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Temperature-Dependent Electron Transport in $In_{0.5}Ga_{0.5}P$/GaAs Grown by MOVPE *

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Hall effect measurements in undoped $In_{0.5}Ga_{0.5}P$/GaAs alloy grown by metal organic vapour-phase epitaxy (MOVPE) have been carried out in the temperature range 15–350 K. The experimental results are analysed using a two-band model including conduction band transport calculated using an iterative solution of the Boltzmann equation. A good agreement was obtained between theory and experiment. The impurity contents of $In_{0.5}Ga_{0.5}P$/GaAs alloy, such as donor density N_D, acceptor density N_A and donor activation energy ε_D, were also determined.

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The ternary alloy $In_{0.5}Ga_{0.5}P$ grown lattice matched to GaAs is one of the most promising materials for applications in devices, such as high electron mobility transistors,[1] InGaP/GaAs heterojunction bipolar transistors,[2] high efficiency tandem solar cells,[3] and photovoltaic devices.[4] Moreover, the InGaP/GaAs material system is proposed to replace AlGaAs/GaAs heterostructure due to its favourable properties.[5] The exact lattice match between $In_{0.5}Ga_{0.5}P$ and GaAs has been realized and in turn this gives an impetus for the growth of $In_{0.5}Ga_{0.5}P$/GaAs heteroepitaxial thin films. InGaP has similar values of band-gap energy and higher valence band discontinuity when compared to AlGaAs/GaAs heterostructures and does not present the same problems as AlGaAs alloys, like surface degradation caused by Al oxidation and DX centre formation.[6,7] This makes InGaP a very suitable material for laser and HBT fabrication. Although the structural and optical properties of $In_{0.5}Ga_{0.5}P$/GaAs have been studied in detail,[8−10] only a few studies dealing with the electrical properties exist,[11−13] which can provide more valuable information for epitaxial layer evaluation and control the growth condition to obtain high-quality epilayer for device applications. In this study, we have measured the electron transport properties as a function of temperature, and the results are analysed using a two-band model including an iterative solution of the Boltzmann equation (ISBE).

In this study, n-type undoped $In_{0.5}Ga_{0.5}P$ layers of about 400 nm thick were grown on a (001) GaAs substrate by a horizontal MOVPE system at 60 mbar and 600°C.[14] For the resistivity, and Hall effect measurements by the van der Pauw method, square-shaped ($5\times5\,\mathrm{mm}^2$) samples were prepared with four contacts at the corners. Using either evaporated or annealed indium dots, ohmic contacts to the samples were prepared and their ohmic behaviour was confirmed by the current voltage characteristics. The measurements were made over a temperature range 15–350 K using a Lakeshore Hall effect measurement system (HMS). In the measurements, the applied current to sample was 1 mA, and the magnitude of the magnetic field was 0.5 T.

The temperature dependence of the carrier density and electron mobility of undoped $In_{0.5}Ga_{0.5}P$ sample are shown in Figs. 1(a) and 1(b), respectively. The room temperature values of carrier density and mobility are in agreement with some of the best material reported elsewhere.[12] The experimental mobility exhibits the general characteristic of III–V group semiconductors. The high temperature mobility is limited by polar optical phonon scattering, which is shown by the increase of mobility as the temperature decreases. The mobility has a maximum near 130 K, being limited by ionized impurity scattering at intermediate temperatures, and tends to be constant at low temperatures. This low temperature behaviour is connected with the temperature dependence of the carrier density, which is given in Fig. 1(a), indicating that the impurity band conduction appears at low temperatures.

