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RF-MBE Grown AlGaN/GaN HEMT Structure with High Al Content*

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Abstract: A Si doped AlGaN/GaN HEMT structure with high Al content ($x = 43\%$) in the barrier layer is grown on sapphire substrate by RF-MBE. The structural and electrical properties of the heterostructure are investigated by the triple axis X-ray diffraction and Van der Pauw-Hall measurement, respectively. The observed prominent Bragg peaks of the GaN and AlGaN and the Hall results show that the structure is of high quality with smooth interface. The high 2DEG mobility in excess of $1260 cm^2/(V \cdot s)$ is achieved with an electron density of $1.429 \times 10^{13} cm^{-2}$ at 297K, corresponding to a sheet-density-mobility product of $1.8 \times 10^{16} V^{-1} \cdot s^{-1}$. Devices based on the structure are fabricated and characterized. Better DC characteristics, maximum drain current of 1.0A/mm and extrinsic transconductance of 218mS/mm are obtained when compared with HEMTs fabricated using structures with lower Al mole fraction in the AlGaN barrier layer. The results suggest that the high Al content in the AlGaN barrier layer is promising in improving material electrical properties and device performance.

Key words: HEMT; GaN; 2DEG; RF-MBE; power device
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1 Introduction

High electron mobility transistors (HEMTs) based on AlGaN/GaN heterostructures have been the focus of intense research for the past several years as promising devices for high temperature, high frequency, and high power microwave applications because of large saturation velocity, high thermal stability, and large band-gap of GaN[1~3]. Their outstanding performance is attributed to being able to achieve two-dimensional electron gas (2DEG) with density higher than $10^{13} cm^{-2}$ at the interface of AlGaN/GaN even without intentionally doping, which is well in excess of those achievable in conventional Ⅲ-Ⅴ material systems, such as GaAs and InP-based hterostuctures. A number of studies have confirmed that the large conduction band discontinuities at the AlGaN/GaN interface and the large piezoelectric and spontaneous polarization of the materials[4,5] are the two dominant origins of the high 2DEG density. Up to now, investigations on GaN-based HEMTs have mainly focused on AlGaN/GaN with low Al fraction (typically in the range of 15%～30%); however, the heterostructures with high Al content have been less studied. Increasing Al content in the AlGaN barrier layer will enhance the spontaneous and piezoelec-

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tric polarization and, therefore, induce a higher 2DEG density in the channel[5]. Furthermore, a higher Al content results in a larger conduction band discontinuity, which will result in better confinement to the electrons at the channel, allowing high mobility to coexist with the large carrier density[6]. In addition, high Al content can get a higher breakdown field and Schottky barrier. However, Zhang *et al.*[7] reported, with the Al content increasing, the effects of the interface roughness on the 2DEG mobility become more serious. Increasing Al content could also make it easy to introduce deep levels in the epi-layers and to degrade its crystal quality. Therefore, growth of and research on the AlGaN/GaN HEMT structure with high Al content in the barrier layer are necessary to improve HEMT performance further.

We have previously reported 1035cm^2/(V·s)[8] electron mobility at room temperature with a sheet electron density of 1.0×10^{13} cm^{-2} for the RF-MBE grown HEMT structures. In this paper, we report the RF-MBE growth of a high Al content ($x = 43\%$) AlGaN/GaN HEMT structure on sapphire substrate. The high Al content structure yields a sheet carrier density in excess of 1.4×10^{13} cm^{-2} at 297K with electron mobility about 1268cm^2/(V·s). To the best of our knowledge, the achieved product of $n_s\times\mu$ is one of the highest ever reported values for AlGaN/GaN HEMT structures grown on sapphire by MBE. Devices fabricated with the structure also exhibit the improved DC performance.

2 Experiment

The AlGaN/GaN HEMT structure with high Al content was grown on 37.5mm C-plane sapphire substrates by a modified home-made MBE system with a RF plasma nitrogen source. The structure is composed of a 1nm GaN cap layer, a 21nm-silicon-doped AlGaN carrier supply layer ($n = 2\times10^{18}$ cm^{-2}), a 3nm-undoped AlGaN spacer layer and a 2.0μm-thick undoped semi-insulating (SI) GaN buffer layer grown on a 20nm AlN nucleation layer, as shown in Fig. 1. The AlN nucleation layer, deposited at 600～700 ℃, was used to control the polarity of the epi-layers and to improve the GaN buffer layer quality. More details about the growth conditions for the epi-layers can be found elsewhere[8]. The subsequent device processing consisted of mesa isolation, Ti/Al/Ti/Au source and drain ohmic contact, and Pt/Ti/Au gate contact. Gate length and width were 0.8μm and 80μm, respectively.

