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# X-Band GaN Power HEMTs with Power Density of 2.23W/mm Grown on Sapphire by MOCVD*

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**Abstract:** The growth, fabrication, and characterization of 0.2μm gate-length AlGaN/GaN HEMTs, with a high mobility GaN thin layer as a channel, grown on (0001) sapphire substrates by MOCVD, are described. The unintentionally doped 2.5μm thick GaN epilayers grown with the same conditions as the GaN channel have a room temperature electron mobility of $741cm^2/(V \cdot s)$ at an electron concentration of $1.52 \times 10^{16} cm^{-3}$. The resistivity of the thick GaN buffer layer is greater than $10^8 \Omega \cdot cm$ at room temperature. The 50mm HEMT wafers grown on sapphire substrates show an average sheet resistance of 440.9Ω/□ with uniformity better than 96%. Devices of 0.2μm × 40μm gate periphery exhibit a maximum extrinsic transconductance of 250mS/mm and a current gain cutoff frequency of 77GHz. The AlGaN/GaN HEMTs with 0.8mm gate width display a total output power of 1.78W (2.23W/mm) and a linear gain of 13.3dB at 8GHz. The power devices also show a saturated current density as high as 1.07A/mm at a gate bias of 0.5V.

**Key words:** AlGaN/GaN; HEMT; MOCVD; power device
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## 1 Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) have recently attracted much attention due to their 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 ($3 \times 10^6 V/cm$), and extremely high peak ($3 \times 10^7 cm/s$) and saturation velocity ($1.5 \times 10^7 cm/s$)[6]. These properties in combination with the large conduction band offset and the high-density two-dimensional electron gas (2DEG) on the order of $10^{13} cm^{-2}$ at the AlGaN/GaN interface, make the AlGaN/GaN heterostructures superior to conventional semiconductor heterostructures such as GaAs-based and InP-based ones in the field of high power and high temperature microelectronic devices[1,4]. Such semiconductor devices are very attractive for power applications at X-band and even above.

In recent years, tremendous progress has been made in the DC and RF performance of GaN based HEMTs due to improving crystal quality in Al-

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GaN/ GaN structures and optimization of device processing. AlGaN/ GaN HEMTs grown on SiC substrates with dimensions of 0.55μm ×246μm and a field-plate length of 1.1μm have already demonstrated a continuous wave output power density of 32.2W/ mm and power-added efficiency (PAE) of 54.8% at 4GHz; devices with a shorter field plate of 0.9μm also generated 30.6W/ mm with 49.6% PAE at 8GHz[7]. A current gain cutoff frequency ($f_T$) of 121GHz and maximum frequency of oscillation ($f_{max}$) of 162GHz were measured on the AlGaN/ GaN HEMT with a 0.12μm gate-length grown on SiC substrate[8].

We have previously reported RF-MBE grown AlGaN/ GaN HEMTs with gate length and width of 1 and 80μm, respectively, and obtained a drain-current density of 925mA/ mm, a peak transconductance of 186mS/ mm, and a $f_T$ of 18.8GHz[9]. We have also reported a RF-MBE grown AlGaN/ GaN HEMT with high Al content[10]. In this paper, X-Band AlGaN/ GaN power HEMTs with a power density of 2.23W/ mm at 8GHz grown by metal organic chemical vapor deposition (MOCVD) on sapphire substrates are reported. To raise the 2DEG mobility in the channel, an unintentionally doped GaN thin layer with high mobility was inserted between AlGaN barrier and GaN buffer with high resistivity. The 50mm HEMT wafers with this structure grown on (0001) sapphire substrates by MOCVD exhibit a sheet resistance of 440.9Ω/ □ with uniformity better than 96%. The HEMT devices with 0.2μm ×40μm gate periphery fabricated using the epi-wafers exhibit a maximum extrinsic transconductance of 250mS/ mm and a $f_T$ of 77GHz. The AlGaN/ GaN HEMTs with 0.8mm gate widths display a total output power of 1.78W (2.23W/ mm) and a linear gain of 13.3dB at 8GHz. The power devices also show a saturated current density as high as 1.07A/ mm at a gate bias of 0.5V.

