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High performance 1 mm AlGa_N/Ga_N HEMT based on SiC substrate

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Abstract This is our first report on the high performance 1 mm AlGa_N/Ga_N high electron mobility transistor (HEMT) which was developed using home-made AlGa_N/Ga_N epitaxy structures based on SiC substrate. Metal-organic chemical vapor deposition (MOCVD) was used to generate the epitaxy layers. Corresponding experiments show that the device has a gate length of 0.8 μm exhibiting drain current density of 1.16 A/mm, transconductance of 241 ms/mm, a gate-drain breakdown voltage larger than 80 V, maximum current gain frequency of 20 GHz and maximum power gain frequency of 28 GHz. In addition, the power gain under the continuous wave condition is 14.2 dB with a power density of 4.1 W/mm, while under the pulsed wave condition, power gain reaches 14.4 dB with power density at 5.2 W/mm. Furthermore, the two-port network impedance characteristics display great potential in microwave application.

Keywords AlGa_N/Ga_N, high electron mobility transistor (HEMT), microwave power, power gain

1 Introduction

The AlGa_N/Ga_N compound semiconductor material system has received much attention for its large band gap (Ga_N 3.4 eV, Al_N 6.2 eV), high breakdown electric strength ($1\text{--}3 \times 10^{10}$ V/cm), high electron saturated drift velocity (2.2×10^{10} cm/s) and good thermal stability.

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Apart from that, AlGa_N/Ga_N heterojunction has large conduction band discontinuity and strong effect of spontaneous and piezoelectric polarization, which result in a high concentration of 2-dimensional electron gas (2DEG) near the interface. Consequently, with the excellent epitaxy material and improved process techniques, Ga_N-based devices can demonstrate power density 5–10 times larger than that of GaAs-based devices. The AlGa_N/Ga_N high electron mobility transistor (HEMT) displays large potentials in the field of high frequency, high temperature and large power [1,2]. Until now, it is being reported that 36 mm Ga_N-based HEMT achieves 368 W output power at the frequency of 2.4 GHz [3], and the power density reaches 4.13 W/mm at the frequency of 35 GHz [4]. However, at present, most of the reports concerning AlGa_N/Ga_N HEMT in China are based on sapphire substrate [5,6], which, due to its disadvantage of bad thermal conduction, limits the extent to which the power density of the device can be improved.

This article reports on the developed large periphery AlGa_N/Ga_N HEMT based on SiC substrate with the gate length of 0.8 μm and total gate width of 1 mm. It exhibits a transconductance of 241 ms/mm, power density of 4.1 W/mm (for continuous wave) and 5.2 W/mm (for pulsed wave) at the frequency of 5.4 GHz.

2 Experiments

The undoped AlGa_N/Ga_N HEMT epitaxy material developed by the Ga_N research group at the Institute of Semiconductors of the Chinese Academy of Sciences was generated through metal-organic chemical vapor deposition (MOCVD) on semi-insulate 6H-SiC substrate. As depicted in Fig. 1, the layer structure contains 20 nm Al_N nucleation layer, 3 μm Ga_N buffer layer, 100 nm high mobility Ga_N layer and 20 nm undoped AlGa_N barrier layer with Al content of 20%. Hall measurement indicates that the 2DEG concentration and mobility are $1.0 \times 10^{13}/\text{cm}^2$ and 1900 cm²/Vs respectively.

AlGaIn 20% UID 20 nm
GaN high mobility 100 nm
GaN UID 3 μm
AlN UID 20 nm
SI 6H-SiC

Fig. 1 Layer structure of the AlGaIn/GaN HEMT

The device isolation was realized by implanted He ions with high energy. The ohm-contact metals are Ti/Al/Ti/Au layers and they demonstrate good surface morphology with specific ohm-contact resistance of $10^{-6} \Omega \cdot \text{cm}^2$ level after having been annealed in the 750°C N_2 atmosphere for 50 s. The source-drain distance is $4 \mu\text{m}$. The gate metals are Pt/Ti/Au with gate length and width of $0.8 \mu\text{m}$ and 1mm respectively. The electroplating method was used to thicken the metal of the whole device to $2.5 \mu\text{m}$, which reduces the parasitic gate-source capacitance and realizes the connection of the source electrodes. The device was passivated to alleviate the current collapse effect by the Si_3N_4 . The shape of the structure is shown in Fig. 2. In addition, the metal was also deposited on the back side of the substrate to improve thermal conduction by the electroplating method. Au bonding was also used to pack the device into the shell for power measurement.

