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MOCVD-Grown AlGaN/AlN/GaN HEMT Structure with High Mobility GaN Thin Layer as Channel on SiC*

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Abstract: AlGaN/AlN/GaN high electron mobility transistor (HEMT) structures with a high-mobility GaN thin layer as a channel are grown on high resistive 6H-SiC substrates by metalorganic chemical vapor deposition. The HEMT structure exhibits a typical two-dimensional electron gas (2DEG) mobility of $1944cm^2/(V \cdot s)$ at room temperature and $11588cm^2/(V \cdot s)$ at 80K with almost equal 2DEG concentrations of about $1.03 \times 10^{13} cm^{-2}$. High crystal quality of the HEMT structures is confirmed by triple-crystal X-ray diffraction analysis. Atomic force microscopy measurements reveal a smooth AlGaN surface with a root-mean-square roughness of 0.27nm for a scan area of 10μm × 10μm. HEMT devices with 0.8μm gate length and 1.2mm gate width are fabricated using the structures. A maximum drain current density of 957mA/mm and an extrinsic transconductance of 267mS/mm are obtained.

Key words: AlGaN/GaN; HEMT; MOCVD; power device; SiC substrates
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1 Introduction

GaN-based wide band gap semiconductors have tremendous potential for applications in high power electronic and optoelectronic devices, which has prompted significant research in epitaxial growth and development[1~5]. Recently, AlGaN/GaN high electron mobility transistors (HEMTs) have attracted much attention due to their potential for high power, high temperature, and high frequency applications. SiC has a much higher thermal conductivity than sapphire and therefore is very promising as a high power device substrate. AlGaN/GaN HEMTs grown on SiC substrates[6~10] with record power performance have been reported. It has also been demonstrated that the two-dimensional electron gas (2DEG) mobility of AlGaN/AlN/GaN heterostructures can be dramatically improved by using a thin AlN interlayer between the GaN and AlGaN layers[10~13]. Shen *et al.*[10] reported a room temperature mobility of $1542cm^2/(V \cdot s)$ with a 2DEG concentration of $1.02 \times 10^{13} cm^{-2}$ for an AlGaN/AlN/GaN heterostructure grown on SiC substrate by metalorganic chemical vapor deposition (MOCVD).

Recently, we have successfully grown high quality AlGaN/GaN heterostructures on sapphire substrates[11~16]. In this paper, the growth and characterization of GaN-based HEMT structures on SiC substrates are investigated. By introducing a thin GaN layer with high mobility as the electron channel, we created an improved AlGaN/AlN/GaN HEMT structure that was grown on high resistive 6H-SiC substrate by MOCVD. The unintentionally doped GaN thin layer with high mobility was inserted between the AlN interlayer and the GaN high-resistive buffer layer, which was proved to further improve channel transport properties compared to our previously reported results[11~16]. By employing the combination of the GaN channel layer with high mobility and the AlN interlayer, we

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obtained high quality AlGaN/AlN/GaN HEMT structures on 6H-SiC substrates, whose 2DEG mobility and concentration at room temperature were 1944cm^2/(V·s) and 1.03 × 10^{13} cm^{-2}, respectively. HEMTs were successfully fabricated using these structures. A HEMT with a 0.8μm × 1.2mm gate periphery exhibited a maximum drain current density of 957mA/mm and an extrinsic transconductance of 267mS/mm.

2 Device structure and fabrication

The AlGaN/AlN/GaN HEMT structures with high mobility GaN thin layer as channel were grown on high resistive 6H-SiC substrates by MOCVD. A cross-section of the structure is shown in Fig. 1. The growth of the HEMT structure began with a thin AlN nucleation layer, followed by deposition of a 1.5μm undoped high resistive GaN buffer layer. Then a 100nm high mobility GaN channel layer, a 1nm AlN interlayer, and a 20nm undoped AlGaN barrier layer were grown in sequence. The thin undoped GaN channel layer with high mobility has a better crystal quality and therefore decreases electron scattering in the channel, which improves the 2DEG transport properties.

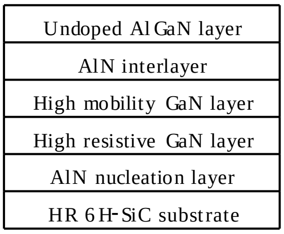

Fig. 1 Schematic cross section of the AlGaN/AlN/GaN/SiC HEMT structure with a high mobility GaN thin layer as channel grown by MOCVD

The crystalline qualities and structural properties of the samples were characterized by triple-crystal X-ray diffraction (TCXRD) measurements. Their surface morphology was analyzed by atomic force microscopy (AFM). Variable-temperature Hall effect measurements were performed using the Van der Pauw technique.