## 2 Structure growth and device fabrication

The AlGaN/ GaN HEMT structures were grown on (0001) sapphire substrates by MOCVD. The cross-section of the HEMT devices is shown in Fig. 1. The growth of the structure began with an unintentionally doped 2.8μm thick high resistive GaN buffer layer, followed by an undoped 110nm thick GaN layer with high mobility as the channel layer. Finally, about 5nm undoped and 150 nm Si-doped AlGaN barrier layers were grown. In contrast to a conventional AlGaN/ GaN HEMT structure, this AlGaN/ GaN HEMT structure employed an undoped high mobility GaN thin layer as the channel layer, which significantly enhancing the mobility of the 2DEG in the channel, and therefore helping to improve the performances of the fabricated AlGaN/ GaN HEMT devices.

The HEMT structural materials were then processed into devices with a source-drain spacing of 3μm and a gate length of 0.2μm. First, the device isolation was achieved by using multiple-energy helium ion implantation. Then, source and drain ohmic contacts were formed by rapid thermal annealing of electron-beam evaporated Ti/ Al/ Ti/ Au in $N_2$ ambient at 750 ℃ for 30s. Finally, the Schottky gate was defined by lift-off technology and the gate metallization was realized by using electron-beam evaporated Pt/ Ti/ Au.

## 3 Results and discussion

To improve 2DEG transport properties of the AlGaN/ GaN HEMT structure, an unintentionally doped 110nm thick GaN layer with high electron mobility was introduced into the HEMT structure. This thin GaN layer was grown between the AlGaN barrier layer and the thick high resistive GaN buffer layer, using the identical growth conditions to those of the 2.5μm thick bulk GaN epilayers. The variable-temperature Hall measurement re-

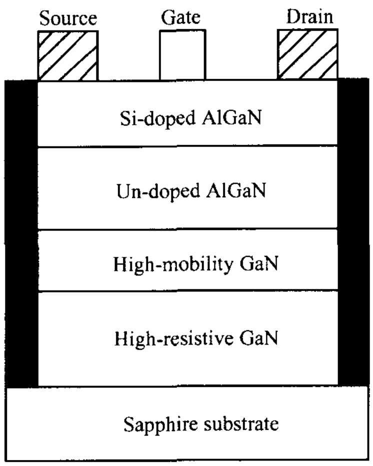


Fig. 1　Schematic cross section of an AlGaN/GaN HEMT

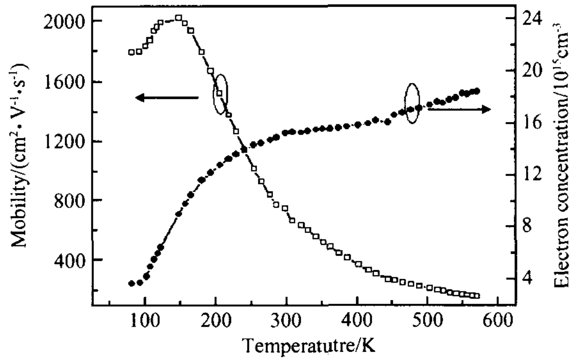


Fig. 2　Electron mobility and concentration as a function of sample temperature for an unintentionally doped 2.5mm thick bulk GaN epilayer on sapphire

sults for the 2.5μm thick bulk GaN epilayer are shown in Fig. 2. From this figure we know that the room temperature Hall mobility of the bulk GaN film grown on sapphire substrate is as high as $741cm^2/(V \cdot s)$ at a background electron concentration of only $1.52 \times 10^{16} cm^{-3}$. As the temperature decreases, the Hall mobility increases gradually, up to its maximum value $2020cm^2/(V \cdot s)$ at 149K, and then decreases. The background electron concentration will increase with raising temperature. To the best of our knowledge, the obtained room temperature mobility value for the unintentionally doped 2.5μm-thick bulk GaN is one of the best results in the world using the same growth technique. The HEMT devices will benefit from the HEMT structure, with the thin GaN layer as the channel, which was grown using the same growth conditions as those of the thick bulk GaN layer with high mobility.

