High-performance AlGa_N double channel HEMTs with improved drain current density and high breakdown voltage

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Abstract

In this work, for the first time, AlGa_N double channel heterostructure is proposed and grown by metal organic chemical vapor deposition (MOCVD), and high-performance AlGa_N double channel high electron mobility transistors (HEMTs) are fabricated and investigated. The implementation of double channel feature effectively improves the transport properties of AlGa_N channel heterostructures. On one hand, the total two dimensional electron gas (2DEG) density is promoted due to the double potential wells along the vertical direction and the enhanced carrier confinement. On the other hand, the average 2DEG density in each channel is reduced, and the mobility is elevated resulted from the suppression of carrier-carrier scattering effect. As a result, the maximum drain current density (I_{max}) of AlGa_N double channel HEMTs reaches 473 mA/mm with gate voltage of 0V. Moreover, the superior breakdown performance of the AlGa_N double channel HEMTs is also demonstrated. These results not only show the great application potential of AlGa_N double channel HEMTs in microwave power electronics, but also develops a new thinking for the studies of group III nitride based electronic devices.

Main Text

Group III nitride based high electron mobility transistors (HEMTs) have been identified as the most promising candidate for next-generation microwave power electronics owing to their fast switching speed and low switching loss [1-5]. Lately, the most advanced nitride HEMTs have achieved initial commercialization up to 650 V. However, with the maturity of device fabrication technology, it has become increasingly difficult to further scaling up the breakdown voltages (BV) and improving the device reliability at high temperatures. Therefore, in view of the larger bandgap and superior thermal stability of AlGa_N over Ga_N, AlGa_N channel devices have been proposed as promising candidate to further improve the performance limits of nitride HEMTs in high-voltage and high-temperature applications [6-13]. Recently, the successful implementation of AlGa_N channel metal-oxide-semiconductor field-effect-transistors (MOSFETs) have also been reported [14].

However, the limitations of the previously reported AlGa_N channel devices are equally obvious. On one hand, on account of the ternary alloy disordered scattering effect, the two dimensional electron gas (2DEG) mobility in AlGa_N channel is much lower than that in Ga_N channel. As a result, the current drive capacity of AlGa_N channel devices are much lower than that of the traditional Ga_N channel devices. On the other hand, in order to induce the same amount of 2DEG in AlGa_N channel, the Al component in AlGa_N barrier layer should be higher than that of conventional Ga_N channel heterostructures, which will increase the difficulties in material growth process. These contradiction seriously inhibit the widespread application of AlGa_N channel devices, and the optimization of heterostructure layout are urgently needed.

Double channel (DC) technique is an intriguing approach to promote the channel carrier density of nitride based heterostructures without any adverse impact on the electron mobility, and the current conduction capability of the devices will be improved [15-17]. However, there is few report on the AlGa_N double channel heterostructures or electron devices up to now. In this work, for the first time, AlGa_N double

channel heterostructure is proposed and grown to resolve the contradiction between the current drive capability and breakdown performance of nitride based electron device. Further, high performance AlGaIn double channel HEMTs based on the novel heterostructures are fabricated and investigated in detail.

The cross section schematic of the AlGaIn double channel heterostructure is shown in **Fig. 1**, and the growth processes can be summarized as follow. Firstly, 1600 nm GaN buffer layer was grown on the sapphire substrate. Then, 500 nm graded AlGaIn buffer layer with Al composition increasing from 0 to 10% was grown, which was beneficial to suppress the formation of parasitic channel. Whereafter, 100 nm lower AlGaIn channel, 1 nm AlN interlayer and 23 nm lower AlGaIn barrier were grown successively, and the Al compositions in the channel and barrier layers are 10% and 31%, respectively. Finally, 30 nm upper AlGaIn channel, 1 nm AlN interlayer and 23 nm upper AlGaIn barrier layers were grown, for which the compositions were the same with the lower layers. The conduction band diagram of the AlGaIn double channel heterostructure can be calculated by self-consistently solving the one dimensional Poisson-Schrödinger equation, and the electron density distribution is also extracted as shown in **Fig.2**. Two deep potential well are formed at the interface of AlN interlayer and $\text{Al}_{0.10}\text{Ga}_{0.90}\text{N}$ channel layers, corresponding to the double 2DEG channels. In addition, the lower AlGaIn barrier also acts as back barrier of the upper channel, which is beneficial to promote the confinement of the 2DEG.

