On the n^+-GaAs/p^+-InGaP/n^--GaAs High-Barrier Camel-Like Gate Transistor for High-Breakdown, Low-Leakage and High-Temperature Operations

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Abstract

A new field-effect transistor using an n^+-GaAs/p^+-InGaP/n-GaAs high-barrier camel-like gate and GaAs/InGaAs heterostructure-channel has been fabricated successfully and demonstrated. Experimentally, an ultra high gate-drain breakdown voltage of 52 V and a high drain-source operation voltage over 20 V with low leakage currents are obtained for a $1 \times 100\ \mu m^2$ device. Furthermore, the studied device also shows high breakdown behaviors at high temperature environment and good microwave characteristics. Therefore, based on these good characteristics, the studied device is suitable for high-breakdown, low-leakage and high-temperature applications.

1. Introduction

Over the past years, due to the large need of high-power devices, many researchers have paid their attention to high breakdown voltage GaAs-based FETs [1], [2]. For conventional metal-semiconductor field-effect transistors (MESFETs) and high electron mobility transistors (HEMTs), the breakdown voltages can be enhanced by reducing the doping density in the channel and carrier supply layer, respectively. However, these reduce the current drivability and hence decrease the output power. Therefore, several structures have been reported to improve breakdown voltage without decreasing current drivability such as the metal-insulator-semiconductor FETs (MISFETs) with low temperature grown (LTG) technology [3], metal-junction FETs (MJFETs) [4], junction-modulated HEMTs (JHEMTs) [5], and camel-gate FETs (CAMFETs) [6]. Among these structures, the CAMFETs, as compared with MESFET and HEMT, have several advantages [6] including the (1) elimination of difficulty in making the high-quality metal-semiconductor contact, (2) relative ease of adjusting the barrier height, and (3) improvement of the reliability in adverse environments. However, as the negative gate bias is increased, the barrier height of the camel diode is reduced and the breakdown voltage is limited. Hence, for further improvement of the device performances, a new heterostructure high-barrier camel-like gate FET is demonstrated in this work. The studied device has an n^+-GaAs/p^+-InGaP/n-GaAs high-barrier camel-like gate structure, a GaAs/InGaAs heterostructure channel, and an inverted delta-doped carrier supply sheet. The p^+-InGaP layer is used to provide the high potential barrier and the n-GaAs layer is employed to further enhance the barrier height. Thus the carrier confinement could be substantially improved. Carriers are designed to transfer from the delta-doped sheet toward the GaAs/InGaAs channel regime and finally are confined in the InGaAs layer. Good carrier confinement is obtained in the studied device. Therefore, low leakage current, high breakdown voltage, and linear transconductance can be expected in this studied device.

On the other hand, high-temperature electronic devices are required for aircraft, automotive, space, and other applications under harshly thermal environments [7], [8]. Many devices such as MESFET and HEMT with high-temperature operation capability have been studied and reported [7], [8]. However, the studies of high-temperature characteristics of high-barrier camel-like gate FETs are rarely found. In this work, the temperature performances of the studied high-barrier camel-like gate FET are investigated from 300 to 480 K. It is known that, from experimental results, this device also exhibits good performances even operated at high temperature environments.

2. Experiments

The studied device was grown on a (100) oriented semi-insulating (S-I) GaAs substrate by a metalorganic chemical vapor deposition (MOCVD) system. The epitaxial structure consisted of a $1\ \mu m$ thick undoped GaAs buffer, a delta-doped sheet $\delta(n^+)=4 \times 10^{12}$ cm^{-2}, a 50 Å thick undoped GaAs, a 100 Å thick undoped $In_{0.15}Ga_{0.85}As$, a 2000 Å thick GaAs ($n=1 \times 10^{17}$ cm^{-3}), a 100 Å thick $In_{0.49}Ga_{0.51}P$ ($p^+=8 \times 10^{18}$ cm^{-3}), and a 200 Å thick GaAs ($n^+=6 \times 10^{18}$ cm^{-3}) layers. After epitaxial growth, wet chemical etching, conventional vacuum evaporation, and liff-off techniques were used to fabricate the mesa type devices. The drain-source contacts were formed on n-GaAs sub-channel layer by alloying evaporated AuGe/Ni metals at 400 ℃ for 30s. Then the mesa etching process was used to etch the wafer into substrate to isolate the devices. Finally, the high-barrier-gate was achieved by evaporating Au metals on n^+-GaAs layer surface. The drain-source and gate electrodes are ohmic contacts. The used gate dimension is 1×100 μm^2. The experimental current-voltage (I-V) characteristics were measured by an HP4156A semiconductor parameter analyzer.

