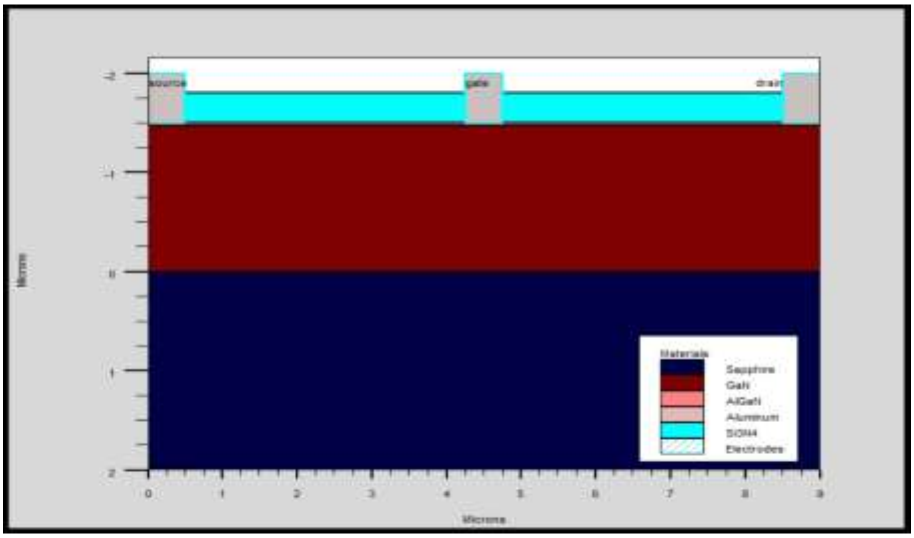

Figure 2 – Basic structure diagram of AlGaN/GaN HEMT device

2.2 Influence of temperature on transfer characteristics

The transfer characteristics of HEMT devices generally show an S-shaped curve, which includes three important parameters: threshold voltage, saturation current, and transfer conductance. The transfer characteristics are simulated and analyzed, and the results are optimized to improve the performance and stability of the device. Under the device structure in this paper, the simulation conditions are: V_d=1V, V_g=-8V~0V, V_{step}=0.1V. The simulation results are shown in Figure.3.

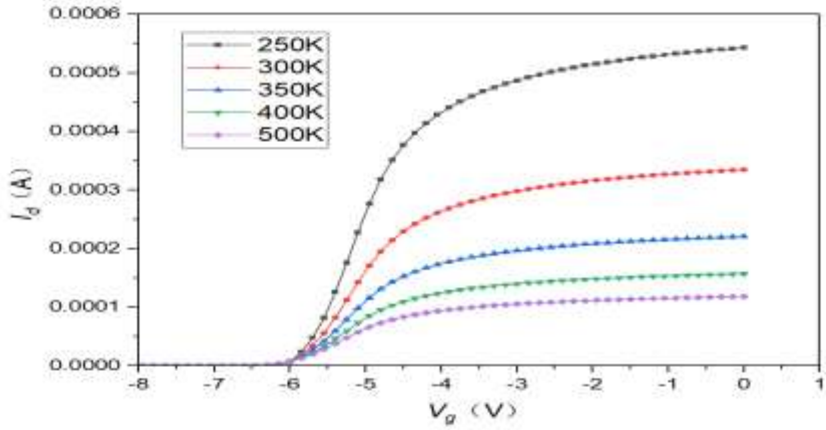

Figure 3 – Device transfer characteristics at different temperatures

Saturated drain current can reflect the carrier concentration and electron mobility of 2DEG. In general, the higher the carrier concentration of 2DEG, the better the electron mobility. It can be seen from the transfer characteristic curve that the saturated drain current Id decreases with the increase of temperature, and the saturated drain current of 250K is the largest, which proves that 2DEG at this temperature has the highest carrier concentration and better electron mobility, which also means that the performance of the device deteriorates with the increase of temperature. The slope of the curve is that the slope of the transconductance of 250K is the largest, and the transconductance value is also the largest. The transfer characteristic diagram can observe the threshold voltage of the device. As shown in Figure 3, it can be roughly seen that the threshold voltage V_{th} of the device is about -6V.

The simulation extracted the threshold voltages of 250K, 300K, 350K, 400K and 450K. Table 1 shows the threshold voltage data at different temperatures. Through Table 1, It can be seen that the threshold voltage increases with the increase of temperature.