As shown in Fig. 1, just below the GaN channel layer with high mobility, there is a thick GaN buffer layer. The first priority of this layer is to have high resistivity to prevent current leakage between source and drain. Using unintentionally doped growth technique, which we have applied for patent, we successfully achieved high resistive GaN layer on sapphire substrate. Its electrical resisitivity dependence on temperature is shown in Fig. 3. From this figure we acquire that the resistivity of the GaN buffer is $2.9 \times 10^8 \Omega \cdot cm$ at room temperature, which corresponding to a sheet resistance larger than $10^{12} \Omega/\square$, about three orders of magnitude higher than the sheet resistance value ($10^9 \Omega/\square$) reported by Lee *et al.* [11]. When the temperature is increased to 673K, the resistivity of the GaN buffer is $2 \times 10^5 \Omega \cdot cm$. Therefore, even at high temperatures, the GaN buffer layer has high resisitivity and can effectively prevent leakage current between source and drain from happening. For high power devices or high operation temperatures, this is very important.

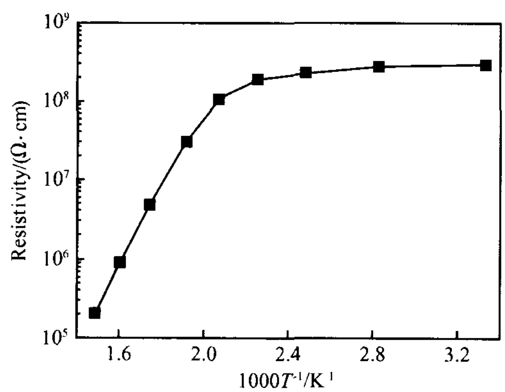


Fig. 3　Temperature dependence of the electrical resistivity of the 2.8μm thick GaN buffer layer grown on sapphire substrates by MOCVD

Sheet resistance mapping of the grown AlGaN/GaN HEMT wafer was conducted by a Lehighton Electronics using a contact-less measurement system. The measured sheet resistance map for the 50mm HEMT wafer is shown in Fig. 4. The wafer exhibits a maximum resistance of 467.3Ω/□ and a minimum value of 417.3Ω/□. The average sheet resistance is 440.9Ω/□, with the resistance uniformity being 96.5%.

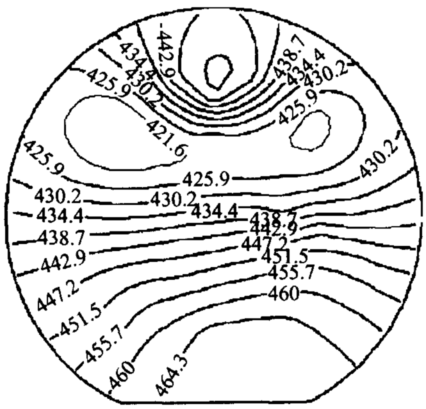


Fig. 4 Sheet resistance mapping of the grown 50mm AlGaN/GaN HEMT wafer

The direct current (DC) characteristics of the AlGaN/GaN HEMT devices fabricated with the 50mm HEMT wafer were measured using HP4142 and HP4155 semiconductor parameter analyser. Shown in Fig. 5 is a typical drain current-voltage ($I_{ds}$-$V_{ds}$) characteristics measured for a device with gate length and width of 0.2μm and 0.8mm, respectively. The source-drain spacing of the device is 3μm. The gate is biased from 0.5 to -5V in the step of -0.5V. The device exhibited a maximum drain current density of 1.07A/mm at a gate bias of 0.5V. The pinch-off voltage of this device was about -5V and the knee voltage was between 4 ~ 5V. At high current levels significant self-heating of the devices took place for the poor thermal conductivity of sapphire substrates, limiting the maximum drain current. This makes it clear that SiC should 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.

