Cyclotron resonance in modulation-doped ZnSe/Zn$_{1-x}$Cd$_x$Se and ZnTe/CdSe single quantum wells

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We report low-temperature (4.2 K) cyclotron resonance measurements on high-mobility, two-dimensional electron gases in modulation-doped ZnSe/Zn$_{1-x}$Cd$_x$Se quantum wells (QWs),$^3$ there has been substantial scientific and technological interest in this family of materials, motivated principally by their use in the active region of short-wavelength diode lasers operating in the green-to-blue spectral range.$^2$ More recently, ZnSe/Zn$_{1-x}$Cd$_x$Se QWs have attracted attention as model systems in which to examine coherent electronic-spin dynamics and quantum transport, both with$^{3,4}$ and without$^5$ the incorporation of magnetic impurities. Despite the widespread interest in the optoelectronic properties of Zn$_{1-x}$Cd$_x$Se, some of the basic electronic band-structure parameters are yet to be experimentally determined. One of these parameters is the effective mass of conduction-band electrons $m^*$ whose direct determination by cyclotron resonance (CR) has been largely obviated by the very low mobilities $\mu$ in thick epitaxial layers of Zn$_{1-x}$Cd$_x$Se.

CR studies were recently reported in low-mobility ($\mu<1000$ cm$^2$/V s) modulation-doped ZnSe/Zn$_{0.75}$Cd$_{0.25}$Se two-dimensional electron gases (2DEGs),$^6$ wherein ultrahigh magnetic fields ($B=150$ T) were necessary to satisfy the cyclotron resonance conditions $\omega_C\tau=\mu B?1$ ($\omega_C=eB/m^*$ is the cyclotron frequency and $\tau$ is the electron scattering time). Consequently, the effective mass was extracted from a limited set of data, and also under high-field conditions not typically relevant to routine optoelectronic studies of these materials. Here, we present CR measurements on high-mobility 2DEGs in modulation-doped ZnSe/Zn$_{1-x}$Cd$_x$Se and ZnTe/CdSe single quantum wells (SQWs). The electron mobility in these samples ranges from 5000 to 16 500 cm$^2$/V s at 4.2 K, permitting detailed CR measurements at relatively low magnetic fields yielding reliable and useful values of $m^*$ in cubic Zn$_{1-x}$Cd$_x$Se for $x=0.06, 0.12, 0.24$, and 1.

The CR experiments were performed on four modulation-doped SQW samples, all grown by molecular beam epitaxy on semi-insulating (100) GaAs substrates after the deposition of an appropriate buffer layer. The sample characteristics are summarized in Table I and growth details are similar to those described elsewhere.$^7,8$ Samples A, B, and C are coherently strained ZnSe/Zn$_{1-x}$Cd$_x$Se SQWs in which a ZnSe buffer layer with a thickness between 1.5 and 2 $\mu$m separates the SQW from the GaAs substrate. Sample D is a modulation-doped ZnTe/CdSe SQW grown on a closely lattice-matched ($\Delta/a\sim0.2\%$) ZnTe buffer layer with a thickness of $\sim1.5$ $\mu$m. The alloy composition and layer thickness in each sample are based on the growth rates calibrated using reflection high-energy electron diffraction oscillations and confirmed by measurements of the band-edge photoluminescence at 4.2 K. All samples show Shubnikov–de Haas oscillations in low-temperature magnetotransport measurements; in addition, samples A, B, and C exhibit a clear integer quantum Hall effect at low temperatures. The Hall mobility in Table I is determined from low-field transport measurements and can differ from that corresponding to the single-particle scattering time relevant to cyclotron resonance. We note that sample A has a record mobility for the ZnSe/(Zn, Cd)Se 2DEG system, reaching a value of 23 000 cm$^2$/V s at 300 mK.$^9$

Magnetotransmission measurements were performed using a Bruker IFS 113v spectrometer coupled by light pipe

TABLE I. Characteristics of all samples studied. Samples A, B, and C contain a modulation-doped ZnSe/Zn$_{1-x}$Cd$_x$Se SQW structure on top of a ZnSe buffer layer, while sample D contains a ZnTe/CdSe SQW grown on a ZnTe buffer layer. Transport measurements are used to determine the sheet density $N_s$ and the mobility $\mu$. All measured quantities are at 4.2 K.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cd content (x) in SQW</th>
<th>SQW thickness (nm)</th>
<th>$N_s$ (cm$^{-2}$)</th>
<th>$\mu$ (cm$^2$/V s)</th>
<th>$(m^*/m_0)$</th>
<th>$M_e/m_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.06</td>
<td>10.5</td>
<td>$1.8\times10^{11}$</td>
<td>16 500</td>
<td>0.145</td>
<td>0.137</td>
</tr>
<tr>
<td>B</td>
<td>0.12</td>
<td>10.5</td>
<td>$2\times10^{11}$</td>
<td>6 800</td>
<td>0.145</td>
<td>0.137</td>
</tr>
<tr>
<td>C</td>
<td>0.24</td>
<td>10.5</td>
<td>$4.5\times10^{11}$</td>
<td>7 900</td>
<td>0.146</td>
<td>0.137</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>10.5</td>
<td>$4.8\times10^{11}$</td>
<td>8 800</td>
<td>0.119</td>
<td>0.112</td>
</tr>
</tbody>
</table>

