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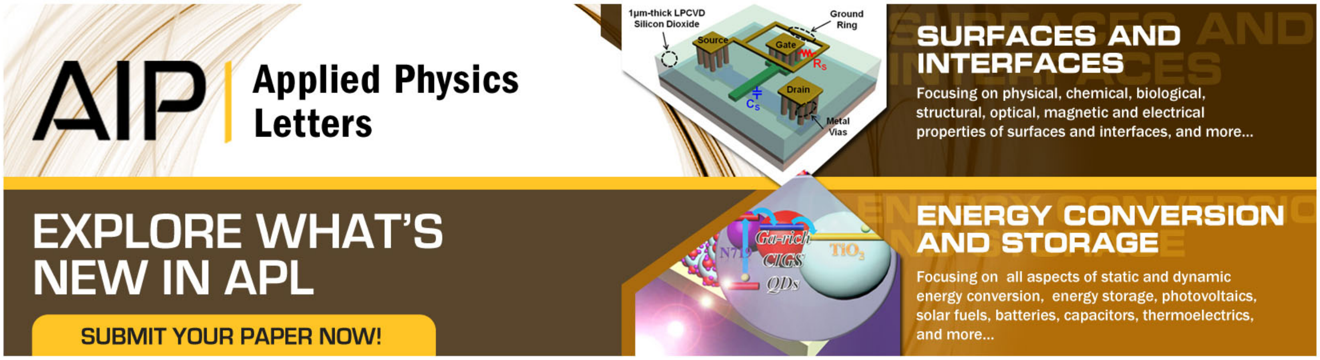

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Cyclotron resonance of two-dimensional holes in strained-layer quantum well structure of (100)$In_{0.20}Ga_{0.80}As/GaAs$

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Cyclotron resonance of the two-dimensional hole gas (2DHG) in the strained-layer quantum well structure of $In_{0.20}Ga_{0.80}As/GaAs$ is observed in far-infrared transmission measurements made at 4.2 K. The cyclotron mass of the 2DHG in the $In_{0.20}Ga_{0.80}As$ channel is $(0.191 \pm 0.008)m_e$ for a 2D hole density $p_{2D} = 8.5 \times 10^{11}/\text{cm}^2$.

There is a great deal of current interest in the strained-layer quantum well structure of (100)$In_xGa_{1-x}As/GaAs$ for applications in high-speed, low-power complementary logic devices.[1-4] In this structure, the $In_xGa_{1-x}As$ layers are grown thin enough such that the lattice mismatch between the $In_xGa_{1-x}As$ and GaAs layers is accommodated entirely by elastic strain rather than by misfit dislocations.[5] The planar compression in the $In_xGa_{1-x}As$ layer removes the degeneracy of the heavy hole and light hole bands at the Brillouin zone center.[6,7] And, as a result, the two-dimensional hole gas (2DHG) confined in the $In_xGa_{1-x}As$ quantum well is expected to have the effective mass of the light hole band. Experimentally, the realization of such a light mass 2DHG system was first reported by Schirber *et al.* in 1985[8] and extensive investigations of the valence-band structure under the influence of the built-in strain have since been carried out.[9-11] In these investigations, the effective mass of the 2DHG is deduced from the temperature dependence of the Shubnikov–de Hass oscillations or from interband optical measurements. To date, there is still no report of direct measurment of it using conventional cyclotron resonance (CR) techniques.

We wish to report in this letter our experimental determination of the effective mass of the 2DHG in a strained-layer quantum well structure of (100)$In_{0.20}Ga_{0.80}As/GaAs$ using far-infrared (FIR) cyclotron resonance. The CR measurements are carried out in combination with quantum transport measurements and thus allow us to determine the 2DHG density (p_{2D}) and its mass (m_{CR}) independently. We find $m_{CR} = 0.191 \pm 0.008 m_e$ at a $p_{2D} = 8.5 \times 10^{11}/\text{cm}^2$. The scattering rate ($\tau_{CR}^{-1}$) obtained from the CR data is $(1.35 \pm 0.15) \times 10^{12}\ \text{s}^{-1}$, which is several times smaller than that deduced from the dc transport measurement.

A schematic illustration of the sample structure (VR533) used in this experiment is shown in Fig. 1. It was grown on a 1.0-μm-thick GaAs buffer layer, on top of which are two *p*-type quantum wells of the same heterostructure. Each quantum well consists of a 100 Å undoped InGaAs well sandwiched on both sides by a 40 Å GaAs spacer layer and a 50 Å Be-doped GaAs layer with a doping concentration of $2 \times 10^{18}/\text{cm}^3$. GaAs has a band gap larger than $In_{0.20}Ga_{0.80}As$ and it is expected to have a 2DHG in each $In_{0.20}Ga_{0.80}As$ quantum well. The lattice constants for GaAs and $In_{0.20}Ga_{0.80}As$ are 5.56 and 5.73 Å, respectively, which give rise to a lattice mismatch of about 1.4%.

