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## FAR-INFARED LASER SPECTROSCOPY OF TWO DIMENSIONAL HOLES IN STRAINED-LAYER HETEROSTRUCTURE AND SUPERLATTICES

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We report far-infrared magneto-transmission data at 4.2 K on a series of p-type strained-layer  $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{In}_y\text{Ga}_{1-y}\text{As}/\text{GaAs}$  quantum well (QW) structure and  $\text{InAs}_{0.15}\text{Sb}_{0.85}/\text{InSb}$  superlattices (SLS). The  $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{In}_y\text{Ga}_{1-y}\text{As}/\text{GaAs}$  QW structure consists of strained  $\text{In}_y\text{Ga}_{1-y}\text{As}$  layers of 100 Å in thickness and a spacer layer having thickness ( $W_{\text{sp}}$ ) ranging from 30 Å to 700 Å. The  $\text{InAs}_{0.15}\text{Sb}_{0.85}/\text{InSb}$  SLS was grown on top of a 1.0 μm  $\text{InAs}_{0.05}\text{Sb}_{0.95}$  strain relief buffer layer consisting of alternating layers of 100 Å  $\text{InAs}_{0.15}\text{Sb}_{0.85}$  and 200 Å  $\text{InSb}$ . The detail of the sample structures has been described elsewhere [1]. The two-dimensional (2D) hole density ( $p_{2D}$ ) of the sample is obtained from the period of the Shubnikov-de Hass oscillations in quantum transport measurements made at 4.2 K. The magneto-transmission experiments are performed in magnetic field ( $B$ ) up to 8.5 T using polarized radiation and the spectrum is displayed as  $4 \text{Log}_{10}[T(B)/T(0)]$ , where  $T(B)$  is the transmittance at  $B$ .

In Fig.1, we show a typical transmission spectra obtained at laser wavelengths  $\lambda = 513, 420$  and  $393 \mu\text{m}$  for a p-type strained-layer  $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{In}_y\text{Ga}_{1-y}\text{As}/\text{GaAs}$  sample G095 having  $p_{2D} = 2.8 \times 10^{11}/\text{cm}^2$  and a low field mobility  $\mu = 2.0 \times 10^4 \text{cm}^2/\text{Vs}$ . The data display a well defined cyclotron resonance (CR) and thus allow a clear identification of the resonance position  $B_{\text{CR}}$ , which yield directly cyclotron mass through  $m^* = eB_{\text{CR}}\lambda/2\pi$ . We find  $m^* = (0.150 \pm 0.003) m_e$  for sample G095, where  $m_e$  is the free electron mass. This light in-plane hole mass has previously been attributed to the preferential population of the ( $J = 3/2, m_j = \pm 3/2$ ) valence band due to the large biaxial strain in the  $\text{In}_y\text{Ga}_{1-y}\text{As}$  layer [2]. Similar measurements were repeated for a total of nine samples having  $p_{2D}$  from  $5.4 \times 10^{10}/\text{cm}^2$  for a  $W_{\text{sp}} = 700 \text{Å}$  sample to  $1.65 \times 10^{12}/\text{cm}^2$  for a  $W_{\text{sp}} = 30 \text{Å}$  sample. We find that, as  $p_{2D}$  increases from  $5.4 \times 10^{10}/\text{cm}^2$  to  $1.65 \times 10^{12}/\text{cm}^2$ ,  $m^*$  increases from  $0.117 m_e$  to  $0.225 m_e$ , which is an enhancement of about 100% in hole mass. These results, as well as the relevant structure parameters for the samples, are summarized in Table I.

The enhancement of  $m^*$  by as much as 100% is indicative of a strong valence band nonparabolicity in the  $m_j = \pm 3/2$  band of the  $\text{In}_{0.20}\text{Ga}_{0.80}\text{As}$  layer. The density dependence of  $m^*$  for our samples can be accounted for by employing a two-band tight binding calculation using the valence band edge mass ( $m_0^*$ ), the strain-induced splitting energy ( $\Delta_c$ ) and a nonparabolicity factor ( $C$ ) as parameters [3]. We fit our data to the model and obtain  $m_0^* = (0.120 \pm 0.005) m_e$  and  $\Delta_c/C = (47 \pm 5) \text{meV}$ . This value of  $m_0^*$  uniquely characterizes the strained-layer  $\text{In}_{0.20}\text{Ga}_{0.80}\text{As}$  valence band parameter,  $1/(\gamma_1 + \gamma_2)$ .