DC transfer characteristics of a typical 0.2μm ×40μm AlGaN/GaN HEMT are shown in Fig. 6, which was measured when the drain-to-source voltage was kept at 6V. On this figure, the drain current and transconductance are plotted against gate bias voltage. It is obvious that this device has reached a maximum extrinsic transconductance of 250mS/mm at $V_g$ = -4.5V. As the gate bias voltage increases, the drain current will increase and incline to saturate gradually. Whereas the transconductance exhibits a different variation tendency: it increases rapidly first, up to its maximum value, and then decreases.

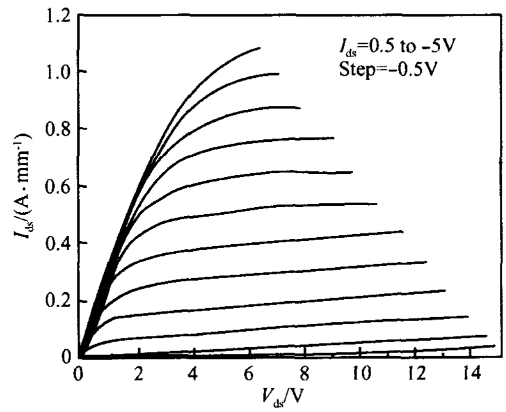


Fig. 5 $I_d$-$V_{ds}$ characteristics of a typical AlGaN/GaN HEMT grown on sapphire substrate with gate length and width of 0.2μm and 0.8mm, respectively

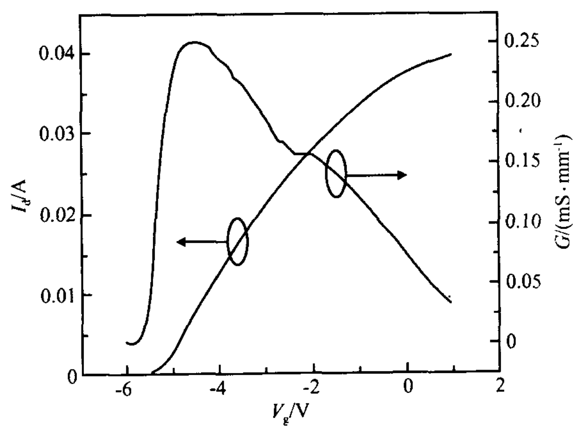


Fig. 6 DC transfer characteristics of a typical AlGaN/GaN HEMT grown on sapphire substrate with gate length and width of 0.2 and 40μm, respectively

To investigate high frequency characteristics of the devices, small-signal $S$-parameter measurements were made. From the $S$-parameters, current gain $h_{(2,1)}$ can be calculated. Figure 7 shows the small signal frequency response from the typical 0. 2μm ×40μm AlGaN/ GaN HEMT device. An extrinsic $f_T$ of 77GHz was extrapolated. We believe that such a high $f_T$ can be partly attributed to the insertion of the thin high mobility GaN layer between the AlGaN barrier and the high resistive GaN buffer layer.

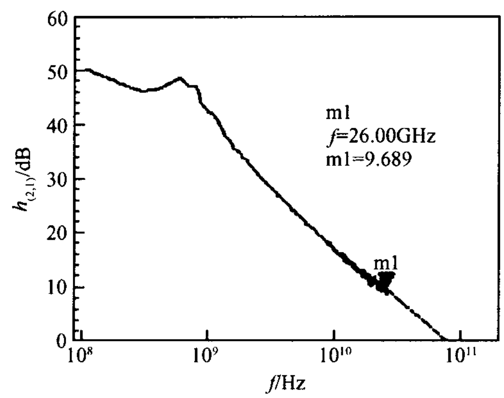


Fig. 7 Small signal RF characteristic of the 0. 2μm × 40μm AlGaN/ GaN HEMT device

On-wafer power measurements at 8GHz were performed using a focus load-pull system. The power performance of the 0. 2μm ×0. 8mm device biased at $V_{ds}$ = 30V is shown in Fig. 8. The device had a linear gain of 13. 3dB. The measured continuous wave (CW) output power is 32. 5dBm (1. 78W) and the corresponding output power density is 2. 23W/ mm.

