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Zinc Selenide

Optical Studies of 2DEGs in ZnSe Quantum Wells in High Magnetic Fields

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Abstract. Optical properties of a two-dimensional electron gas in ZnSe/(Zn,Be,Mg)Se quantum well structures have been examined by means of photoluminescence and reflectivity techniques in external magnetic fields up to 50 T. For these structures the Fermi energy of the two-dimensional electron gas is falling in the range between the trion binding energy and the exciton binding energy, which keeps the dominating role of Coulombic interaction between electrons and photoexcited holes. Characteristic peculiarities of optical spectra are discussed.

1. Introduction

It is well known that a ground state of a photogenerated electron-hole pair in undoped quantum wells (QW's) is an exciton (X), formed via Coulomb interaction. In QW's with very high electron concentration, such as a Fermi energy of electron gas is larger than an exciton binding energy $E_F > E_B^X$, a Fermi-edge singularity (FES) appears in optical spectra. It reveals as a result of interaction of photocreated hole with Fermi-sea of electrons. Evolution of optical spectra from excitonic one to FES is an interesting field for investigation, which still having a number of open questions.

In QW's with a dilute two-dimensional electron gas (2DEG) a negatively charged exciton (T) could exist [Lamp, Cox93]. Charged exciton or trion (T), being constructed of two electrons and a hole, appears in optical spectra at a few meV below of exciton resonance. Energy separation between T and X in the limit of zero electron concentration gives a trion binding energy E_B^T, which is usually varied from 5 to 20% of the trion binding energy.

In QW's containing a dense 2DEG with the Fermi energy falling in the range between the trion binding energy and the exciton binding energy (i.e. $E_B^X > E_F > E_B^T$), the trion states are strongly modified due to screening. However, excitons are still robust and their interaction with a 2DEG reveals in new peculiarities in optical properties. The aim of this proceeding is to give experimental insight into modification of photoluminescence (PL) and reflectivity spectra in high magnetic fields (to 50 T) in this regime of 2DEG.

Electronic systems of high density and their properties in high magnetic fields have been studied in great detail for III-V semiconductor heterostructures and there is only limited information about II-VI heterostructures. II-VI heterostructures, due to a strong Coulombic interaction, are attractive for investigation of Coulombic correlation effects in a dense 2DEG. Recently, several reports on modulation-doped CdTe-based QW's have been presented (see e.g. [CdTe1, CdTe2] and references therein). ZnSe-based QW's provide even stronger Coulombic interaction (exciton binding energy in bulk ZnSe is 20 meV compared with 4 meV in GaAs and 10 meV in CdTe).

The system to be examined in this paper is ZnSe-based QW with a 2DEG containing $5\times10^{11}\,\mathrm{cm}^{-2}$ electrons. The Fermi energy of this 2DEG is 7.7 meV.

Exciton binding energy is 30 meV and trion binding energy is 5.3 meV, i.e. the condition $E_B^X > E_F > E_B^T$ is hold.

2. Experimentals and optical spectra in the absence of magnetic field

A modulation-doped QW structure was grown by molecular-beam epitaxy on a (100)-oriented GaAs substrate. The structure consists of a 67-Å-thick ZnSe single quantum well embedded between 1000-Å-thick $Zn_{0.82}Be_{0.08}Mg_{0.10}Se$ barriers. To prevent the loss of carriers escaping into the substrate and recombining at the surface, the structure was confined by $Zn_{0.71}Be_{0.11}Mg_{0.18}Se$ barriers. Both barrier materials are lattice matched to the GaAs substrate. The modulation-doped layer with Iodine donors is separated from the QW by a 100-Å-thick spacer layer. Optical methods, first one based on properties of trion absorption (reflection) [Ast02] and second one reported here, allow us evaluation of the 2DEG density in the QW $n_e = 5\times10^{11}\,\text{cm}^{-2}$. This corresponds to Fermi energy of 2DEG $E_F = 7.7$ meV with electron effective mass $m_e = 0.15\, m_0$. For comparison trion binding energy in such a QW is $E_B^T = 5.3$ meV and exciton one is $E_B^X = 30$ meV [Oss02, Ast02a]. Polarized magneto-luminescence and magneto-reflectivity have been measured at T=1.6 K in long-pulse magnetic fields up to B=47 T applied perpendicular to the QW plane (Faraday geometry). Details of the setup are given in Ref. [Ast02a].

