Nearly lattice-matched InAlN/GaN high electron mobility transistors grown on SiC substrate by pulsed metal organic chemical vapor deposition

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We report on a growth of nearly lattice-matched InAlN/GaN heterostructures on 4H–SiC substrates by pulsed metal organic chemical vapor deposition, and an excellent device characteristic of high electron mobility transistors (HEMTs) fabricated on these InAlN/GaN heterostructures. The electron mobility is 1032 cm²/Vs together with a high two-dimensional-electron-gas density of 1.59×10¹⁰ cm⁻² for the In₀.₁₇Al₀.₈₃N/AlN heterostructures. HEMTs with gate dimensions of 0.5×50 µm² and 3 µm source-drain distance exhibits a maximum drain current of 1 A/mm, a maximum extrinsic transconductance of 310 mS/mm, and current gain and maximum oscillation cutoff frequencies of 18 GHz and 39 GHz, respectively. © 2011 American Institute of Physics. [doi:10.1063/1.3567529]

For the past decade, AlGaN/GaN heterostructures have attracted a good deal of research, and significant progresses have been made for high frequency and high power microwave electronics applications because of its outstanding combination of fundamental physical properties, such as large band gap, large breakdown field, and strong spontaneous and piezoelectric polarization fields. However, AlGaN/GaN HEMTs currently utilize a strained barrier layer to improve the sheet carrier density by taking advantages of both types of polarizations in the heterostructure. This inherent strain at the AlGaN/GaN interfaces is detrimental to AlGaN/GaN HEMTs performances, especially to the long term reliability. To address this issue, Kuzmik proposed to use InAlN as an excellent candidate for AlGaN barrier layer, which can be grown lattice-matched to GaN buffer and is expected to reduce the stress in the barrier layer, so as to eliminate the strain-related reliability limitations. Also, the sheet carrier density in lattice-matched InAlN/GaN heterostructures was predicated to be 2.7×10¹⁳ cm⁻², provided by the strong spontaneously polarization even without an in-plane stress. In addition, this higher sheet carrier density could also cause high output current density and, potentially, high power density.

Despite such superior properties, InAlN is an alloy known to be difficult to grow with high quality in III-nitride group, from the epitaxial point of view. Phase separation and composition inhomogeneity always occur in the InAlN film. Only recently, some research groups succeeded in the growth of InAlN/GaN heterostructures by molecular beam epitaxy, and metal organic chemical vapor deposition (MOCVD). Different from these methods, we have grown nearly lattice-matched InAlN/GaN heterostructures by employing pulsed MOCVD (PMOCVD). In this letter, we present the results of nearly lattice-matched InAlN/GaN heterostructures grown by PMOCVD, as well as the HEMTs performances fabricated on these heterostructures.

InAlN/GaN heterostructures were grown on 2 in. 4H–SiC substrates in a homemade vertical low pressure MOCVD system. Trimethylgallium, trimethylaluminum (TMAI), trimethylindium (TMIn), and ammonia (NH₃) were used as the precursors of Ga, Al, In, and N, respectively. The growth was initiated with a 80 nm AlN nucleation layer grown at 960 °C, followed by an 1.4 µm insulating GaN buffer at 940 °C. In order to improve the electron mobility by suppressing the alloy disorder scattering and enhancing the sheet carrier confinement, a 1 nm AlN interlayer was deposited at 940 °C on GaN buffer. After that, the growth temperature was cooled down to 720 °C for the 13 nm InAlN barrier layer growth by PMOCVD. No GaN cap layer was used in the present structure. As the carrier gas, Hydrogen was used for the growth of the AlN and GaN layers, and Nitrogen for InAlN barrier layer. After growth, the sample’s structural properties were characterized by high resolution x-ray diffraction (HRXRD) and atomic force microscopy (AFM). Both van der Pauw Hall and capacitance-voltage (C–V) measurements were carried out to investigate the electrical properties of InAlN/GaN heterostructures. Moreover, HEMTs with a gate length of 0.5 µm and gate width of 50 µm were fabricated on this heterostructure and the performances were tested to prove the advantages of PMOCVD method.

InAlN barrier was deposited by PMOCVD, in which the reactive atoms were separately supplied to the reactor at different times. The growth sequence of PMOCVD is described in Fig. 1. As it can be seen, there are two unit cells, 6 s pulses of TMAI, NH₃ and 24 s pulse of TMIn were introduced alternately into the MOCVD reactor. An ammonia pulse always followed the metalorganic pulses. The growth parameters for InAlN have been optimized in our laboratory. The use of PMOCVD allowed us to reduce the growth temperature and hence significantly increased the indium incorporation to get a high quality InAlN layers. Furthermore, PMOCVD increases the surface mobility of adatoms and enables them to find energetically favorable sites, and hence improves the material composition uniformity. In this study, the indium content in the InAlN barrier layer was around 17%, close to perfect lattice-matched to GaN buffer.
previously published results,5,6 and suggesting that the
additional contribution on depth is shown in Fig. 4, measured by HRXRD.

