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Characteristics of AlGaN/GaN HEMTs Grown by Plasma-Assisted Molecular Beam Epitaxy*

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Abstract: AlGaN/GaN high electron mobility transistor (HEMT) materials are grown by RF plasma-assisted molecular beam epitaxy (RF-MBE) and HEMT devices are fabricated and characterized. The HEMT materials have a mobility of $1035\mathrm{cm}^2/(\mathrm{V\cdot s})$ at sheet electron concentration of $1.0\times10^{13}\mathrm{cm}^{-2}$ at room temperature. For the devices fabricated using the materials, a maximum saturation drain-current density of 925mA/mm and a peak extrinsic transconductance of 186mS/mm are obtained on devices with gate length and width of 1μm and 80μm respectively. The f_t, unit-current-gain frequency of the devices, is about 18.8GHz.

Key words: HEMT; GaN; FET; RF-MBE
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1 Introduction

AlGaN/GaN heterostructures have recently attracted much attention due to the potential for their applications in high-power, high-temperature, high-frequency microelectronic devices[1~5]. GaN possesses large band gap (3.4eV), very high breakdown field (3×10^6V/cm), and extremely high peak (3×10^7cm/s) and saturation velocity (1.5×10^7cm/s)[6]. These properties in combination with the large conduction band offset and the high-density two-dimensional electron gas (2DEG) on the order of $10^{13}\mathrm{cm}^{-2}$ at the AlGaN/GaN interface, make the AlGaN/GaN heterostuctures superior to conventional semiconductor heterostuctures such as GaAs-based and InP-based ones in the field of high power and high temperature microelectronic devices[1,4]. Such semiconductor devices will find applications in power amplifiers for base station transmitters for wireless telephone systems, HDTV transmitters, power modules for phase-array radars and so on[7].

The room temperature Hall electron mobility as high as $2000\ \mathrm{cm}^2/(\mathrm{V\cdot s})$ at sheet electron density of $10^{13}\mathrm{cm}^{-2}$ was achieved in AlGaN/GaN heterostructures grown on 6H-SiC by using low-pressure metal organic chemical vapor deposition (MOCVD)[1]. Mobility as high as about $1500\mathrm{cm}^2/(\mathrm{V\cdot s})$ at room temperature was observed both in MOCVD- and MBE-grown AlGaN/GaN heterostuctures at a sheet carrier density of about 8.5×

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10^{12} cm^{-2}[4,6,8,9]. AlGaN/GaN HEMTs and microwave power amplifiers grown on SiC substrates by MOCVD have already demonstrated a record power density of 9.8W/mm with power added efficiency (PAE) about 47% and CW output power of 14W at 8GHz on 4-mm-wide devices[6].

Sapphire has been the most widely used substrate material as it is readily available and of low cost for the growth of Ⅲ nitrides. However, the growth of device-quality heterostuctures on sapphire remains difficult due to the large lattice and thermal mismatches between sapphire and GaN. Furthermore, the GaN-based HEMT device processing technology needs to be further explored and improved. Before the application of the AlGaN/GaN HEMT materials and power devices there is still much work to do.

We have previously reported 730 $cm^2/(V\cdot s)$ mobility at 300K ($n_s = 7.6\times10^{12}cm^{-2}$) for the MBE-grown piezoelectrically-doped AlGaN/GaN heterostructures and the DC and small signal characteristics of the fabricated HEMT device[2]. Recently, we reported two-dimensional electron gas materials with AlN/GaN superlattice structure grown by plasma-assisted MBE, whose mobility at room temperature is $1086cm^2/(V\cdot s)$ at a sheet electron concentration of $7.5\times10^{12}cm^{-2}$[5]. In this paper, our recent progress on the performances of the modulation-doped AlGaN/GaN HEMT materials are reported. The HEMT devices grown by RF plasma-assisted MBE on sapphire substrates are fabricated. The HEMT materials and devices exhibit good characteristics.