3. Results and Discussion

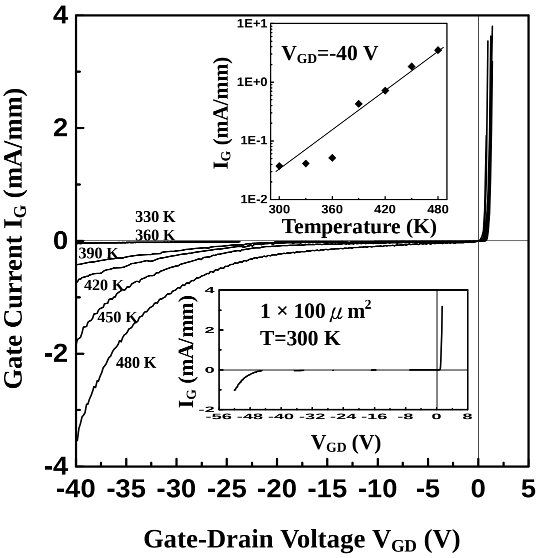

Figure 1. The gate-drain I-V characteristics at various temperatures. The upper inset shows the gate leakage current $|I_G|$ at V_{GD}=40 V at different temperature. The lower inset shows the extended I-V characteristics at 300 K.

The gate-drain I-V characteristics of the studied device at different temperatures are shown in Fig. 1. The gate-drain breakdown voltage BV_{GD}, defined at I_{GD}=1 mA/mm, as shown in the lower inset of Fig. 1, is as high as 52 V at room temperature. This value is significantly higher than those of LTG MISFET (42 V) [3], MJFET (20 V) [4], JHEMT (31 V) [5], and n^+-GaAs/p^+-GaAs CAMFET (21 V) [6] with the same or larger gate length. Thus, the camel-like heterostructure gate FET is one of the prominent candidates to achieve the high breakdown behaviors. The upper inset in Fig. 1 shows the gate leakage current $|I_G|$ versus different temperatures. The gate leakage currents, measured at V_{GD}=40 V, are 37, 41, 51, 430, 720 μA/mm, 1.85, and 3.5 mA/mm at the temperature of 300, 330, 360, 390, 420, 450, and 480 K, respectively. The gate leakage current is increased with increasing the temperature. This is primarily caused by the tunneling mechanism with thermionic emission and partly due to the reduced barrier height when the temperature is increased [9]. In the studied device, the high-barrier n^+-GaAs/p^+-InGaP/n-GaAs camel-like diode is used to prevent carriers tunneling to gate electrode. In addition, the GaAs/InGaAs heterostructure channel provides good carrier confinement. Even at high temperature, the device also reveals the relatively low leakage behaviors. On the other hand, the turn-on voltages (V_{on}) are 1.2, 1.13, 1.05, 0.98, 0.87, 0.8, and 0.7 V at the temperature of 300, 330, 360,390, 420, 450, and 480 K, respectively. Indeed, the heterostructure camel-like gate structure still has high V_{on} at high-temperature regime. The small gate leakage current and higher turn-on voltage at high-temperature regime indicate that a large current level can be “stored” in the channel [10]. Therefore, the high-power handling capability can be achieved even in high-temperature environments.

Figure 2 shows the common-source I-V characteristics of the studied device measured at various temperatures. All I-V curves show good pinch-off and saturation characteristics. The measured threshold voltages (V_{th}) are -1.9, -1.92, -1.94, -1.95, -1.99, -2.09, and -2.25 V at T=300, 330, 360, 390, 420, 450, and 480 K, respectively. The relatively temperature-insensitive performances of V_{th} especially at T≦420 K are observed. The maximum drain-source operational voltage ($V_{DS,max}$) is over 20 V and no significant gate leakage current is found at V_{GS}=+1 V. It is believed that, due to the high turn-on voltage, the gate leakage current is reduced in the gate forward-biased region. Therefore, the output current density and output power handling capability can be enhanced.

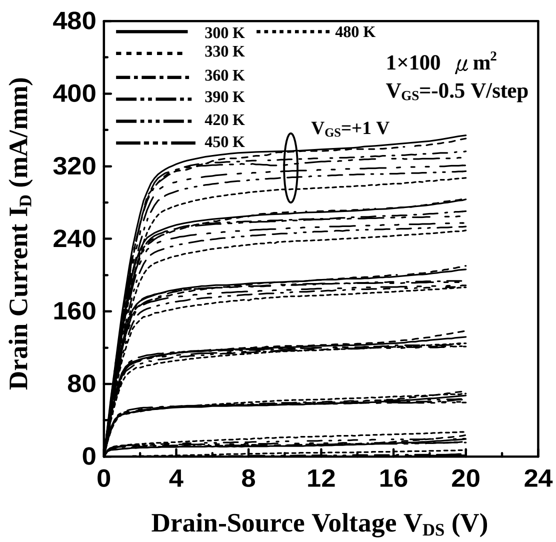

Figure 2. The measured common-source I-V characteristics of the studied device at various temperatures.