The mobility increases with decreasing temperature in the temperature range of 350–130 K. Below this temperature the mobility decreases as the temperature decreases, while the corresponding Hall carrier density goes through a minimum before increasing at lower temperatures. This well-known effect is a characteristic of electron transfer from the conduction

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band to an impurity band. In this case, the measured carrier density and mobility depends on the density and mobility of the carriers in the two bands. As is well known, these transport properties cannot be explained in terms of conduction band transport alone. We have used a two-band model that includes electron transport within a donor impurity band (with carrier density n_{IB} and mobility μ_{IB}) as well as in the conduction band (with carrier density n_C and mobility μ_C). The electron mobility in the impurity band is taken as the measured low temperature mobility while the electron mobility in the conduction band has been calculated by the ISBE. In the presence of two-band conduction, for the measured Hall carrier density and mobility we have[15]

$$n_H = \frac{(n_C\mu_C + n_{IB}\mu_{IB})^2}{n_C\mu_C^2 + n_{IB}\mu_{IB}^2}, \quad (1)$$

$$\mu_H = \frac{n_C\mu_C^2 + n_{IB}\mu_{IB}^2}{n_C\mu_C + n_{IB}\mu_{IB}}, \quad (2)$$

where subscripts C and IB refer to the conduction band and the donor impurity band, respectively.

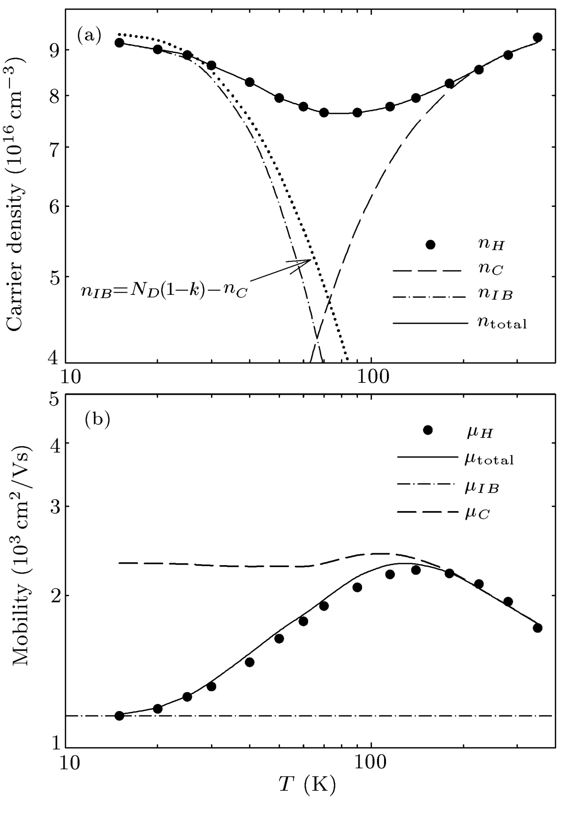

Fig. 1. Temperature dependence of (a) carrier density and (b) mobility. Circles represents the measured data. The dashed and dot-dashed lines represent the conduction band and the impurity band. The solid line is the total carrier density and mobility, respectively.

To apply the two-band model, the conduction band carrier density and mobility must be determined independently. Firstly, the conduction band carrier density is calculated from the following equation derived from non-degenerate statistics,[16]

$$n_C = 2(N_D - N_A)\left\{1 + \frac{N_A}{gN_C}\exp(\varepsilon^*) \cdot \left[\left(1 + \frac{N_A}{gN_C}\exp(\varepsilon^*)\right)^2 + \frac{4(N_D - N_A)}{gN_C}\exp(\varepsilon^*)\right]^{1/2}\right\}^{-1}, \quad (3)$$

where N_D and N_A are the densities of donors and acceptors, $\varepsilon^* = \varepsilon_D/kT$ with ε_D being the ionization energy of donors, N_C is the density of states, $N_C = 5.44 \times 10^{15}\ (m^*/m_0)^{3/2}\,\mathrm{cm}^{-3}$, and g is the spin degeneracy taken to be 2. Here N_D, N_A and ε^* are used as the fitting parameters. The conduction band carrier density n_C obtained from Eq. (3) with the parameters $N_D = 1.4\times10^{17}\,\mathrm{cm}^{-3}$, $N_A = 4.2\times10^{16}\,\mathrm{cm}^{-3}$ and $\varepsilon_D = 6.47\,\mathrm{meV}$ is given in Fig. 1(a) (dashed line). It can be seen from Fig. 1(a) that the conduction band carrier density n_C is in agreement with the measured carrier density at high temperatures and it decreases with decreasing temperatures as expected. The compensation ratio ($k = N_A/N_D$) is also obtained to be 0.3. It is noted that the obtained impurity parameters (N_D, N_A, k and ε_D) are in agreement with the previously reported ones.[13,17]