2 Material growth and device fabrication

The device structures presented in this paper were grown on 1.5-inch *c*-plane sapphire substrates by a modified home-made molecular-beam epitaxy system using a RF plasma nitrogen source. Conventional Knudsen effusion cells were used as Ga and Al sources. The substrates were degreased ultrasonically in organic solvents and were next etched in a hot solution of H_2SO_4 and H_3PO_4 ($H_2SO_4 : H_3PO_4 = 3:1$) mixture for about 20min. They were then rinsed in deionized water. After spinning dry, the substrates were mounted on molybdenum substrate holders, and loaded into the load lock.

The growth of the device structures started with a 20nm AlN nucleation layer deposited on the sapphire substrates at 600~ 700℃, followed by an actual GaN buffer with a thickness of about 1.5μm grown at 800℃ with a nitrogen gas flow of 1.2sccm and a RF power of 400W. On the top of the buffer layer an $Al_xGa_{1-x}N$ barrier donor layer was grown, consisting of an unintentionally-doped 3nm spacer layer, a 21nm Si-doped carrier-supply layer with carrier concentration of $2\times10^{18}cm^{-3}$, and finally an undoped 1nm GaN cap layer. The mole fraction of Al in the $Al_xGa_{1-x}N$ layer was 20%, as determined by double crystal X-ray diffraction (DCXRD) measurement.

The HEMT structural materials were then processed into HEMTs with conventional processing steps. First, the device isolation was achieved by optical lithography and mesa formation with Cl-based reactive-ion etching (RIE). The mesa height was typically 150nm. Then, source and drain Ohmic contacts were applied directly to the AlGaN layer without a "recess" etching. The Ohmic contact source and drain metallization consisted of electron-beam evaporated Ti/Al/Ti/Au (40nm/220nm/40nm/50nm) annealed in N_2 ambient at 900℃ for 30s. Prior to the evaporation the samples were rinsed in HCl and in-situ cleaned by an Ar^+ ion beam. This resulted in specific Ohmic contact resistance of $R_c = 2\times10^{-4}\Omega\cdot cm^2$. Finally, the Schottky gate was defined by lift-off technology and the gate metallization employed was vacuum evaporated Pt/Ti/Au (50nm/40nm/150nm).

3 Results and discussion

Figure 1 shows the electron mobility and sheet density characterized by variable-temperature Van der Pauw-Hall measurements for a typical AlGaN/GaN HEMT structural sample. The sample was characterized over the temperature range from 77K to 568K to confirm the two-dimensional nature of the electron distribution. The Hall mobility was measured to be as high as 2653cm^2/(V · s) at 77K, 1035cm^2/(V · s) at room temperature and 233cm^2/(V · s) at 568K. The sheet electron densities for this sample were 9.6×10^{12}cm^{-2} at 77K, 1.0×10^{13}cm^{-2} at room temperature and 1.6×10^{13}cm^{-2} at 568K. At 77K the electron mobility increased more than twice the value at RT whereas the sheet carrier densities kept almost constant, as expected for a two dimensional electron gas. The formation of 2DEG in the current structure originated from both the piezoelectric field and modulation-doped effects.

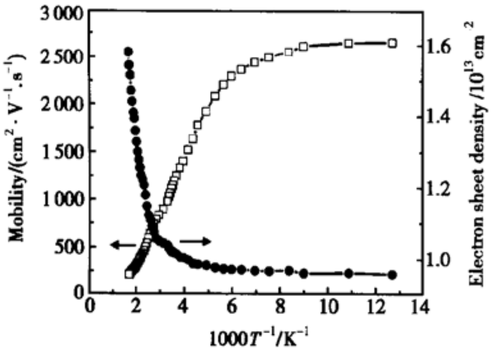

Fig. 1 Variable-temperature Hall effect measurements for an AlGaN/GaN HEMT sample grown on (0001) sapphire substrate by RF-MBE

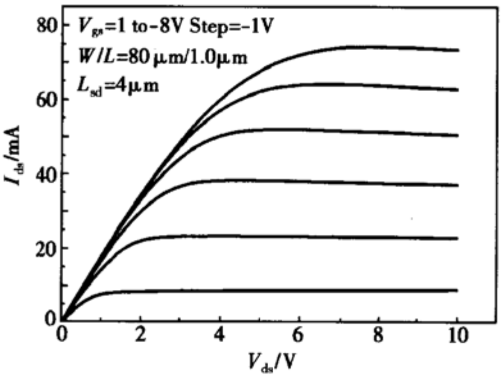

Fig. 2 I_{ds}-V_{ds} characteristics at room temperature for an AlGaN/GaN HEMT with L_g= 1μm and W_g= 80μm

