Cyclotron Resonance Mass Enhancement and Electron-hole Hybridisation of InAs/GaSb Heterostructures

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ABSTRACT

The effect of electron-hole hybridisation on the cyclotron resonance of a bilayer-bipolar InAs/GaSb structure is investigated for samples with varying electron-hole separation. At low magnetic fields it is found that the cyclotron resonance mass of the electrons is significantly enhanced when the electrons and holes are closer together. A two band model shows excellent agreement with the experimental results, giving strong evidence that the effect is the result of single particle coupling.

Keywords: cyclotron resonance, electron-hole hybridisation, InAs/GaSb, far-infrared spectroscopy

1. INTRODUCTION

We report a magneto-optical characterisation of the commercially attractive InAs/GaSb heterostructures. Due to its potential applications in the mid- and far-infrared as emitting and detecting devices, the semimetallic InAs/GaSb system has become a subject of much interest in the past few decades. The recent observation of the oscillations of cyclotron resonance mass, amplitude, and linewidth in such a system has provoked a great deal of controversy [1–7]. Current interpretations divide essentially into two possible explanations: electron-hole Bose-Einstein condensation [2, 3], and electron-hole hybridisation assisted by inter-layer resonant tunnelling [4–6]. To date, experimental evidence has been inconclusive in resolving this debate, though the weight of evidence favours the second explanation [7–9]. This paper presents not only another strong evidence supporting electron-hole hybridisation as a cause of these oscillations, it also gives a systematic study of the effects of such hybridisation on electron effective mass enhancement. The strength of the hybridisation is experimentally controlled by varying the InAs well width and by inserting a barrier between the electrons and holes. The experimental results are compared to a simple two-band coupling model including the effect of the minigap that appears where the conduction band and valence band cross. Additionally, when the barrier is introduced between the electrons and holes all evidence of the electron-hole coupling is removed.

2. THEORETICAL BACKGROUND

2.1 Type-I Nonparabolicity

It is well known that the cyclotron resonance mass can be enhanced relative to the band edge free carrier mass as a result of conduction band nonparabolicity, with higher energy electrons having a greater effective mass due to interactions with other bands [10–17]. This type of nonparabolicity is identified as type-I nonparabolicity [4] and its effect on electron cyclotron mass enhancement has been shown both theoretically [12–14] and experimentally [15, 16] to be dependent on the carrier confinement energy. A three band formula for the energy dependence of the effective mass \( m^*_e \) in a nonparabolic system [17] is given approximately by

\[
\frac{m^*_0}{m^*_e} = 1 + 2 \frac{\kappa}{E_G} \epsilon,
\]

with the nonparabolicity parameter \( \kappa = -0.86 \) for InAs [18, 19]. \( m^*_0 \) is the band edge mass, \( E_G \) is the energy gap of the bulk InAs which has a value of 418 meV, and \( \epsilon = E_0 - E_b + (N + 1)\hbar\omega_c \) is the confinement energy of the \( N \)th Landau level, with \( E_0 \) and \( E_b \) being the ground state subband energy and the band edge energy, respectively.

2.2 Type-II Nonparabolicity

In narrow band gap semiconductors made with materials such as InAs, it has been reported that type-I nonparabolicity alone is not sufficient to explain the mass enhancement. Theoretical [19, 20] and experimental [21] investigations show that tunnelling of the electron wave functions into the barrier layers can lead to electron effective mass enhancement. Recent reports on the cyclotron resonance effective mass in bipolar InAs/GaSb systems have included studies of the dependence on layer thickness in InAs/GaSb bilayers [18, 22], in InAs/GaSb superlattices [18, 23, 24], and in InAs/AlSb/Al\(_{1-x}\)Ga\(_x\)Sb structures [3, 7, 25], although none of the previous work has sought to establish clear relationships that might exist between the effective mass and the strength of the electron-hole hybridisation. Oscillations of the mass with mag-
Fig.1: Calculated electron and hole band dispersions for (i) $E_g = 0$, $\Delta M = 0$, (ii) $E_g = 80$, $\Delta M = 0$, (iii) $E_g = 80$, $\Delta M = 10$ with the atomic spacing $a = 6\AA$.

netic field are found to occur which are opposite in phase to those observed due to type-I nonparabolicity and are thus sometimes termed as antinonparabolicity [3]. This is also referred to elsewhere as type-II nonparabolicity [4].

