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High electron mobility in nearly lattice-matched AlInN/AlN/GaN heterostructure field effect transistors

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High electron mobility was achieved in $Al_{1-x}In_xN/AlN/GaN$ (x=0.20–0.12) heterostructure field effect transistors (HFETs) grown by metal-organic chemical vapor deposition. Reduction of In composition from 20% to 12% increased the room temperature equivalent two-dimensional-electron-gas density from 0.90×10^{13} to 1.64×10^{13} cm^{-2} with corresponding electron mobilities of 1600 and 1410 cm^2/V s, respectively. The 10 K mobility reached 17 600 cm^2/V s for the nearly lattice-matched $Al_{0.82}In_{0.18}N/AlN/GaN$ heterostructure with a sheet carrier density of 9.6×10^{12} cm^{-2}. For comparison, the AlInN/GaN heterostructure without the AlN spacer exhibited a high sheet carrier density (2.42×10^{13} cm^{-2}) with low mobility (120 cm^2/V s) at room temperature. The high mobility in our samples is in part attributed to ~1 nm AlN spacer which significantly reduces the alloy scattering as well as provides a smooth interface. The HFETs having gate dimensions of 1.5×40 μm^2 and a 5 μm source-drain separation exhibited a maximum transconductance of ~200 mS/mm with good pinch-off characteristics and over 10 GHz current gain cutoff frequency. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2794419]

AlGaN/GaN heterostructure field effect transistors (HFETs) have recently attracted a good deal of attention for high-frequency and high-power microwave electronics.[1] Owing to the piezoelectric and spontaneous polarizations, AlGaN/GaN HFETs grown on *c*-plane sapphire or SiC have two-dimensional electron gas (2DEG) densities of ~1×10^{13} cm^{-2}, even without doping the barrier.[1] Moreover, by increasing the Al composition in the barrier, the sheet carrier density can be increased further, which is desirable for high power and high frequency applications.[2] When a 7 nm AlN barrier is used, 2DEG densities could be as high as 5×10^{13} cm^{-2}, which is near the polarization limit.[3] However, the quality of the barrier with high Al% significantly reduces the mobility.[3,4] To address this issue, Kuzmík proposed using nearly lattice-matched AlInN/GaN to improve the performance of HFETs with high sheet carrier densities provided by spontaneous polarization only.[5,6] Due to the difficulty of AlInN growth, reports on AlInN and AlInN/GaN heterostructures in the literature are limited.[7,8] An ultrathin AlN layer is usually deposited before the AlGaN barrier to effectively reduce the alloy scattering and provide better confinement of electrons.[9] Similarly, by using the AlN barrier, Gonschorek *et al.*[10] improved the mobility to ~1170 cm^2/V s for an undoped nearly lattice-matched AlInN/GaN heterostructure, but the low temperature mobility was still low (~3170 cm^2/V s at 77 K) compared to the more established AlGaN/GaN structures.[9] In this letter, we study the temperature dependent Hall effect for the AlInN/AlN/GaN system with In mole fraction tuned from 20% to 12%, straddling the lattice matched condition. For the nearly lattice-matched $Al_{0.82}In_{0.18}N/AlN/GaN$ HFET structure, the Hall mobility reached 1510 cm^2/V s at 300 K and 17600 cm^2/V s at 10 K, the latter representing a substantial improvement over previous reports.

AlInN/GaN HFET structures were grown on 2 in. (0001) sapphire substrates in a vertical low-pressure metal-organic chemical vapor deposition (MOCVD) system. The growth was initiated with a 200 nm AlN buffer layer grown at ~1050 °C, followed by an ~3 μm GaN. After depositing an ~1 nm AlN interlayer, the wafer was cooled down to 750–800 °C for the AlInN barrier (unintentionally doped) and ~2 nm GaN cap deposition. Hydrogen was used as the carrier gas for the AlN and GaN buffer growth, and nitrogen was used as the carrier gas for the AlInN growth. The background doping of the GaN buffer was ~1×10^{16} cm^{-3}, as determined by Hall measurements. The In composition in the barrier was varied from 20% to 12%, which was controlled by the growth temperature. After growth, the samples were characterized by high resolution x-ray diffraction (XRD), atomic force microscopy (AFM), and Hall measurements. Moreover, HFETs having gate dimensions of 1.5×40 μm were fabricated and tested to complete our characterization.