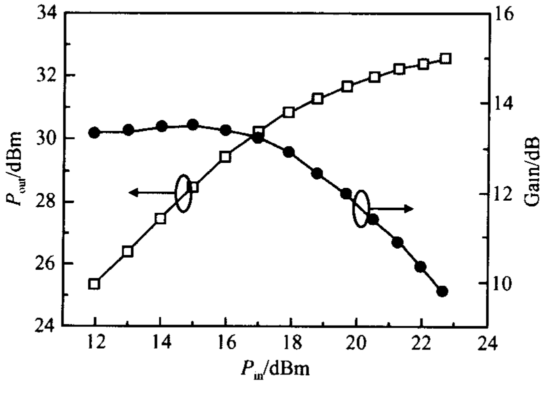


Fig. 8 Power performance of the 0. 2μm ×0. 8mm AlGaN/ GaN HEMT at 8GHz The device was biased at $V_{ds}$ = 30V.

## 4 Conclusion

50mm AlGaN/ GaN HEMT wafers with a high mobility GaN thin layer as the channel are grown by MOCVD on (0001) sapphire substrates and 0. 2μm gate-length HEMT devices are fabricated. The unintentionally doped bulk GaN epilayers with thickness of 2. 5μm have a room temperature mobility of $741cm^2/(V·s)$ at an electron concentration of $1.52 \times 10^{16} cm^{-3}$. The resistivity of the GaN buffer layer is greater than $10^8 \Omega·cm$ at room temperature. The 50mm HEMT wafer shows an average sheet resistance of 440. 9Ω/ □ with uniformity better than 96 %. The fabricated HEMT devices exhibit a high drain current and DC transconductance of 1. 07A/ mm and 250mS/ mm, respectively. The current-gain cut-off frequency of the devices with gate width of 40μm is measured to be about 77GHz. The devices with gate width of 0. 8 mm also display a high total output power of 1. 78 W (2. 23 W/ mm) with a linear gain of 13. 3dB at 8 GHz. Our results show that GaN HEMT with a thin layer of high mobility GaN as a channel between the AlGaN barrier and the high resistive GaN buffer layer has strong potential for power applications at X-band frequencies.

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# 输出功率密度为 2.23W/ mm 的 X 波段 AlGaN/ GaN 功率 HEMT 器件 *

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**摘要**: 用 MOCVD 技术在蓝宝石衬底上制备出具有高迁移率 GaN 沟道层的 AlGaN/ GaN HEMT 材料. 高迁移率 GaN 外延层的室温迁移率达 $741 cm^2/(V \cdot s)$ ,相应背景电子浓度为 $1.52 \times 10^{16} cm^{-3}$ ;非有意掺杂高阻 GaN 缓冲层的室温电阻率超过 $10^8 \Omega \cdot cm$ ,相应的方块电阻超过 $10^{12} \Omega/\square$. 50mm HEMT 外延片平均方块电阻为 $440.9\Omega/\square$, 方块电阻均匀性优于 96 %. 用此材料研制出了 0.2μm 栅长的 X 波段 HEMT 功率器件 ,40μm 栅宽的器件跨导达到 250mS/ mm ,特征频率 $f_T$ 为 77GHz ;0.8mm 栅宽的器件电流密度达到 1.07A/ mm ,8GHz 时连续波输出功率为 1.78W ,相应功率密度为 2.23W/ mm ,线性功率增益为 13.3dB.

**关键词**: AlGaN/ GaN ; 高电子迁移率晶体管 ; MOCVD ; 功率器件
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