The HEMT structural materials were then processed into devices with gate lengths of 0.8μm and gate widths of 1.2mm. First, source and drain ohmic contacts were formed by rapid thermal annealing of electron-beam evaporated Ti/Al/Ti/Au in N_2 ambient. Then, device isolation was achieved by using multiple-energy helium ion implantation. Finally, the Schottky gate was defined by lift-off technology, with the gate metallization being realized by using electron-beam evaporated Ni/Au.

3 Results and discussion

Figure 2 shows the TCXRD spectrum of the HEMT structure. In the figure, four diffraction peaks are clearly observed. They were identified as GaN(0002), AlGaN(0002), SiC(0006), and AlN(0002), as shown in the figure. The full width at half maximum (FWHM) of the GaN(0002) peak was 3.9′ from the rocking curve measurement. This small value of the GaN FWHM was attributed to the high epitaxial quality of the GaN layer. The Al content in the AlGaN layer was determined to be about 18% by using Vegard's law of linearity of lattice constant composition for a ternary compound.

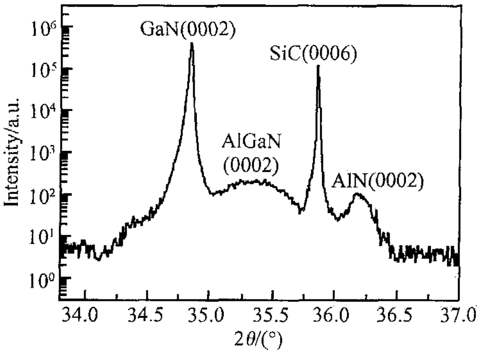

Fig. 2 TCXRD spectrum of the HEMT structure

The surface morphology of the HEMT structure was characterized by AFM and is shown in Fig. 3. The sample exhibited a very smooth surface with a root-mean-square roughness (RMS) of 0.27nm for a scan area of 10μm × 10μm. No cracks or obvious pits were observed in the surface of the sample. Surface pits in AlGaN/GaN HEMT structures usually indicate the surface termination of threading dislocations[17,18]. This shows that our AlGaN/AlN/GaN HEMT structures grown on 6H-SiC have both smooth surface morphology and high crystal quality.

Figure 4 shows the temperature dependence of the 2DEG mobility and concentration in the HEMT structure. The measured temperature varied from

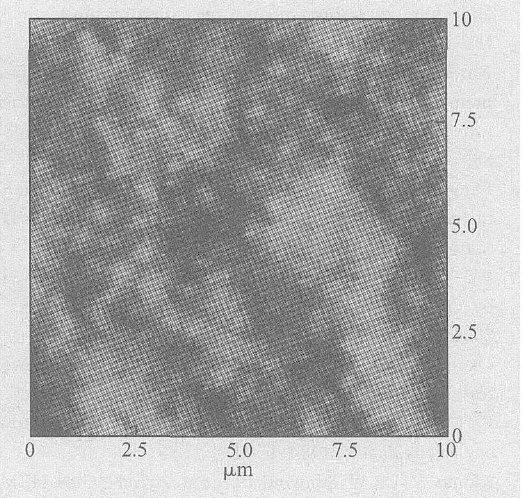

Fig. 3 AFM image of the surface of the HEMT structure

80 to 700K. 2DEG mobilities of 1944cm^2/(V·s) at room temperature and 11588cm^2/(V·s) at 80K were realized. As the temperature increased from room temperature, the mobility decreased slowly. The mobility was still as high as 968cm^2/(V·s) at 400K and 577cm^2/(V·s) at 500K, showing the potential of the HEMT structure for high temperature applications. The 2DEG concentration was almost independent of the temperature when the temperature varied from 80 to 700K. A concentration of 1.03×10^{13}cm^{-2} was achieved both at room temperature and 80K, indicating that the 2DEG was almost entirely confined in the channel. The excellent 2DEG transport properties were mainly attributed to three factors: (1) The high mobility GaN channel layer provided a high quality electron transport channel and therefore increased the 2DEG mobility, which was proved by the Hall measurement and our previously reported results[12~16]; (2) The insertion of a thin AlN interlayer increased the effective conduction band offset ΔE_c and reduced alloy disorder scattering from the AlGaN barrier layer. Thus it was very effective to suppress the electron penetration from the GaN channel into the AlGaN barrier and also increased the 2DEG mobility; (3) The use of 6H-SiC as substrate gave the epitaxial films better crystal quality due to its closer lattice match to GaN.