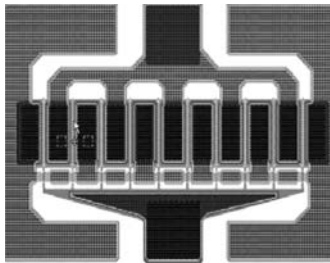


Fig. 2 AlGaIn/GaN HEMT with gate length of $0.8 \mu\text{m}$ and total gate width of 1mm

3 Results and discussion

The DC characteristics were measured with the HP4155 semiconductor parameter analyzer instrument and the results are shown in Figs. 3 and 4. The conditions of the I - V characteristic measurement were $-5 \text{ V} < V_{\text{gs}} < +1 \text{ V}$ and $0 \text{ V} < V_{\text{ds}} < 10 \text{ V}$, where V_{gs} is the gate voltage and V_{ds} is the source-drain voltage. As can be seen in Fig. 3, the maximum saturated current of the device is 1.16 A (the corresponding current density is 1.16 A/mm) and the cut-off voltage is -5 V .

Moreover, it can be seen that the drain current of the SiC-based GaN HEMT device does not reduce as the

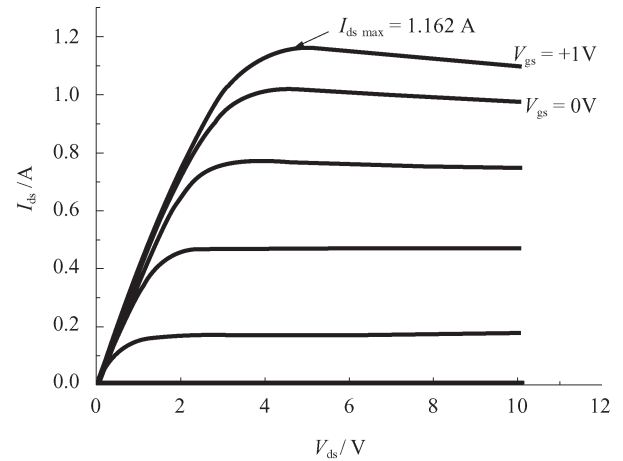


Fig. 3 I - V characteristics of the AlGaIn/GaN HEMT

high source-drain voltage increases, which is clear in the sapphire-based devices. This is due to the fact that the SiC substrate exhibits better thermal conduction performance than the sapphire substrate under high power condition, which leads to small thermal resistance and improved overall performance of the device.

The transconductance of the device is shown in Fig. 4. The source-drain voltage is 7 V and the gate voltage changes from -5 V to 2 V . As seen in Fig. 4, the passivated device exhibits a maximum transconductance (g_m) of 241 mS/mm at the gate voltage of -2 V .

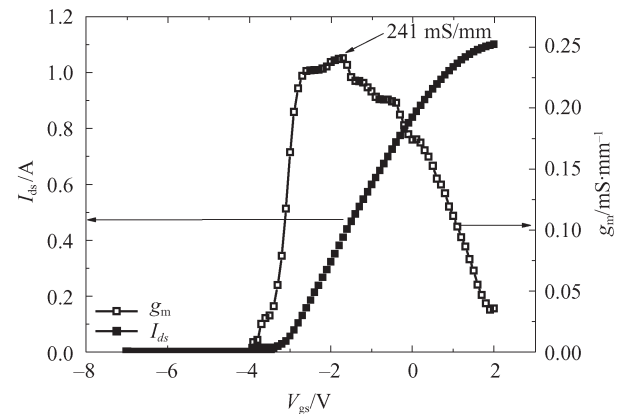


Fig. 4 Transfer and transconductance of the AlGaIn/GaN HEMT

The high frequency characteristic of the device was measured by the HP 8510C network analyzer with Agilent IC-CAP system. The source-drain voltage is 20 V and the gate voltage is -3 V . The forward current gain (H_{21}) and maximum available gain (MAG) are shown in Fig. 5. As can be seen from it, the maximum current gain cut-off frequency, f_T , is 20 GHz and the maximum power gain cut-off frequency, f_{max} , is 28 GHz . After excluding the parasitic effects of the electrode, the corresponding results are $f_T = 23 \text{ GHz}$ and