Secondly, the theoretical mobility μ_C in conduction band has been calculated using an iterative solution of the Boltzmann equation (ISBE) including the most relevant scattering mechanisms: polar optic,[18] acoustic deformation potential,[19] piezoelectric,[20] alloy disorder[21] and ionized impurity scattering (with Brooks–Herring theory),[22] as the usual case. The technique was initially suggested by Rode,[23] and has been developed in a number of papers by Rode[24,25,22] and Rode and Knight.[26] In the technique energy band non-parabolicity, electron wave function admixture, degeneracy of distribution function and electron screening have also been incorporated. In the ISBE calculations the magnetic field was used as an input parameter having the same value as that used in the experiment, which is 0.5 T.

In the ISBE, the following material parameters are used as input parameters: effective mass ratio $m^* = 0.092m_0$, lattice constant $a = 5.6532$ A, band gap $E_g = 1.991$ eV, static dielectric constant $\varepsilon = 11.8$ high-frequency dielectric $\varepsilon_h = 9.35$, longitudinal optic phonon equivalent temperature 540 K, alloy scattering potential $E_{al} = 0.435$ eV, deformation potential constant $E_{ac} = 12$ eV.[12] N_A is taken as $N_A = 4.2\times10^{16}\,\mathrm{cm}^{-3}$, which is estimated from Eq. (3). Figure 2 shows the temperature dependence of the measured Hall mobility (μ_H) and the conduction band mobility (μ_C) calculated from the ISBE. The ISBE is in good agreement with experiment at high temperatures

($T > 120\,\mathrm{K}$) where only the conduction band transport is present while it fails to predict temperature dependent mobility at low temperatures where impurity band conduction occurs. The conduction band mobility reaches a maximum near 120 K as does the experimental mobility. At low temperatures it tends to be constant, but higher than the measured mobility, while the measured mobility decreases. This is connected to the measured carrier concentration. The measured carrier concentration becomes degenerate at a temperature, which is close to the carrier concentration minimum. In this case the mobility is calculated by varying the occupancy of states at the Fermi level. For such a degenerate electron distribution the mobility is independent of temperature.[27] It should also be noted that if space charge scattering is included in the ISBE, any improvement are not obtained in the temperature dependent mobility.

To complete the modelling we can now apply the two-band model given in Eqs. (1) and (2). Impurity band mobility is assumed to be a constant and it is taken as the low temperature mobility ($\mu_{IB} = 1155.34\,\mathrm{cm^2/Vs}$). To obtain the impurity band carrier density (n_{IB}) we fit Eq. (1) to the measured carrier density using previously calculated conduction band carrier density (n_C), conduction band mobility (μ_C) and impurity band mobility (μ_{IB}). The obtained impurity band carrier density (n_{IB}) from the fit is given with the dot-dashed line in Fig. 1(a). On the other hand we have also calculated the carrier density in impurity band using the relation of $n_{IB} = N_D(1-k) - n_C$. It is given with dotted line in Fig. 1(a). It can be seen from Fig. 1(a) that the calculated impurity band carrier densities in both the ways exhibit similar behaviour with temperature.

