Growth and characterization of 0.8-μm gate length AlGaN/GaN HEMTs on sapphire substrates

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Abstract AlGaN/GaN high electron mobility transistor (HEMT) structures were grown on 2 inch sapphire substrates by MOCVD, and 0.8-μm gate length devices were fabricated and measured. It is shown by resistance mapping that the HEMT structures have an average sheet resistance of approximately 380 Ω/sq with a uniformity of more than 96%. The 1-mm gate width devices using the materials yielded a pulsed drain current of 784 mA/mm at V_{gs}=0.5 V and V_{ds}=7 V with an extrinsic transconductance of 200 mS/mm. A 20-GHz unity current gain cutoff frequency (f_T) and a 28-GHz maximum oscillation frequency (f_{max}) were obtained. The device with a 0.6-mm gate width yielded a total output power of 2.0 W/mm (power density of 3.33 W/mm) with 41% power added efficiency (PAE) at 4 GHz.

Keywords: HEMT, GaN, MOCVD, power device.

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GaN-based high electron mobility transistors (HEMTs) are promising devices for high power and high temperature applications[1−4]. Improvements over the years in material growth and device design have produced state-of-the-art AlGaN/GaN HEMTs with continuous output power densities greater than 30 W/mm^{3}. However, despite the impressive achievements, there exist some problems in developing the devices for application purposes, such as the current leakage through the GaN buffer layer[5], the high gate leakage at the elevated temperature[6,7], and the reduction in current available at high frequency compared to dc conditions[1,8]. Stacia Keller et al.[9] have developed a two-step process to grow the semi-insulating GaN buffer layer to mitigate the buffer current leakage. Surface passivation, using a dielectric layer for channel passivation or/and gate insulator, can reduce both the gate leakage and current dispersion problems to a certain

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extent[5,10−12]. But, the specific reasons responsible for the dispersion and the physical mechanisms by which the passivation reduces these problems are still not well known. Further investigations towards high quality heterostructurs and optimal device structures for powerful and reliable AlGaN/GaN HEMTs are required. Recently, we have successfully grown high quality AlGaN/GaN heterostructures by molecular beam epitaxy (MBE)[13,14]. In this paper, we report on the metal organic chemical vapor deposition (MOCVD) growth high quality and uniformity HEMT structures. The semi-insulating GaN buffer layer is prepared using a special two-step process to decrease the current leakage through the buffer and enhance the device performance. The devices with 0.8-μm gate length but different gate widths are fabricated and characterized.

1 Material growths and device fabrication

Fig. 1 shows a schematic drawing depicting the structure of the HEMT. The whole structure was grown by MOCVD on c-plane sapphire substrates with the 2-inch diameter. The growth process began with a 20-nm-thick GaN nucleation layer, followed by an unintentionally doped 3.6-μm-thick GaN buffer layer, a 30-nm-thick undoped AlGaN barrier layer. The Al content of the barrier layer was determined to be 30%. The first 20-nm-thick GaN nucleation layer was deposited at 400—500℃ to ensure complete wetting of the substrate before the temperature was raised above 1000℃ for the growth of the main GaN buffer layer. To minimize the current leakage through the buffer and to facilitate device pinch-off, the unintentionally doped 3.6-μm-thick main GaN buffer constituted two layers: a 3.5-μm-thick highly resistive (HR) GaN layer deposited at low pressure and a 100-nm-thick high mobility GaN channel layer deposited at higher pressure than that of the HR layer. The HR layer has a high resistivity of about 6.6×10^8

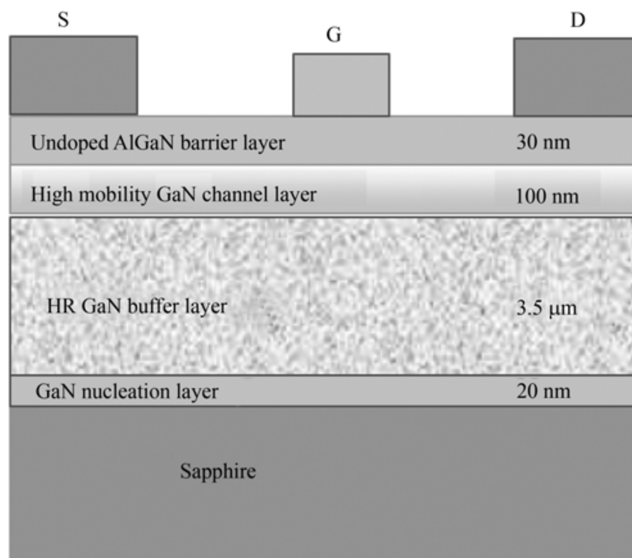

Fig. 1. Schematic cross section of the AlGaN/GaN HEMT structure.

