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High-field splitting of the cyclotron resonance absorption in strained *p*-InGaAs/GaAs quantum wells

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We report a systematic study of the cyclotron resonance (CR) absorption of two-dimensional holes in strained InGaAs/GaAs quantum wells (QWs) in the quantum limit. The energies of the CR transitions are traced as a function of magnetic field up to 55 T. A remarkable CR line splitting was evidenced when the resonant field exceeds 20 T. We analyze our data with a 4×4 Luttinger Hamiltonian including strain and QW potentials using two different methods to calculate Luttinger parameters for ternary alloys. We found excellent agreement with the experiment when linear interpolation of the Luttinger parameters is used.

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Nowadays strained-layer InGaAs/GaAs heterostructures remain potentially interesting for many applications, such as high-frequency electronics, solar cells, and infrared lasers (see for review Ref. 1). Additionally, during the last few years, the rapidly growing area of spintronics has increased the interest in these structures due to demonstration of efficient spin injection[2,3] and circular-polarized electroluminescence in InGaAs/GaAs Schottky diodes, as well as the discovery of the anomalous Hall effect in Mn δ-doped InGaAs/GaAs quantum wells.[4,5]

When the thickness of the InGaAs epilayer grown on a GaAs substrate remains below a critical thickness, the lattice mismatch between the substrate and the epilayer can be accommodated entirely by an elastic biaxial strain rather than by formation of misfit dislocations. The strain provokes significant changes in the valence-band structure, removing the Brillouin-zone-center degeneracy and shifting the light-hole (lh) band down with respect to the heavy-hole (hh) one, which becomes the uppermost (lowest hole energy). Decoupling of the light- and heavy-hole bands leads to the so-called mass reversal effect—the light-hole behavior of the heavy-hole band. The confinement potential in quantum wells tends to maximize the effect. The mass reversal in InGaAs/GaAs quantum wells was experimentally observed first by measurements of temperature dependence of the Shubnikov–de Haas oscillations and then confirmed by direct measurements via cyclotron resonance (CR) technique.[6–8] Since the energy separation between the lh and hh bands is relatively small, the dispersion of the hh band is expected to be strongly nonparabolic.[9] So far, however, there are only few systematic studies of the valence-band nonparabolicity, and the situation with the band dispersion remains unclear, while understanding of the valence-band structure is particularly important for the device modeling. For example, Warburton *et al.*[10] studied CR absorption in a set of $In_{0.18}Ga_{0.82}As$/GaAs QW samples with various carrier concentrations under magnetic fields up to 17 T and did not find any pronounced nonlinearity. On the other hand, Lin *et al.*[11] using similar approach (CR absorption in a set of $In_{0.2}Ga_{0.8}As$/GaAs QWs) found the cyclotron mass rising from $0.123m_e$ up to $0.191m_e$ while the 2DHG density changes from 0.54×10^{11} up to 8.5×10^{11} cm^{-2}.

In this work we investigate CR absorption in *p*-type $In_{0.14}Ga_{0.86}As$/GaAs QWs under high magnetic fields of up to 55 T. In contrast to the above cited authors, we scan the dispersion of the cyclotron mass by changing the excitation wavelength rather than carrier concentration. For each given excitation wavelength the CR absorption line is recorded as a function of magnetic field. We used various types of excitation sources from usual CO_2 pumped gas lasers (at LNCMP, Toulouse) to quantum cascade lasers (QCLs) and free-electron laser (at FZD, Dresden) covering the wide spectral range from 420 down to 65 μm. We found that the uppermost valence subband is strongly nonparabolic. The CR absorption line exhibits a pronounced splitting when the excitation wavelength decreases below 100 μm, while the corresponding resonant field rises above 20 T.

To analyze the data we calculated the hole Landau levels and the CR transition energies as a function of magnetic field. We used a 4×4 Luttinger Hamiltonian that includes also strain and QW potentials. The Luttinger parameters for ternary alloys, however, are not known *a priori*. It is generally accepted that the Luttinger parameters have to be linearly interpolated from the values of the parent binary compounds.[12] On the other hand, several authors propose nonlinear interpolation schemes for cubic semiconductors (see, for example, Refs. 13–15). The particular feature of strained systems is the significant simplification of the valence-band structure compared to the unstrained case, allowing to consider them as a model system to probe different theoretical approaches. We therefore compared in our analysis two interpolation schemes for Luttinger parameters: linear and nonlinear according to Ref. 14. We found much better agreement with the experiment when the linear interpolation scheme is used.

