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Characterisation of multiple carrier transport in indium nitride grown by molecular beam epitaxy

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Quantitative mobility spectrum analysis (QMSA) was performed on multiple magnetic field Hall effect measurements of indium nitride grown by molecular beam epitaxy. This enables two clearly distinct electron species to be identified, which are attributed to the bulk and a surface accumulation layer. In this material, single magnetic field data corresponds to neither electron species, as both contribute significantly to the total conduction. The bulk electron distribution has an extracted average Hall mobility of 3570 $\mathrm{cm}^2/(\mathrm{Vs})$ at 300 K with a concentration of 1.5×10^{17} cm^{-3}, while the surface electrons have sheet charge density that is an order of magnitude higher than previously reported surface concentrations. The high quality bulk characteristics revealed emphasise the importance of using multi-carrier analysis when performing transport measurements on InN.

1 Introduction

Indium nitride (InN) growth techniques have recently developed to the stage where the successful growth [1–3] of high quality crystalline InN layers is now achievable. Characterisation and improvement of electrical properties are the next logical focus. The overwhelming majority of InN transport characterisation is conducted in the conventional manner, whereby determination of transport properties is performed via a Hall measurement at a single magnetic field. This technique, however, only calculates transport properties as an averaged contribution of all carriers in the sample, and if more than one carrier species is present, may not give results that are representative of any individual carrier species.

This is especially important for InN, as while all InN films exhibit strong n-type conduction, capacitance-voltage (C-V) measurements [4, 5] and transport properties of layers grown with decreasing thickness [2–4, 6] have established that a surface electron accumulation layer exists, in addition to a bulk electron species, with a sheet concentration of mid-10^{13} cm^{-2} and mobility much lower than the underlying bulk material. Reported transport results for indium nitride, measured via conventional methods, are then unlikely to accurately represent the bulk electron properties due to the significant accumulation layer of electrons that exists at the surface. This work makes use of variable magnetic field Hall measurements with a multiple carrier analysis

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technique to reveal two electron species in the material, as well as the high electrical quality of the InN material under study.

2 Experimental

The 2.7 µm InN layer was grown by plasma-assisted molecular beam epitaxy (PAMBE) on a semi-insulating (Fe-doped) Ga-polar GaN template. In-polar InN was deposited at a substrate temperature of 450 °C under In-droplet conditions on an optimized GaN buffer layer [2,3]. Eight-contact Hall bars were defined by hydrogen/methane inductively coupled plasma reactive ion etching (ICP RIE). Contacts were thermally evaporated. Variable field resistivity and Hall measurements were performed between 0 and 12 T on an Oxford Instruments superconducting magnet. A continuous flow liquid helium cryostat was used to provide measurement temperatures between 77 and 300 K. At a given temperature, measurements were made at 30 values of magnetic field, for each magnetic field polarity.

Quantitative mobility spectrum analysis (QMSA) was performed using the Lakeshore iQMSA software package, which is based on the improved algorithm outlined by Vurgaftman *et al.* [7]. The QMSA algorithm takes the experimental multi-field Hall and resistivity data and produces a spectrum showing the conductivity contributions of electrons and holes in the mobility domain. The magnetic field dependent contribution to the conductivity tensor components σ_{xx} and σ_{xy} of a single electron or hole species of a given mobility can be described by a basis function. The measured conductivity tensors are simply a linear combination of the basis functions of each individual carrier species present in the material, scaled and shifted according to the individual densities and mobilities. The iQMSA algorithm, described in detail in Ref. [7], fits to both measured σ_{xx} and σ_{xy}, and their slopes, in generating the mobility spectra. Unlike traditional multi-carrier fitting techniques, QMSA makes no *a priori* assumptions about the carriers present in the material. The power of this method therefore lies in the fact that the bulk properties can be extracted regardless of surface or interface contributions, and no assumptions on the magnitude of surface accumulation need to be made. Previous multi-field measurements on indium nitride have only been performed with magnetic fields up to 4.5 T [6]. In this work, measurements were taken using magnetic fields of up to 12 T which enable the extraction of low mobility carriers, less than 1000 cm^2/(Vs), with much greater confidence.

3 Results and discussion

Measurement results from the Hall bar structure show clear signs of multi-carrier contributions to transport in both Hall coefficient, R_H, and the conductivity tensor, σ_{xy}. R_H varies significantly over the 0 to 12 T range, whereas for a single carrier R_H would be constant as a function of magnetic field. σ_{xy}, given in Fig. 1, shows a distinct flattening of the curve at high magnetic field values, indicating the presence of at least a second carrier with lower mobility.

