Shubnikov-de Haas and cyclotron resonance results are presented for GalnAs-AllnAs heterojunctions in both perpendicular and tilted magnetic fields. Tilted fields cause magnetic shifts and mixing of the electric subbands. The g-factor is measured by the method of coincidences and shown to be exchange enhanced to values of order 9.

Strongly enhanced electron mobilities have been reported recently for Ga_{0.47}In_{0.53}As-Al_{0.48}In_{0.52}As heterojunctions grown by MBE(1). Low field Shubnikov-de Haas measurements(2,3) have shown that the electrons are accumulated on the GalnAs side of the interface and behave as a two dimensional electron gas (2DEG) at 4.2 K. In the samples studied with electron concentrations of order 7x10^{11} cm^{-2} two electric subbands were found to be occupied(2,3), while for GaInAs-InP structures with n < 5x10^{11} cm^{-2}, only one electric subband has been found to be occupied(4,5). We report here recent measurements on this system made at the high magnetic field laboratories in Oxford and Grenoble.

The formation of a 2DEG at a semiconductor heterojunction interface was first reported by Störmer et al(6) for GaAs-GaAlAs, who showed that electron confinement takes place in the smaller gap material (GaAs). In the present case Ga_{x}In_{1-x}As-Al_{y}In_{1-y}As samples were grown lattice matched to InP with x=0.47, y=0.48. The sample characteristics have been described in detail by Cheng et al(1). At 4 K the band gaps of GalnAs and AllnAs will be 0.81 eV and 1.7 eV respectively. There will be only a small discontinuity in the valence bands of order 100 meV, since the effect of passing from ~ 50% GaAs to 50% AlAs will introduce a step of half of the difference of valence band energies of GaAs and AlAs which is known to be of order 200 meV(7). The conduction band discontinuity will thus be of order 0.8 eV. The 2DEG concentration is then determined by the depletion of the AlInAs which in the present samples gives values of order 8x10^{11} cm^{-2} with electron mobilities of 93,000 cm^{2}V^{-1}s^{-1} at 4.2 K (1).

Fig.1: A Plot of the relative positions of the Landau levels arising from the two occupied electronic subbands E_0 and E_1 with an applied magnetic field perpendicular to the surface. The position of the Fermi level is also shown as a function of the field, assuming infinitely sharp Landau levels. The lower half shows an experimental recording of the magnetoresistance at 1.6 K.
Magnetoresistance measurements were made on long bar shaped samples at temperatures down to 1.6 K. Very pronounced Shubnikov-deHaas oscillations appear directly in the magnetoresistance as is shown in Fig.1. The oscillations clearly reveal the occupation of the two electric subbands (E₀ and E₁) which produce the two obviously very different periodicities (2). The low frequency oscillations visible at low field give a periodicity of (1.9 T)^-1 which gives a population of the higher subband = 0.92x10¹¹ cm⁻². The periodicity of the high frequency (E₀) series oscillates, with the periodicity of the second. When the Fermi level (Eₚ) is in the region between two Landau levels of E₁ then its contribution to the density of states is no different from that of a filled level of E₀, so that the periodicity measures the total number of electrons = 6.9x10¹¹ cm⁻². When Eₚ lies within a Landau level of E₁ then both sets of Landau levels are filled simultaneously and the periodicity of the E₀ series falls. We may thus deduce the low magnetic field populations of E₀ and E₁ to be 0.92 x10¹¹ cm⁻² and 6.0x10¹¹ cm⁻² respectively. In high fields however the well resolved nature of the Landau levels leads to oscillating populations in the two electric subbands. This is illustrated in Fig.1 which shows the Landau levels of both subbands, together with the resulting movement of the Fermi energy, calculated assuming infinitely sharp levels.

Using tilted magnetic fields introduces a parallel magnetic field component B∥. This has been shown (8,9) to shift the relative positions of the two subbands by an amount proportional to the square of the magnetic field and the spread of the wavefunction. At large angles between the surface normal and the applied magnetic field, the parallel component is sufficient to totally depopulate the E₁ subband for magnetic fields of order 6 T and above. This effect is seen directly in the magnetoresistance at 90⁰ where a fall in resistance of approximately 25% occurs around 6 T, due to the suppression of the inter subband scattering. A similar fall has been seen for GaAs-GaAlAs (10), as a function of electron concentration. The magnetic field induced shift in the E₁-E₀ separation may be deduced from the changes in population (3) as being given by:

\[(E₁ - E₀) = 0.26 \text{ meV/T}^2\]

It is also necessary to invoke the presence of a very large spin splitting of the Landau levels in order to explain the higher field peaks in Fig.1. This spin splitting becomes more pronounced in tilted magnetic fields, as may be seen in Fig.2, since the Landau level separation is determined only by the perpendicular component of magnetic field B⊥, while the spin splitting comes from the total field. By observing the relative amplitudes of the oscillations and their angular dependence (11,12), the relative values of the spin and Landau splittings may be deduced at one or more of the conditions:

\[r = \frac{g¹μB}{hc} = \frac{g¹m* B}{2m_0 B⊥} = 1/2, 1, 3/2, 2...\]

where for unresolved spin splittings the half integer conditions correspond...