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FIG. 2. Cyclotron frequency ($\omega_C$) vs magnetic field ($B$) for all the samples studied. The linear fits are weighted toward low fields ($<10$ T) since at higher fields electron–phonon coupling to the LO line becomes significant. All the fits pass through the origin within an uncertainty of $\pm 0.5$ cm$^{-1}$. Inset shows a comparison between the measured and calculated values of $m^*$ as a function of Cd composition. Note that the $x=1$ sample is not subject to much strain, while the other samples are subject to an in-plane compressive strain.

Haas oscillations ($m^* \approx 0.12 \pm 0.02 \; m_0$). By using the measured cyclotron mass, the scattering time deduced from the CR linewidth is comparable to the Drude scattering time extracted from transport measurements. However, we note that the CR linewidth varies with magnetic field, particularly in the vicinity of integer Landau level filling factors. A more detailed discussion of this behavior will be given at a later stage.

Since wide-band-gap II–VI semiconductors have large Fröhlich electron–phonon interaction constants (for instance, $\alpha_{\text{ZnSe}} = 0.42$, $\alpha_{\text{CdSe}} = 0.45$), the measured cyclotron mass $m^*$ contains a polaronic correction to the bare effective mass $m^*_e$ at photon energies $h\omega < h\omega_{LO}$. For bulk Zn$_{1-x}$Cd$_x$Se ($x < 0.24$) $h\omega_{LO} \sim 31$ meV, while for CdSe $h\omega_{LO} = 25.4$ meV. The bare electron mass $m^*_e$ can be extracted from $m^*$ using the relation $m^* = m^*_e (1 + \alpha/2)(1 + \alpha/3)^{-1}$ and is also included in Table I by using linearly interpolated values of $\alpha$ for Zn$_{1-x}$Cd$_x$Se. Finally, we note that the low-field measurements presented here are in the regime $h\omega \ll h\omega_{LO}$ where resonant polaronic effects are not important. The variation of the effective mass close to the polaron frequency and other effects at high magnetic fields will be discussed in a future paper.

It is relevant to compare the measured values of the cyclotron mass in these epitaxial materials to literature values of $m^*$ in bulk crystals of the “end-point” CdSe and ZnSe. Our measured value of $m^* = (0.119 \pm 0.002) m_0$ in sample D agrees within the experimental accuracy with the literature value given for wurtzite (hexagonal) CdSe ($m^* = 0.12 m_0$). We note that the fundamental gap of zinc-blend CdSe is about 3% smaller than that of the wurtzite phase, implying a similar small decrease in the effective mass. However, this discrepancy is within the error bars of our measurements. The effective mass reported for bulk
ZnSe lies in the range \((0.141-0.145) m_0\) for carrier densities ranging up to \(~8 \times 10^{17}\ \text{cm}^{-3}\). To a first approximation, the effective mass in \(\text{Zn}_{1-x}\text{Cd}_x\text{Se}\) should interpolate between the values at the ZnSe and CdSe end points, which can be qualitatively understood within a simple three-band \(k\rightarrow p\) model. In contrast, our measurements in samples A, B, and C suggest that—within experimental error—\(m^*\) does not change much in \(\text{Zn}_{1-x}\text{Cd}_x\text{Se}\) QWs over the range \(0.06 < x < 0.24\). Hence, a more detailed band-structure calculation that properly includes the interplay between the effects of strain and confinement is needed for a better understanding of the effective mass in these heterostructures.

In order to investigate this, we have carried out calculations of \(m^*\) and \(m^*_p\) (with and without the polaronic correction, respectively) for the investigated system using a five-band \(k\cdot p\) model. The results of the calculation are depicted in the inset to Fig. 2 as a function of the Cd composition in the QW region. The values of the interband matrix elements, spin-orbit splitting, and energies of the higher bands (\(\Gamma_7^*\) and \(\Gamma_6^*\)) are determined using a linear interpolation between the corresponding parameters of ZnSe and (cubic) CdSe. In this approximation, confinement effects in the QWs are taken into account via the experimentally determined changes in the energy gaps between the conduction band and light-and heavy-hole subbands in the valence band only. The main trend in the calculations is a decrease in effective mass with increasing Cd composition in the QW, which is mainly determined by changes of the fundamental gap from 2.8 eV for ZnSe to 1.75 eV for CdSe.

In conclusion, we have performed cyclotron resonance measurements of high-mobility \(\text{Zn}_{1-x}\text{Cd}_x\text{Se}\) heterostructures. These experiments yield reliable values of the cyclotron mass for the range \(0 < x < 0.24\) and for \(x = 1\). The data presented here provide valuable input for interpreting magneto-optical and magnetotransport measurements in these materials.

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