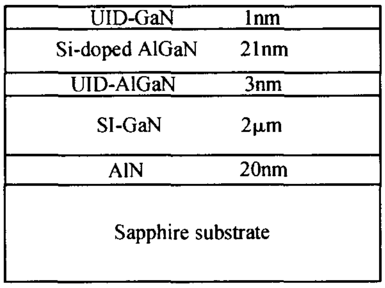

Fig. 1　AlGaN/GaN HEMT structure grown on (0001) sapphire substrate by RF-MBE

Our previously reported AlGaN/GaN HEMT structure materials have an Al content in the AlGaN barrier of about 20%[8]. However, for the present structure, the Al mole fraction in the AlGaN barrier is increased to about 43%, about two times higher than the previous one. In addition, the thickness of the GaN buffer layer has also been increased, from 1.5μm in the previous structure to 2μm in the present one. The motivation of raising the Al content in the AlGaN barrier is mainly to enhance the sheet electron concentration in the channel. The purpose for choosing a thicker SI-GaN buffer layer is to improve the overall performance of the HEMT structure.

The epi-layers quality of the HEMT structure and the Al mole fraction of AlGaN barrier layer are estimated by the triple axis X-ray diffraction (TAXRD) measurement. The Van der Pauw-Hall measurement is used to estimate the 2DEG density and electron mobility of the samples at various temperatures between 80K and 580K. HP4142 and

HP4155 semiconductor parameter analyzers were used for device DC measurement.

3 Results and discussion

Figure 2 is the TAXRD spectrum for the grown AlGaN/GaN HEMT structure. From this figure the prominent Bragg peaks for the GaN (0002) at $2\theta=34.56°$ and AlGaN (0002) at $2\theta=35.7°$ are observed. The intense GaN (0002) peak with small diffraction width shows that the SI-GaN buffer layer is of high quality, which is attributed to the optimized growth parameters and the thicker SI-GaN buffer layer. For the high Al mole fraction AlGaN barrier layer, as its thickness is very thin, about 24nm, its (0002) diffraction peak has a comparatively weaker intensity with wide diffraction width. This phenomenon is also observed by other research groups[9,10]. Using Vegard's Law, the Al content in the AlGaN layer can be estimated to be 43%, about two times higher than that of the previous HEMT structure[8]. It should be noticed that the in-plane biaxial strain in the AlGaN barrier layer has not been taken into account when estimating its Al mole fraction. If the stain is considered, the actual Al content in the AlGaN barrier layer will be a little smaller than the estimated value of 43%.

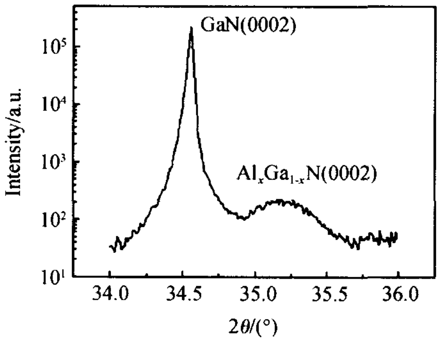

Fig. 2 Triple axis X-ray diffraction pattern of the AlGaN/GaN heterostructure grown on (0001) sapphire substrate by RF-MBE

Figure 3 shows the temperature dependence of the 2DEG mobility and its corresponding sheet density in the AlGaN/GaN HEMT structure sample. The measurement temperature varies from 80K to 580K. From this figure we can see that the 2DEG mobility reaches as high as $1268cm^2/(V\cdot s)$ with a very high sheet electron concentration of $1.429\times10^{13}cm^{-2}$ at room temperature. When temperature decreases from the room temperature, the mobility increases rapidly. At about 100K, the mobility reaches its maximum value of $2500cm^2/(V\cdot s)$ and changes little when the temperature is further decreased. When the temperature increases from room temperature, the mobility decreases slowly. Even at 500K, it is still as high as $552cm^2/(V\cdot s)$, which indicates that the material structure is potentially capable of high temperature device applications. The sheet electron density is almost independent of temperature when the temperature is lower than 440K. When the temperature increases from 440K to 580K, the sheet electron concentration will increase slowly. At 580K, the sheet electron density is $1.621\times10^{13}cm^{-2}$. The variable temperature Hall measurement clearly shows the typical behavior of the 2DEG, confirming the formation of 2DEG at the AlGaN/GaN interface in the GaN side. Since the 2DEG is almost completely confined in the channel for the large conduction band discontinuity between AlGaN and GaN layers, the sheet electron density is almost independent of the temperature variation. The achieved product of $n_s\times\mu$ at room temperature is $1.8\times10^{16}V^{-1}\cdot s^{-1}$, one of the highest ever reported values

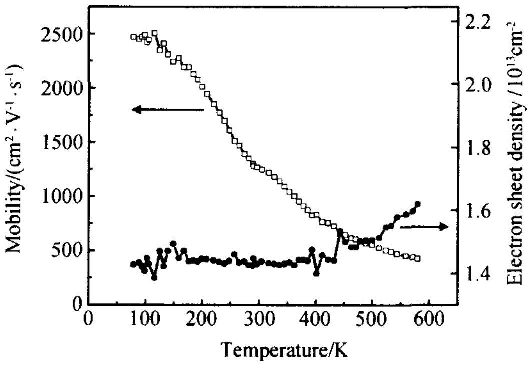

Fig. 3 Variable-temperature Hall effect measurements for the AlGaN/GaN HEMT material grown on (0001) sapphire substrate by RF-MBE

for AlGaN/ GaN HEMT structures grown on sapphire substrates by MBE. These results show that the high Al-content AlGaN/ GaN HEMT structure materials with thick SI-GaN buffer layer grown under the optimized conditions have high electrical performance and are promising for high frequency and high power HEMT applications.