The electron mobility spectrum generated by iQMSA for the Hall bar sample is given in Fig. 2 for 300 K. Very similar spectra were obtained for 77, 100, 150, 200, and 250 K. All mobility spectra clearly show two electron peaks. The conductivity given in the QMSA spectra is for sheet conduction, as we do not initially assume any particular knowledge of the depth profile for each carrier. The mobility spectra show a low mobility electron carrier with significant conduction contributions at mobilities ranging from approximately 300 to 1000 cm^2/(Vs), and a high mobility electron distributed between 3000 and 7000 cm^2/(Vs), depending on the measurement temperature.

We assign the low mobility carrier to the surface electron, as the mobility compares to that in the literature found via Hall measurements on InN layers of decreasing thickness [4,6]. The high

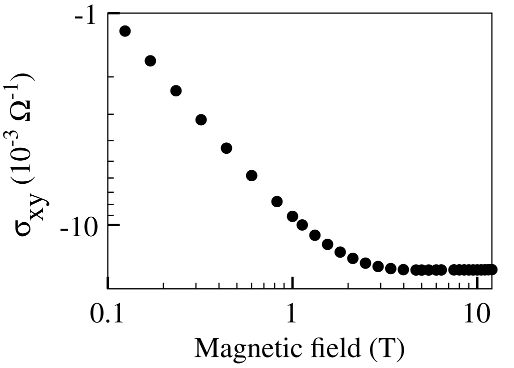

Fig. 1 Conductivity tensor, σ_{xy}, as a function of magnetic field at 300 K.

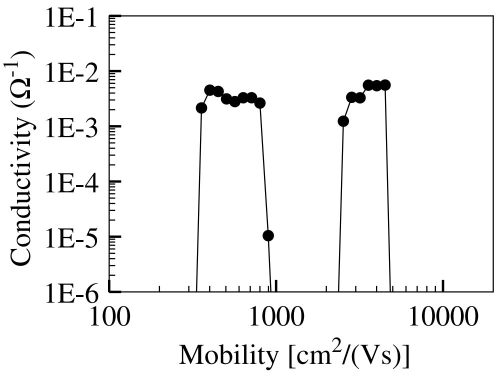

Fig. 2 InN mobility spectrum at 300 K determined from Hall bar measurements using the iQMSA algorithm.

mobility electron species is assigned to the electrons throughout the bulk of the InN layer. Similar distinction is made by Swartz *et al.* in Ref. [6]. While Hall measurements alone cannot give any depth profile of carrier distributions, it is possible that the range of mobilities in the bulk peak is in fact distributed with depth, most likely with the highest mobility electrons residing near the surface, where crystal quality is higher, and the lower range of the peak residing closer to the growth interface.

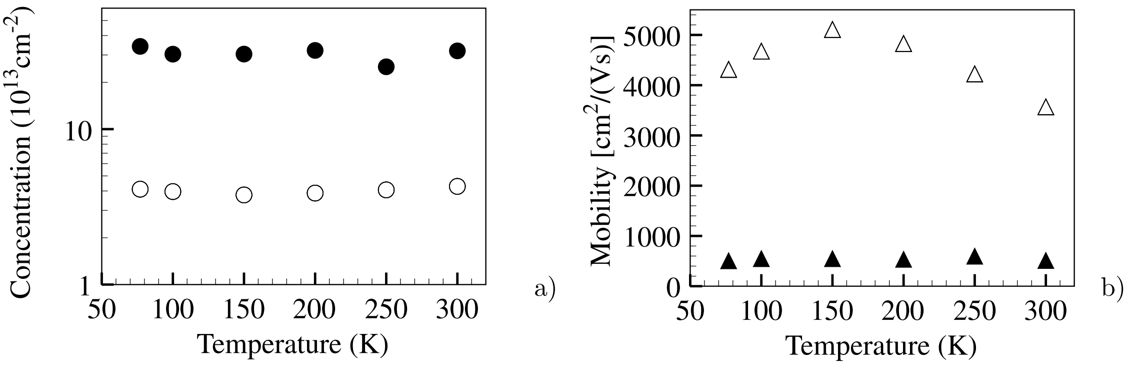

Fig. 3 The extracted sheet carrier density (a) and mobility (b) of bulk electron (open symbols) and surface electron (closed symbols) species in MBE grown InN as a function of temperature.

The extracted transport properties for the two electron species are given in Fig. 3. The mobility of each electron species is a weighted average over the entire peak in the mobility spectrum, and represents the mobility of the electron species as a whole.

