Recessed gate AlGaN/GaN modulation-doped field-effect transistors on sapphire

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A recessed gate AlGaN/GaN modulation-doped field-effect transistor (MODFET) has been grown on a sapphire substrate by metalorganic chemical vapor deposition. The two-dimensional electron gas mobility as high as 9260 $cm^2/V\,s$ with the sheet carrier density $4.8\times10^{12}\,cm^{-2}$ was measured at 4.6 K for the AlGaN/GaN heterostructure on the sapphire substrate. The recessed gate device showed the maximum extrinsic transconductance 146 mS/mm and drain-source current 900 mA/mm for the AlGaN/GaN MODFET with a gate length 2.1 μm at 25 °C. At an elevated temperature of 350 °C, the maximum extrinsic transconductance and drain-source current were 62 mS/mm and 347 mA/mm, respectively. [S0003-6951(00)01401-7]

AlGaN/GaN modulation-doped field-effect transistors (MODFETs) are useful for devices operating under high-power, high-frequency and high-temperature conditions due to large sheet carrier density, small gate leakage, and large breakdown voltage.[1,2] It is substantial to improve the two-dimensional electron gas (2DEG) mobility and reduce the parasitic source resistance for fabrication of high-performance AlGaN/GaN MODFETs. However, the $Al_xGa_{1-x}N$/GaN heterostructures grown on sapphire exhibited lower 2DEG mobilities than those on SiC because of 13.8% lattice mismatch between sapphire and GaN.[3] To minimize the parasitic source resistances, the recessed gate process has been applied for the GaN-based FETs.[4,5] The transconductances of 41 mS/mm for the GaN metal–semiconductor field-effect transistor (MESFET) with the gate length (L_g) 1.3 μm and 45 mS/mm for the AlGaN/GaN MODFET with $L_g=0.4\,\mu$m were reported by use of the recessed gate process. On the other hand, we have shown that the conventional GaN MESFET exhibited the maximum transconductance of 33 mS/mm for the gate length of 2 μm.[6] Thus, previous devices do not show the sufficient performance although they were fabricated by use of the recessed gate process. Further advances in performance of AlGaN/GaN MODFETs are expected to occur with improvements in 2DEG mobility at the AlGaN/GaN heterointerface with low source resistance. In this study we have achieved the transconductance as high as 146 mS/mm for the AlGaN/GaN MODFET with the gate length of 2.1 μm on sapphire by use of the high-quality AlGaN/GaN heterostructure and recessed gate process.

Figure 1 shows the cross-sectional structure of the $Al_{0.26}Ga_{0.74}N$/GaN MODFET grown on a (0001) sapphire substrate by metalorganic chemical vapor deposition (MOCVD). The epitaxial layers consist of a 30-nm-thick GaN nucleation layer, a 2.5-μm-thick undoped GaN layer, a 10-nm-thick $Al_{0.26}Ga_{0.74}N$ spacer layer, a 20-nm-thick n^+-$Al_{0.26}Ga_{0.74}N$ layer with Si doped to $1\times10^{18}\,cm^{-3}$, and a 20-nm-thick n^+-GaN layer with Si doped to $1\times10^{19}\,cm^{-3}$. For the growth of undoped GaN layer, the flow rates of NH_3 and TMG were 5 ℓ/min and 69 μmol/min, respectively. The flow rates of NH_3, TMG, and TMA were 5 ℓ/min, 29.5 μmol/min and 5.2 μmol/min, respectively, for the growth of $Al_{0.26}Ga_{0.74}N$ layers. The Al content in the $Al_{0.26}Ga_{0.74}N$ layer was determined by the double crystal x-ray rocking curve measurement (ω scan). The mesa isolation and the gate recess etch were formed by use of reactive ion etching (RIE) in a BCl_3 plasma at the rf power of 10 W and a chamber pressure of 3 Pa. The drain-source ohmic contacts were obtained with Ti/Al (25 nm/150 nm) annealed at 900 °C for 60 s. The gate metallization was done by vacuum evaporation of