The sample we studied in this work is a *p*-type InGaAs multiple quantum well structure metal-organic chemical-vapor deposition grown on a semi-insulating GaAs substrate oriented along the [001] direction. One period of the heterostructure consists of an undoped 70 Å wide $In_{0.14}Ga_{0.86}As$ QW sandwiched between 500 Å wide GaAs barriers. The barriers contain two carbon delta-doped layers separated from each quantum well by a 150 Å thick spacer. The nominal hole concentration is 4.5×10^{11} cm^{-2}/QW; the total number of periods is 50.

We performed all experiments in pulsed magnets in Faraday configuration, where the wave vector of the electromagnetic radiation is parallel to the magnetic field and to the growth direction of the heterostructure. Most of the measurements were carried out in the Dresden High Magnetic Field Laboratory (HLD). The magnet we have used is a 55 T coil with a 24 mm clear bore diameter. The coil produces roughly 150 ms long pulses with a rise time close to 12 ms. The cool-down time after a full-energy pulse remains below 1.5 h. The excitation light was guided by a polished stainless-steel waveguide to the sample mounted in the center of the coil. The transmitted light was then focused on a Ge:Ga photodetector installed 200 mm below the sample to minimize the modulation of the sensitivity by magnetic field. In addition to the main waveguide, we used a reference one, containing no sample, in order to compensate possible fluctuations of the excitation source intensity.

As the main excitation source we used the free-electron laser facility at the Forschungszentrum Dresden-Rossendorf (FELBE).[16] The infrared light is fed through a 50 m long beamline to the pulsed magnets of the high magnetic field facility. In contrast to most of the free-electron lasers (FELs), FELBE is capable to deliver a continuous train of short Fourier-limited pulses with 13 MHz repetition rate. Therefore, no synchronization of the FEL with the magnetic field pulses is necessary. The emission wavelength is tunable between 4 and 230 μm with average power up to 30 W. In addition to the FEL, we utilized semiconductor QCLs which recently became available in terahertz range.[17–19] This type of lasers is easily portable, allowing to mount them very close to the sample. Along with the portability, QCLs are relatively easy to operate since they work under electrical current injection; therefore no optical excitation or alignment is necessary. However, only a limited number of wavelengths are currently available.

Experiments above the longest wavelength available at FELBE were performed at the Toulouse High Magnetic Field Laboratory (LNCMP). This laboratory is equipped with a long-pulse coil, delivering magnetic fields up to 40 T with a total pulse length of 800 ms. On the optical side, at the LNCMP several CO_2 pumped gas lasers emitting in far-infrared or submillimeter range are available. The experimental setup is very similar to the one in Dresden. In all measurements the temperature was set to 4.2 K.

Figure 1 represents a set of typical transmission spectra obtained under FEL and QCL excitations. The radiation wavelength is given on the left-hand side of the figure, while corresponding energy values are shown on the right-hand side. Two curves marked with QCL were taken using terahertz quantum cascade lasers running in a pulsed mode with 500 ns pulse width and 20 kHz repetition rate. As can be seen the signal-to-noise ratio is comparable to the FEL-based traces, confirming that QCLs have a large unexplored potential in spectroscopic applications.