Figure 3 illustrates the drain saturation current (I_{DS}) and transconductance (g_m) versus gate-source voltage (V_{GS}) at different temperatures. The maximum transconductance $g_{m,max}$ are 147.4, 147.1, 146.6, 144.4, 137.9, 133.3, and 123.21 mS/mm at T=300, 330, 360, 390, 420, 450, and 480 K, respectively. The deviations of $g_{m,max}$ and V_{th} at different temperatures are insignificant. The flat region, defined as the drop of 10 % from the $g_{m,max}$, is 225 mA/mm (-0.7 V$\leq V_{GS} \leq$0.9 V) and 175 mA/mm (-0.7 V$\leq V_{GS} \leq$0.8 V) at room temperature and 480 K, respectively.

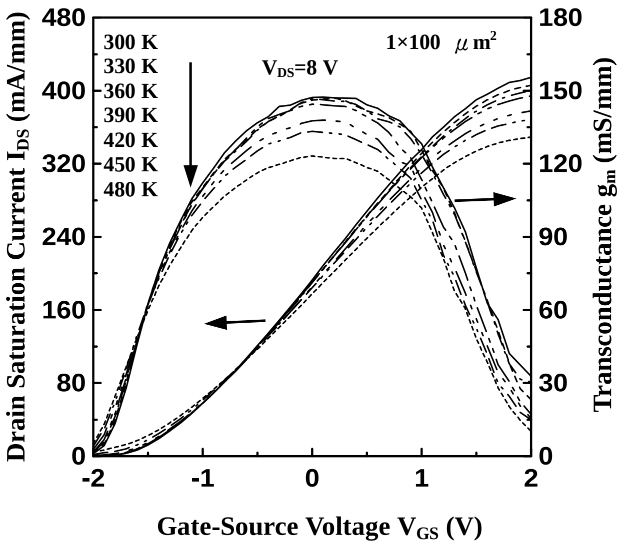

Figure 3. The drain saturation current I_{DS} and transconductance g_m versus gate-source voltage V_{GS} at different temperatures.

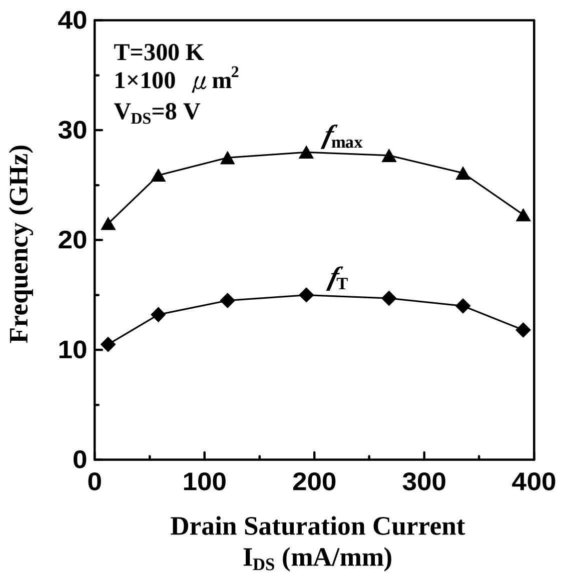

Figure 4. The measured f_T and f_{max} versus drain saturation current I_{DS} at room temperature.

The microwave characteristics of the studied device are measured by an HP8510B network analyzer in conjunction with Cascade probes. For a 1×100 μm^2 device, the unity current gain cut-off frequency f_T and maximum oscillation frequency f_{max} are 15 and 28 GHz, respectively, under the biased condition of V_{DS}=8 V and V_{GS}=0 V. The measured f_T and f_{max} versus drain saturation current I_{DS} are illustrated in Fig. 4. Obviously, the f_T and f_{max} exhibit wide and flat V_{GS} and I_{DS} operation regimes. Therefore, the studied device also shows great potential in high-frequency circuit applications.

4. Conclusion

In summary, a new high-barrier camel-like gate FET with a high breakdown voltage and low leakage current has been fabricated successfully and demonstrated. In the studied 1×100 μm^2 device, due to the use of n^+-GaAs/p^+-InGaP/n-GaAs high-barrier camel-like gate and GaAs/InGaAs heterostructure channel structure, good carrier confinements are obtained. Therefore, the leakage current is reduced and the breakdown characteristics are improved. Experimentally, good device performances are obtained at room temperature. In addition, the device also exhibits the high breakdown characteristics at high temperature environment and good microwave behaviors. Consequently, based on these good performances, the studied device shows a great promise for high-breakdown, low-leakage, and high-temperature applications.

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