AlGaN/GaN/InGaN/GaN HEMTs with an InGaN-notch


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We report an AlGaN/GaN/InGaN/GaN double hetero junction HEMT (DH-HEMT) with reduced buffer leakage and high-mobility two-dimensional-electron-gas (2DEG). A 3-nm thin In$_x$Ga$_{1-x}$N (x = 0.1) layer was inserted into the conventional AlGaN/GaN HEMT structure. A 2DEG mobility of around 1300 cm$^2$/Vs and a sheet resistance of 480 $\Omega$/sq were obtained at room temperature on this new DH-HEMT structure grown on sapphire substrate with MOCVD-grown GaN buffer. A peak transconductance of 230 mS/mm, a peak current gain cutoff frequency ($f_T$) of 14.5 GHz, and a peak power gain cutoff frequency ($f_{max}$) of 45.4 GHz were achieved on a 1×100 $\mu$m device. The off-state source-drain leakage current is as low as ~5 $\mu$A/mm at $V_{DS} = 10$ V and the gate leakage current is about 10 $\mu$A/mm at a reverse bias of 20 V. For the devices on sapphire substrate, maximum power density of 3.4 W/mm and PAE of 41% were obtained at 2 GHz.

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1 Introduction

With high power handling capability at high frequencies, AlGaN/GaN HEMTs are emerging as promising candidates for next-generation RF and microwave power amplifiers. With tremendous progresses made during the last decade in material quality and device processing, conventional AlGaN/GaN HEMTs have been improved significantly in both DC and RF performances [1–5]. At the same time, more advanced device structures are being proposed for further performance improvement. For example, double-channel HEMTs and composite-channel HEMTs have been studied for higher carrier density and improved linearity [6–8]. To improve carrier confinement which may result in improved carrier mobility and pinch-off behavior, double-heterojunction HEMTs [9] are also being investigated. Using AlGaN buffer layer with Al composition of 4% [10], Micovic et al. demonstrated a GaN double heterojunction HEMT with improved buffer isolation. However, a high Al composition in the AlGaN buffer layer is still difficult to achieve. Simin et al. has implemented AlGaN/InGaN/GaN HEMTs and MOSHFETs [11, 12] in which the channel material is InGaN, which is confined from both sides by AlGaN and GaN. However, cluster-free high-mobility InGaN layer is an obstacle. The highest 2DEG mobility reported in the AlGaN/InGaN/GaN DH-HEMTs is 730 cm$^2$/Vs [11, 12], significantly lower than that in conventional AlGaN/GaN HEMTs. In this paper, we report an AlGaN/GaN/InGaN/GaN DH-HEMT that features an InGaN-notch in the channel region, in which the mobility degradation that usually occurs in InGaN channel layer is avoided since the major channel is still GaN. On the other hand, the opposite piezoelectric polarization field in the InGaN layer [13, 14] can help to create an additional potential barrier between the channel and the buffer layer. This additional barrier leads to better carrier confinement and better buffer isolation, which in turn, enables improved device performance, i.e., higher 2DEG mobility and lower leakage current.

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2 Device structure and fabrication

Figure 1(a) shows the cross section of the AlGaN/GaN/InGaN/GaN DH-HEMT structure, which was grown on (0001) sapphire substrates in an Aixtron AIX 2000 HT MOCVD system. After initial desorption at 1200 °C, a GaN nucleation layer was grown at 550 °C, followed by a 2.5-µm-thick unintentionally doped GaN buffer layer. Then the InGaN-notch layer, which is 3 nm thick with 10% indium composition, was grown with pure nitrogen carrier gas at 810 °C. Ammonia (NH₃), trimethyl-gallium (TMG) and trimethyl-indium (TMI) were used as source materials. Then a 6-nm-thick GaN channel layer was grown at 810 °C. The barrier layer was grown at 1100 °C, which consists of a 3-nm undoped spacer, a 15-nm doped (2×10¹⁸ cm⁻³) carrier supplier layer, and a 2-nm undoped cap layer. As shown in the SIMS result shown in Fig. 1(b), a well-defined InGaN layer exists below the major GaN channel. Device active regions were defined using mesa etching by ICP-RIE. It is followed by the source/drain ohmic contacts formation by a rapid thermal annealing of e-beam evaporated Ti/Al/Ni/Au at 850 °C for 30 seconds. Using on-wafer transfer length method (TLM) patterns, the ohmic contact resistance was typically 0.8 ohm-mm. Gate electrodes with 1 µm length were then defined by contact photolithography, Ni/Au e-beam evaporation and lift-off, subsequently. The devices have a source-gate spacing of \( L_{sg} = 1 \) µm and a gate-drain spacing of \( L_{gd} = 1 \) µm. Finally, the devices were passivated using PECVD-grown SiN.