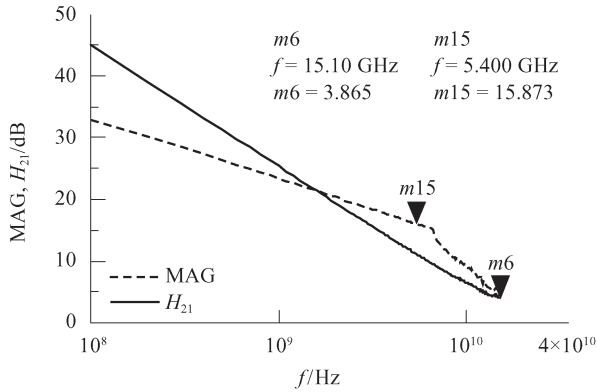


Fig. 5 Forward current gain (H_{21}) and maximum available gain (MAG) characteristics of the AlGaIn/GaN HEMT

$f_{\max} = 30$ GHz, which demonstrate the good frequency characteristics of the AlGaIn/GaN HEMT device with a total gate width of 1 mm. This is the first China-based report on the frequency characteristics of the 1 mm AlGaIn/GaN HEMT device based on SiC substrate.

The loadpull power measurement system was used to evaluate the microwave large signal characteristic of the packaged 1 mm SiC AlGaIn/GaN HEMT device with the results shown in Fig. 6. Under the 5.4 GHz continuous wave condition, when the bias point is $V_{gs} = -3.5$ V, $V_{ds} = 30$ V, the 1 mm AlGaIn/GaN HEMT device exhibits a maximum output power of 36.17 dBm, power density of 4.1 W/mm and power gain of 14.2 dB. The corresponding results are 37.2 dBm, 5.2 W/mm and 14.4 dB while under the pulsed condition with signal duty cycle of 10%. This is the highest output power and power gain of a home-made AlGaIn/GaN HEMT device ever reported in China. It can be seen that both the power gain and output power of the device have been improved for the reduced thermal resistance under the pulsed signal condition.

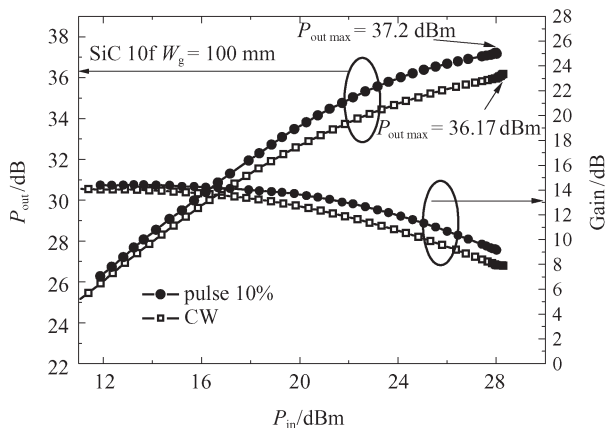


Fig. 6 Power characteristics of the 1 mm AlGaIn/GaN HEMT

Through analyzing the two port S-parameters, it can be observed that both the real and imaginary part of the 1 mm GaN HEMT device are large (nearly 50Ω). Consequently, the AlGaIn/GaN HEMT has a lower impedance transfer ratio (Z_1/Z_S) which makes it easier to design the matching network and realize large band amplification.

4 Conclusions

This is the first AlGaIn/GaN power HEMT device developed on the home-made AlGaIn/GaN epitaxy material structure based on SiC substrate. The gate length and width are 0.8 μm and 1 mm respectively. The device demonstrates a maximum transconductance of 241 mS/mm, current gain cut-off frequency of 15 GHz and power gain cut-off frequency of 28 GHz. Two port network S-parameters display its large output impedance, which makes it easier to design the matching network. Under the continuous wave condition, the output power density and power gain are 4.1 W/mm and 14.2 dB respectively. The results reach 5.2 W/mm and 14.4 dB while under the pulsed wave condition. These record levels of output power and power gain of the AlGaIn/GaN HEMT device can be achieved by combining the home-made AlGaIn/GaN epitaxy and device processing technologies. But further efforts are needed to improve the performance of the device.

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