Owing to the weak diffraction signal intensity related with thin InAlN barrier layer, we conduct (0004) symmetric reflections to separate InAlN peak from GaN peak distinctly. Figure 2 shows the (0004) HRXRD $\omega - 2\theta$ scan for a typical InAlN/GaN sample with InAlN thickness of 13 nm. Noted that there is no indication of phase separation for InAlN barrier layer between InN and AlN peaks from XRD analysis. The indium content was estimated to be $17 \pm 1\%$, using $c_{\text{InN}} = 0.498$ nm, $c_{\text{InN}} = 0.57033$ nm, $d_{\text{InN}} = 0.3111$ nm, $d_{\text{AlN}} = 0.35378$ nm,7,8 and Vegard’s law. As the reported deviation of $c_{\text{AlN}}/H11006$ and $c_{\text{InN}}/H11003$ and Vegard’s law. As the reported deviation of $c_{\text{AlN}}/H11006$ and $c_{\text{InN}}/H11003$ from Vegard’s law, the actual indium content is still somewhat debatable.

Figure 3 shows a typical AFM image with a $2 \times 2$ $\mu$m$^2$ scan area taken from the InAlN barrier layer terminated surface in the nearly lattice-matched InAlN/GaN heterostructures. The image clearly shows a smooth surface morphology with atomic steps and a few pits that correspond to dislocations from GaN buffer layer. The surface roughness in terms of root mean square (rms) was measured to be approximately 0.37 nm, which is consistent with the previously published results5,6 and suggesting that the PMOCVD can lead to a monatomic smooth layer for thin InAlN film.

The dependence curve of the carrier concentration distribution on depth is shown in Fig. 4, measured by $C - V$ for this nearly lattice-matched InAlN/GaN heterostructures. It indicates the two dimensional electron gas (2DEG) peak is sharp and located about 14 nm below the surface, which includes 13 nm InAlN barrier and 1 nm AlN interlayer. The decrease amount of the confined 2DEG density with the increasing bias voltage (shown inset) indicates a complete depletion at the respective pinch-off voltage of $-3$ V. From the Hall measurements using van der Pauw geometry, the 2DEG density is $1.59 \times 10^{13}$ cm$^{-2}$ with an electron mobility of 1032 cm$^2$/V s at room temperature and the sheet resistance is $380 \Omega$/sq. It should be noticed that the electron mobility is lower than the previously reported values by other groups.6 This is attributed to the strong alloy disorder scattering in InAlN alloy9 and further optimization of growth parameters, for example, AlN interlayer thickness is under pursued to improve the electron mobility. Our sample has a smaller 2DEG density than the previously reported values,10,11 which is ascribed to the thick InAlN barrier layer. Therefore, a similar 2DEG density can be achieved for a thick barrier layer.

The HEMTs devices with dimensions of $0.5 \times 50$ $\mu$m$^2$ and $3 \mu$m source-drain distance were fabricated on this nearly lattice-matched InAlN/GaN/GaN heterostructures. Figure 5 shows the dc $I_{\text{DS}}(V_{\text{DS}})$, $I_{\text{DS}}(V_{\text{GS}})$, and $G_m(V_{\text{GS}})$ characteristics. A maximum drain current of 1 A/mm is obtained at $V_{\text{GS}} = 2$ V, and a maximum extrinsic transconductance of 310 mS/mm is achieved at $V_{\text{DS}} = 10$ V. Small signal measurements were performed at a bias $V_{\text{DS}} = 10$ V and $V_{\text{GS}} = -1$ V, which exhibited a current gain cutoff frequency...
rolloff, as shown in Fig. 6. Further improvement of output growth.\textsuperscript{12} As seen in inset of Fig. 6, the gate diode leakage reduces the surface defects related to the gate leakage.\textsuperscript{14}

In summary, we have grown InAlN/GaN heterostructures by PMOCVD and studied their structural and electrical properties. A smooth surface with rms value of 0.37 nm is obtained for the nearly lattice-matched InAlN/GaN heterostructures. The 2DEG density is $1.59 \times 10^{13}$ cm$^{-2}$ with an electron mobility of 1032 cm$^2$/V s at room temperature. The HEMTs with gate dimensions of 0.5 $\times$ 50 $\mu$m$^2$ exhibited a maximum drain current of 1 A/mm and a maximum extrinsic transconductance of 310 mS/mm. Excellent frequency response is achieved with a maximum $f_t$ of 18 GHz and $f_{max}$ of 39 GHz. The gate diode leakage current is as low as $10^{-5}$ mA/mm. The results demonstrate the promising potential of PMOCVD growth method for InAlN/GaN millimeter wave power electronics applications. Also, further optimization of PMOCVD should be pursued to enhance the electrical properties of InAlN/GaN heterostructures.

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\begin{figure}[h]
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\includegraphics[width=\textwidth]{fig5}
\caption{(Color online) (a) dc $I_{ds}(V_{ds})$ characteristics of InAlN/InAlN/GaN HEMTs with gate dimensions of 0.5 $\times$ 50 $\mu$m$^2$ measured at $V_{gs}=2$ to $-6$ V in steps of $-1$ V and $V_{ds}=10$ V with $G_m(V_{gs})$ of the same transistor.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6}
\caption{(Color online) Frequency performance of InAlN/InAlN/GaN/AlN HEMTs measured at $V_{ds}=10$ V and $V_{gs}=-1$ V. The inset shows the gate diode characteristics of the same HEMTs.}
\end{figure}

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