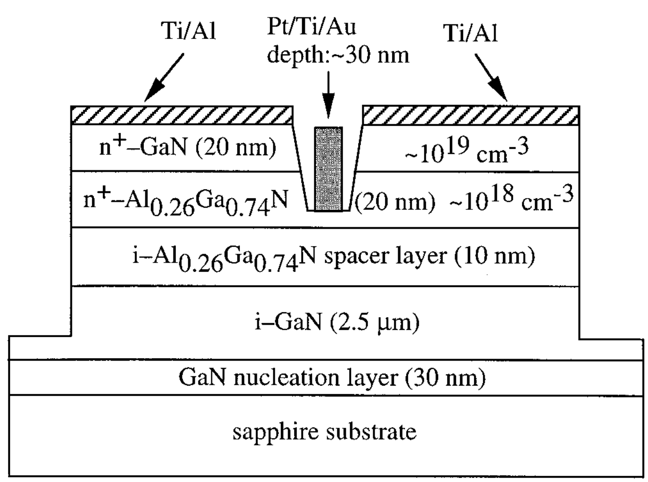

FIG. 1. Cross-sectional structure of recessed gate $Al_{0.26}Ga_{0.74}N$/GaN MODFET grown on sapphire by MOCVD. The gate length and width were 2.1 and 15 μm, respectively, and the channel opening (source to drain distance) was 10 μm. The mesa isolation and the gate recess etch were formed by use of reactive ion etching in a BCl_3 plasma.

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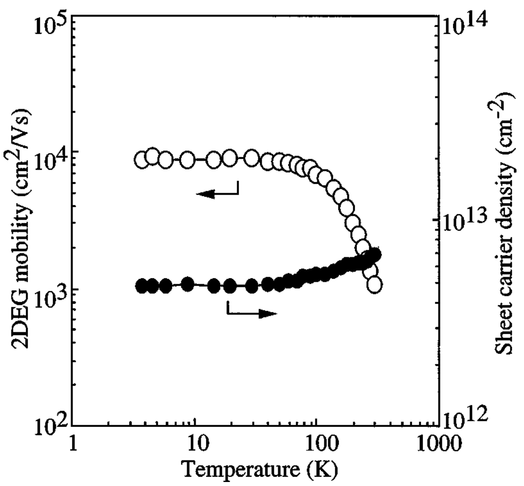

FIG. 2. 2DEG mobility and sheet carrier density as a function of temperature for AlGaN/GaN heterostructure on sapphire grown by MOCVD.

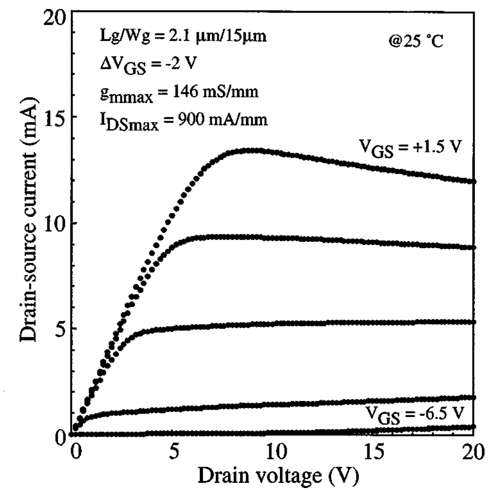

FIG. 3. Drain-source current I_{DS} characteristic of recessed gate AlGaN/GaN MODFET at 25 °C as a function of the drain-source voltage V_{DS}. The gate biases V_{GS} was changed from 1.5 to -6.5 V in steps of -2 V.

Pt/Ti/Au (10 nm/40 nm/100 nm). The separate photolithographic steps were used for the etch and gate metal deposition. The gate length and width were 2.1 and 15 μm, respectively, and the channel opening (source to drain distance) was 10 μm. The distance from the gate metal to the recess edge was 2 μm. The anneal step to remove the surface damage was not used in the fabrication of the recessed gate AlGaN/GaN MODFET. The Hall effect measurements at the magnetic field of 0.4 T were performed for the AlGaN/GaN heterostructure using the Van der Pauw Hall method.

Figure 2 shows the electron mobility and sheet carrier density in the AlGaN/GaN heterostructure as a function of temperature. Above 100 K, the electron mobility decreased rapidly and the sheet carrier density increased weakly with an increase in the sample temperature. At lower temperatures, where the ionized impurity scattering would be expected to dominate, the electron mobility and the sheet carrier density were independent of the temperature. The electron mobility of 1100 $cm^2/V\,s$ with the sheet carrier density of $6.8\times 10^{12}\,cm^{-2}$ was measured at 300 K. The electron mobility as high as 9260 $cm^2/V\,s$ was obtained for the AlGaN/GaN heterostructure with the sheet carrier density of $4.8\times 10^{12}\,cm^{-2}$ at 4.6 K. These results indicate that the high-quality AlGaN/GaN heterointerface has been grown on sapphire by MOCVD.