Table 1 – Threshold voltages of devices at different temperatures

Temperature（K）	**Threshold voltages（V）**
250	-6.0
300	-5.96
350	-5.91
400	-5.82
450	-5.70

In additio, combined with Figure 3, we can further find that with the increase of temperature, the threshold voltage of the device increases, but the saturation drain current decreases. At 250K, the threshold voltage of the device is minimum, but the drain current is maximum. This indicates that the output performance of the device may be better at lower temperatures, but it also faces the risk of limiting the stability of the device. On the contrary, with the increase of temperature, the threshold voltage will increase, but the drain current will decrease, so that the thermal stability of the device will be enhanced. Therefore, when selecting the operating temperature of the device, it is necessary to consider the performance, stability and actual working conditions of the device.

2.3 Influence of temperature on output characteristics

The output characteristic is also an essential feature of simulation for AlGaN/GaN HEMT devices. This feature can help us to understand the variation of the output current and output voltage of the device with the grid voltage, so as to evaluate the performance of the device. Output power is the product of output current and output voltage, which is an important index to measure the performance of the device. Under the device structure simulated in this paper, the simulation conditions are: given V_g=-5V and V_g=-3.5V, V_d=0~12V, and V_{step} = 0.2V.

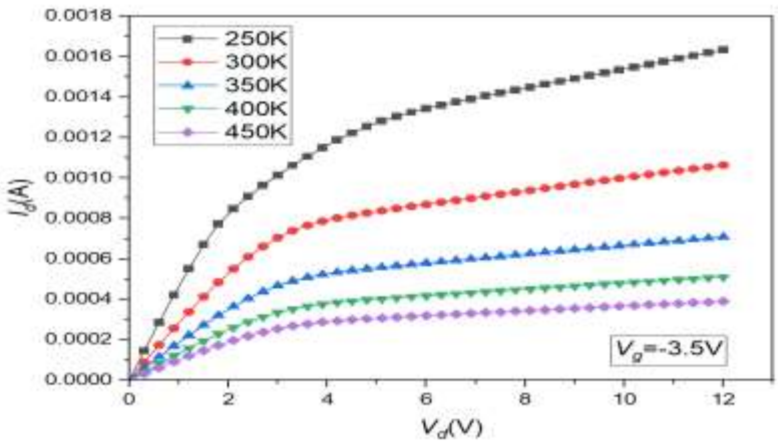

Figure 4 – Output characteristics of the device at V_g=-5V

A comparative analysis of Figure 4and Figure 5 shows that when V_g increases from -5V to -3.5V, the output current increases at the same temperature, indicating that with the increase of V_g, the output current increases, and the electron mobility in the device also increases, proving that the output characteristics are controlled by V_g. At the same temperature, with the increase of the grid voltage, the grid voltage reaching saturation current also increases. Under the same gate voltage, the high temperature device reaches the saturation output current with relatively low gate voltage. the series resistance between source and drain of devices with high temperature is larger, which will lead to the decrease of channel electric field strength and electron saturation rate, so higher drain voltage is needed to achieve electron saturation rate.

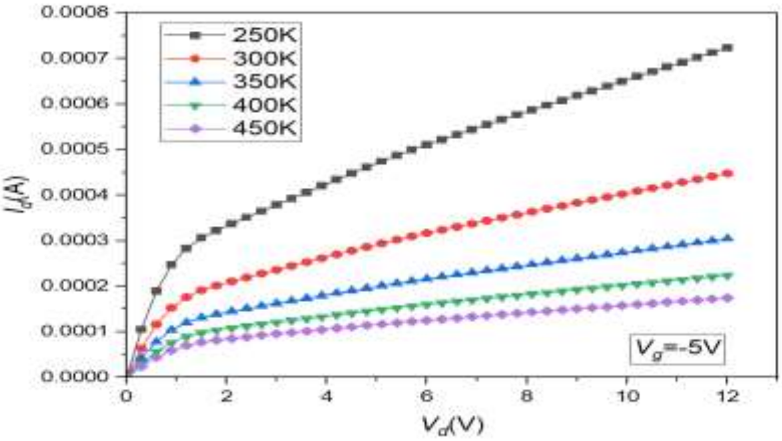

Figure 5 – Output characteristics of the device at V_g=-3.5V

2.4 Influence of temperature on energy band characteristics

In semiconductors, conduction band refers to the band with the highest electron energy, and valence band refers to the band with the lowest electron energy. The energy difference between them is called the band gap, and the size of the band gap determines the conductive property of the semiconductor.

This simulation extracts the conduction band peaks and valence band peaks of 250K, 300K, 350K, 400K and 450K, and lists all the values in Table 2.