The crystal quality of AlInN is believed to be the main impediment to high quality AlInN/GaN HFETs because of the low growth temperature of the AlInN compound. Normally, AlN requires high temperature, low pressure, and low

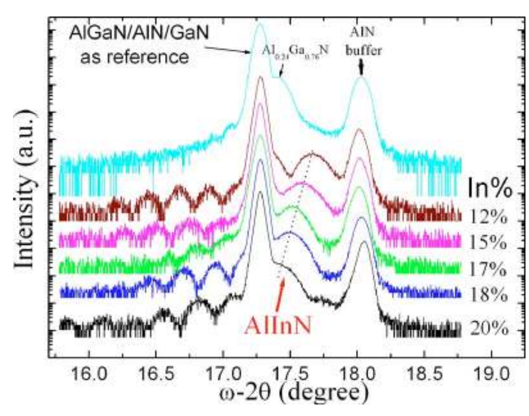

FIG. 1. (Color online) High resolution XRD (0002) ω-2θ scans of $Al_{1-x}In_xN/AlN/GaN$ HFET structures with In compositions in the range of 20% to 12%. XRD datum for a conventional $Al_{0.24}Ga_{0.76}N/AlN/GaN$ HFET is also plotted for comparison. The plots are vertically shifted for clarity.

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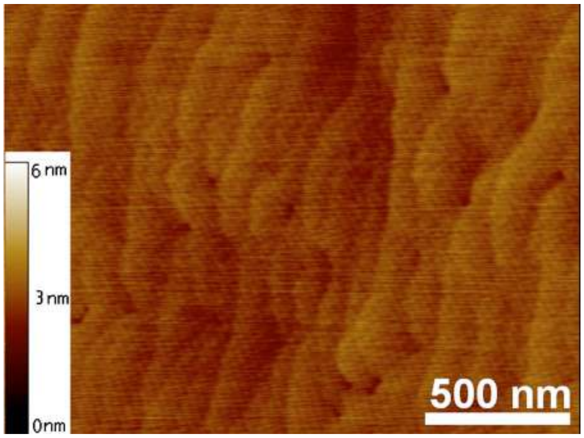

FIG. 2. (Color online) AFM image of an $Al_{0.82}In_{0.18}N/AlN/GaN$ sample with a 2 nm GaN cap layer.

ammonia flow rate, while InN needs low temperature, high ammonia partial pressure, and relatively high chamber pressure to increase In incorporation efficiency. In our system, AlInN is grown at temperatures used for InGaN with similar indium composition, but with lower growth pressure (50 torr) and relatively lower NH_3 flow rates [4000–7600 SCCM (SCCM denotes cubic centimeter per minute at STP)]. When the NH_3 flow rate is below 4000 sccm, the incorporation rate of indium is dramatically reduced, and as a result, an ~100 nm AlInN layer exhibited gray color (by the naked eye) which is similar to the observation of Carlin *et al.*[11] because of the residual indium metal. Under optimized conditions, we did not observe any obvious phase separation by XRD measurements for calibration layers (100–200 nm thick) with In concentrations ranging from 22% to 7%. Figure 1 shows the (0002) XRD ω-2θ scan for all the representative AlInN/AlN/GaN samples with nominal barrier thicknesses of ~22 nm. The AlInN XRD peaks (guided by the dotted line) are clearly observed. Using $c_{AlN}=4.982$ Å, $c_{InN}=5.760$ Å, $a_{AlN}=3.112$ Å, $a_{InN}=3.548$ Å,[1] and Vegard's law, the In compositions were determined as 20%, 18%, 17%, 15%, and 12%, respectively (see Fig. 1). The actual In composition is still somewhat debatable since the deviation from Vegard's law has been reported.[12] XRD data for one of our $Al_{0.24}Ga_{0.76}N/AlN/GaN$ HFET structure grown at 1030 °C is also plotted for comparison. Clear thickness fringes are observed in the AlInN/GaN structure which indicate abrupt interfaces. Those fringes are more pronounced in structures with high In composition (20% and 18%), suggesting that the abrupt interface may be related to the growth temperature (low growth temperature resulting in sharper interfaces). For comparison, no obvious fringes were observed in the AlGaN/AlN/GaN structure.

