

Static Characteristics of AlGa_N/Ga_N High Electron Mobility Transistors with Different Thickness of AlGa_N Layer*

Wu Tong, Hao Zhibiao, Tang Guang, Guo Wenping, Hu Hui,
Sun Changzheng and Luo Yi

(State Key Laboratory on Integrated Optoelectronics, Department of Electronic Engineering,
Tsinghua University, Beijing 100084, China)

Abstract: The growth and device fabrication of AlGa_N/Ga_N high electron mobility transistors (HEMTs) are carried out by using metal-organic vapor phase epitaxy (MOVPE) system. Specially the performances of HEMT devices with different thickness of AlGa_N layer are compared. The device with thinner spacer layer exhibits better static performance. And a maximum saturation current density of 650mA/mm and a peak extrinsic transconductance of 100mS/mm are obtained from the devices with gate length of 1μm.

Key words: HEMT; Ga_N; power devices

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1 Introduction

One of the remaining frontiers for solid-state electronic devices is the high microwave power realm, which has been dominated by vacuum tubes since the inception of wireless systems. If available, high microwave power solid-state electronic devices would have great potential of application due to the high reliability, small size, and low cost. However, solid-state devices based on conventional semiconductor materials generally have low breakdown voltage, and this prohibits their operation at the voltages necessary to efficiently generate high RF power.

Recent progresses in the epitaxial growth of wide bandgap semiconductor materials such as

GaN-based alloys provide the opportunity for new design and fabrication of microwave transistors that demonstrate performance previously available only with microwave tubes. GaN possesses properties such as large bandgap (3.4eV), very high breakdown field (3.5×10^6 V/cm), and extremely high peak (3×10^7 cm/s) and saturation velocity (2×10^7 cm/s)^[1-3], which make it superior to conventional semiconductors in high microwave power electronic devices. These properties along with the large band offset and the high electron mobility are observed in AlGa_N/Ga_N heterostructures^[4], which promise an excellent microwave power performance of GaN-based high electron mobility transistors (HEMTs).

Up to now, state-of-the-art AlGa_N/Ga_N HEMTs and microwave power amplifiers have al-

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Wu Tong male, master postgraduate. His main research interest is fabrication of AlGa_N/Ga_N HEMTs.

Hao Zhibiao male, lecturer. His current interests include MBE growth and fabrication of novel devices.

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ready yielded power density on the order of 10W/mm with power-added efficiency (PAE) about 47% and CW output power of 14W at 8GHz on 4mm-wide device^[5]. The RF output power capability of this device compares very favorably with that of 1W/mm available with GaAs MESFETs, especially at the elevated temperature. Such wide bandgap semiconductor devices will find applications in power amplifiers for base station transmitters for wireless telephone systems, HDTV transmitters, power modules for phased-array radars and so on^[6]. At the moment, however, there are still several critical issues that must be addressed for practical application of AlGa_N/Ga_N HEMTs, including the growth of high quality semi-insulating Ga_N films, an efficient heat management, and dispersion problem caused by traps in the device structure^[7]. Moreover, some fundamental concepts, for example, the influence of layer structure on the performances of HEMT devices, have not been studied thoroughly.

In this paper, AlGa_N/Ga_N HEMT devices have been successfully realized including both material growth and device fabrication. The HEMT devices exhibit good static characteristics. Especially, the performances of devices with different thickness of AlGa_N layer are compared.

2 Material growth and device fabrication

In this work, AlGa_N/Ga_N HEMT structures were grown on 50mm *c*-plane sapphire substrates by low-pressure metal-organic vapor phase epitaxy (LP-MOVPE). The Ga, N, Al, and Si precursors were TMGa, NH₃, TMAI, and SiH₄, respectively. Conventional doped heterostructure was used to enhance the two-dimensional electron gas (2-DEG) channel conductivity. Initially, a 25nm-thick low-temperature Ga_N nucleation layer was deposited on (0001) sapphire substrate, followed by a 3μm-thick unintentionally doped (UID) Ga_N layer. Then an UID AlGa_N spacer layer and finally a Si-doped Al-

GaN carrier-supply layer with carrier concentration of $5 \times 10^{18} \text{ cm}^{-3}$ were grown. Determined by X-ray diffraction (XRD) measurement, the mole fraction of Al was 0.28 in the AlGa_N layers. During the growth of the UID Ga_N, hydrogen was used as carrier gas and the reactor pressure was about $2 \times 10^4 \text{ Pa}$. For the growth of AlGa_N layers, the reactor was pumped down to 10^4 Pa to decrease the pre-reaction between TMAI and NH₃.