Fig.3 displays the high resolution x ray diffraction (HRXRD) ω -2 θ scan result of the AlGaIn double channel heterostructures from symmetric (0004) reflection. The diffraction peaks of AlN nucleation layer, GaN buffer, AlGaIn graded buffer, AlGaIn channel and AlGaIn barrier layers can be observed at 75.3°, 71.6°, 72.2° and 72.8°, indicating the distinct multi-layer structure and the sophisticated control of the growth process. Capacitance-voltage (C-V) measurement with mercury-probe configuration was performed to investigate the double channel characteristics of the heterostructures. As shown in the inset of **Fig.4**, two distinct capacitance steps can be observed at around -2.5 V and -10 V with the applied voltage swept from 0V to -15V, corresponding to the depletion of 2DEG at AlN/ $\text{Al}_{0.10}\text{Ga}_{0.90}\text{N}$ interfaces. In addition, the carrier distribution properties can be extracted from C-V curve and the result is illustrated in **Fig.4**. Two carrier concentration peaks locate at 23 and 78 nm with the values of $6.1 \times 10^{13} \text{ cm}^{-3}$ and $2.5 \times 10^{13} \text{ cm}^{-3}$, which is in accordance with the calculated result as shown in **Fig.2**. Specially, no parasitic conduction channel can be observed until the test depth reached 500 nm, suggesting the successful achievement of double channel properties of the heterostructure. In addition, the 2DEG sheet density and mobility were determined to be $1.3 \times 10^{13} \text{ cm}^{-2}$ and $1130 \text{ cm}^2/\text{V}\cdot\text{s}$ by the Hall effect measurement.

The standard HEMTs fabrication process was carried on the AlGaIn double channel heterostructure. The device fabrication process started with ohmic contact formed with Ti/Al/Ni/Au multilayer metal stack deposited by electron beam evaporation, followed by a rapid thermal anneal at 850 °C for 30 s in N_2 atmosphere. Then, the mesa isolation was performed by Cl_2/BCl_3 inductively coupled plasma etching to a depth of 200 nm, and 100-nm-thick SiN passivation layer was formed by plasma enhanced chemical vapor deposition. Afterwards, a gate area with a length (L_G) of 0.8 μm was defined by photolithography after etching the top SiN with CF_4 plasma, and then a Ni/Au schottky gate electrode was deposited. The

gate-source (L_{GS}) and gate-drain (L_{GD}) distances are 0.8 and 1 μm , respectively. For comparison purposes, two additional HEMTs samples based on the conventional AlGaIn single channel and GaN single channel heterostructures were also fabricated, and the cross section schematics are shown in **Fig.1(b)** and **1(c)**. The device process and characteristic parameters of the additional HEMT samples are exactly the same with the AlGaIn double channel HEMTs. The output and transfer properties of the devices were carried out with Keithley 4200 semiconductor parameter analyzer and the breakdown characteristics were performed using Agilent B1505A high-voltage semiconductor analyzer system.