The simplest model used to describe the conduction-valence band hybridisation and the emergence of minigaps in the InAs/GaSb structure considers two bands [26, 27]: the ground electron subband $E_0$ in the InAs layer, and the ground hole subband $H_0$ in the GaSb layer. The in-plane dispersion relation is initially assumed to be parabolic and the two states hybridise according to the matrix equation:

$$
\begin{pmatrix}
E_0 & \Delta M \\
\Delta M & H_0
\end{pmatrix}
\begin{pmatrix}
\varphi_{E_0} \\
\varphi_{H_0}
\end{pmatrix}
= E
\begin{pmatrix}
\varphi_{E_0} \\
\varphi_{H_0}
\end{pmatrix},
$$

where $E_0(k) = \hbar^2 k^2/(2m_e)$, $H_0(k) = E_g - \hbar^2 k^2/(2m_h)$, and $E_g$ is the band gap. The parameter $\Delta M$ is related to the size of the minigap: the minimum energy separation of the bands is approximately $2\Delta M$. The solutions to this equation are mixed conduction-like and valence-like bands $E_C$ and $E_V$ with energies given by

$$
E_C = \frac{1}{2}(H_0 + E_0) + \frac{1}{2}\sqrt{(H_0-E_0)^2+4\Delta M^2},
$$

$$
E_V = \frac{1}{2}(H_0 + E_0) - \frac{1}{2}\sqrt{(H_0-E_0)^2+4\Delta M^2}.
$$

Figure 1 shows the calculated dispersion relation for the cases (i) $E_g = 0$ meV, $\Delta M = 0$ meV, (ii) $E_g = 80$ meV, $\Delta M = 0$ meV, and (iii) $E_g = 80$ meV, $\Delta M = 10$ meV. The electron mass and the hole mass values, $m_e = 0.023 m_0$ [28] and $m_h = 0.10 m_0$ [29], are the values estimated at the band edges. In an ideal parabolic system the electron and hole densities are in equilibrium and therefore the Fermi energy will lie at the crossing point of the two bands. However, the samples studied here are slightly n-type although the individual layers are not doped. This is due to pinning of the Fermi level by surface states and acceptors in the GaSb layers [30, 31]. The Fermi energy will therefore lie slightly above the crossing point of the two bands. Assuming isotropy, the magnitude of the two dimensional electron and hole number densities are given through the standard equations $k_Fe = \sqrt{2\pi N_e}$ and $k_Fh = \sqrt{2\pi N_h}$, where $k_Fe$ and $k_Fh$ are the values of $k$ where the Fermi energy $E_F$ crosses the electron-like and hole-like segments of the conduction band dispersion, respectively. $N_e$ and $N_h$ can be determined experimentally via transport measurements, and for a given value of $N_e/N_h$ we can therefore deduce the value of $k_F$.

2.3 Cyclotron Resonance Mass

In the low magnetic field semi-classical limit, the cyclotron resonance mass $m_{CR}^*$ can be expressed in terms of a closed cyclotron orbit in $k$-space with an area $A$ which depends on the cyclotron orbit energy $E$ and the in-plane wavevector magnitude $k$. The low field cyclotron mass is given [32] by

$$
m_{CR}^* = \frac{\hbar^2}{2\pi} \left| \frac{\partial A}{\partial E} \right|_{E=E_F}. \tag{5}
$$

In the case of a parabolic dispersion, assuming co-axial and isotropic conduction and valence bands, a cross section area $A$ of an orbit is given by $\pi k^2$. Assuming chain rules, the mass can be written as

$$
m_{CR}^* = \frac{\hbar k^2}{2\pi} \left| \frac{dE}{dk} \right|_{E=E_F}. \tag{6}
$$

We can thus calculate the cyclotron resonance mass of the conduction (electron) and valence (hole) bands from the derivatives of Equations 3 and 4, respectively.