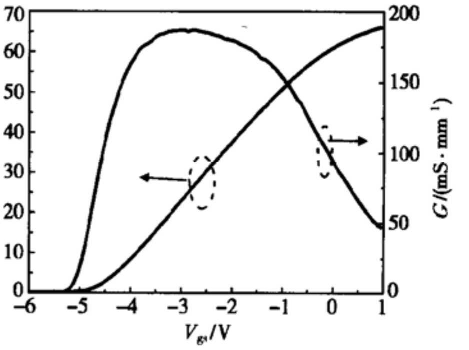

Fig. 3 Transfer characteristics of the AlGaN/GaN HEMT with 1μm gate length

The performances of the devices were first measured with I-V characterization. Shown in Figs. 2 and 3 are the output and transfer characteristics, respectively, of a typical 1 finger HEMT with 1μm gate length, 80μm gate width and 4μm source-drain spacing. DC measurements on this device yielded a maximum extrinsic transconductance of 186mS/mm and a maximum saturation drain current density of 925mA/mm (V_{gs} = 1V). The pinch-off voltage of this device was about −5V and the knee voltage was between 4～5V. The breakdown voltage of the gate-drain was lager than 40V. The device performances were still limited by the high series resistance since in this case the specific Ohmic contact resistance was $10^{-4}\Omega\cdot\text{cm}^2$, as obtained by transmission line model (TLM). At high current levels significant self-heating of the devices took place, limiting the maximum drain current. The self-heating became even more dominant as the gate width increased. This makes clear that a suitable thermal management by flip bonding must be performed or SiC must be chosen as a thermally highly conductive substrate to overcome the self-heating problem. All the HEMT devices measured exhibit good saturation and pinch-off characteristics.

To investigate high frequency characteristic of the devices, small-signal S-parameter measurements have been made. From the s-parameters, current gain (h_{21}) can be calculated. An example is shown in Fig. 4, for the 1μm gate length device mentioned above. For the typical device measured, current gain cutoff frequency is $f_t = 18.8$GHz. Power performances for these devices are still under test and will be reported in the future.

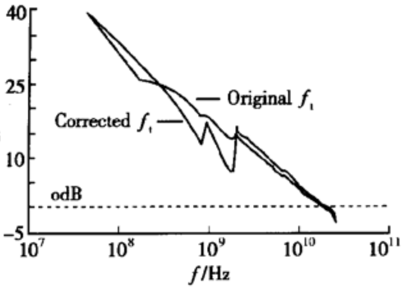

Fig. 4 Small signal RF characteristic of the 1μm gate AlGaN/GaN HEMT device

4 Summary

AlGaN/GaN high electron mobility transistor materials are grown by RF plasma-assisted molecular beam epitaxy and HEMT devices are fabricated successfully. The mobility as high as 1035$\mathrm{cm^2/(V \cdot s)}$ at a sheet electron concentration of $1.0 \times 10^{13}\mathrm{cm^{-2}}$ at room temperature has been achieved. A maximum saturation drain-current density of 925mA/mm and a peak extrinsic transconductance of 186mS/mm are obtained on devices with gate length and width of 1μm and 80μm respectively. The current-gain cut-off frequency f_t of the devices is measured to be about 18.8GHz.

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RF-MBE 生长的 AlGaN/GaN 高电子迁移率晶体管特性*

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摘要: 用射频分子束外延技术研制出了室温迁移率为 1035cm^2/(V·s), 二维电子气浓度为 1.0×10^{13}cm^{-2}, 77K 迁移率为 2653cm^2/(V·s), 二维电子气浓度为 9.6×10^{12}cm^{-2}的 AlGaN/GaN 高电子迁移率晶体管材料. 用此材料研制的器件(栅长为 1μm, 栅宽为 80μm, 源-漏间距为 4μm) 的室温非本征跨导为 186mS/mm, 最大漏极饱和电流密度为 925mA/mm, 特征频率为 18.8GHz.

关键词: 高电子迁移率晶体管; 氮化镓; 场效应晶体管; RF-MBE
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