In order to investigate the influence of the thickness of AlGa_N spacer layer and carrier-supply layer on the device performance, three HEMT structures with different thickness of AlGa_N layers were grown. The thickness of the AlGa_N spacer and carrier-supply layers for structure A, B, and C are 10 and 15nm, 5 and 20nm, 5 and 15nm, respectively. Their 2-DEG properties were characterized by Van der Pauw Hall measurement at both room temperature (RT) and 77K low temperature. The applied magnetic field was 0.3T, and electrical contacts were obtained by soldered indium. The results are summarized in Table 1. At 77K, the electron mobilities increase more than twice the values at RT whereas the sheet carrier densities stay almost constant, as expected for a 2-DEG.

Table 1 2-DEG characteristics of different HEMT structures

Structure	RT		77K	
	n_s / 10^{13} cm^{-2}	μ / $(\text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1})$	n_s / 10^{13} cm^{-2}	μ / $(\text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1})$
A	1.73	564	1.71	1400
B	1.88	704	1.82	2089
C	2.00	800	1.93	2237

It is generally considered that polarization including both spontaneous and strain-induced piezoelectric polarization has an important effect on the 2-DEG characteristics in AlGa_N/Ga_N heterostructures. In Ga-polarity system, the polarization charges cause the band bending and any free carriers, if present in the system, would tend to assemble in Ga_N layer very close to the AlGa_N/Ga_N interface to screen the polarization charges. These free carriers, which form a 2-DEG, may come from

native defects, impurity dopants, and surface states^[8]. The above HEMT structures, with the same growth condition, AlGaIn composition and Si-dopant concentration, are different merely in the thickness of the UID and Si-doped AlGaIn layers. For structures A and B, which have the same total thickness of AlGaIn layer and thus the same level of polarization, the structure with thinner spacer layer shows higher sheet carrier density. Therefore, we suppose that thinner spacer layer can increase the efficiency of carrier injection into the 2-DEG channel. However, for structure C, we have not made clear why its sheet carrier density and electron mobility are higher than those of structure B. Anyway, it is apparently presented that the structure of AlGaIn layer has a remarkable influence on the 2-DEG properties of AlGaIn/GaN heterostructures, which will ultimately affect the performances of AlGaIn/GaN HEMT devices, as will be discussed below.

Then the HEMT devices were fabricated by using conventional process steps. First, mesa isolation was completed by optical lithography and BCl_3/Cl_2 based inductive coupled plasma (ICP) dry etching^[9]. The mesa height was typically 100nm. The source and drain Ohmic contacts were made from vacuum evaporation of Ni/Al/Ni/Au (50nm/100nm/50nm/100nm) and subsequent annealing at 800°C in N_2 ambient for 120s. By using transmission line method (TLM) patterns^[10], the transfer Ohmic contact resistances were measured to be 29.14, 14.98, and 13.98 $\Omega \cdot \text{mm}$ for structures A, B, and C, respectively. Finally the gate was defined by lift-off technic and the gate metallization was vacuum evaporated Ni/Au (50nm/150nm). Devices with different source-to-drain separation, gate length and gate width were fabricated. Figure 1 shows the micrograph of one typical HEMT device.

3 Device performance and discussion

The results of static characteristic test of the

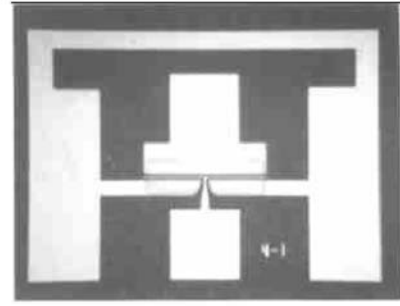


Fig. 1 Micrograph of AlGaIn/GaN HEMT device with source-to-drain separation, gate length, and gate width of 4 μm , 1 μm and 100 μm , respectively

HEMT devices fabricated from structures A, B, and C are shown in Fig. 2. The source-to-drain separation, gate length, and gate width of the devices under test are 4, 1, and 100 μm , respectively (see Fig. 1). It can be seen from Fig. 2 that all the HEMT devices exhibit good saturation and pinch-off characteristics. The slightly negative slope on the I - V curves at large channel current is due to self-heating as a result of the poor thermal conductivity of the sapphire substrate. The test results along with the calculated DC parameters are summarized in Table 2. High frequency and power performance test for these devices are still in progress and will be reported in the future.