The sample was cut into a Van der Pauw pattern and its substrate was wedged 5° in order to avoid multiple interference in the CR experiment. Ohmic contacts to the 2DHG were made by alloying In at 400 °C for 10 min in a hydrogen atmosphere. The quality of the 2DHG in the heterostructure can be assessed by studying the magnetoresistance and the associated quantum oscillations at 4.2 K. In Fig. 2, we show the high-field Hall effect and the Shubnikov–de Haas effect measurements with the magnetic field perpendicular to the sample surface. The 2D hole density calculated from the quantum oscillations is $8.5 \times 10^{11}/\text{cm}^2$ for each well and the hole mobility is $\sim 1500\ \text{cm}^2/\text{V s}$.

The cyclotron resonance experiment was performed in magnetic fields (B) up to 8.5 T using an optically pumped, linearly polarized, far-infrared molecular gas laser at 4.2 K. The transmitted radiation was detected by a Ge bolometer placed below the sample. The spectrum was displayed as $4 \ln[T(B)/T(0)]$, where $T(B)$ is the transmittance at the magnetic field B.

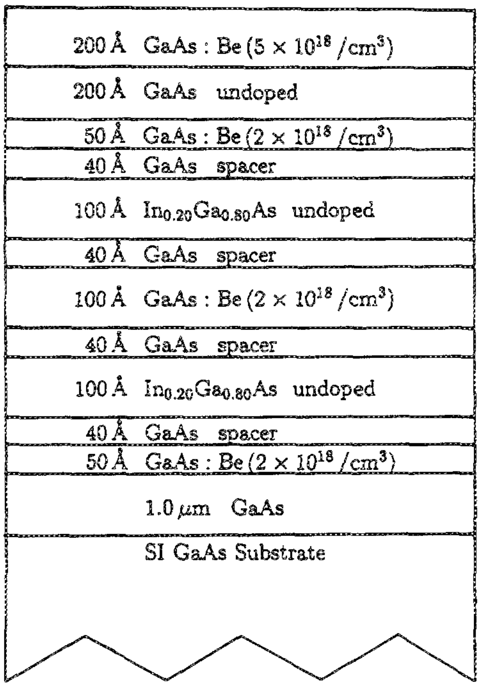

FIG. 1. Schematic drawing of the *p*-type $GaAs/In_{0.20}Ga_{0.80}As/GaAs$ strained-layer quantum well structures.

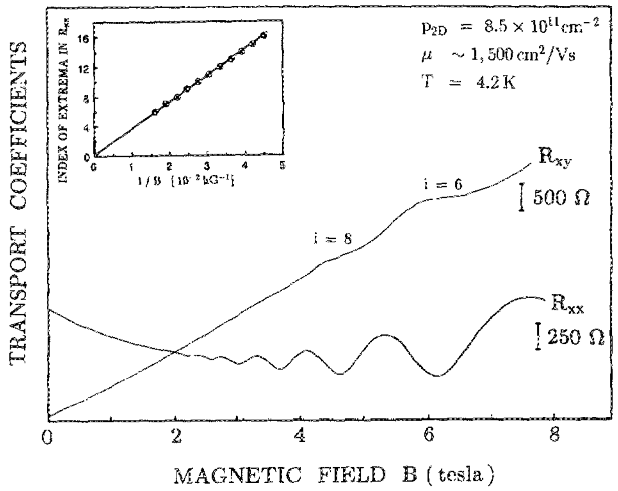

FIG. 2. Hall resistance R_{xy} and longitudinal resistance R_{xx} as a function of magnetic field B for one quantum well at 4.2 K.

Figure 3 shows the magnetic field dependence of the $4 \ln[T(B)/T(0)]$ signal obtained at two laser wavelengths: $\lambda = 393$ and $513\,\mu$m. We fit the data to the Drude model, as described in Ref. 12, using $m_{\rm CR}$ and $\tau_{\rm CR}^{-1}$ as the fitting parameters. The results from the best computer fit are shown in Fig. 3 as the dashed curves. For $\lambda = 393\,\mu$m, we find $m_{\rm CR} = 0.194 m_e$ and $\tau_{\rm CR}^{-1} = 1.5 \times 10^{12}$ s^{-1}. For $\lambda = 513\,\mu$m, the resonance line shape has a shoulder in the high B side, but the low B side of the line can be fitted well using $m_{\rm CR} = 0.188 m_e$ and $\tau_{\rm CR}^{-1} = 1.2 \times 10^{12}$ s^{-1}. The shoulder is suggestive of an additional resonance at $B \sim 6$ T, corresponding to a mass of $\sim 0.29 m_e$. The resonance may originate from 2D holes in small regions of the sample where strain relaxation through misfit dislocation may have occurred, as discussed in the following paragraph. In any case, the values for $m_{\rm CR}$ and $\tau_{\rm CR}^{-1}$ extracted from the two CR curves agree with each other to better than 4%. Their mean value is $0.191 m_e$ and 1.35×10^{12} s^{-1}. This hole mass is considerably smaller than the bulk GaAs hole mass of $\sim 0.35 m_e$. For our sample structure, the in-plane energy splitting between the uppermost light hole band and the heavy hole band is about 60 meV.[13] At this splitting energy, only the ground level is occupied at our experimental temperature of 4.2 K. Therefore, it is expected that the observed hole mass is derived from the light hole band.