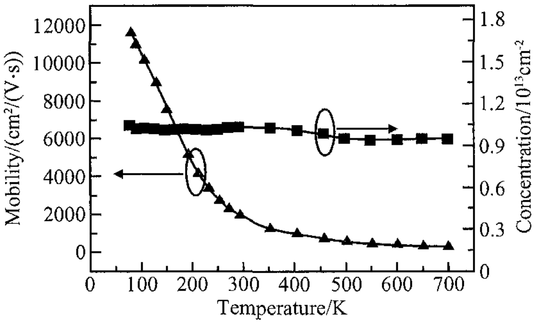

Fig. 4 Temperature dependence of the 2DEG mobility and concentration in the HEMT structure

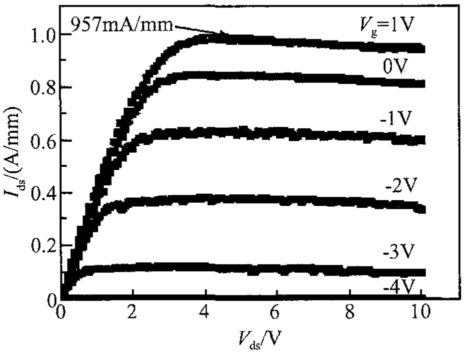

Fig. 5 Current-voltage (I_{ds}-V_{ds}) characteristics of the HEMT

The direct current (DC) characteristics of a typical device with a 0.8μm × 1.2mm gate periphery were measured using HP4155 semiconductor parameter analyzers. Figure 5 shows the typical current-voltage (I_{ds}-V_{ds}) characteristics of the device. The gate was biased from 1 to -4V in steps of -1V. The maximum drain current density was measured to be 957mA/mm at a gate bias of 1V. The device exhibited excellent pinch-off characteristics and pinched off completely at the gate bias of -4V. The knee voltage was between 3 and 4V. At gate biases of 1 and 0V, no obvious current drop was observed even for a gate bias of up to 10V. This was primarily due to effective heat sinking through the SiC substrate, which has excellent thermal conductivity. In contrast, at high current levels, a serious self-heating phenomenon was observed in the HEMTs grown on sapphire due to the poor thermal conductivity of sapphire substrate, limiting the maximum drain current and output power[19]. The DC transfer characteristics of the same device are shown in Fig. 6. At a gate bias of -2.8V, a maximum extrinsic transconductance of 267mS/mm was measured, which was much higher than the transconductance of 200mS/mm previously obtained on devices using sapphire as substrate[16]. The improved DC performance suggested the excellent current handling capability of the devices, resulting from the combination of high thermal conductivity of SiC and further improvement of the material quality.

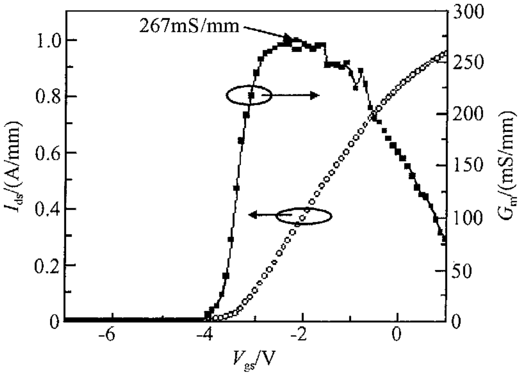

Fig. 6 Transfer characteristics of the HEMT

4 Conclusion

High quality AlGaN/AlN/GaN HEMT structures with high mobility GaN thin layer as channel were grown on 50mm high resistive 6H-SiC substrates by MOCVD. Based on these structures, devices with a 0.8μm ×1.2mm gate periphery were fabricated successfully. High 2DEG mobilities of $1944cm^2/(V \cdot s)$ at room temperature and $11588cm^2/(V \cdot s)$ at 80K were achieved with almost equal 2DEG concentrations of about $1.03 \times 10^{13} cm^{-2}$. AFM measurement revealed a smooth AlGaN surface with an RMS of 0.27nm for a scan area of 10μm ×10μm. The device exhibited a maximum drain current density of 957mA/mm and an extrinsic transconductance of 267mS/mm. The results clearly suggest that the HEMT structure is of high quality and is promising in device fabrication, due to the combined employing of the high mobility GaN channel layer, AlN interlayer, SiC substrate, and optimized growth parameters.

References

[1] Asif Khan M, Bhattarai A, Kuznia J N, et al. High electron mobility transistor based on a GaN-$Al_xGa_{1-x}N$ heterojunction. Appl Phys Lett, 1993, 63(9): 1214

[2] Miyoshi M, Ishikawa H, Egawa T, et al. High-electron-mobility AlGaN/AlN/GaN heterostructures grown on 100-mm-diam epitaxial AlN/sapphire templates by metal organic vapor phase epitaxy. Appl Phys Lett, 2004, 85(10): 1710

[3] Xiao Hongling, Wang Xiaoliang, Wang Junxi, et al. Growth and characterization of InN on sapphire substrate by RF-MBE. J Cryst Growth, 2005, 276: 401