$\Omega \cdot$cm at room temperature (RT), which can effectively prevent the current leakage from happening. The 100-nm-thick high mobility GaN channel layer is of better quality than that of the HR layer. Therefore, the sheet electron mobility is raised and the sheet resistance of the HEMT structures is reduced. These changes will improve the HEMT performances.

The basic device fabrication included mesa isolation in an inductively-coupled-plasma reactive ion etch (ICP-RIE) system, ohmic contacts formation using Ti/Al/Ti/Au and gate formation by Pt/Ti/Au. With on-wafer transfer length method (TLM) patterns, the ohmic contact resistance was typically $8.86\times10^{-6}\ \Omega \cdot \mathrm{cm}^2$. The gate length of the devices tested was 0.8 μm while the gate widths were 0.6 and 1 mm. Silicon nitride (Si_3N_4) was finally deposited to passivate the devices.

2 Results and discussion

The sheet resistance mapping of the wafer was conducted by Lehighton Electronics using a contact-less measurement system. The measured sheet resistance map of the 2 inch HEMT wafer is shown in Fig. 2. The wafer exhibits a maximum resistance of 401.5 Ω/sq and a minimum value of 359.5 Ω/sq. The average sheet resistance is 380.4 Ω/sq, with the resistance uniformity better than 96%. As we all know, the 2DEG of undoped AlGaN/GaN structure is formed by the piezoelectric effect and spontaneous polarization of materials, so the variation of the sheet resistance is mainly caused by the fluctuation

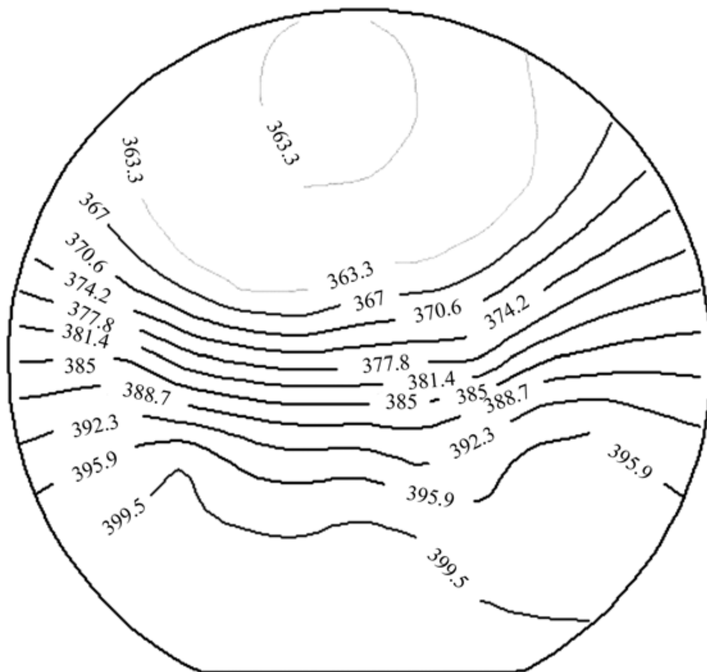

Fig. 2. Sheet resistance mapping of the AlGaN/GaN HEMT structure grown on 2 inch sapphire substrate. The average sheet resistance is 380.4 Ω/sq, with the resistance uniformity better than 96%.

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of aluminum composition and the thickness of the AlGaN layer. The sheet resistance is also an accurate measure of the charge and mobility in the 2DEG of the HEMT structure (proportional to the inverse of sheet charge times mobility). For comparison, we have taken multiple Hall measurement across the whole wafer. The typical sheet carrier concentration and electron mobility is 1.04×10^{13} cm^{-2} and 1575 cm^2/Vs, respectively, which is in good agreement with the results of sheet resistance mapping. These results indicate a high quality and uniformity of the HEMT structure.