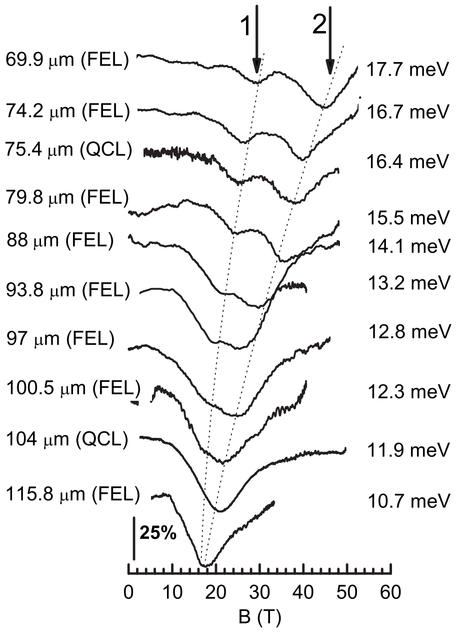

FIG. 1. Selected transmission curves of $In_{0.14}Ga_{0.86}As/GaAs$ multiple quantum wells as a function of magnetic field, measured under FEL and QCL excitation. The excitation wavelengths are indicated on the left side, while the corresponding photon energies are given on the right side of the figure. Arrows 1 and 2 point to minima corresponding to the transitions $0s_1\rightarrow1s_1$ and $3a_1\rightarrow4a_1$, respectively, at the highest photon energy (see explanation in the text). Dotted lines are plotted to simplify the identification of the resonances.

The CR absorption line exhibits a pronounced splitting when the excitation energy rises above 12 meV ($\approx$100 μm) which pushes the corresponding resonant magnetic field above 20 T. The dotted lines are drawn to guide the eyes. Up to approximately 20 T the position of the CR absorption line scales nearly linearly with magnetic field, which is consistent with measurements from Ref. 10. Above this value the CR line splits into two well resolved components with strongly nonlinear magnetic field dependencies.

To analyze the obtained data we have developed a model based on a 4×4 Luttinger Hamiltonian that includes the deformation potential and the rectangular QW energy profile.[20] The eigenfunctions of the Hamiltonian were calculated in a vector-potential gauge given by $\mathbf{A}=1/2[\mathbf{H}\times\mathbf{r}]$. The Luttinger parameters γ_1, γ_2, γ_3, and κ are usually calculated via linear interpolation between GaAs and InAs values for the given In content. In order to understand how the Luttinger parameters affect the transition energies and, especially, the relative position of two lowest hh Landau levels (see discussion below), we have performed additional calculations using the nonlinear interpolation scheme for cubic semiconductors proposed initially by Lawaetz[14] and successfully used recently by Winkler *et al.*[15] Initial values of the Luttinger parameters for bulk InAs and GaAs were taken from Ref. 12.

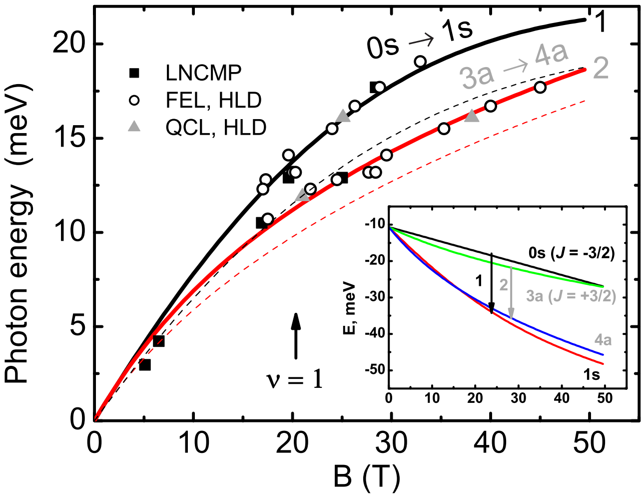

FIG. 2. (Color online) Energies of cyclotron resonance transitions as a function of magnetic field, calculated (lines) and measured (squares, circles, and triangles). The vertical arrow labeled $\nu=1$ indicates the magnetic field when the Landau-level filling factor ν is equal to unity. Solid lines correspond to the calculations made with linearly interpolated Luttinger parameters, while thin dashed lines represent results given by use of nonlinearly interpolated parameters. The inset shows the energies of the four lowest Landau levels versus magnetic field calculated using linearly interpolated Luttinger parameters. Arrows 1 and 2 indicate the transitions corresponding to lines 1 and 2 on the main figure, respectively.

The Luttinger parameters are connected via the following expression:[21]

$$\kappa = \frac{1}{3}(\gamma_1 - 2\gamma_2 - 3\gamma_3 + 2) - \frac{1}{2}q. \tag{1}$$

The parameter q is usually neglected since it is around 0.04 for both GaAs and InAs. We also neglected the nondiagonal terms in the Hamiltonian, proportional to $(\gamma_2 - \gamma_3)$, meaning that the anisotropy in the QW plane (XY) was not taken into account (axial approximation).

