# In-plane hole effective masses in $In_xGa_{1-x}As/Al_{0.15}Ga_{0.85}As$ modulation-doped heterostructures

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We have determined the strain dependence of the in-plane hole effective mass in pseudomorphic $In_xGa_{1-x}As/Al_{0.15}Ga_{0.85}As$ modulation-doped heterostructures by low-temperature Shubnikov–de Haas measurements. An effective mass equal to $0.18m_0$ is measured for $x = 0.2$. The measured values are in good agreement with theoretical calculations.

Growth techniques such as molecular beam epitaxy have enabled the realization of heterostructures with precise control over their electronic and optical properties. The inclusion of biaxial strain in a pseudomorphic layer gives an additional degree of freedom in the tailoring of the material properties. Such strain not only changes the fundamental band gap, but also alters the conduction- and valence-band structure, resulting in changes in carrier effective masses and their transport properties.[1,2] Theoretical calculations[2] indicate that the changes in the hole band structure and effective masses are more dramatic than those in the conduction band. Biaxial strain splits the light and heavy hole subbands and causes the light hole band to rise above the heavy hole one. As a result the in-plane hole effective mass is significantly reduced. In fact hole effective masses as low as the electron masses have been predicted in InGaAs/GaAs heterostructures under biaxial compressive strain. Preliminary measurements of hole masses in an $In_{0.2}Ga_{0.8}As/GaAs$ heterostructure by Fritz *et al.*[3] have indicated this trend. Primarily due to the growth-related difficulties of the AlGaAs/InGaAs system, no results have been reported in this important system. In this letter we report experimental results obtained from Shubnikov–de Haas measurements of hole masses in modulation-doped pseudomorphic $In_xGa_{1-x}As/AlGaAs$ heterostructures for $0 \leqslant x \leqslant 0.2$. The measured masses for different sheet charge densities are in reasonably good agreement with theoretical predictions.

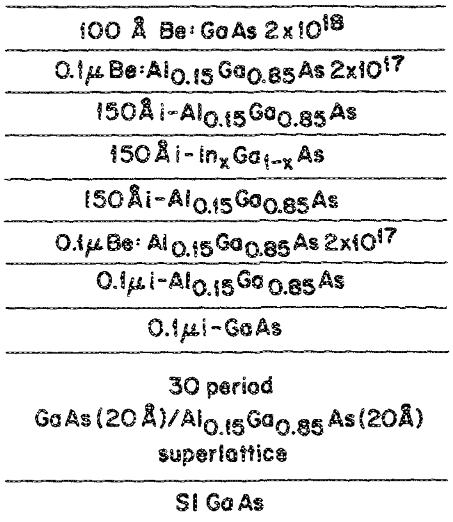

FIG. 1. Schematic structure of symmetrically doped *p*-type $In_{0.1}Ga_{0.9}As/Al_{0.15}Ga_{0.85}As$ MODFET grown by molecular beam epitaxy.

In order to calculate the hole masses, we have used our recently developed formalism[2] which allows us to self-consistently solve the Schrödinger equation with the Kohn–Luttinger Hamiltonian and the Poisson equation for the valence band. This self-consistent solution is complicated for the *p*-type system because the hole masses are not fixed, but depend on the strain and on the confining potential.

The experimental $In_xGa_{1-x}As/Al_{0.15}Ga_{0.85}As$ modulation-doped samples for Shubnikov–de Haas measurements were grown by molecular beam epitaxy in a Varian Gen II system. The schematic structure of the *p*-type heterostructure is shown in Fig. 1 and consists of a single quantum well $In_xGa_{1-x}As$ channel. The samples were modulation doped from top and bottom to maintain symmetry. Typical growth temperatures and growth rates of the $In_xGa_{1-x}As$ system were 550 °C and 1 μm/h, respectively.

