Composition dependence of the in-plane effective mass in lattice-mismatched, strained \( \text{Ga}_{1-x}\text{In}_x\text{As}/\text{InP} \) single quantum wells

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The composition dependence of the in-plane conduction band effective mass in strained 15-nm-thick lattice-mismatched \( \text{Ga}_{1-x}\text{In}_x\text{As}/\text{InP} \) single quantum wells was determined by conventional cyclotron and optically detected cyclotron resonance techniques. Our results are in agreement with a self-consistent calculation taking into account effects due to nonparabolicity, confinement, strain, and finite two-dimensional carrier densities.

The potential applications of \( \text{Ga}_{1-x}\text{In}_x\text{As} \) quantum wells (QWs) imbedded into InP barrier and grown on InP substrates for electronic and optoelectronic devices are widely discussed and explored. The band-gap engineering is possible by the confinement of two-dimensional carriers in ultrathin layers. The freedom to grow \( \text{Ga}_{1-x}\text{In}_x\text{As} \) QWs apart from the lattice-matched composition \((x=0.53)\) in lattice-mismatched composition offers a new possibility of affecting the conduction and valence band structure. If the layer thickness is small enough, below the critical layer thickness, misfit dislocations can be avoided and the layers are coherently strained.\(^1\) It has been shown that by increasing the InAs mole fraction superior field-effect transistors could be realized.\(^2\) It is connected in part with reduced scattering by alloy disorder. In stress compensated modulation-doped \( \text{Ga}_{1-x}\text{In}_x\text{As} \) on InP structures exceptionally high mobilities above \( 120\,000\,\text{cm}^2/\text{V}\cdot\text{s} \) at 77 K have been reported.\(^3\)

Strain and confinement effects also influence the electronic levels in QWs and these effects are reflected in the photoluminescence properties of the QWs.\(^4,6\) The biaxial stress splits the valence band degeneracy. Under compression, when the band gap is larger than in the unstrained layer of the same composition, the radiative recombinations involve the conduction band and heavy hole valence bands, whereas under tension (the band gap being smaller), conduction band and light hole valence bands take part. For \( k_{\|} \) lying in the growth plane and \( k_{\perp} \) along the growth direction in biaxial compression the highest valence band \((3/2\, 3/2)\) is heavy along \( k_{\perp} \) and light along \( k_{\parallel} \). Under tension, the highest valence band is \((3/2\, 1/2)\), the anisotropy is reversed.\(^7\) The strain also affects properties of the conduction band, e.g., effective mass. So far only theoretical calculations of \( m^* \) in the (quasi-three-dimensional) strained \( \text{Ga}_{1-x}\text{In}_x\text{As}/\text{InP} \) system are available.\(^6,10\)

We present here the results of cyclotron resonance (CR) experiments on strained \( \text{Ga}_{1-x}\text{In}_x\text{As}/\text{InP} \) samples having a fixed QW thickness of 15 nm but differing in the alloy composition. To our knowledge these are the first experiments reporting the composition dependence of the electron mass in \( \text{Ga}_{1-x}\text{In}_x\text{As}/\text{InP} \) strained QWs (CR measurements of electron effective masses in strained \( \text{AlGAs/GaAs} \) pseudomorphic structures were reported by Liu et al.\(^11\) for \( 0<x<0.3 \)). We compare our results with theoretical calculations.

