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Effects of AlN and AlGaN Interlayer on Properties of InAlN/GaN Heterostructures *

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InAlN/GaN heterojunction structures are grown on two-inch c-face(0001) sapphire substrates by metalorganic chemical vapour deposition. AlN and AlGaN interlayers are intentionally inserted into the structure to improve the electrical properties. The lowest sheet resistance of 359 Ω/sq and the highest room-temperature two-dimensional electron gas (2DEG) mobility of 1051 $cm^2 V^{-1} s^{-1}$ is obtained in the structure with AlN thickness of 1.3 nm. The structure with AlN thickness of 2 nm exhibits the highest 2DEG concentration of 1.84×10^{13} cm^{-2}. The sample with an AlGaN interlayer gives a smoother surface morphology compared to the one using an AlN interlayer, indicating potential applications of this technique in device fabrication.

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Nitride-based high-electron mobility transistors (HEMTs) have attracted a great of attention for high-frequency and high-power microwave applications because these material systems have many desirable fundamental physical properties, such as a large band gap, large breakdown field, strong spontaneous and piezoelectric polarization fields.[1–3] A traditional AlGaN-barrier GaN-channel HEMT contains a high-mobility two-dimensional electron gas (2DEG) caused by polarization and piezoelectric fields even without doping the barrier.[4] By increasing the Al composition in the barrier, the 2DEG density can be increased further, which is desirable for high power and high frequency applications. When a 7-nm AlN barrier is used, the 2DEG density could be as high as 5×10^{13} cm^{-2}, which is nearly the polarization limitation.[5] This high 2DEG density is achieved at the inherent cost of a lattice mismatch between AlGaN and GaN. The resultant strain may cause device degradation through defect generation, particularly at high electric fields and temperatures, both of which are present in high-power HEMTs.[6] To address this issue, Kuzmík[7] proposed to use nearly lattice-matched AlInN/GaN to improve the performance of HEMTs by high sheet carrier densities provided by merely spontaneous polarization. By removing strain effects from the device, the strain induced degradation of GaN-based HEMTs, which is accelerated by high temperature process or by the change of growth condition, can potentially be eliminated. This unique approach accommodates thinner barrier layers than generally required without compensating for the sheet charge densities. Moreover, due to the high stability of InAlN at high temperature, the device could operate at 1000°C.[8]

Despite the potential, the InAlN alloy is much less understood, which should be essentially ascribed to lacking the capability to grow high quality InAlN materials. Indeed, growth of high quality crystalline InAlN material is difficult due to the large lattice mismatch between InN and AlN bonds, and eventually causes phase separation and composition inhomogeneity. In addition, it is difficult to incorporate indium into AlN due to the large difference in typical growth temperature between InN (∼ 500°C) and AlN (∼ 1100°C).

In this Letter, we report the growth and characterization of InAlN/GaN heterostructures. A thin AlN or an AlGaN interlayer is intentionally inserted into the structure. Effects of AlN thickness on the electrical properties are studied and the advantage of the AlGaN interlayer is also discussed.

InAlN/GaN heterostructures were deposited on two-inch c-face(0001) sapphire substrates by metalorganic chemical vapour deposition (MOCVD). Trimethylgallium (TMGa), trimethylaluminum (TMAl), trimethylindium (TMIn) and ammonia (NH_3) were used as Ga, Al, In, N precursors, respectively. The In mole fraction was kept at 18% in InAlN to in-plane lattice matched to GaN.

Six samples were prepared in our experiments. The samples parameters were kept to be the same except the AlN or AlGaN interlayer. The detail process can be described as follows. First, the substrate was annealed in situ at 1080°C for 5 min in H_2 ambient, and then the temperature was lowered to 550°C for

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25-nm GaN nucleation layer growth. The substrate temperature was again increased to 1050°C to grow 2-μm semi-insulating GaN. Finally a 7-nm InAlN barrier layer was then deposited at 770°C on top of GaN. Sample A is InAlN/GaN without any interlayers. For sample B, a 2-nm $Al_{0.25}Ga_{0.75}N$ interlayer grown at 1000°C was sandwiched between the GaN channel and the InAlN barrier. For samples C, D, E, F, the interlayer is changed to AlN with thickness of 0.4, 0.9, 1.3, 2 nm, respectively.

The sheet resistance of the heterostructure was studied by a Lehighton sheet resistance mapper. Hall-effect measurements with Van der Pauw geometry were performed to evaluate the transport properties of our samples. An atomic-force microscope (AFM) was used to characterize the surface morphology.