3. EXPERIMENTAL DETAILS

Cyclotron resonance was measured in a far-infrared Fourier transform spectrometer at 2.2 K in Faraday configuration with magnetic field up to 14 T. The samples substrates were wedged by $2^\circ$ to prevent interference distorting the cyclotron resonance lineshape. The resulting transmission spectra were normalised to the spectrum at zero magnetic field, giving a relative spectrum $T = T(B)/T(0)$. Lineshapes were fitted to the spectra according to the transmission relation given in [33, 34], and the effective mass $m^* = eB/\omega_c$ was deduced from the cyclotron energy.

Figure 1: Calculated electron and hole band dispersions for (i) $E_g = 0$, $\Delta M = 0$, (ii) $E_g = 80$, $\Delta M = 0$, (iii) $E_g = 80$, $\Delta M = 10$ with the atomic spacing $a = 6\AA$. The samples substrates were wedged by $2^\circ$ to prevent interference distorting the cyclotron resonance lineshape. The resulting transmission spectra were normalised to the spectrum at zero magnetic field, giving a relative spectrum $T = T(B)/T(0)$. Lineshapes were fitted to the spectra according to the transmission relation given in [33, 34], and the effective mass $m^* = eB/\omega_c$ was deduced from the cyclotron energy. The measurements were performed on two sets of samples, labelled the well width series, and spacer series. All samples were grown by Metal Organic Vapour Phase Epitaxy (MOVPE) on GaAs substrates and consist of a well layer of InAs sandwiched between a 1200Å GaSb capping layer and a thick (2µm) GaSb strain-accommodating buffer layer. The structures in the well width series were grown with InAs growth time varying in the range 30–80 seconds. The
Table 1: The nominal well width \(W\), carrier densities and mobilities of the samples studied. \(\dagger\) denotes \(N_e\) estimate based on results at 20 K. \(\ddagger\) Magnetotransport results indicate the presence of a significant number of holes but simple modelling could not fit the data.

<table>
<thead>
<tr>
<th>Sample</th>
<th>(W) (Å)</th>
<th>At interfaces</th>
<th>(N_e) by CR (10^{15} m^{-2})</th>
<th>(N_e) (10^{15} m^{-2})</th>
<th>(N_h) (10^{15} m^{-2})</th>
<th>(\mu_e) (m²/Vs)</th>
<th>(\mu_h) (m²/Vs)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Well Width Series</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W30</td>
<td>120</td>
<td>-</td>
<td>-</td>
<td>0.63(^\dagger)</td>
<td>0.29</td>
<td>1.9</td>
<td>0.68</td>
</tr>
<tr>
<td>W35</td>
<td>140</td>
<td>-</td>
<td>-</td>
<td>3.68</td>
<td>1.8</td>
<td>0.84</td>
<td>4.2</td>
</tr>
<tr>
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<td>160</td>
<td>-</td>
<td>-</td>
<td>4.27</td>
<td>5.6</td>
<td>4.1</td>
<td>4.4</td>
</tr>
<tr>
<td>W50</td>
<td>200</td>
<td>-</td>
<td>-</td>
<td>7.56</td>
<td>7.6</td>
<td>6.1</td>
<td>7.9</td>
</tr>
<tr>
<td>W60</td>
<td>240</td>
<td>-</td>
<td>-</td>
<td>7.69</td>
<td>7.3</td>
<td>6.2</td>
<td>18.7</td>
</tr>
<tr>
<td>W70</td>
<td>280</td>
<td>-</td>
<td>-</td>
<td>8.47</td>
<td>6.8</td>
<td>6.2</td>
<td>17.5</td>
</tr>
<tr>
<td>W80</td>
<td>320</td>
<td>-</td>
<td>-</td>
<td>7.42</td>
<td>6.0</td>
<td>6.0</td>
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<td><strong>Spacer Series</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>S1-1</td>
<td>240</td>
<td>1 SL</td>
<td>1 SL</td>
<td>7.06</td>
<td>6.4</td>
<td>3.4</td>
<td>21.0</td>
</tr>
<tr>
<td>S5-5</td>
<td>240</td>
<td>5 SL</td>
<td>5 SL</td>
<td>6.29</td>
<td>4.7</td>
<td>3.7</td>
<td>9.6</td>
</tr>
<tr>
<td>S10-0</td>
<td>240</td>
<td>10 SL</td>
<td>0 SL</td>
<td>6.68</td>
<td>5.0</td>
<td>4.3</td>
<td>9.1</td>
</tr>
<tr>
<td>S0-10</td>
<td>240</td>
<td>0 SL</td>
<td>10 SL</td>
<td>6.55</td>
<td>6.5</td>
<td>(\dagger)</td>
<td>(\dagger)</td>
</tr>
<tr>
<td>S10-10</td>
<td>240</td>
<td>10 SL</td>
<td>10 SL</td>
<td>4.94</td>
<td>4.0</td>
<td>0.5</td>
<td>14.0</td>
</tr>
</tbody>
</table>