The samples have been grown by low pressure metalorganic vapor phase epitaxy using dimethylaminopropyl-diethylindium, triethyl-gallium, AsH\(_3\), and PH as respective precursors.\(^12\) The growth was carried out at 620 °C and at 80 mbar. A 10 nm \( n \)-doped InP layer with a carrier density of \( 5\times10^{17}\,\text{cm}^{-3} \) was placed into the top InP barrier separated from the 15 nm GaInAs single QW by a 5 nm undoped InP spacer. A 60 nm InP cap layer was grown on top of the sample. To be transparent for the far-infrared laser irradiation the substrate has to be high resistive (InP:Fe). The substrate was separated from the QW by a 150 nm buffer layer. The quality of the samples was checked by the Hall effect, photoluminescence, and magnetoluminescence. Details will be reported elsewhere.\(^13\) For the CR experiments, a CO\(_2\)-pumped far infrared (FIR) laser (118.8 \( \mu \)m) was used; the maximum available magnetic field was 8 T, provided by a superconducting magnet. The sample temperature was 6 K. Detection of the CR lines was either via the QW luminescence (more details can be found in a recent publication in which the quantum confinement effect of the in-plane effective mass in lattice-matched QWs has been studied)\(^14\) or in standard CR using a bolometer. Hall effect measurements (77 K) showed mobilities around 40 000 cm\(^2/\text{V}\cdot\text{s} \) so that the CR experiments were successful.

In Fig. 1 we show CR lines for different compositions \( x \). The range studied is from \( 0.4<x<0.8 \). From the respective magnetic field positions the effective masses are calculated (see also Table I) and presented in Fig. 2 together with the theoretical calculation (see below). The measured conduction band mass decreases considerably from \( m=0.054\) \((x=0.4)\) to \( m=0.039\) for \( x=0.8 \). However, due
FIG. 1. CR lines for different compositions of 15 nm Ga$_{1-x}$In$_x$As/InP strained single QWs ($\lambda = 118.8 \mu m$, $T = 6$ K).

to the modulation doping and confinement the measured values do not represent the masses at the bottom of the conduction band. We therefore need to know the two-dimensional carrier densities ($N_{2D}$). The carrier densities for each composition were extracted from the $1/B$ periods of the Shubnikov–de Haas (SdH) oscillations. We have recently demonstrated that with a contactless technique using a 9 GHz electron paramagnetic resonance spectrometer, the SdH oscillations can be detected at low temperatures and low magnetic fields with high sensitivity and accuracy. As an example we present such a measurement in Fig. 3. If the plane of the QW is oriented perpendicular to the static magnetic field in the microwave conductivity measurements a strong, broad background signal (subtracted in Fig. 3) on top of which the oscillating signal resides is observed. Because of the field modulation used ($\Delta B = 6$ G at the 100 kHz) the signals are detected as derivatives of the absorption signals. $N_{2D}$ was determined in the same samples on which the CR measurements were performed for all x values from the $1/B$ periods. The data are collected in Table I.

In the theoretical calculations of the conduction band effective mass in Ga$_{1-x}$In$_x$As QWs we have taken into account the change of the band structure of the well material with change of the composition, strain-induced changes in band structure, confinement effects, and nonparabolicity of the materials. For modulation-doped systems, where the 2D electron density is high, we have used a self-consistent calculation of the electrostatic potential in the structure. The theory is based on a three-band model including strain effects. We have used as input parameters the relevant parameters (energy gaps, momentum matrix elements, band bottom effective masses, elastic constants) of unstrained bulk well and barrier materials. The three-band model has been adjusted by addition of quadratic terms, representing the influence of higher bands, to reproduce the effective masses at the conduction band bottom in the unstrained well and barrier materials.

The calculations have yielded the physical characterization of the studied QWs: quantized energy levels, Fermi energy, potential profile. In all cases only one electron subband was occupied. The calculated effective masses at the Fermi level are presented in Fig. 2. Two lines describe the

TABLE I. The composition dependence of the electron effective mass in 15-nm-wide Ga$_{1-x}$In$_x$As/InP single QWs.