Fig. 1 shows PL and reflectivity spectra recorded at a zero magnetic field at temperature $T = 1.6$ K. The PL spectrum has been excited by a He-Cd laser with a photon energy of 3.8 eV. It consists of a broad band with a maximum at 2.810 meV and with a full width at a half maximum (FWHM) of 7 meV. This value is very close to the value of the 2DEG Fermi energy 7.7 meV. In the reflectivity spectrum a strong resonance is detected at 2.817 meV. We label it as a C-line and the origin of this transition is a subject of discussion. The C-line is blue shifted in respect to PL maximum at about 7 meV, the value is comparable with E_F. Its position coincide with a high energy wing of PL band, i.e. with the spectral position which is often associated for the modulation-doped QWs with a "Fermi edge singularity (FES)". The FES is commonly associated with a optical transition when the absorbed photon excited electron from the valence band to the Fermi level in the conduction band and therefore is classified as a band-to-band absorption line. We will show here that this interpretation should be revised for the II-VI heterostructures with strong Coulombic interaction, i.e. for the regime when the exciton binding energy exceeds the Fermi energy of a 2DEG. In light of that we would not like to apply FES notification to the C-line.

Let us discuss in more detail properties of the C-line. It is very surprising that broadening of this resonance of 2 meV is noticeably smaller than FWHM of the PL band. The broadening is very sensitive to the bath temperature and increases strongly with temperatures growing from 1.6 K to 20 K. We would like to stress here that at T=1.6 K the C-resonance looks very similar to the exciton resonance in undoped QWs (see e.g. [Ast02]). Namely it has very similar linewidth and comparable oscillator strength (i.e. amplitude). However, the exciton resonance in the undoped ZnSe-based QW shows very small broadening with increasing temperatures to 20 K. Therefore, we have qualitatively different behavior for the C-line and exciton line.

Another important point is the energy position of the C-line. By no means it can be associated with a band-to-band transition, which is expected for these structures at energies of about 2.847 eV (i.e. 30 meV higher that the C-line is located). 30 meV is the binding energy of a quasi-two-dimensional exciton in this QW [Ast02a]. The exciton itself is only slightly modified by the presence of the 2DEG with Fermi energy of 7.7 meV only. This conclusion is confirmed by the value of diamagnetic shift of exciton line in high fields, which is identical to that in undoped QWs. In case of the screened exciton with smaller binding energy the diamagnetic shift should be large. Also we can not expect that the band gap renormalization in the studied QWs will have a value of about 30 meV for presence of a 2DEG with a Fermi energy of 7.7 meV. These facts let us suggest that the C-line reflects the properties of the 2DEG at the energies close to the Fermi level, but we detect them at energies shifted by about the binding energy of exciton.

The second resonance in the reflectivity spectrum in Fig.1(a) labeled as $e-lh$ is related to the light-hole subband, splitted by the strain and quantum confinement effects.

3. Modification of optical spectra in high magnetic fields

First we will concentrate on the photoluminescence spectra. The strong modification of the PL spectra occurs in magnetic fields (see Fig.1(b)). In the limit of high magnetic fields (e.g. B=40 T) instead of the briad PL band one can see two narrow lines. This emission spectrum is very similar to the spectrum of undoped QWs with exciton (X_{hh}) and trion (T) lines (for details see Ref.[Oss02]). With increasing magnetic field the PL band splits into a set of lines, which shift linearly to higher energies. Energy positions of these lines *vs* magnetic fields are plotted in Fig. 2a. All plotted lines show nonmonotonic behavior with changing slopes. The lowest energy peak reveals a linear shift with a slope of 0.38 meV/T in fields below 10.3 T, which converts at higher fields into a diamagnetic shift typical for excitonic states [Oss02]. Such a behavior has been reported recently for GaAs-based QW's [Gek96, Yoo97]. These authors demonstrated that the transition occurs at a filling factor $\nu = 2$, and at high magnetic fields the emission is indistinguishable from trions. For our structure the Landau level fan shown by dashed lines in Fig. 2a corresponds to the pure electron effective mass $m_e = 0.15 m_0$. It describes reasonably well the behavior of PL lines in magnetic fields for filling factors $\nu > 2$. This property is rather general and has been noticed in GaAs QW's as well [Yoo97].