The relationship of sheet resistance of the five structures (samples A, C, D, E, F) with the AlN thickness is shown in Fig. 1. The sheet resistance dramatically decreases from 3020 Ω/sq for sample A (without AlN interlayer) to 359 Ω/sq for sample E (1.3 nm AlN). The sheet resistance of 359 Ω/sq corresponds to a $\eta_s\mu$ product value of $1.74 \times 10^{16}\,\mathrm{V^{-1}s^{-1}}$, which is an important characteristic of the current-carrying capability of the HEMTs. The result indicates that this structure is very suitable for high power device applications. However, the samples with further increasing AlN thickness to 2 nm have increased the resistance up to 514 Ω/sq, which can be explained by the significant decreasing of 2DEG mobility and will be discussed in the following.

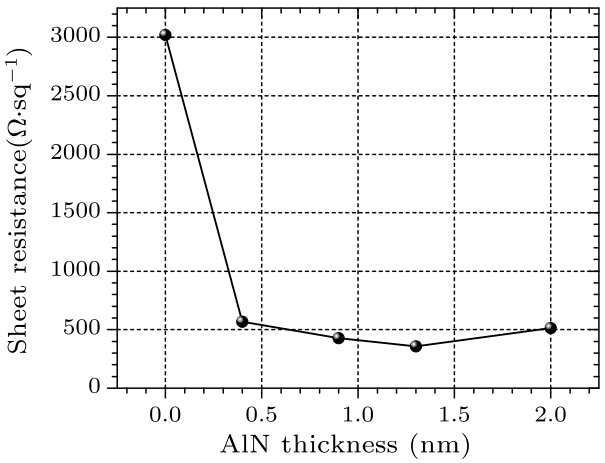


Fig. 1. Sheet resistance of the InAlN/AlN/GaN structures as a function of AlN thickness (samples A, C, D, E, F).

AlN has been widely used as the interlayer and has been very successful in AlGaN/GaN heterostructures. By including an ultrathin AlN interlayer, the alloy scattering can be reduced by better confining the carriers in the GaN channel region, thus the 2DEG mobility increases. Alloy disorder is indeed very high in InAlN, and a 350-meV photoluminescence line width with a Stokes shift over 500 meV was measured by Carlin *et al.*[9] Thus the AlN interlayer method should be an effective way to improve the transport properties in InAlN/GaN heterostucture. Room-temperature carrier mobility and 2DEG concentration of InAlN/AlN/GaN structures versus AlN thickness are plotted in Fig. 2. In the sample without the AlN linterlayer, the Hall mobility at room temperature is extremely low (about $156\,\mathrm{cm^2V^{-1}s^{-1}}$). The mobility increases dramatically with an AlN interlayer and reaches $1051\,\mathrm{cm^2V^{-1}s^{-1}}$ with AlN thickness of 1.3 nm. Further increasing AlN thickness can decrease the mobility down to $660\,\mathrm{cm^2V^{-1}s^{-1}}$ in sample F (2 nm AlN). With the increasing AlN thickness, dislocations are generated to minimize the strain induced by lattice mismatch between GaN and AlN. The defect formation will result in the degradation of crystalline quality and increase the interface roughness, consequently, will reduce the electron mobility, similarly to the AlGaN/GaN system.[10]

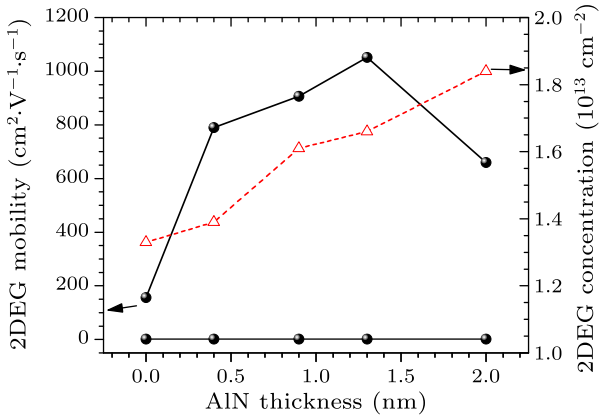


Fig. 2. Room-temperature mobility and 2DEG concentration vs AlN thickness.