In our model the Landau levels are characterized by three parameters: ns_i is the Landau-level (LL) number n, the in-plane symmetries called s for symmetric and a for antisymmetric states, and finally the index of the size-quantization subband i. Note that the Landau-level number n in the model is given by $n = r + (M + |M|)/2$, where $r = 0, 1, \ldots, \infty$ and $M = J_z/\hbar + 3/2$. The inset of Fig. 2 shows the energies of the first four LLs of the first size-quantization subband as a function of magnetic field (linear interpolation scheme was used for the calculations). For the given carrier density, the filling factor unity corresponds to a magnetic field of 18 T. On the other hand, according to our calculation, the energy separation between the first two LLs, $0s_1$ and $3a_1$, is comparable to $k_B T$; therefore both of them should be populated. We then attribute the two CR absorption lines observed in the spectra at high magnetic fields (see Fig. 1) to the CR transitions $0s_1 \rightarrow 1s_1$ (low-field line) and $3a_1 \rightarrow 4a_1$ (arrows 1 and 2 in the inset of Fig. 2, respectively). The lines in Fig. 2 show the field-dependent transition energies 1 and 2 calculated according to our model using linear (solid lines) and nonlinear (dashed lines) interpolation schemes. In the same figure, we summarize the experimentally obtained energies of all resonances as a function of magnetic field. We found excellent agreement between the measured and calculated transition energies without any fit parameters when linear interpolation scheme was used. From the model we could extrapolate the band-edge effective mass $m_0^* = (0.118 \pm 0.003) m_0$ that is in good agreement with previously reported values.[11]

Another interesting feature we found relates to the ratio of the spectral weight of transitions 1 and 2. As can be seen in Fig. 1, the low-field line, which corresponds to the transition $0s_1 \rightarrow 1s_1$, has a lower spectral weight than the high-field line, corresponding to the $3a_1 \rightarrow 4a_1$ transition. In contrast, our calculations show that the initial state of the first transition $0s_1$ lies above (i.e., lower hole energy) the initial state of the second transition $3a_1$. At low temperatures this implies a higher hole occupation of the $0s_1$ state and, therefore, a larger spectral weight of the corresponding transition $0s_1 \rightarrow 1s_1$ (assuming the oscillator strengths are similar). On the other hand, our experiment shows the opposite behavior.

We attribute this unusual behavior to the crossover of the first two LLs, $0s_1$ and $3a_1$. In terms of our model, the crossover point shifts to the lower fields when the κ parameter reduces. The linearly interpolated value $\kappa = 2.2$ results to the crossover in magnetic field of 50 T, while the value $\kappa = 1.5$ would shift the crossover point toward 20 T. Surprisingly, use of the nonlinear interpolation scheme, which gives significantly smaller value of $\kappa = 1.62$, does not help so much since the changes in the other Luttinger parameters γ_i result into strong deviation of the calculated transition energies from the experiment (see dashed lines in Fig. 2).

Changes in the κ parameter can also be provoked by hole-hole interaction [similar to the exchange enhancement of the effective electron g factor (see, for example, Ref. 22)]. The importance of hole-hole interaction in strained InGaAs/GaAs structures was evidenced earlier by Warburton *et al.*[10] Detailed analysis of the present effect, however, requires additional studies and is beyond the topic of the present Brief Report.

In conclusion, we have reported systematic energy-dependent measurements of the cyclotron resonance absorption in a strained InGaAs/GaAs heterostructure. We traced the resonance positions as a function of magnetic field upon the excitation wavelength changes from 420 down to 65 μm. We found the upper hole subband strongly nonparabolic. Pronounced CR line splitting was evidenced when the resonance field rises above 20 T. We calculated the CR transition energies using a 4×4 Luttinger Hamiltonian that includes the quantum well potential profile as well as the strain potential. Two different approaches to calculate Luttinger parameters for InGaAs/GaAs were probed. We found excellent agreement with the experimental data taking linearly interpolated Luttinger parameters for the given In content with no additional fit parameters. On the other hand, our calculations that use nonlinearly interpolated parameters fail to fit experimental data. We found unexpected spectral weight distribution of the spin-split components of the CR line, which we suggest to attribute to a renormalization of the Luttinger parameter κ due to hole-hole interaction.

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