In magnetic fields above 10.3 T ($\nu < 2$), PL spectrum consists of two lines, which diamagnetic shifts are similar to that of heavy-hole exciton (X_{hh}) and trion (T) in undoped QW. Solid curves in Fig. 2a represent behavior of X_{hh} and T, measured in undoped QW. Small energetic shift for these dependencies has been done in order to coinside them with our experimental points for the doped QW in high magnetic fields (above 30 T) [Oss02]. From these dependencies the transition energy of "bare" charged exciton in zero magnetic field is estimated to be 2.812 meV (shown by arrows in panels (a) and (c)). It is only 2 meV higher than PL maximum in doped QW; and is not equal to Fermi energy. We should note here, that energy of "bare" charged exciton in doped QW might not coincide with energy of charged exciton in undoped QW with the same design, due to effect of band-gap renormalization [Oss02].

The energy shift of the lowest PL maximum is nonmonotonic (Fig. 2a). It shows an upward cusp at integer filling factors from 1 to 4, and downward convex curves between them [Oss02]. The behavior is qualitatively similar to the reported results for GaAs and CdTe structures. The most pronounced feature at 10.3 T corresponds to ν=2.

Critical behavior at the integer filling factor has been also detected in the magnetic field dependence of the polarization degree of PL line. Very pronounced features are observed for the even ν=2, 4, 6 and 8 for the PL circular polarization degree, which has minimum when the Landau level is fully occupied (Fig. 2b). From the magnetic field value corresponding to the ν=2 we got the 2DEG density $n_e = 5\times10^{11}\,\mathrm{cm}^{-2}$ and calculate the expected fields for the set of integer filling factors. These fields are marked by vertical dotted lines in panels (a), (b) and (c). This coincides well with the data on the optical detection resonance spectroscopy with the use of far-infrared radiation reported in Ref.[Oss02].

Let us now turn to the discussion of the reflectivity spectra in magnetic fields. Figure 2c presents resonance energies of reflectivity lines *vs* magnetic fields in doped QW (symbols). Solid lines in this figure are taken from Fig. 2a and represent behavior of unscreened exciton and trion states. It is clearly seen, that the C-resonance at zero magnetic field is blue shifted by about 5 meV in respect to the energy of "bare" charged exciton. With growing magnetic fields the C-line transforms into a set of lines (TrCR1 and TrCR2). They shifted linearly with slopes 0.5 meV/T and 1.5 meV/T (dashed lines in Fig. 2c). These values are close to one half and three half of electron cyclotron energy $\eta\omega_c$, respectively. The energies of TrCR1 and TrCR2 lines being extrapolated to a zero magnetic field meet the energy of "bare" charged exciton, and therefore have trion origin. We ascribe these lines to four-particle process, referred as a combined trion-cyclotron resonance (TrCR), in which a photo generation of the trion is accompanied by an excitation of additional electron between Landau levels [Oss01, Koch02].

At filling factor $\nu = 2$ low energy shoulder of C-line appears in reflectivity spectra, transforming to charged exciton resonance (T) in high magnetic fields. The lines of neutral excitons X_{hh} and X_{lh} (related to heavy-hole and with light-hole subbands, respectively) become detectable at filling factor $\nu = 1$ and rise their intensities with further growing magnetic fields.

At magnetic field of 10.3 T ($\nu = 2$) the line of exciton-cyclotron resonance (ExCR) reveals in reflectivity spectra. This resonance is due to a process, in which a photocreation of neutral exciton occurs simultaneously with a transition of background electron between Landau levels [Yak97]. ExCR shifts linearly with magnetic fields as 0.9 meV/T (dashed line in Fig. 2c). This value is very close to 0.96 meV/T taken from the theoretical approach of Ref. [Yak97], as $\left(1+m_e/\left(m_e+m_{hh}\right)\right)\hbar\omega_c$ with heavy-hole mass $m_{hh}=0.44\,m_0$ [Ast02a].

4. Conclusions

We present a set of experimental data on modification of emission and reflectivity spectra of ZnSe-based QW with a dense 2DEG in high magnetic fields. In considered case the Fermi energy of the 2DEG was four time smaller that the exciton binding energy and exceeds slightly the binding energy of charged exciton. In this regime the properties of 2DEG, visualized in optical spectra, are strongly influenced by the Coulombic interaction between electrons and photoexcited holes.