The DC characteristics of a 0.8-μm gate length, 1-mm gate width device were measured and the results are shown in Fig. 3. Fig. 3(a) shows the typical DC and pulsed drain current-voltage (*I-V*) characteristics of the device. The gate bias (V_{gs}) applied to the device ranged from 0.5 to −5 V in steps of 0.5 V. The knee voltage is less than 5 V, indicating a good nature of the ohmic contacts. At the gate bias of 0.5 V and drain bias of 6 V, the maximum drain current density is measured to be 784 and 670 mA/mm under pulsed and DC gate bias conditions, respectively. No current dispersion is observed from

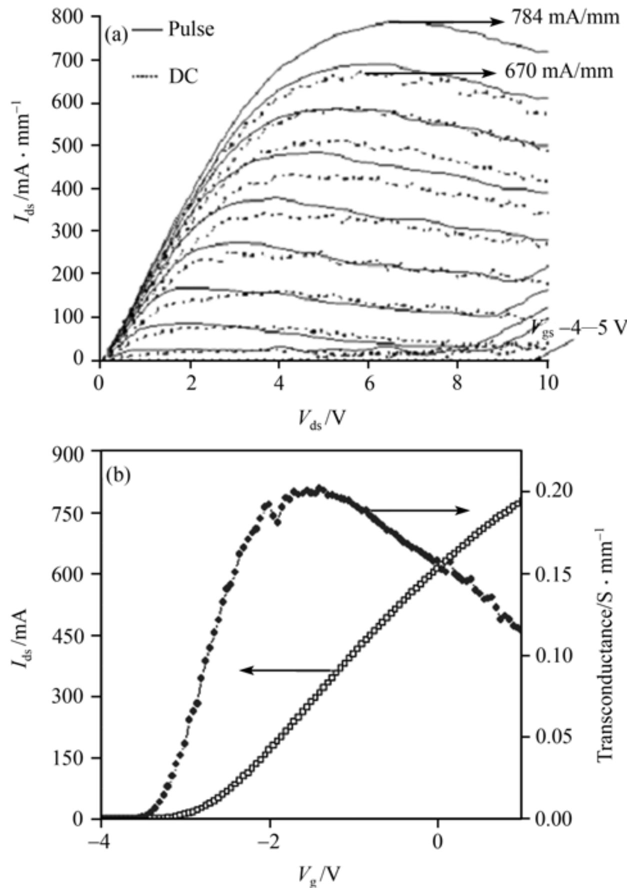

Fig. 3. (a) *I-V* characteristics of the 0.8 μm×1 mm AlGaN/GaN HEMT under DC and pulsed gate bias. The gate bias was swept from −5 to 0.5 V in a step of 0.5 V. (b) Transfer characteristics of the 0.8 μm×1 mm AlGaN/GaN HEMT. The drain bias was 6.0 V.

the pulse measurement at the measured frequency. The distinct reduction of the drain current between DC and pulsed values is attributed to self-heating of the device, which originates from the poor thermal conductivity of sapphire substrate. The same effect also accounts for the current drop at high bias. However, the current is still pinch off completely at about –4 V gate bias. Fig. 3(b) presents the DC transfer characteristics of the devices at the drain bias of 6 V. A peak extrinsic transconductance of 200 mS/mm was measured at the gate bias of −1.8 V, suggesting the high channel current modulation efficiency.

High-frequency S-parameters of the devices have also been measured with a HP8510C network analyzer and Agilent ICCAP system. Fig. 4 shows the short circuit current gain (h_{21}) (Fig. 4(a)) and the maximum available power gain (MAG) (Fig. 4(b)) derived from the S-parameters measurements. From the figure, an f_T value of 20 GHz and an f_{max} value over 28 GHz can be extrapolated.