In addition, the valence band offset  $\Delta E_v$  of the heterostructure is calculated using the charge transfer model, as outlined in Ref.[4], which relates the  $\Delta E_v$  at the interface to

the carrier density in the QW and the  $W_{sp}$  in the barrier layer. We have calculated  $\Delta E_v$  for each sample, using the experimentally determined  $p_{2D}$  and  $m^*$ , listed in Table I, and assuming a Be acceptor binding energy of 65 meV. For the six GaAs/In<sub>0.20</sub>Ga<sub>0.80</sub>As/GaAs QW samples, the average value of  $\Delta E_v$  is 122 meV with a standard deviation of 15 meV. For the three Al<sub>x</sub>Ga<sub>1-x</sub>As/In<sub>0.18</sub>Ga<sub>0.82</sub>As/GaAs samples, the  $\Delta E_v$  at the Al<sub>x</sub>Ga<sub>1-x</sub>As/In<sub>0.18</sub>Ga<sub>0.82</sub>As interface is estimated to be 250, 280 and 330 meV for  $x=0.20, 0.30$  and  $0.40$  respectively. We note that the use of Al<sub>0.40</sub>Ga<sub>0.60</sub>As as a barrier layer greatly enhances the  $\Delta E_v$  (from 122 meV to 330 meV) and the 2D holes still have relatively light  $m^*$  ( $0.225 m_e$ ).

Fig.2 shows the relative transmittance of two InAs<sub>0.15</sub>Sb<sub>0.85</sub>/InSb samples, VL695 and VL701, as a function of  $B$  at  $\lambda = 118.8 \mu\text{m}$  in the Faraday geometry ( $\vec{B} \perp \vec{E}$ ). The incident radiation is circularly polarized in the hole CR-active (CRA) sense of polarization (85%). The samples VL695 and VL701 have  $p_{2D} = 9.4 \times 10^{10}/\text{cm}^2$  per layer and  $p_{2D} = 1.4 \times 10^{11}/\text{cm}^2$  per layer, respectively. In the high  $B$  regime ( $\geq 2T$ ), both traces display a similar doublet structure which dominates the spectrum in the hole CRA polarization. The doublet is attributed to CR of 2D holes in the InSb layers having two CR masses [1]. The observed hole masses increase from  $0.033 m_e$  and  $0.054 m_e$  for sample VL695 to  $0.035 m_e$  and  $0.067 m_e$  for sample VL701. Such a large mass increase for a small increase in  $p_{2D}$  ( $4.6 \times 10^{10}/\text{cm}^2$ ) suggests a strong valence band nonparabolicity in the InSb layer.

In the low  $B$  regime, both traces show a sharp resonance at an identical resonance position,  $B = 1.33T$ . The transition is found to be allowed in the hole CR-inactive (CRI) sense of circular polarization. Upon tuning the incident radiation energy from 2.4 meV to 18 meV, the resonance  $B$  shows a linear dependence on the laser energy and has a zero intercept at zero field. Thus, this transition cannot be due to the 1s to 2p-like impurity transition of electrons since this type of transition energy extrapolates back to a large zero-field offset. Moreover, for semiconductors either having narrow band gap, such as InSb, or under uniaxial strain, it has been predicted that spin resonance of holes in the  $m_j = \pm 3/2$  band can be excited when  $\vec{B} \perp \vec{E}$  and the incident radiation is polarized in the hole CRI sense [5]. We attribute the observed transition to spin resonance of the 2D holes in the InAs<sub>0.15</sub>Sb<sub>0.85</sub>/InSb SLS and an effective  $g$ -factor of 140 is deduced.

In summary, far-infrared magneto-transmission experiments have been performed in Al<sub>x</sub>Ga<sub>1-x</sub>As/In<sub>y</sub>Ga<sub>1-y</sub>As/GaAs heterostructures and InAs<sub>0.15</sub>Sb<sub>0.85</sub>/InSb SLS. We find that the valence band of the In<sub>0.20</sub>Ga<sub>0.80</sub>As strained-layer can be described by a two-band tight binding model having  $m_0^* = (0.120 \pm 0.005) m_e$  and  $\Delta_c/C = (47 \pm 5) \text{meV}$ . It is also shown that the 2D holes in InAs<sub>0.15</sub>Sb<sub>0.85</sub>/InSb SLS have light in-plane masses and an effective  $g$ -factor of 140.

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Table I Summary of experimental results and relevant structure parameters for all nine  $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{In}_y\text{Ga}_{1-y}\text{As}/\text{GaAs}$  heterostructure samples.