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References

[Lamp] M.A.Lampert, Phys. Rev. Lett. **1**, 450 (1958).

[Cox93] K.Kheng, R.T.Cox, Y.Merle d'Aubigne, F.Bassani, K.Saminadayar, and S.Tatarenko, Phys. Rev. Lett. **71**, 1752 (1993).

[CdTe1] Y.Imanaka, T.Takamasu, G.Kido, G.Karczewski, T.Wojtowicz, and J.Kossut, J. Crystal Growth **214/215**, 240 (2000).

[CdTe2] J.X.Shen, Y.Oka, W.Ossau, F.Fischer, A.Waag, and G.Landwehr, Physica B **249-251**, 589 (1998).

[Ast02] G.V.Astakhov, V.P.Kochereshko, D.R.Yakovlev, W.Ossau, J.Nürnberger, W.Faschinger, G.Landwehr, T.Wojtowicz, G.Karczewski, and J.Kossut, Phys.Rev.B **65**, 115310 (2002).

[Ast02a] G.V.Astakhov, D.R.Yakovlev, V.P.Kochereshko, W.Ossau, W.Faschinger, J.Puls, F.Henneberger S.A.Crooker, Q.McCulloch, D.Wolverson, N.A.Gippius, and A.Waag, Phys.Rev.B **65**, 165335 (2002).

[Gek96] D.Gekhtman, E.Cohen, Arza Ron, and L.N.Pfeiffer, Phys. Rev. B **54**, 10320 (1996).

[Yoo97] H.W.Yoon, M.D.Sturge and L.N.Pfeiffer, Solid State Commun. **104**, 287 (1997).

[Oss02] W.Ossau, D.R.Yakovlev, G.V.Astakhov, A.Waag, C.J.Meinig, H.A.Nickel, B.D.McCombe, and S.A.Crooker, Physica E **12**, 512 (2002).

[Oss01] W.Ossau, V.P.Kochereshko, G.V.Astakhov, D.R.Yakovlev, G.Landwehr, T.Wojtowicz, G.Karczewski, and J.Kossut, Physica B **298**, 315 (2001).

[Koch02] V.P.Kochereshko, G.V.Astakhov, D.R.Yakovlev, W.Ossau, W.Faschinger, and G.Landwehr, Phys. Stat. Sol. (b) **229**, 543 (2002).

[Yak97] D.R.Yakovlev, V.P.Kochereshko, R.A.Suris, H.Schenk, W.Ossau, A.Waag, G.Landwehr, P.C.M.Christianen, and J.C.Maan, Phys. Rev. Lett. **79**, 3974 (1997).

Figure captions

Fig. 1 Photoluminescence (PL) and reflectivity (Ref.) spectra of a 67-Å-thick ZnSe/$Zn_{0.82}Be_{0.08}Mg_{0.10}Se$ QW, with a dense 2DEG of $n_e = 5\times10^{11}\,\text{cm}^{-2}$. $T = 1.6$ K. (a) at a zero magnetic field, (b) at B=40 T.

Fig. 2 Experimental data of magnetic field behaviour of optical spectra in a 67-Å-thick ZnSe/$Zn_{0.82}Be_{0.08}Mg_{0.10}Se$ QW with $n_e = 5\times10^{11}\,\text{cm}^{-2}$. (a) Energies of PL maxima *vs* magnetic field strength of detected in σ^+ (open symbols) and σ^- (closed symbols) polarizations. Exciton (X_{hh}) and trion (T) diamagnetic shifts for an undoped QW of the same width are shown by solid lines. They are slightly shifted in energy positions for comparison with the relevant QW. Dashed lines show Landau level fan (LL0, LL1 and LL2) of electron with effective mass $m_e = 0.15 m_0$. Arrow indicates the energy of "bare" charged exciton at zero magnetic field, taken from solid line. Dotted lines indicate magnetic fields of integer filling factors.

(b) Circular polarization degree of low energy PL line as a function of magnetic fields. Dotted lines indicate magnetic fields of even filling factors.

(c) Energies of reflectivity lines *vs* magnetic field strength detected in σ^+ (open symbols) and σ^- (closed symbols) polarizations. Intensities of resonances are displayed by a size of symbols. Similar to (a) exciton (X_{hh}) and trion (T) diamagnetic shifts in undoped QW show by solid lines. Dashed curves are linear fittings for TrCR1, TrCR2 and ExCR resonances.