Large conduction band offset produces a large spontaneous polarization, thus increasing the 2DEG concentration in the InAlN/GaN structure. It is evident that the 2DEG concentration goes up steadily with the increasing AlN thickness and reaches $1.84 \times 10^{13}\,\mathrm{cm^{-2}}$ in sample F as illustrated in Fig. 2. In the AlGaN/GaN system, researchers usually use barrier thickness above 20 nm to obtain 2DEG concentration approaching $1 \times 10^{13}\,\mathrm{cm^{-2}}$. It is noted that in our samples, the InAlN barrier thickness is only 7 nm. The barrier thickness is a crucial parameter for the HEMT design. Indeed, thin barriers are required for small-signal high frequency operation to suppress short channel effects.

Room-temperature Hall measurements was also carried out for sample B (with 2 nm $Al_{0.25}Ga_{0.75}N$ interlayer), the 2DEG concentration is $1.39 \times 10^{13}\,\mathrm{cm^{-2}}$,

nearly the same as sample A without any interlayer; mobility is 912 $cm^2V^{-1}s^{-1}$, lower than sample E but significantly surpasses sample A.

AFM images of two control samples (2 nm $Al_{0.25}Ga_{0.75}N$ and 2 nm $In_{0.18}Al_{0.82}N$ grown on 2 μm GaN) with growth conditions identical to sample B (interlayer and barrier layer, respectively) were compared in Fig. 3. The surface of InAlN is much rougher (giving an RMS roughness value of 0.459 nm compared to 0.220 nm for 2 nm $Al_{0.25}Ga_{0.75}N$), this can be possibly ascribed to a low mobility of adatoms, especially that of Al, at low growth temperature (770°C), would prohibit the step-flow growth mode which could be clearly observed in $Al_{0.25}Ga_{0.75}N$. Although there exists alloy disorder in AlGaN, it is not so serious like in InAlN, since an AlGaN/GaN heterosructure without any interlayer always exhibit a room-temperature 2DEG mobility about 1000 $cm^2V^{-1}s^{-1}$ in our laboratory. Thus it could be rationalized that the increasing interface quality together with the reduced alloy disorder scattering are responsible for the increasing transport property in the InAlN/GaN heterostucture when an AlGaN interlayer is used.

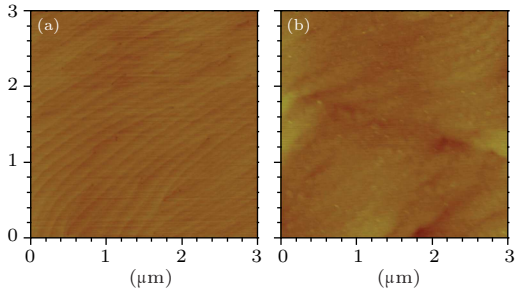


Fig. 3. AFM images of (a) 2 nm $Al_{0.25}Ga_{0.75}N$ and (b) 2 nm $In_{0.18}Al_{0.82}N$ (data scale is 20 nm, scan size is 3 μm).

Figure 4 presents the AFM images of the surface morphology of samples E and B. The surface of sample E is filled by pits, with a density above 10^9 cm^{-2} (similar results could be found in other samples with the AlN interlayer and not shown here), for sample B, pit density significantly reduces to about 10^7 cm^{-2}. Pits act as leakage current paths and lead to premature breakdown,[11] which is harmful to device operation. Considering the improved surface quality when an AlGaN interlayer is used, this method may be a choice for device fabrication in InAlN/GaN heterosructure.

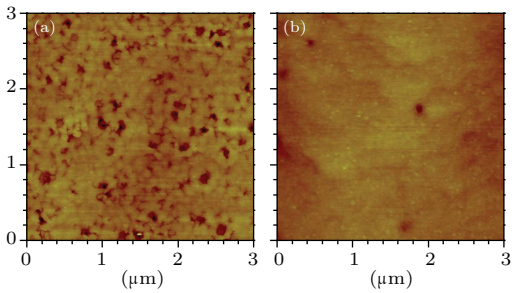


Fig. 4. AFM images of surface morphology of (a) sample E and (b) sample B (data scale is 20 nm, scan size is 3 μm).

In summary, InAlN/AlN/GaN heterojunction structures with AlN thickness of 0, 0.4, 0.9, 1.3 and 2 nm have been characterized and compared. The Hall mobility and 2DEG concentration of the heterostructures are improved by introducing an AlN interlayer. The AlN interlayer with a thickness of 1.3 nm is appropriate for the design of the InAlN/AlN/GaN HEMT structure. For the structure with a 2-nm $Al_{0.25}Ga_{0.75}N$ interlayer, not only the electrical properties but also the surface quality are improved.

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