Finally, using the obtained parameters above ($n_C, \mu_C, n_{IB}, \mu_{IB}$) as inputs parameters, the theoretical total mobility is calculated from Eq. (2), without using any fitting parameter. The result is given with the solid line in Fig. 1(b). It can be seen from Fig. 1(b) that a clear agreement is obtained between the measured mobility and the theoretical total mobility calculated from the two-band model. This agreement is an evidence of the obtained impurity parameters (N_D, N_A and ε_D) correctly predicted from Eq. (3). At high temperatures the conduction band transport is dominant while at low temperatures the impurity band conduction is controlling transport properties of $In_{0.5}Ga_{0.5}P/GaAs$ alloy.

In summary, we have carried out Hall effect measurements in n-type $In_{0.5}Ga_{0.5}P/GaAs$ alloy grown by MOVPE in the temperature range 14–350 K. The measurement results are analysed using a two-band model including the conduction band electron mobility calculated by the ISBE and the conduction band carrier density predicted from non-degenerate statistics. Analysis of the results show that a self-consistent agreement can be obtained for both the mobility and the carrier density with the parameters of $N_D = 1.40 \times 10^{17}\,\mathrm{cm^{-3}}$, $N_A = 4.2 \times 10^{16}\,\mathrm{cm^{-3}}$ and $\varepsilon_D = 6.47\,\mathrm{meV}$. It has also been shown that the ISBE is in good agreement with experiment at high temperatures where only the conduction band transport occurs while it fails to predict temperature-dependent mobility at low temperatures where impurity band conduction occurs.

References

[1] Tsai M K, Tan S W, Wu YW, Lour W S and Yang Y J 2002 *Semicond. Sci. Technol.* **17** 156
[2] Ma Y and Li G P 2006 *J. Electrostat.* **64** 88
[3] Khan A, Yamaguchi M and Takamoto T 2004 *Appl. Phys. Lett.* **85** 3098
[4] Bosi M and Pelosi C 2007 *Prog. Photovolt: Res. Appl.* **15** 51
[5] Krutogolov Y K, Kunakín Y I and Matyash A A 2001 *J. Mater. Sci.: Mater. Electron.* **12** 645
[6] Lothian J R, Kuo J M, Rem F and Pearton S J 1992 *J. Electon. Mater.* **21** 441
[7] Biswas D, Debbar N, Battacharya, P Razeghi M, Defour M and Omnes F 1990 *Appl. Phys. Lett.* **56** 833
[8] Bensaada A et al 1994 *J. Appl. Phys.* **75** 3024
[9] Bettini J, Carvalho M M G, Cotta M A and Ugarte D 2003 *Surf. Sci.* **540** 129
[10] Jiang G C et al 1995 *J. Appl. Phys.* **78** 2886
[11] Yoon I T 1998 *J. Mat. Sci. Lett.* **17** 2043
[12] Nag B R and Das M 1998 *J. Apply. Phys.* **83** 5862
[13] Kanga H I et al 2002 *Solid State Commun.* **122** 591
[14] Pelosi C et al 2005 *Cryst. Res. Technol.* **40** 982
[15] Look D C and Molnar R J 1997 *Appl. Phys. Lett.* **70** 3377
[16] Blakemore J S 1962 *Semiconductor Statistics* (New York: Pergamon)
[17] Yoon I T and Park H L 1999 *Thin Solid Films* **340** 297
[18] Fortini A, Diguet D and Lugand J 1970 *J. Appl. Phys.* **41** 3121
[19] Bardeen J and Shockley W 1950 *Phys. Rev.* **80** 72
[20] Zook J D 1964 *Phys. Rev.* **136** A869
[21] Littlejohn M A et al 1978 *Solid State Electron.* **21** 107
[22] Rode D L 1975 *Semiconductors and Semimetals* ed Willardson R K and Beer A C (New York: Academic) vol 10 chap 1
[23] Rode D L 1970 *Phys. Rev.* B **2** 1012
[24] Rode D L 1971 *Phys. Rev.* B **3** 3287
[25] Rode D L 1973 *Phys. Status Solidi* B **55** 687
[26] Rode D L and Knight S 1971 *Phys. Rev.* B **3** 2534
[27] Kasap M and Lancefield D 1997 *Phys. Status Solidi* B **199** 481