The limiting well width at which the band overlap disappears and the structure becomes semiconducting. The 8-band \(k \cdot p\) model predicts this limit to be at approximately 90 Å.

4. RESULTS AND DISCUSSION

4.1 General Observations

Contour plots of the cyclotron resonance spectra for a narrow well sample (W40), an intermediate well sample (W60), a wide well sample (W80), and a sample with 10 period of superlattices at both interfaces (S10-10) are shown in Figure 2 (i), (ii), (iii), and (iv) respectively. Darker regions indicate greater absorption within each plot: maximum absorption increases from (i) to (iv).

It is seen in all samples that at low magnetic field, typically \(B < 3\) T, the cyclotron resonance is dominated by a single transition peak which is due to the cyclotron motion of the two-dimensional electrons in the InAs well. However, at higher fields the four samples show very different transition features. Sample W40, which has the narrowest well width of the four samples, displays a series of clear transitions with similar slopes, but which are shifted from each other by different offsets. In addition there are a series of weaker transitions with steeper slopes such as that at 4 T, which breaks off from the electron cyclotron resonance line and increases rapidly in energy as the field increases. This transition is then replaced by another transition which emerges from the low energy...
side. A general feature of all the spectra is that new features appear from the low energy side replacing those that tail off to the high energy region. These phenomena resemble observations reported in the literature [6, 7, 39], but are much more pronounced due to the narrower well widths studied. In the wider well width structures of samples W60 and W80, the spectra have stronger resonance amplitudes due to the greater carrier densities, smaller splittings and narrower linewidths. The transitions in these samples have similar overall features to those of W40 but the couplings are seen to occur at higher magnetic field and the resonances occur within a smaller envelope around a constant mass value. For comparison, selected transition couplings are indicated in Figure 2 by $(\alpha)$, $(\beta)$, and $(\delta)$. It is clear that these coupling features have the same pattern and that they shift to higher magnetic field as the well width increases. However, in sample S10-10, with the large spacer layers at both interfaces, these coupling features are absent. We note that similar splitting features to those observed in sample W60 are observed in other samples in the spacer series (not shown here), but with smaller magnitude. In particular, the features in S10-0 and S0-10 are noticeably similar to each other to within 0.1 T indicating the symmetrical nature of the coupling.