Figure 3 shows the drain-source current I_{DS} characteristic of the AlGaN/GaN MODFET as a function of drain-source voltage V_{DS} for the gate biases V_{GS} ranging from $+1.5$ to -6.5 V at 25 °C. The maximum extrinsic transconductance g_{mmax} and I_{DSmax} as high as 146 mS/mm and 900 mA/mm were obtained for the recessed gate AlGaN/GaN MODFET with $L_g = 2.1\,\mu$m, respectively. The MODFET exhibited the modulation characteristic with pinchoff at a threshold voltage of approximately -6.8 V. The reverse voltage was about 45 V at the reverse current density of 1 mA/mm. The relative low reverse voltage of the recessed gate device is due to the damage by the RIE in a BCl_3 plasma. We estimated that the source resistance was approximately 6.1 Ω mm and the calculated maximum intrinsic transconductance to be $g_{m0} = 1335$ mS/mm. In spite of relative long gate length, the MODFET in this study showed the superior characteristics when it was compared with the previous results of $g_{mmax} = 45$ mS/mm and $I_{DSmax} = 135$ mA/mm for the recessed gate MODFET with $L_g = 0.4\,\mu$m.[5] Furthermore, the AlGaN/GaN MODFET was tested at high temperatures in order to study the performance at high temperatures. The $I_{DS}-V_{DS}$ characteristic of the AlGaN/GaN MODFET at 350 °C is shown in Fig. 4. With increasing temperature, the g_{mmax} decreased from 146 mS/mm at 25 °C to 62 mS/mm at 350 °C. The decrease in the transconductance at high temperatures is probably due to the reduction of 2DEG mobility. The threshold voltage decreased from -12.1 V at 25 °C to -17.1 V at 350 °C for the GaN MESFET on sapphire.[6] However, the threshold voltages of the AlGaN/GaN MODFET were -6.8 and -7.1 V at 25 and 350 °C, respectively. Note that the temperature dependence of the threshold voltage is very weak for the AlGaN/GaN MODFET. As shown in Fig. 4, the AlGaN/GaN MODFET showed the good $I_{DS}-V_{DS}$ characteristics up to 350 °C even though the transconductance was reduced. After measurements at elevated temperatures up to 350 °C, the device was tested again at 25 °C. No observable changes were revealed in the $I_{DS}-V_{DS}$ characteristics.

In conclusion, we have improved the characteristics of

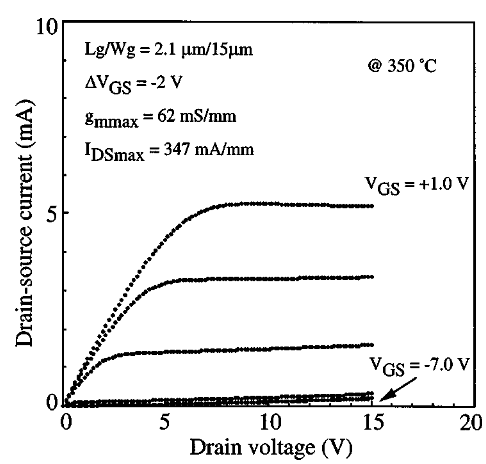

FIG. 4. Drain-source current I_{DS} characteristic of AlGaN/GaN MODFET at 350 °C as a function of the drain-source voltage V_{DS}. The gate biases V_{GS} was changed from 1.0 to -7.0 V in steps of -2 V.

the MOCVD-grown AlGaN/GaN MODFET on sapphire by use of the recessed gate process. The electron mobility and the sheet carrier density in the AlGaN/GaN heterostructure were 1100 $cm^2/V\,s$ and $6.8\times10^{12}\,cm^{-2}$ at 300 K, and 9260 $cm^2/V\,s$ and $4.8\times10^{12}\,cm^{-2}$ at 4.6 K, respectively. The recess etched device showed the large transconductance 146 mS/mm and the high drain-source current level 900 mA/mm for AlGaN/GaN MODFET with the gate length 2.1 μm. The AlGaN/GaN MODFET exhibited the stable operation at high temperatures and the very weak temperature dependence of the threshold voltage.

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