3 Device characteristics and discussion

Figure 2 shows the conduction band profile of the AlGaN/GaN/InGaN/GaN DH-HEMT and conventional AlGaN/GaN HEMT, which is calculated by solving the Poisson’s equation. The conduction-band offset at InGaN/GaN hetero-interface and the polarization charge density in the InGaN layer are set to be \( \Delta E_C = 0.12 \) eV and \( 6.68 \times 10^{12} \) e/cm², respectively [13]. Due to the opposite piezoelectric polarization in the InGaN layer compared to the AlGaN layer, the conduction band at the hetero-interface between the InGaN-notch and GaN buffer is raised and a sharper potential barrier is formed at the back side of 2DEG channel in the InGaN DH-HEMT. Such a barrier can help confine the electrons better and improve the buffer isolation.
Room temperature Hall measurements of the DH-HEMT structure was performed on a Hall-bridge pattern fabricated on wafer by photolithography, which yielded an electron mobility of 1300 cm²/Vs and a sheet resistance of 480 Ω/sq. Unlike some other works [11, 12], the mobility obtained in this work is higher than that of our conventional AlGaN/GaN HEMT devices, which is normally around 1000 cm²/Vs. This indicates that the inserted InGaN-notch layer plays positive role in enhancing the 2DEG confinement and then improving the mobility.

The DC characteristics of the AlGaN/GaN/InGaN/GaN DH-HEMT and conventional HEMTs are shown in Fig. 3. A maximum drain current density of 850 mA/mm was achieved in a 1×10 μm DH-HEMT device. The pinch-off voltage is about -4 V, with an off-state breakdown voltage larger than 60 V. The positive shift of the pinch-off voltage in the DH-HEMT is due to the polarization field in the InGaN layer, which is opposite to that in the AlGaN barrier. A peak transconductance of about 230 mS/mm is obtained in the DH-HEMT, which is about 10% higher than that in our conventional HEMT devices. The buffer leakage current density of a 1×10 μm DH-HEMT device is about 5 μA/mm at V_DS = 10 V, significantly lower than that in our conventional HEMT devices (~20 μA/mm). This reduced leakage current strongly indicates that the potential barrier between the channel and the buffer layer can effectively improve the buffer isolation.

Fig. 2 The calculated conduction band diagram of the conventional HEMT (top) and the DH-HEMT (bottom).

Fig. 3 DC characteristics of DH-HEMT (circle) and conventional HEMT (square): (a) The transfer and transconductance characteristics at V_DS = 10 V; (b) the I-V characteristics of the gate-drain Schottky diode.
RF performances of a 1×100 μm DH-HEMT device were characterized by measuring the on-wafer S-parameters. Current gain ($|h_{21}|^2$) and maximum available/stable power gain (MAG/MSG) are extracted and plotted in Fig. 4. A $f_T$ of 14.5 GHz and a $f_{max}$ of 45.4 GHz were obtained in the DH-HEMT devices. Large-signal load-pull measurement was carried out using Maury’s MT982B01 tuners. Tuning for maximum output power ($P_{out}$) at 2 GHz, a $P_{out}$ of 3.4 W/mm and a peak PAE of 41% were obtained with a 35 V drain supply voltage, as shown in Fig. 5.

Fig. 4 Frequency-dependent current gain and maximum available/stable power gain of the DH-HEMT, with a $f_T$ of 14.5 GHz and a $f_{max}$ of 45.4 GHz.

Fig. 5 Power performances of the DH-HEMT measurement with a signal sources at 2.0 GHz.

In the conventional AlGaN/GaN single heterojunction HEMT structure, the GaN channel layer is directly on the top of GaN buffer layer. The homogeneously continuous conduction band profile from GaN channel layer to GaN buffer layer results in a relatively flat conduction band profile below the AlGaN/GaN hetero-interface. Due to this feature, the electrons in the channel of the conventional AlGaN/GaN HEMT structure can spill over to the GaN buffer, which is not always insulating, resulting in large buffer leakage. In our AlGaN/GaN/InGaN/GaN DH-HEMT structure, the inserted InGaN-notch layer plays a key role in reducing buffer leakage and improving 2DEG mobility. The InGaN layer has an opposite piezoelectric polarization field compared to AlGaN [13, 14], which results in a very sharp rise
of the conduction band below the 2DEG channel. The raised potential barrier for the electrons can help enhance the confinement of the 2DEG, and then improve the electron mobility. The potential barrier also prevents 2DEG from spilling over to the buffer layer, and therefore, assists in reducing the buffer leakage current. Another important advantage of our DH-HEMT structure compared to other HEMT structures featuring InGaN layer [11, 12] is that the direct use of InGaN layer as the channel is avoided. Due to the more severe alloy scattering in InGaN compared to GaN and imperfect material quality, an InGaN channel layer has so far shown degraded 2DEG mobility.

4 Conclusions

In conclusion, a novel AlGaN/GaN/InGaN/GaN double heterojunction HEMT with improved 2DEG mobility and reduced buffer leakage current has been demonstrated on sapphire substrate. Taking advantage of the unique piezoelectric polarization feature of the InGaN layer, additional potential can be created on the back of the 2DEG channel, leading to enhanced carrier confinement. The electron mobility obtained this DH-HEMT structure is shown to be 30% higher than that obtained in a conventional AlGaN/GaN single heterojunction HEMT structure.

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References