The typical output characteristics of the HEMTs are illustrated in **Fig.5**, for which the V_{GS} and V_{DS} were swept from 0 ~ -10V and 0 ~ 10V. The maximum drain current density (I_{max}) and differential on-resistance (R_{on}) of the AlGaIn single channel sample are 265.3 mA/mm and 27.1 $\Omega\cdot\text{mm}$, much inferior than that of the GaN single channel devices. This result is in accord with the previous reports, suggesting the deficiency of AlGaIn channel HEMTs in current drive capacity. However, for the AlGaIn double channel HEMTs, the I_{max} dramatically increases to 473 mA/mm, which is 1.8 times higher than that of AlGaIn single channel HEMTs and even higher than the results of GaN single channel HEMTs. We attribute the improvement in I_{max} to the superior transport properties of the AlGaIn double channel heterostructures. On one hand, double channel structure possesses two potential wells along the vertical direction, and the carrier storage capability of the AlGaIn conduction channel is promoted. On the other hand, although the total channel carrier density is increased, the average electron density in each channel is reduced. As a result, the carrier-carrier scattering effect is suppressed and the channel electron mobility is elevated. However, it can be observed that the R_{on} of AlGaIn double channel HEMTs is 12.5 $\Omega\cdot\text{mm}$, still larger than that of GaN single channel HEMTs. This phenomenon is related to the large contact barrier height of the AlGaIn barrier layers, for which the Al composition is as high as 31%. Moreover, due to the self-heating effect resulted from the high power dissipation, negative differential resistance effect can be observed for the GaN single channel HEMTs when $V_G > 2\text{V}$ and $V_D > 5\text{V}$. Nevertheless, for the AlGaIn channel HEMTs (both single channel and double channel), this negative differential resistance effect is significantly suppressed, manifesting the superior performance of AlGaIn channel HEMTs in elevated temperature condition.

The off-state breakdown characteristics of the HEMTs based on different heterostructures are measured and shown in **Fig.7**. The breakdown voltage (V_b) is defined by the criteria of leakage current reaching 0.5 $\mu\text{A/mm}$. It can be observed that all the three samples present hard breakdown characteristics, and the breakdown performance of AlGaIn channel HEMTs are obviously better than that of the GaN channel HEMTs. The V_b of the AlGaIn double channel HEMTs is 143.5 V, more than two times higher than that of the GaN single channel HEMTs. Taking the $L_{GD}=1 \mu\text{m}$ into consideration, the $V_{b,\text{standard}}$ (defined by V_b/L_{GD}) is as high as 143.5 V/ μm for the AlGaIn double channel HEMTs. The I_{max} and $V_{b,\text{standard}}$ results of the AlGaIn double channel HEMTs in this work are benchmarked against the GaN channel and AlGaIn channel HEMTs reported by other groups in **Fig.8**. It is obvious that the breakdown performance of AlGaIn channel HEMTs is generally better than that of GaN channel HEMTs, accompanying with the deterioration

in $I_{\max}$. Noticeably, the $I_{\max}$ in this work is the highest result in AlGaIn channel HEMTs, which is comparable to most results of the GaN channel HEMTs. Moreover, it is necessary to note that the $I_{\max}$ value in our experiments is obtained at $V_{GS}=0$ V, which is conservative and can be further improved by applied positive gate voltage. Therefore, these results convincingly demonstrate the enormous potential of AlGaIn double channel HEMTs in microwave power device applications with requiring 1200 V.

In summary, AlGaIn double channel heterostructure is proposed to fabricate high performance HEMTs. The superior transport properties of AlGaIn double channel heterostructure is revealed, leading to the improved current drive capability of the HEMTs. In addition, the excellent breakdown performance of the AlGaIn double channel HEMTs is demonstrated. The results in this work show the great potential of AlGaIn double channel devices in microwave power applications in the future.

Declarations

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Figures

Figure 1

Cross-sectional view (not to scale) of (a) AlGaIn double channel, (b) AlGaIn single channel and (c) GaN single channel heterostructures (HEMTs)

Figure 2

Conduction band diagram and electron density distribution of AlGaIn double channel heterostructure

Figure 3

HRXRD (0004) plane ω - 2θ scan of AlGaN double channel heterostructure

Figure 4

C-V characteristics and electron distribution curve of AlGaIn double channel heterostructure

Figure 5

Output characteristics of AlGaIn double channel, AlGaIn single channel and GaN single channel HEMTs

Figure 6

Transfer characteristics of AlGaIn double channel, AlGaIn single channel and GaN single channel HEMTs

Figure 7

Breakdown characteristics of AlGaN double channel, AlGaN single channel and GaN single channel HEMTs

Figure 8

Benchmark of I_{max} and $V_{b,standard}$ in state-of-the-art AlGaN channel and GaN channel HEMTs