Table 2 Static characteristics of HEMT devices with different thickness of AlGaIn layer

Structure	A	B	C
Layer thickness of n-AlGaIn/i-AlGaIn/nm	15/10	20/5	15/5
Peak extrinsic transconductance/($\text{mS} \cdot \text{mm}^{-1}$)	40	75	100
Maximum saturation current density/($\text{mA} \cdot \text{mm}^{-1}$)	240	500	650
Pinch off voltage/V	-7	-7	-7
Knee voltage/V	9	7	7
Source-drain breakdown voltage/V	> 50	> 50	> 50

The differences between the static characteristics of these HEMT devices are mainly due to their different thickness of AlGaIn spacer layer and carrier-supply layer, and thus different 2-DEG characteristics. Since the maximum channel current is proportional to the sheet carrier density^[7], we can clearly see that the measured maximum density of saturation current increases with the carrier density. The transconductance is affected by several fac-

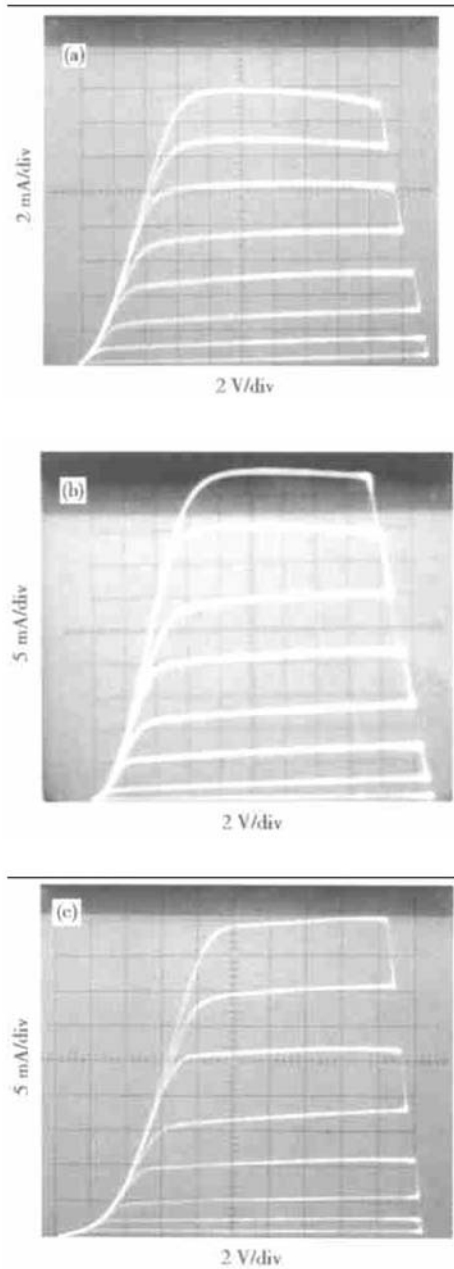


Fig. 2 Static characteristics of AlGa_N/Ga_N HEMT devices fabricated from structure A (a), structure B (b) and structure C (c). V_{GS} is from 0 to $-7V$ by step of $-1V$.

tors. The increase of measured peak extrinsic transconductance from structure A to C can be partially explained by the increase of electron mobility. The increase is also related to the reduced contact resistances of source and drain electrodes, to which attributed to the lower knee voltages of structures B and C. Therefore, the best overall device performance exhibited by structure C can be

attributed to the higher sheet carrier density and electron mobility, the reduced Ohmic contact resistance, and in addition, the thinner AlGa_N layer^[11].