Figure 2 shows a typical AFM image of an $Al_{0.82}In_{0.18}N/AlN/GaN$ sample with a 2 nm GaN cap layer. The surface morphology is similar to that observed for the AlGaN/GaN HFET structures with clear atomic steps. For an ~100 nm thick $In_{0.18}Al_{0.82}N$ calibration layer (not shown), AFM indicates small hexagonal "domains" of around 200 nm diameter, similar to that reported by Butté *et al.*[13] At low growth temperatures, the low mobility of adatoms, especially that of Al, would prohibit the step-flow growth mode. This would also explain the structural degradation observed from the XRD rocking curve measurements in thick InAlN layers (>250 nm).[11]

Temperature-dependent Hall measurements were carried out from 10 to 300 K using a van der Pauw configuration in a LakeShore system. Ohmic contacts were prepared by 60 s rapid thermal annealing of Ti/Al/Ti/Au (30/100/30/30 nm) at 850 °C. Figure 3 shows the temperature-dependent Hall mobility and the sheet carrier density for two nearly lattice-matched $Al_{0.82}In_{0.18}N/GaN$ HFETs, with and without an AlN spacer. When the AlN spacer is not used, the Hall mobility at room temperature is extremely low (~120 $cm^2/V\,s$) with a high sheet carrier density of $n_s = 2.42\times10^{13}$ cm^{-2}, which is similar to that reported by other groups.[8,10] The temperature-dependent measurements revealed that the conduction in this sample is similar to that in bulk material (see Fig. 3). Around 190 K, the Hall mobility reaches its maximum and decreases to 100 $cm^2/V\,s$ at 10 K. Ungated FET structures show good current saturation at ~10 V for a 5 μm source-drain separation, which indicates that the conduction is mainly due to the 2DEG. When an ~1 nm AlN spacer is used, the Hall mobility dramatically improved and exceeded 1400 $cm^2/V\,s$ at room temperature (see Table I) for all the samples under investigation. Gonschorek *et al.* have found that the AlN spacer is critical to

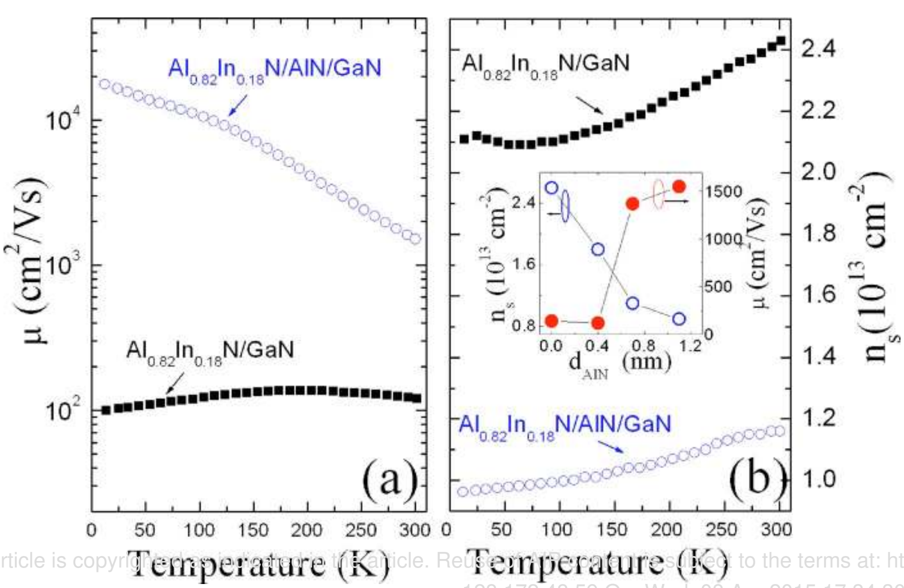

FIG. 3. (Color online) Temperature dependent (a) Hall mobility and (b) sheet carrier density for the nearly lattice-matched $Al_{0.82}In_{0.18}N/GaN$ HFETs with and without a 1 nm AlN spacer. The inset shows the effect of AlN spacer on Hall mobility and sheet carrier density of $Al_{0.845}In_{0.155}N/AlN/GaN$ HFET structures.

TABLE I. Measured Hall mobility and sheet carrier density for $Al_{1-x}In_xN/AlN/GaN$ HFETs at 300 and 10 K.