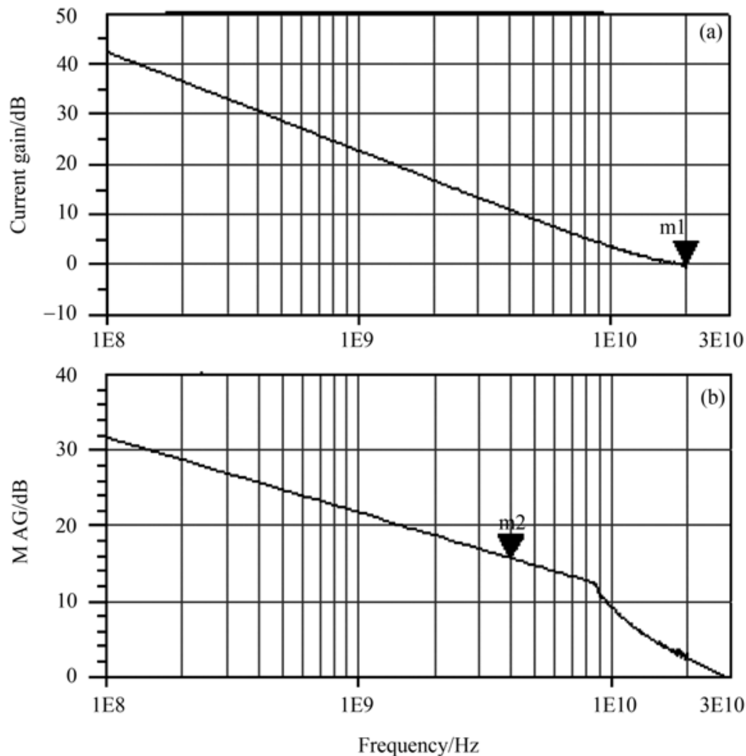

Fig. 4. (a) Short-circuit current gain (h_{21}); (b) maximum available gain (MAG) of the 0.8 μm×1 mm AlGaN/GaN HEMT.

Finally, the large signal power performance of the device is characterized using a load-pull system at 4 GHz. Fig. 5 shows the measured results for a 0.6-mm gate width device. It is biased at 20 V on the drain and −3 V on the gate. At an input power of 21 dBm, the output power is 33.01 dBm (2.0 W), corresponding to a power density of 3.33

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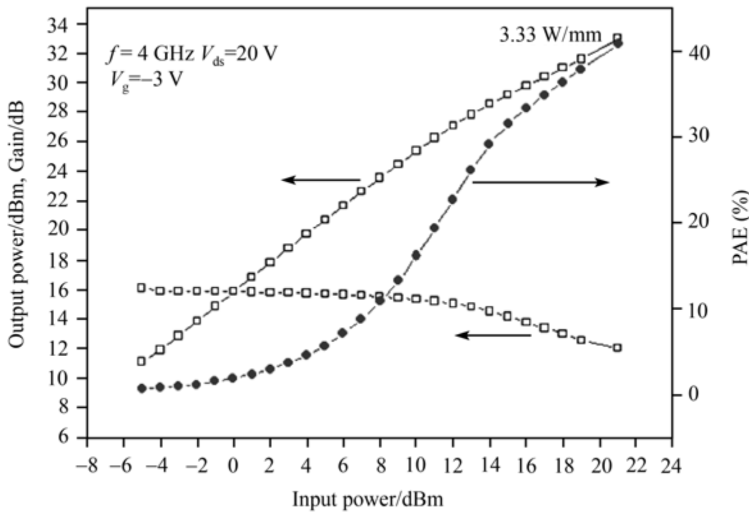

Fig. 5. Large-signal characteristics of the 0.8 μm×0.6 mm device measured at 4 GHz.

W/mm. The associated power gain and PAE are 12.01 dB and 41%, respectively. The slight gain compression in the figure is attributed to the effectiveness of the HR GaN layer adopted to prevent the current leakage through the buffer layer, so the signal swing is increased. It should be noted that the output power has not yet been saturated. The PAE continues to increase even at the highest input drive used in this measurement.

3 Conclusion

High quality and uniform AlGaN/GaN HEMT structures have been successfully grown on 2 inch sapphire substrates using MOCVD, based on which, 0.8-μm gate length devices are fabricated. Using a two-step growth process, the GaN buffer layer is made to constitute a HR layer and a high mobility layer, which could effectively decrease the leakage current through the buffer and ensure a good performance of the devices. The sheet resistance mapping reveals an average sheet resistance of approximately 380 Ω/sq with a uniformity of more than 96%. The pulsed current density of 784 mA/mm, transconductance of 200 mS/mm, f_T value of 20 GHz, and f_{max} value over 28 GHz are obtained for the fabricated 0.8-μm gate length, 1-mm gate width device. For a 0.6-mm gate width device, the measured total output power and PAE are 2.0 W (3.33 W/mm) and 41% at 4 GHz, respectively.

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