Devices are fabricated using the structure with high Al mole fraction and characterized. Figure 4 illustrates the typical *I-V* (a) and transfer (b) characteristics. A maximum drain current of 1. 0A/ mm at V_{gs} = 1V and a peak extrinsic transconductance of 218mS/ mm are obtained on devices with gate length L_g = 0. 8μm and gate width W_g = 80μm. Compared with our previously fabricated devices with a lower Al mole fraction[8] ,the drain current is a little higher ,but the peak transconductance increases from 186mS/ mm to 218mS/ mm, about 117 % of that with the lower Al mole fraction. The improved DC performance confirms the improvement of the electrical properties ,resulting from the increased Al mole fraction.

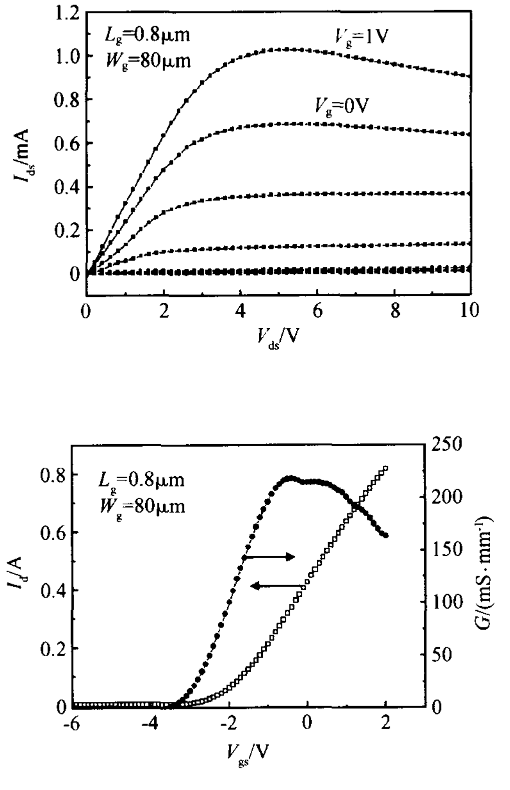

Fig. 4 Typical *I-V* (a) and transfer (b) characteristics for HEMT devices fabricated using the structure with high Al mole fraction (43 %) in the barrier layer.

4 Summary

A high Al content Si-doped AlGaN/ GaN HEMT structure is grown on sapphire substrate by plasma-assisted MBE and its structural and electrical properties are investigated. TAXRD analysis suggested that the Al content of the AlGaN barrier layer is 43 % and the HEMT structure has a high quality. Sheet carrier density in excess of 1. 4 $\times10^{13}$cm^{-2} with electron mobility about 1268cm^2/ (V ·s) at room temperature has been achieved ,indicating the high electrical properties of the structure. To the best of our knowledge ,the achieved product of $n_s \times \mu$,about 1. 8 $\times10^{16}$V^{-1} ·s^{-1} ,is one of the highest ever reported values for AlGaN/ GaN HEMT structures grown on sapphire by MBE. HEMTs fabricated with this structure have maximum extrinsic transconductance of about 218mS/ mm and saturation drain current of 1. 0A/ mm at V_{gs} = 1V ,exhibiting improved DC performance. The results show that increasing the Al content in the barrier layer will help to increase the product of n_s $\times\mu$ and to realize high performance HEMT devices.

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RF-MBE生长的高Al势垒层AlGaN/GaN HEMT结构*

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摘要: 采用RF-MBE技术,在蓝宝石衬底上生长了高Al组分势垒层AlGaN/GaN HEMT结构. 用三晶X射线衍射分析得到AlGaN势垒层的Al组分约为43%,异质结构晶体质量较高,界面比较光滑. 变温霍尔测量显示此结构具有良好的电学性能,室温时电子迁移率和电子浓度分别高达$1246cm^2/(V \cdot s)$和$1.429\times10^{13}cm^{-2}$,二者的乘积为$1.8\times10^{16}V^{-1}\cdot s^{-1}$. 用此材料研制的器件,直流特性得到了提高,最大漏极输出电流为1.0A/mm,非本征跨导为218mS/mm. 结果表明,提高AlGaN势垒层Al的组分有助于提高AlGaN/GaN HEMT结构材料的电学性能和器件性能.

关键词: 高电子迁移率晶体管; GaN; 二维电子气; RF-MBE; 功率器件

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