The Shubnikov–de Haas effect consists of oscillations in resistivity with magnetic field at low temperatures. We used an Oxford superconducting magnetocryostat to subject our samples to up to 7 T of magnetic field and take them down to temperatures as low as 1.5 K. A typical plot of measured resistivity versus magnetic field at a given, constant temperature is shown in Fig. 2. The effective mass is related to the variation of the amplitude of these oscillations with temperature and magnetic field. The results of the measurements are

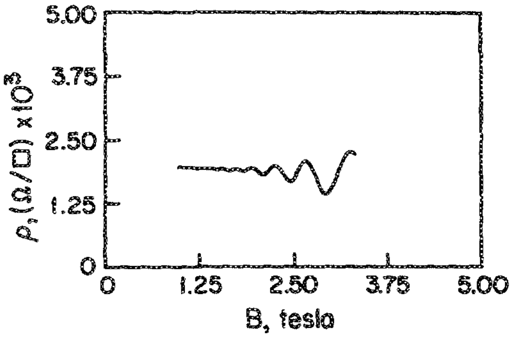

FIG. 2. Typical observed Shubnikov–de Haas oscillations in a *p*-type pseudomorphic MODFET (sample 448) at 1.84 K.

TABLE I. Measured transport parameters in lattice matched and pseudomorphic $In_xGa_{1-x}As/Al_{0.15}Ga_{0.85}As$ *p*-MODFETs.

| Sample number | Channel composition | Sheet charge ($\times 10^{11}$) $cm^{-2}$ | Hall mobility ($cm^2/V\,s$) 77 K | 4.2 K | Effective mass |
|---|---|---|---|---|---|
| 447 | GaAs | 7.3 | 2 931 | 26 700 | 0.52 |
| 448 | $In_{0.10}Ga_{0.9}As$ | 3.5 | 2 279 | 7 300 | 0.28 |
| 449 | $In_{0.2}Ga_{0.8}As$ | 7.2 | 3 636 | 6 700 | 0.19 |

summarized in Table I. It may be observed that the low-temperature mobilities at 77 and 4.2 K are lower than expected on the basis of the changes in carrier mass. The values are, however, comparable to recently published values for similar heterostructures.[4] The lack of correlation between carrier masses and mobilities at this point may be due to growth-related issues in these structures. Preliminary low-temperature photoluminescence measurements have been made to ascertain the composition and quality of the channel material. The peaks corresponding to the channel emission energies were at slightly lower energies than calculated values. This tends to indicate that either there are inhomogeneities and that the strain may be partially relieved in some regions, or the indium content in the channel may be somewhat lower.

As was stated earlier, the *p*-type samples which we measured were symmetrically doped. This was because in a normal modulation-doped field-effect transistor (MODFET), the lack of inversion symmetry lifts the spin degeneracy.[5] This causes holes in the top subband to be split into two populations of different effective masses, which causes beats in the Shubnikov–de Haas oscillations and prevents the accurate measurement of an effective mass. Figure 3 compares the measured masses with theoretically calculated[2] average hole masses in symmetrical *p*-type MODFETs for varying sheet carrier concentration. The measured effective masses, also listed in Table I, seem to be a bit high. The measured masses should correspond to the 0 K curves in each case. As mentioned in the last paragraph, the discrepancy may be due to partial release of strain in some areas or a lower indium content in the channel. Nevertheless, a clear trend is apparent from both theory and measurements that the hole effect mass decreases rapidly with increased biaxial compressive strain in the channel.

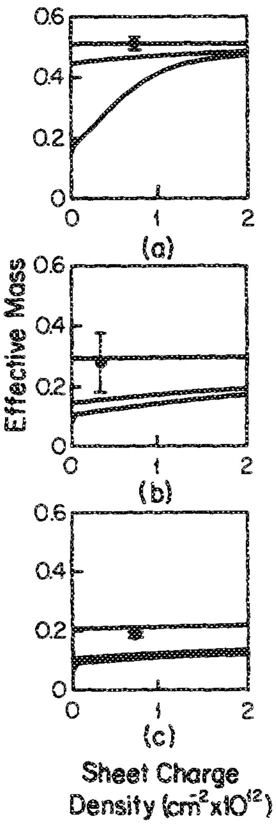

FIG. 3. Calculated and measured (data points) hole effective mass for (a) lattice matched, (b) 10% indium channel, and (c) 20% indium channel pseudomorphic *p*-type MODFET as a function of sheet charge density. In each case, the upper curve is the average mass at 300 K, the middle curve is at 77 K, and the bottom curve is at 0 K.

In conclusion, we have calculated and measured the hole effective masses in InGaAs/AlGaAs biaxially strained modulation-doped heterostructures as a function of In content and sheet charge density. An in-plane effective mass as low as $0.18m_0$ is measured in an $In_{0.2}Ga_{0.8}As/Al_{0.15}Ga_{0.85}As$ heterostructure. The measured masses are in good agreement with theoretical calculations.

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