### 4.2 Mass Enhancement at Low Field

We now examine the effective mass of InAs conduction band electrons in the low magnetic field region. The electron cyclotron resonance appears in measurements as a single peak transition with an effective mass $m^* = eB/\omega_c$. Figure 3 shows the transmission spectra at 3 T of all the well width and spacer series samples. We observe that the cyclotron resonance position increases with increasing separation between electron and hole gases. The spectra for all samples appear to be of approximately Lorentzian lineshape, but there are clear differences in linewidth and amplitude between them. As the electron-hole separation decreases, the spectrum linewidth generally becomes wider and the transition amplitude reduces. Table 2 summarises the values of the cyclotron resonance frequency $\omega_c$, full-width-half-maximum $w_L$, and intensity $I$, estimated from fitting transmission lineshapes.
Table 2: The cyclotron resonance fitting parameters: cyclotron frequency ($\omega_c$), full linewidth ($w_L$), intensity ($I$), carrier density and effective mass for the single resonance observed at 3 T for different samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$W$ (Å)</th>
<th>$\omega_c$ (cm$^{-1}$)</th>
<th>$w_L$ (cm$^{-1}$)</th>
<th>$I$</th>
<th>$N_e$ at 3 T ($10^{15}$m$^{-2}$)</th>
<th>$m^*$ ($m_0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well Width Series</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W30</td>
<td>120</td>
<td>56.1</td>
<td>18.4</td>
<td>0.0354</td>
<td>0.63</td>
<td>0.0499</td>
</tr>
<tr>
<td>W35</td>
<td>140</td>
<td>60.5</td>
<td>27.2</td>
<td>0.0885</td>
<td>3.68</td>
<td>0.0463</td>
</tr>
<tr>
<td>W40</td>
<td>160</td>
<td>65.5</td>
<td>24.7</td>
<td>0.0914</td>
<td>4.27</td>
<td>0.0428</td>
</tr>
<tr>
<td>W50</td>
<td>200</td>
<td>68.2</td>
<td>24.4</td>
<td>0.174</td>
<td>7.56</td>
<td>0.0411</td>
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<tr>
<td>W60</td>
<td>240</td>
<td>74.2</td>
<td>16.8</td>
<td>0.260</td>
<td>7.69</td>
<td>0.0378</td>
</tr>
<tr>
<td>W70</td>
<td>280</td>
<td>80.5</td>
<td>17.8</td>
<td>0.291</td>
<td>8.47</td>
<td>0.0348</td>
</tr>
<tr>
<td>W80</td>
<td>320</td>
<td>87.2</td>
<td>11.6</td>
<td>0.381</td>
<td>7.42</td>
<td>0.0321</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1-1</td>
<td>240</td>
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<td>14.1</td>
<td>0.303</td>
<td>7.06</td>
<td>0.0338</td>
</tr>
<tr>
<td>S5-5</td>
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<td>14.5</td>
<td>0.321</td>
<td>6.29</td>
<td>0.0283</td>
</tr>
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<td>86.4</td>
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<td>0.279</td>
<td>6.68</td>
<td>0.0323</td>
</tr>
<tr>
<td>S0-10</td>
<td>240</td>
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</tr>
<tr>
<td>S10-10</td>
<td>240</td>
<td>100.0</td>
<td>13.8</td>
<td>0.268</td>
<td>4.94</td>
<td>0.0280</td>
</tr>
</tbody>
</table>

Fig.3: Cyclotron resonance spectra at 3 T.

to the samples’ spectra at 3 T. The carrier densities and effective masses shown are deduced from the fitted parameters. We see that in the well width series the electron density decreases as the well width decreases due to the increase of the confinement energy in the InAs well. By contrast, the spectral linewidth, corresponding to the electron scattering rate, is generally higher for narrower wells.

For narrowing well width (decreasing electron hole separation), the spectra show a consistent marked increase of the effective mass at low field. The smallest separation, corresponding to a narrow well width of 120 Å ($d = 90$ Å), shows an effective mass of $m^* = 0.050 m_0$, while the addition of 10 period superlattices at the interfaces ($d = 550$ Å) sees this fall to $m^* = 0.028 m_0$, which is only slightly higher than the bulk InAs band edge mass.

4.2.1 Well Width Series

Type-I nonparabolicity predicts increasing cyclotron resonance mass with decreasing well width [16]. An approximation using the analysis of Warburton et al. [17] is given in terms of electron confinement energy by Equation 1. The confinement energy of the lowest electron level $E_0$ is estimated from the self-consistent 8-band $k \cdot p$ model [40]. The lowest electron and highest hole levels $E_{0+}$ and $E_{0-}$ at 3 T are estimated by inclusion of the Zeeman spin splitting term and using the band edge masses for the spin up ($\uparrow$) and spin down ($\downarrow$) respectively. Using these approximations, the effect of type-I nonparabolicity on electron effective mass is plotted against the well width $W$ in Figure 4 as a dashed line. For comparison we plot the experimental data from the well width series as solid circles in the same graph. The mass enhancement observed in the well width series is substantially larger than predicted by type-I nonparabolicity. This suggests that as expected additional type-II nonparabolicity is very important.