<table>
<thead>
<tr>
<th>Ga$_{1-x}$In$_x$As composition</th>
<th>$m^*/m_0$</th>
<th>$N_{2D}$ ($10^{10}$ cm$^{-2}$)</th>
<th>$m^*/m_0$ bulk values$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x = 0.40$</td>
<td>0.054</td>
<td>64</td>
<td>0.048</td>
</tr>
<tr>
<td>$x = 0.45$</td>
<td>0.0525</td>
<td>70</td>
<td>0.050</td>
</tr>
<tr>
<td>$x = 0.53$</td>
<td>0.050</td>
<td>61</td>
<td>0.047</td>
</tr>
<tr>
<td>$x = 0.55$</td>
<td>0.049</td>
<td>59</td>
<td>0.043</td>
</tr>
<tr>
<td>$x = 0.60$</td>
<td>0.048</td>
<td>69</td>
<td>0.038</td>
</tr>
<tr>
<td>$x = 0.80$</td>
<td>0.039</td>
<td>5</td>
<td>0.032</td>
</tr>
</tbody>
</table>

$^a$From Ref. 20.

FIG. 2. The electron effective mass as a function of the composition x in Ga$_{1-x}$In$_x$As/InP single QWs (full squares: experimental values; open circles: calculation, full triangle: experimental value for a 15 nm unstrained well obtained by Frei et al. (Ref. 18). The calculated dependence on x is given for two carrier densities: $6 \times 10^{11}$ cm$^{-2}$ (dashed line) and $1 \times 10^{10}$ cm$^{-2}$ (dashed drawn line).

FIG. 3. Microwave detection of the SdH oscillations in a 15 nm Ga$_{1-x}$In$_x$As/InP single QW ($x = 0.5$). The $1/B$ periods (see the inset) correspond to a 2D carrier density of $6 \times 10^{11}$ cm$^{-2}$.
behavior of the effective mass for two values of the electron density in the QW. The higher density, $6 \times 10^{11}$ cm$^{-2}$ is an average density found in our sample, characteristic of modulation-doped samples. The value of $1 \times 10^{10}$ cm$^{-2}$ corresponds to nominally undoped samples, and is very close to the effective mass near the subband bottom. Because of the nonparabolicity, for a direct comparison of the theoretical calculations with experimental results, it has been necessary to use the values of $N_{2D}$ given by the SdH experiments. The results are presented in Fig. 2 as circles. In all cases they are in a very good agreement with experimental values (full squares in Fig. 2). For $x=0.80$ the electron density was considerably lower and hence should be compared with the calculation performed for densities of $1 \times 10^{10}$ cm$^{-2}$ (dashed line in Fig. 2). We have also included the value for the 15 nm lattice-matched single QW (full triangle in Fig. 2) as obtained by Frei et al.\textsuperscript{18} In their single QW structures the density of the 2D electron gas was below $2.4 \times 10^{11}$ cm$^{-2}$. In both cases close agreement with the calculation is found.

Bulk Ga$_{1-x}$In$_x$As samples were studied by conduction spin resonance\textsuperscript{19} in a limited range of $x$ ($x<0.15$), giving in linear variation $m^*(x) = 0.067 - 0.041 x$. A complete series was investigated by plasma reflection.\textsuperscript{20} The values deduced from this study are shown in comparison with our results in Table I. For the higher In fractions ($x>0.55$) significantly lower masses are found.

The influence of strain on the valence band structure is more difficult to resolve. Magnetoluminescence experiments\textsuperscript{13} which showed contributions from the strain split valence bands were successful only in a limited range of $x$. However, high mobility, $p$-modulation doped Ga$_{1-x}$In$_x$As/InP samples are now available, which make an application of CR techniques possible, contributing to the understanding and interpretation of the valence band dispersion relations.

To summarize, CR experiments resolve the composition dependence of the electron effective mass in strained, lattice-mismatched Ga$_{1-x}$In$_x$As/InP single QWs. A self-consistent theory (three-band model) which takes into account effects of nonparabolicity, the dependence of all band parameters on strain, and confinement gives a very good agreement with the experimental data.

\textsuperscript{13} M. Drechsler, Al. L. Efros, B. K. Meyer, V. Härle, and F. Scholz (unpublished).