Cyclotron resonance in modulation-doped $ZnSe/Zn_{1-x}Cd_xSe$ 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 $ZnSe/Zn_{1-x}Cd_xSe$ ($x=0.06$, 0.12, and 0.24) single quantum wells, as well as in a modulation-doped ZnTe/CdSe single quantum well. These experiments carried out in magnetic fields ranging up to 17 T yield reliable measurements of the effective mass m^* of conduction-band electrons in $Zn_{1-x}Cd_xSe$ alloys, including the measurement of m^* in cubic CdSe.
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Ever since the first epitaxial growth of cubic $Zn_{1-x}Cd_xSe$ $(0\leqslant x\leqslant 1)$ and derivative-modulated semiconductor structures such as $ZnSe/Zn_{1-x}Cd_xSe$ quantum wells (QWs),[1] 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, $ZnSe/Zn_{1-x}Cd_xSe$ 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 $Zn_{1-x}Cd_xSe$, 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 μ in thick epitaxial layers of $Zn_{1-x}Cd_xSe$.

CR studies were recently reported in low-mobility ($\mu<1000\,\mathrm{cm^2/V\,s}$) modulation-doped $ZnSe/Zn_{0.75}Cd_{0.25}Se$ two-dimensional electron gases (2DEGs),[6] wherein ultrahigh magnetic fields ($B\sim150$ T) were necessary to satisfy the cyclotron resonance conditions $\omega_C\tau=\mu B\gg 1$ ($\omega_C=eB/m^*$ is the cyclotron frequency and τ 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 $ZnSe/Zn_{1-x}Cd_xSe$ and ZnTe/CdSe single quantum wells (SQWs). The electron mobility in these samples ranges from 5000 to 16 500 $\mathrm{cm^2/V\,s}$ at 4.2 K, permitting detailed CR measurements at relatively low magnetic fields yielding reliable and useful values of m^* in cubic $Zn_{1-x}Cd_xSe$ 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 $ZnSe/Zn_{1-x}Cd_xSe$ SQWs in which a ZnSe buffer layer with a thickness between 1.5 and 2 μm separates the SQW from the GaAs substrate. Sample D is a modulation-doped ZnTe/CdSe SQW grown on a closely lattice-matched ($\Delta a/a\sim0.2\%$) ZnTe buffer layer with a thickness of ~1.5 μm. 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 $\mathrm{cm^2/V\,s}$ 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 $ZnSe/Zn_{1-x}Cd_xSe$ 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 μ. All measured quantities are at 4.2 K.

Sample	Cd content (x) in SQW	SQW thickness (nm)	$N_S(\mathrm{cm^{-2}})$	μ ($\mathrm{cm^2/V\,s}$)	(m^*/m_0) 0.002	M_e/m_0
A	0.06	10.5	1.8×10^{11}	16 500	0.145	0.137
B	0.12	10.5	2×10^{11}	6 800	0.145	0.137
C	0.24	10.5	4.5×10^{11}	7 900	0.146	0.137
D	1	10.5	4.8×10^{11}	8 800	0.119	0.112

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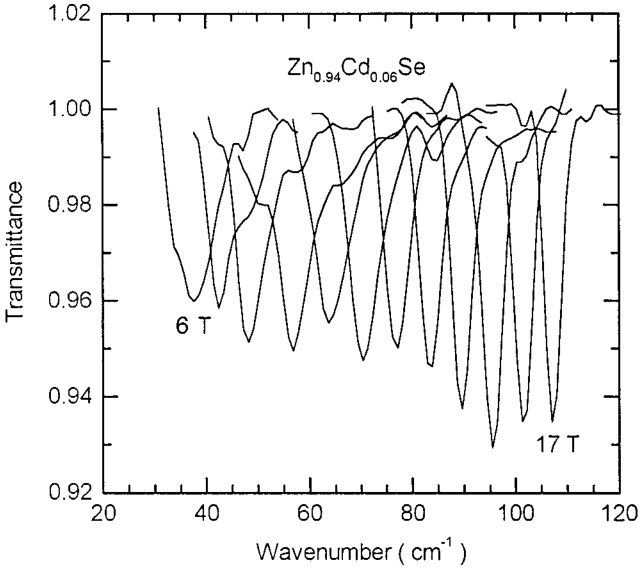

FIG. 1. Magnetotransmittance (at a nominal temperature of 4.2 K) of sample A taken at 1 T intervals.