Compared with other report^[5], the relatively small transconductance and high knee voltage of our fabricated devices are mainly due to the relatively larger Ohmic contact resistance. Nevertheless, this will not discourage us from inspecting qualitatively the influence of the layer structure on device performance. Although the fabrication process is same for structures A, B, and C, the contact resistance for structures B and C are much lower. We think this is also related to the thickness of AlGa_N layers. It is apparent that thinner spacer layer can make Ohmic contact easier, thus enhance the device performance.

4 Conclusion

AlGa_N/Ga_N HEMT devices with good static characteristics are realized successfully, including both material growth and device fabrication. A maximum saturation current density of $650\text{mA}/\text{mm}$, good pinch off at gate bias of $-7V$ and a peak extrinsic transconductance of $100\text{mS}/\text{mm}$ are obtained from the devices with gate length of $1\mu\text{m}$. The performances of devices with different thickness of AlGa_N layer are also discussed. The differences in device performance are mainly due to the different AlGa_N layer structures and Ohmic contact resistance.

References

- [1] Trew R J. Wide bandgap semiconductor transistors for microwave power amplifiers. *IEEE Microw Mag*, 2000, 1: 46
- [2] Mishra U K, Wu Y F, Keller B P, et al. Ga_N microwave electronics. *IEEE Trans Microw Theory Tech*, 1998, 46: 756
- [3] Keller S, Wu Y F, Parish G, et al. Gallium nitride based high power heterojunction field effect transistors: process development and present status at UCSB. *IEEE Trans Electron Devices*, 2001, 48: 552
- [4] Sun D Z, Hu G X, Wang X L, et al. AlGa_N/Ga_N polarization-induced 2-DEG materials grown by RF plasma assisted molecular beam epitaxy. *Chinese Journal of Semiconductors*,

- 2001, 22: 1425 (in Chinese) [孙殿照, 胡国新, 王晓亮, 等. RF-MBE 生长 AlGa_N/Ga_N 极化感应二维电子气材料. 半导体学报, 2001, 22: 1425]
- [5] Wu Y F, Kapolnek D, Ibbetson J P, et al. Very-high power density AlGa_N/Ga_N HEMTs. IEEE Trans Electron Devices, 2001, 48: 586
- [6] Ohno Y, Kuzuhara M. Application of Ga_N-based heterojunction FETs for advanced wireless communication. IEEE Trans Electron Devices, 2001, 48: 517
- [7] Xing H, Keller S, Wu Y F, et al. Gallium nitride based transistors. J Phys Condens Matter, 2001, 13: 7139
- [8] Morkoc H, Carlo A D, Cingolani R. Ga_N-based modulation doped FETs and UV detectors. Solid-State Electron, 2002, 46: 157
- [9] Wu T, Hao Z B, Tang G, et al. Dry etching characteristics of AlGa_N/Ga_N heterostructures using inductively coupled H₂/Cl₂, Ar/Cl₂ and BCl₃/Cl₂ plasmas. Jpn J Appl Phys, 2003, 42: L257
- [10] Wu Y F, Keller B P, Keller S, et al. Very high breakdown voltage and large transconductance realized on Ga_N heterojunction field effect transistors. Appl Phys Lett, 1996, 69: 1438
- [11] Ladbroke P H. MMIC design: GaAs FETs and HEMTs. Boston: Artech House, 1989

不同 AlGa_N 层厚度的 AlGa_N/Ga_N 高电子迁移率晶体管的静态特性*

吴 桐 郝智彪 唐 广 郭文平 胡 卉 孙长征 罗 毅

(清华大学电子工程系 集成光电子学国家重点实验室, 北京 100084)

摘要: 利用金属有机化合物气相外延技术研究了 AlGa_N/Ga_N 高电子迁移率晶体管 (HEMT) 结构的外延生长及器件制作, 重点比较了具有不同 AlGa_N 层厚度的 HEMT 器件的静态特性. 实验发现具有较薄 AlGa_N 隔离层的结构表现出较好的器件特性. 栅长为 1 μm 的器件获得了 650 mA/mm 的最大饱和电流密度和 100 mS/mm 的最大跨导.

关键词: 高电子迁移率晶体管; 氮化镓; 功率器件

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吴 桐 男, 硕士研究生, 主要研究方向是 AlGa_N/Ga_N 高电子迁移率晶体管.

郝智彪 男, 讲师, 主要从事分子束外延生长以及新型器件的研究.

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