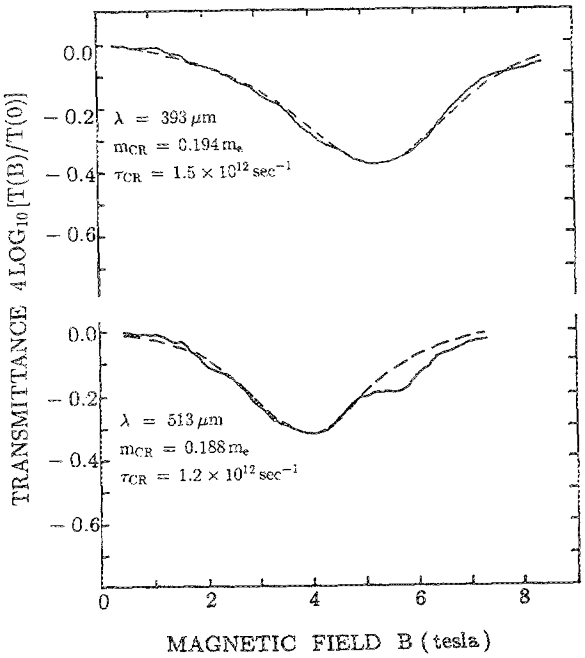

FIG. 3. Relative transmittance vs magnetic field. Solid curves: CR traces from sample (VR533) using the $\lambda = 393\,\mu$m and 513 μm laser lines. Dashed curves: fits to the Drude model, using $m_{\rm CR}$ and $\tau_{\rm CR}^{-1}$ given in the figure.

Recently, stability criteria for the strained heterostructure have been derived by Tsao *et al.* for both single-kink and double-kink dislocation mechanisms.[14,15] They proposed that a measure of stability, or metastability, of a strained heterostructure against a particular plastic flow is the excess stress which acts as the driving force for strain relief. By evaluating the excess stress as a function of position within the structure for both mechanisms, the degree of stability can be determined. Based on this model, we have calculated the degree of stability of our device structure against both dislocation mechanisms and found that our device is close to the stable-metastable boundary for single-kink dislocations. Strain relaxation through misfit dislocation can give rise to inhomogeneity and degrade the sample quality. Since the effective thickness of the strained layers in our device is only marginally below the stability requirement, it is possible to have the strain in some small regions of the sample relaxed by misfit dislocations. The relatively low dc mobility in our transport measurement and the presence of a heavier mass in our CR data might be the consequences of this strain relaxation.

Owing to the high 2-D hole density in the $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ quantum well, it is important to consider the nonparabolicity contribution to the hole effective mass. Using a tight binding approximation, Osbourn *et al.* have calculated the CR hole mass in terms of the layer strain, the valence-band nonparabolicity, and the valence-band strain-splitting energy (Δ).[7] The cyclotron mass at the Fermi level is approximated by

$$m_{\rm CR}(E) = m_v^0 [1 + 2(C/\Delta)E], \qquad (1)$$

for $E < \Delta/2$. Here C is the valence-band nonparabolicity parameter and m_v^0 is the band-edge mass. Since $m_{\rm CR}$ and p_{2D} are independently determined in our experiment, the Fermi energy can be obtained by integrating the valence-band density of states. The value of Δ/C can be obtained from Eq. (1) if m_v^0 is known. For $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ with an In mole fraction of $0.15 < x < 0.25$, m_v^0 is known to be $\sim 0.09 m_e$.[16,17] We find, by using $m_v^0 = 0.09 m_e$, Δ/C to be 26 meV for our sample. The error associated with Δ/C results mainly from m_v^0 and is estimated to yield ~15% uncertainty. This value is in agreement with those obtained from recent magnetoluminescence measurements made on similar sample structures.[13,16]

In conclusion, we have measured for the first time the effective mass of the 2DHG in the strained-layer quantum well structure of $(100)\mathrm{In}_{0.20}\mathrm{Ga}_{0.80}\mathrm{As/GaAs}$ using far-infrared CR techniques at 4.2 K. The CR mass from two laser energies is determined to be $(0.191 \pm 0.008) m_e$ at p_{2D}

$= 8.5 \times 10^{11}/\text{cm}^2$. This reduction in hole mass is a result of the strain-induced valence-band splitting and the valence-band nonparabolicity. Based on this direct mass measurement, the ratio of the valence-band splitting to the nonparabolicity factor is determined to be 26 meV.

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