Table 2 – Conduction band peak, valence band peak and Forbidden bandwidth of the device at different temperatures

Temperature (K)	**Conduction band peak (eV)**	**Valence band peak (eV)**	**Forbidden bandwidth (eV)**
250	8.97293	5.08580	3.88713
300	8.95137	5.08665	3.86482
350	8.92730	5.08746	3.83984
400	8.90098	5.08850	3.81248
450	8.87266	5.08968	3.78298

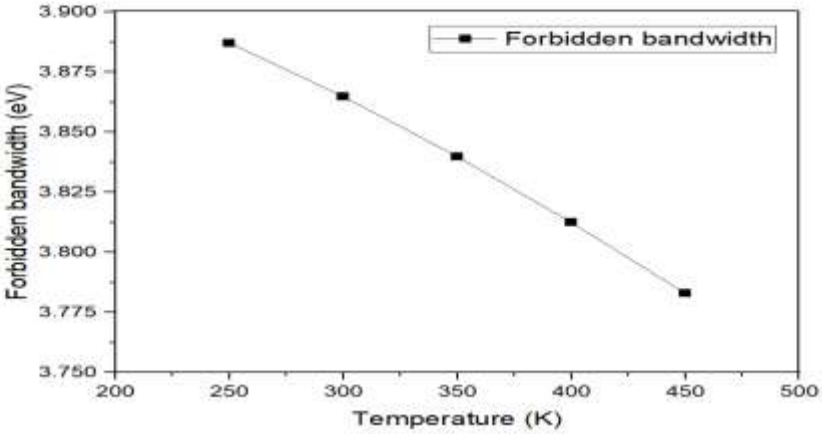

Figure 6 – Influence of temperature on forbidden bandwidth

It can be seen more intuitively from Figure 6 that the forbidden bandwidth decreases with the increase of temperature. In GaN, as the temperature increases, the thermal excitation of electrons and holes in the semiconductor material increases, leading to changes in the band structure. With the increase of temperature, the band gap of valence band and conduction band will shrink, which will lead to the increase of effective mass of electrons and holes, which is not conducive to the aggregation of 2DEG, and thus lead to the decrease of electron mobility. As a result, the performance of HEMT devices decreases with increasing temperature.

The above simulation results show that in terms of transfer characteristics, the carrier concentration decreases with the increase of temperature, which proves that the electron mobility of the device decreases with the increase of temperature. In terms of output performance, under a certain gate voltage, the output curve decreases with the increase of temperature, indicating that the electron mobility of the device decreases with the increase of temperature. From the point of view of the change of device energy band at different temperatures, the band gap will shrink with the increase of temperature, which will also lead to the reduction of electron mobility. These characteristics all reflect the increase of temperature and the decrease of electron mobility of the device.

4 Concluding Remarks

With the development of The Times, the development of GaN materials and GaN HEMT devices has attracted much attention from various countries. In this paper, only high temperature characteristics of GaN HEMT devices are studied, but simulation results show that GAN HEMT devices perform better at low temperatures, and their performance is improved by increasing electron mobility and carrier concentration. In areas such as aerospace and medical devices, where device performance is demanding, equipment is not only required to operate at high temperatures, but also to operate at extremely low temperatures. Therefore, the research on low temperature characteristics can be carried out based on this paper in the future to further understand the advantages of GaN HEMT devices and promote its application in more fields.

Список литературы

1. Компьютерное моделирование работоспособности финишных процедур и паразитных элементов в программно-аппаратном комплексе проектирования микросхем / А. С. Ягодкин, Н. Н. Литвинов, П. С. Иванин, А. С. Грошев // Моделирование систем и процессов. – 2024. – Т. 17, № 3. – С. 106-115. – DOI 10.12737/2219-0767-2024-104-113. – EDN NICLOY.

2. Хуке М.А., Элиза С.А., Рахман Т. и др. Зависящая от температуры аналитическая модель для характеристик тока-напряжения алгана/ганского силового хемта [J]. Твердотельная электроника, 2009, 53(3) : 341-348.

3. Яо З.В., Чжу Х., Ли И.Л. и др. Изучение характеристик ловушек под обратным пьезоэлектрическим действием в устройствах AlGaN/GaN HEMT при комнатной температуре и низкой температуре [J]. Наука и техника, 2023, 38(5) : 35520-35528.

References

1.Computer modeling of efficiency of finishing procedures and parasite elements in the software and hardware complex of designing chips / A. S. Yagodkin, N. N. Litvinov, P. S. Ivanin, A. S. Groshev // Modeling of systems and processes. – 2024. – Т. 17, № 3. – С. 106-115. – DOI 10.12737/2219-0767-2024-104-113. – EDN NICLOY.

2.Huque M.A., Eliza S.A., Rahman T. et al. Temperature dependent analytical model for current–voltage characteristics of AlGaN/GaN power HEMT[J]. Solid-State Electronics, 2009, 53(3) : 341-348.

3.Yao Z.W., Zhu H., Li Y.L. et al. Investigation of trap characteristics under the inverse piezoelectric effect in AlGaN/GaN HEMT devices at room temperature and low temperature[J]. Semiconductor Science and Technology, 2023, 38(5) : 35520-35528.