[4] Ran Junxue, Wang Xiaoliang, Hu Guoxin, et al. Study on Mg memory effect in npn type AlGaN/GaN HBT structures grown by MOCVD. Microelectronics Journal, 2006, 37(7): 583

[5] Fang Cebao, Wang Xiaoliang, Wang Junxi, et al. Deep levels in high resistivity GaN epilayers grown by MOCVD. Phys Status Solidi C, 2006, 3(3): 585

[6] Wu Y F, Saxler A, Moore M, et al. 30-W/mm GaN HEMTs by field plate optimization. IEEE Electron Device Lett, 2004, 25(3): 117

[7] Okamoto Y, Ando Y, Hataya K, et al. Improved power performance for a recessed-gate AlGaN-GaN heterojunction FET with a field-modulating plate. IEEE Trans Microw Theory Tech, 2004, 52(11): 2536

[8] Kumar V, Lu W, Schwindt R, et al. AlGaN/GaN HEMTs on SiC with f_T of over 120GHz. IEEE Electron Device Lett, 2002, 23(8): 455

[9] Chini A, Coffie R, Meneghesso G, et al. 2.1A/mm current density AlGaN/GaN HEMT. Electron Lett, 2003, 39(7): 625

[10] Shen L, Heikman S, Moran R, et al. AlGaN/AlN/GaN high-power microwave HEMT. IEEE Electron Device Lett, 2001, 22(10): 457

[11] Wang Xiaoliang, Wang Cuimei, Hu Guoxin, et al. Room temperature mobility above $2100cm^2/(V \cdot s)$ in $Al_{0.3}Ga_{0.7}N$/AlN/GaN heterostructures grown on sapphire substrates by MOCVD. Phys Status Solidi C, 2006, 3(3): 607

[12] Wang Cuimei, Wang Xiaoliang, Hu Guoxin, et al. The effect of AlN growth time on the electrical properties of $Al_{0.38}$-$Ga_{0.62}N$/AlN/GaN HEMT structures. J Cryst Growth, 2006, 289(2): 415

[13] Wang Cuimei, Wang Xiaoliang, Hu Guoxin, et al. Influence of AlN interfacial layer on electrical properties of high-Al-content $Al_{0.45}Ga_{0.55}N$/GaN HEMT structure. Appl Sur Sci, Available online 20 February 2006

[14] Wang Xiaoliang, Liu Xinyu, Hu Guoxin, et al. X-band GaN power HEMTs with power density of 2.23W/mm grown on sapphire by MOCVD. Chinese Journal of Semiconductors, 2005, 26(10): 1865

[15] Wang Xiaoliang, Wang Cuimei, Hu Guoxin, et al. Improved DC and RF performance of AlGaN/GaN HEMTs grown by MOCVD on sapphire substrates. Solid-State Electron, 2005, 49(8): 1387

[16] Wang Xiaoliang, Wang Cuimei, Hu Guoxin, et al. Growth and characterization of 0.8-μm gate length AlGaN/GaN HEMTs on sapphire substrates. Science in China Ser F, 2005, 48(6): 808

[17] Heying B, Tarsa E J, Elsass C R, et al. Dislocation mediated surface morphology of GaN. J Appl Phys, 1999, 85(9): 6470

[18] Zhang A P, Rowland L B, Kaminsky E B, et al. Correlation of device performance and defects in AlGaN/GaN high-electron mobility transistors. Journal of Electronic Materials, 2003, 32(5): 388

[19] Gaska R, Osinsky A, Yang J W, et al. Self-heating in high-power AlGaN-GaN HFETs. IEEE Electron Device Lett, 1998, 19(3): 89

MOCVD 生长的 SiC 衬底高迁移率 GaN 沟道层 AlGaN/AlN/GaN HEMT 结构*

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摘要: 用 MOCVD 技术在高阻 6H-SiC 衬底上研制出了具有高迁移率 GaN 沟道层的 AlGaN/AlN/GaN 高电子迁移率晶体管(HEMT)结构材料,其室温和 80K 时二维电子气迁移率分别为 1944 和 $11588\mathrm{cm}^2/(\mathrm{V}\cdot\mathrm{s})$,相应二维电子气浓度为 $1.03\times10^{13}\mathrm{cm}^{-2}$;三晶 X 射线衍射和原子力显微镜分析表明该材料具有良好的晶体质量和表面形貌,$10\mu\mathrm{m}\times10\mu\mathrm{m}$ 样品的表面粗糙度为 0.27nm.用此材料研制出了栅长为 $0.8\mu\mathrm{m}$,栅宽为 1.2mm 的 HEMT 器件,最大漏极饱和电流密度和非本征跨导分别为 957mA/mm 和 267mS/mm.

关键词: AlGaN/GaN; 高电子迁移率管; MOCVD; 功率器件; 碳化硅衬底
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