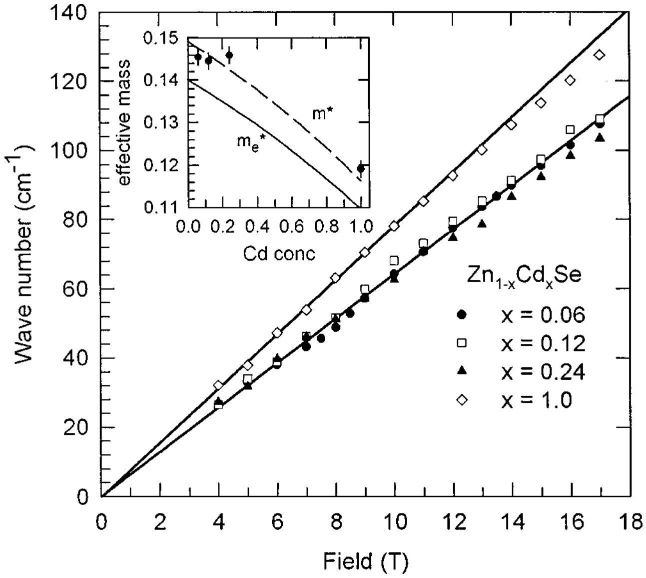

FIG. 2. Cyclotron frequency (ω_C) vs magnetic field (B) for all the samples studied. The linear fits are weighted toward low fields ($<$10 T) since at higher fields electron–phonon coupling to the LO line becomes significant. All the fits pass through the origin within an uncertainty of $\pm 0.5\ \mathrm{cm}^{-1}$. 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.

optics to an Oxford superconducting magnet located at the National High Magnetic Field Laboratory in Tallahassee. Additional measurements carried out in fields greater than 17 T using a Bitter magnet capable of achieving fields up to 30 T will be reported elsewhere. The modulated infrared (IR) signals are detected using a composite Si bolometer. In all our measurements, the applied magnetic field is perpendicular to the sample surface and for samples B and C a light emitting diode (LED) was used to enhance the carrier density (and hence, the absorption coefficient). It should be noted that the use of a LED did not influence the CR absorption frequency, suggesting that over the range of carrier densities studied, the densities do not change the nonparabolicity in the band structure. To get rid of interference fringes in the transmission spectra, the GaAs substrates on all our samples were wedged at an angle of 4° prior to experiments.

Figure 1 shows the transmittance spectra for the highest mobility sample (A) at several magnetic fields. In order to eliminate all spectral features that were not related to the magnetic field, the transmitted intensity $T(B)$ was systematically normalized to the reference value $T(0)$ recorded at zero magnetic field. Figure 1 clearly shows a field dependence in the absorption minimum that occurs when the cyclotron resonance condition $\omega_C\tau = eB\tau/m^* = \mu B \geqslant 1$ is satisfied. The remaining three samples also show clear absorption spectra, albeit with a broader linewidth due to the lower mobility. All the spectra are fitted with a Lorentzian line shape using the Marquardt–Levenberg algorithm to obtain the linewidth and the frequency of the absorption minimum.[10]

A plot of the resonance frequency versus magnetic field for all four samples is shown in Fig. 2. Linear regression fits to the data weighted for low fields pass through the origin, yielding the values of m^* shown in Table I. The weighting towards low fields is necessary since the magnetic-field dependence of the CR frequency deviates from linearity as it approaches the longitudinal optical (LO) phonon frequency ω_{LO}.[11] The effective mass m^* for $Zn_{1-x}Cd_xSe$ SQWs deduced from this direct measurement can be compared with early estimates extracted from the analysis of Shubnikov–de Haas oscillations ($m^* \sim 0.12 \pm 0.02\ m_0$).[12] 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, $\alpha_{\mathrm{ZnSe}} = 0.42$, $\alpha_{\mathrm{CdSe}} = 0.45$),[13,14] the measured cyclotron mass m^* contains a polaronic correction to the bare effective mass m_e^* at photon energies $\hbar\omega < \hbar\omega_{\mathrm{LO}}$.[15] For bulk $Zn_{1-x}Cd_xSe$ ($x<0.24$) $\hbar\omega_{\mathrm{LO}} \sim 31$ meV,[16] while for CdSe $\hbar\omega_{\mathrm{LO}} = 25.4$ meV.[17] 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 α for $Zn_{1-x}Cd_xSe$. Finally, we note that the low-field measurements presented here are in the regime $\hbar\omega \leqslant \hbar\omega_{\mathrm{LO}}$ 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 ($m^* = 0.12\ m_0$).[14] We note that the fundamental gap of zinc-blende 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 $\sim 8\times 10^{17}\,\mathrm{cm}^{-3}$.[15,18,19] To a first approximation, the effective mass in $Zn_{1-x}Cd_xSe$ should interpolate between the values at the ZnSe and CdSe end points, which can be qualitatively understood within a simple three-band $\mathbf{k}\leftrightarrow\mathbf{p}$ model. In contrast, our measurements in samples A, B, and C suggest that—within experimental error—m^* does not change much in $Zn_{1-x}Cd_xSe$ 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_e^* (with and without the polaronic correction, respectively) for the investigated system using a five-band $k\cdot p$ model.[20] 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 (Γ_7^c and Γ_8^c) are determined using a linear interpolation between the corresponding parameters of ZnSe and (cubic) CdSe.[21] 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 $Zn_{1-x}Cd_xSe$ 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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