The extracted mobility of the bulk electrons is 3570 $cm^2/(Vs)$ at 300 K, which is to our knowledge the highest ever reported for MBE-grown indium nitride. From 77 to 300 K the mobility of the bulk has a clear temperature dependence, peaking at over 5100 $cm^2/(Vs)$ at 150 K, shown in Fig. 3. Modelling by Polyakov and Schwierz in Ref. [9] calculates the maximum mobility in InN with electron concentration of around 10^{17} cm^{-3} at 300 K to be approximately 4000 $cm^2/(Vs)$. This suggests that the 300 K mobility of this film is approaching the theoretical limit, and thus the indium nitride grown is of high crystal and electrical quality. At 77 K, however, the theoretical limit calculated by Chin, Tansley and Osotchan in Ref. [8] for 10^{17} cm^{-3} InN is 12 000 $cm^2/(Vs)$ which is more than twice the mobility measured. This indicates that a large number of defect, ion or impurity related scattering centres may exist and be limiting the low temperature mobility of this material.

The bulk electron sheet density does not appear to exhibit any temperature dependence and is equal to around 4×10^{13} cm^{-2}, which equates to a bulk density of approximately 1.5×10^{17} cm^{-3} over the 2.7 μm thickness of the layer. For comparison, single field Hall results for this sample (at 1 T) give a bulk concentration of 6×10^{17} cm^{-3} at 300 K. Clearly, the surface electron layer has a significant influence on the results; the electron concentration, when determined from a single magnetic field, is four times the actual bulk electron concentration.

The surface electron has a largely temperature independent mobility of about 500 $cm^2/(Vs)$, comparable with reported values [4,6]. The low mobility electron peak in the mobility spectrum has been assumed in this analysis to belong solely to the surface accumulation, however the peak would also contain any other carriers of similar mobility in the material that contribute to conduction, such as a theorised GaN/InN growth interface charge [4]. If such an accumulation of electrons does exist with similar mobility values it is unlikely to be resolved, since Hall measurements cannot differentiate between carriers with similar mobility located in different regions of the material.

For the low mobility carrier attributed to surface accumulation electrons, the sheet charge density of around 3×10^{14} cm^{-2} (Fig. 3) is an order of magnitude higher than that reported by Lu *et al.* from C-V and variable thickness Hall measurements [4]. The origin of the very high density surface charge seen in this particular sample remains under investigation. Possible contamination from processing, handling and bonding procedures were all investigated on other control samples, with no process found to induce excess surface carriers.

4 Conclusion

We have used variable magnetic field resistivity and Hall measurements, combined with QMSA to separate and extract the transport properties of two electron species present in a 2.7 μm indium nitride layer grown by molecular beam epitaxy at temperatures between 77 and 300 K. The revelation of the high quality bulk material, masked by the highly conductive low mobility layer, emphasises the importance of using multi-carrier analysis when performing transport measurements on InN.

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References

[1] H. Lu, W. J. Schaff, J. Hwang, H. Wu, G. Koley, and L. F. Eastman, Appl. Phys. Lett. **79**, 1489 (2001).

[2] C. S. Gallinat, G. Koblmuller, J. S. Brown, S. Bernardis, J. S. Speck, G. D. Chern, E. D. Readinger, H. Shen, and M. Wraback, Appl. Phys. Lett. **89**, 032109 (2006).

[3] G. Koblmuller, C. S. Gallinat, S. Bernardis, J. S. Speck, G. D. Chern, E. D. Readinger, H. Shen, and M. Wraback, Appl. Phys. Lett. **89**, 071902 (2006).
[4] H. Lu, W. J. Schaff, L. F. Eastman, and C. E. Stutz, Appl. Phys. Lett. **82**, 1736 (2003).
[5] R. E. Jones, K. M. Yu, S. X. Li, W. Walukiewicz, J. W. Ager, E. E. Haller, H. Lu, and W. J. Schaff, Phys. Rev. Lett. **96**, 125505 (2006).
[6] C. H. Swartz, R. P. Tompkins, N. C. Giles, T. H. Myers, H. Lu, W. J. Schaff, and L. F. Eastman, J. Cryst. Growth **269**, 29 (2004).
[7] I. Vurgaftman, J. R. Meyer, C. A. Hoffman, D. Redfern, J. Antoszewski, L. Faraone, and J. R. Lindemuth, J. Appl. Phys. **84**, 4966 (1998).
[8] V. W. L. Chin, T. L. Tansley, and T. Osotchan, J. Appl. Phys. **75**, 7365 (1994).
[9] V. M. Polyakov and F. Schwierz, Appl. Phys. Lett. **88**, 032101 (2006).