In in the barrier (%)	AlN spacer (nm)	μ_{Hall} ($cm^2/V\,s$)		n_s ($\times 10^{13}\ cm^{-2}$)	
		300 (K)	10 (K)	300 (K)	10 (K)
20	1	1560	15 340	0.90	0.77
18	1	1510	17 600	1.16	0.96
17	1	1410	11 710	1.24	1.05
15	1	1600	11 800	1.27	1.15
12	1	1420	14 100	1.64	1.33
18	None	120	100	2.42	2.12
15.5	None	140	130	2.60	2.47

obtain high electron mobilities in AlInN/GaN HFET structures, and that the thickness of the spacer can dramatically influence the surface morphology and can result in the variation of the mobility.[10] In our samples, when the In mole fraction was reduced from 20% to 12%, the room-temperature sheet carrier density slightly increased from 0.90×10^{13} to $1.64\times10^{13}\ cm^{-2}$ due to the increase of the polarization field. Furthermore, the low-temperature Hall mobility values of our samples (20%–12%) are much higher than the data of Gonschorek *et al.*[10] ($\sim$3170 $cm^2/V\,s$ at 77 K) and Hiroki *et al.*[14] ($\sim$2600 $cm^2/V\,s$ at 77 K). At 10 K, we achieved a mobility value as high as 17 600 $cm^2/V\,s$ for the nearly lattice-matched $Al_{0.18}In_{0.82}N/AlN/GaN$ sample with a sheet carrier density of $0.96\times10^{13}\ cm^{-2}$. It is interesting to note that our samples with AlN spacers have a smaller electron sheet carrier density than the previously reported values [(2.2–3) $\times10^{13}\ cm^{-2}$] for a similar barrier thickness.[8,10]

To investigate the effect of AlN spacer, we have grown a set of samples by changing only the nominal thickness of AlN spacer (0, 0.4, 0.7, and 1.1 nm) without GaN cap layer. XRD data together with the simulation (not shown) for the sample without AlN spacer were used to determine the $Al_{0.845}In_{0.155}N$ barrier thickness to be $\sim$29.5 nm. 300 K Hall measurements (see inset in Fig. 3) showed that for 0, 0.4, 0.7, and 1.1 nm AlN spacer thicknesses, the sheet carrier densities were 2.6×10^{13}, 1.8×10^{13}, 1.1×10^{13}, and 0.9 $\times10^{13}\ cm^{-2}$, with Hall mobilities of 140, 120, 1370, and 1550 $cm^2/V\,s$, respectively. The AlN spacer thickness was maintained below the critical thickness and as such that the strain is invariant to a first extent.[15] This rules variable strain as being the cause of the reduction in sheet density as the AlN thickness is increased. The plausible explanation would be electron transfer from the unintentionally doped AlInN barrier layer and/or the surface.[16–18]

Finally, we have fabricated HFET devices, and the typical current-voltage (*I-V*) characteristics are shown in Fig. 4. The particular device shown has a 1.5 μm gate length and 5 μm source-drain separation and shows very good pinch-off characteristics at a -4.3 V gate bias. The peak transconductance reaches 200 mS/mm at 5 V drain bias. Small signal scattering parameter measurements revealed a 10.2 GHz current gain cutoff frequency ($|h_{21}|$).

In summary, we have grown $Al_{1-x}In_xN/GaN$ HFET structures by MOCVD and investigated their structural and transport properties. While the 300 K Hall mobility was only 120 $cm^2/V\,s$ for samples without an AlN spacer, inclusion of an $\sim$1 nm AlN spacer layer increased the Hall mobility values to between 1410 and 1600 $cm^2/V\,s$. For the nearly lattice-matched $Al_{0.18}In_{0.82}N/AlN/GaN$ structures, the Hall mobility was 1510 $cm^2/V\,s$ at 300 K which increased to 17 600 $cm^2/V\,s$ at 10 K. HFETs with a 1.5 μm gate length and 40 μm gate width exhibited a maximum transconductance of 200 mS/mm and current gain cutoff frequency of 10.2 GHz. Our results suggest that the lattice-matched AlInN/GaN HFETs are very promising for high power microwave device applications.

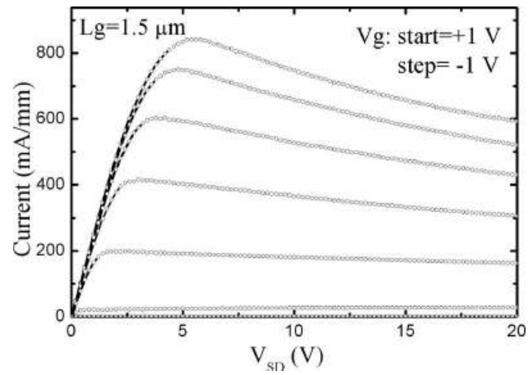

FIG. 4. Typical *I-V* characteristics of FETs fabricated on the nearly lattice-matched $Al_{0.82}In_{0.18}N/AlN/GaN$ samples. The gate length is 1.5 μm, gate width is 40 μm, and the source-drain separation is 5 μm. The maximum transconductance is $\sim$200 mS/mm.

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