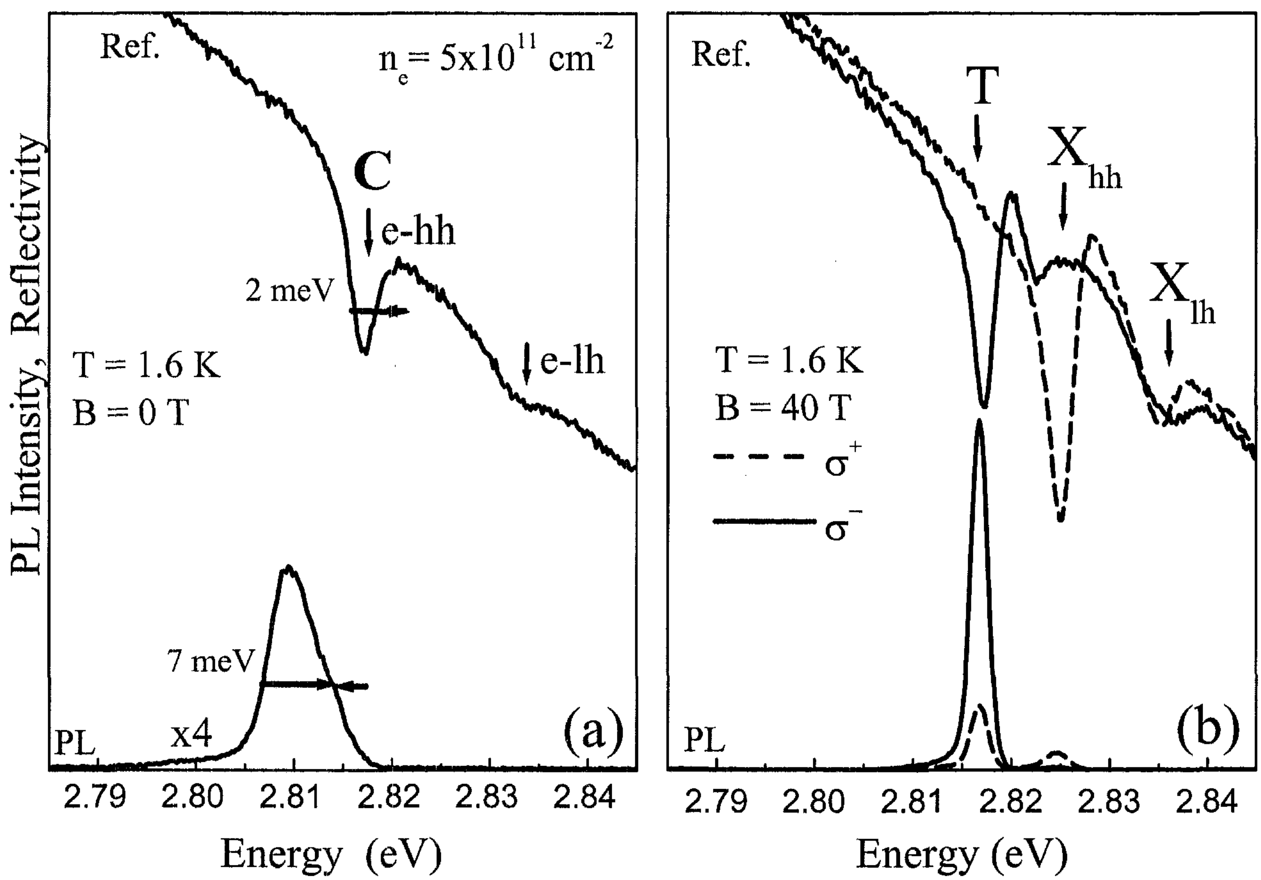
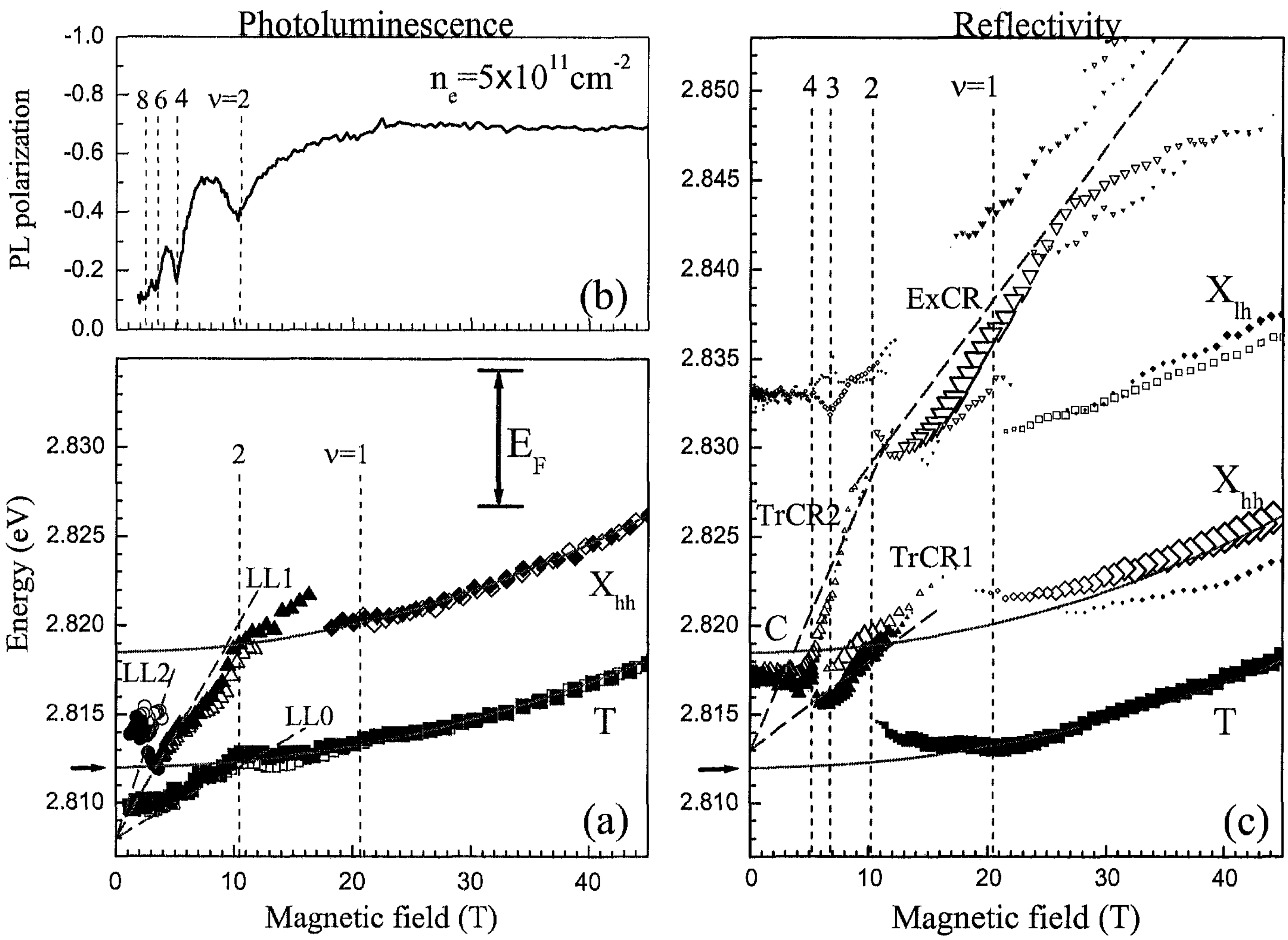

PL Intensity, Reflectivity
Ref.
n_e = 5x10^11 cm^-2
C
e-hh
2 meV
e-lh
T = 1.6 K
B = 0 T
7 meV
PL
x4
(a)
2.79 2.80 2.81 2.82 2.83 2.84
Energy (eV)
Ref.
T
X hh
X lh
T = 1.6 K
B = 40 T
σ+
σ−
PL
(b)
2.79 2.80 2.81 2.82 2.83 2.84
Energy (eV)

Fig.1



Photoluminescence
Reflectivity
PL polarization
n_e=5x10^{11}cm^{-2}
8 6 4 ν=2
(b)
Energy (eV)
E_F
2 ν=1
LL1
LL2
LL0
X_{hh}
T
(a)
Magnetic field (T)
4 3 2 ν=1
ExCR
X_{lh}
TrCR2
TrCR1
C
X_{hh}
T
(c)
Magnetic field (T)

Fig.2