Sample	G161	G159	G095	G098	VR535	VR534	G111	G117	G118
x	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.30	0.40
y	0.20	0.20	0.20	0.20	0.20	0.20	0.18	0.18	0.18
$W_{sp}$ (Å)	700	500	300	150	40	40	30	30	30
$P_{2D}$ ( $10^{11}\text{cm}^{-2}$ )	0.54	0.63	2.8	5.2	6.5	8.6	12.3	13.8	16.5
$m^*$ ( $m_e$ )	0.117	0.127	0.150	0.160	0.171	0.194	0.205	0.210	0.225
$\Delta E_v$ (meV)	129	121	137	134	102	108	250	280	330

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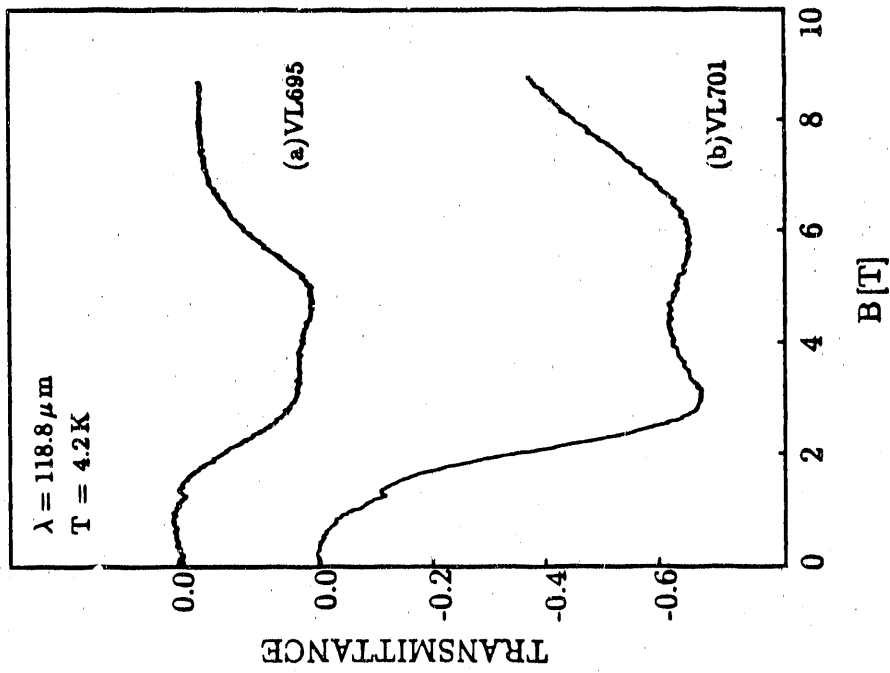


Fig.1 Relative transmittance vs magnetic field at three laser wavelengths  $\lambda = 513, 420$  and  $393 \mu\text{m}$  for a p-type strained-layer  $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{In}_y\text{Ga}_{1-y}\text{As}/\text{GaAs}$  sample, G095, having  $p_{2D} = 2.8 \times 10^{11}/\text{cm}^2$  and  $\mu = 2.0 \times 10^4 \text{ cm}^2/\text{Vs}$  at 4.2 K.

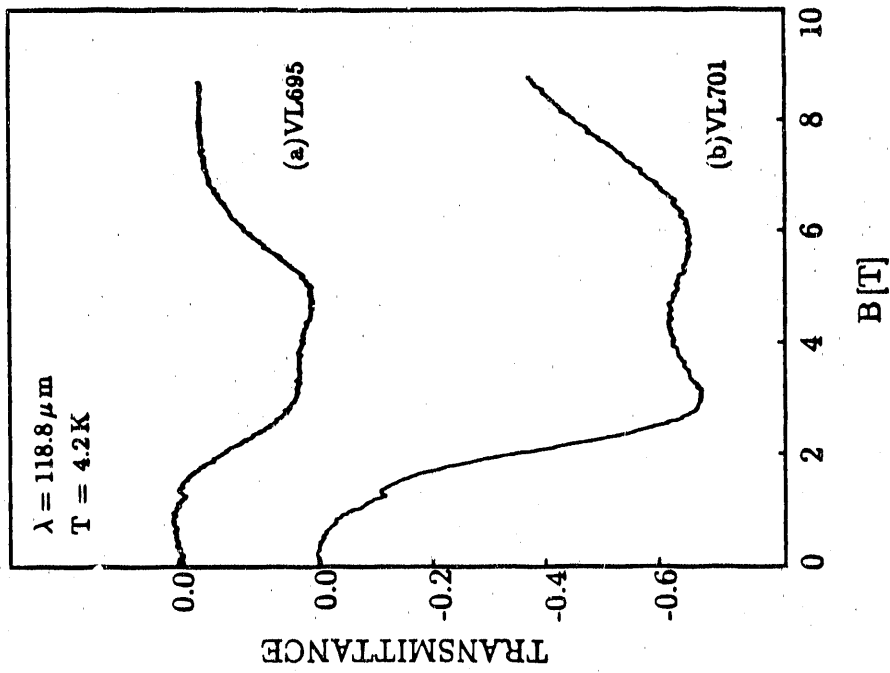


Fig.2 Magneto-transmittance of two p-type  $\text{InAs}_{0.15}\text{Sb}_{0.85}$  InSb SLS samples, VL695 and VL701, at  $\lambda = 118.8 \mu\text{m}$  in the Faraday geometry. The incident radiation is circularly polarized in the hole CR-active sense.

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