The type-II nonparabolic mass is strongly dependent on the relative positions of the minigap and the Fermi energy $E_F$, whose value is affected by the additional hole charges in the system. In order to model a systematic behaviour with well width we make the assumption that $N_e/N_h = 3/2$ which allows us to calculate the Fermi energy using $k_{Fe}^2/k_{Fh}^2 = 3/2$ and
Fig. 4: Calculated mass $m_e^*$ obtained from the hybridisation model for three values of $\Delta M$. The well width series sample data (points), the band edge mass $m_e^*$ (dotted line) and the type-I nonparabolicity effective mass (dashed line) are included for comparison.

Fig. 5: Calculated values of the Fermi energy for different well widths. Electron/hole density ratio $N_e/N_h = 3/2$ is assumed. In Figure 6 the effective mass is shown, calculated according to the coupled two band model using both type-II nonparabolicity alone and combining both type-I and type-II contributions together. This shows that the data can be well fitted with a value of $\Delta M = 4 \text{ meV}$. This value is consistent with the theoretical prediction of minigaps [40], our own 8-band $k\cdot p$ calculation on bilayer structures and the experimental values measured for superlattices [41].

4.2.2 Spacer Series

As samples in the spacer series have constant well width, the confinement energies are almost constant, with a slight increase expected due to the increased confinement of the spacer layers. Effective mass variation in this series is therefore almost entirely due to the type-II nonparabolicity. Figure 7 shows the measured effective masses plotted against the number of superlattice periods at both interfaces. The effective mass approaches the top of the hole band in the GaSb barrier.

In Figure 6 the effective mass is shown, calculated according to the coupled two band model using both type-II nonparabolicity alone and combining both type-I and type-II contributions together. This shows that the data can be well fitted with a value of $\Delta M = 4 \text{ meV}$. This value is consistent with the theoretical prediction of minigaps [40], our own 8-band $k\cdot p$ calculation on bilayer structures and the experimental values measured for superlattices [41].
electron mass of sample W60 is included as a sample without any spacer. We observe that the addition of superlattice layers between electrons and holes at both interfaces reduces the cyclotron resonance mass sharply from 0.0378m₀ (no superlattice) to 0.028m₀ (10 superlattice periods at each interface), which corresponds closely to type-I nonparabolicity mass for this well width (dashed line). It is likely that the tunnelling effect is much more strongly suppressed by the superlattice layers at the interfaces than possible electron-hole Coulomb interactions, and therefore the effect of type-II nonparabolicity at these interfaces is strongly reduced. It is evident that 10 superlattice periods at both interfaces are enough to remove the type-II nonparabolicity effect completely, eliminating the minigap so that ∆M = 0. This conclusion is similar to the qualitative studies by [3, 7, 25, 39] who demonstrated that the inclusion of an AlSb barrier with a thickness of order 2–4 nm was also enough to remove all evidence of electron-hole hybridisation.

Samples S10-0 and S0-10 are shown indicatively in Figure 7 as open circles. Although 10 periods of superlattice at one interface would remove hybridisation completely from that interface, hybridisation at the other interface should be unaffected. This is consistent with the measured effective masses of S10-0 and S0-10 being approximately halfway between W60 and S10-10. The fact that the results from these two samples are so similar suggests that the structures are symmetric with both interfaces being very similar. Comparison with the other samples in the series then suggests that the addition of 1–2 periods of the superlattice is sufficient to halve the coupling strength.

5. CONCLUSION

In conclusion, we have demonstrated that the effects of electron-hole hybridisation on InAs/GaSb structures are very significant, and they can be controlled in a consistent way by varying the structures studied. In the low field limit, the effective mass is additionally enhanced as a result of the type-II band nonparabolicity, caused by the electron and hole coupling. The experimental findings can be fitted successfully by a simple two band model with a minigap size of 8 meV. The use of superlattice spacer layers between the electrons and holes also shows that the coupling can be rapidly reduced thus reducing the cyclotron resonance mass.

References


Cattleya is a lecturer at the Physics Department, Thammasat University. She received her Doctoral degree from Oxford University U.K. where the experimental work for this paper was conducted. Her current research interests include spectroscopy and magneto-optical characterisation of semiconductors and laser devices, and nanophotonics for Bio-medical application. This work was supported by the Institute of Development and Promotion of Science and Technology Talent of Thailand (DPST).