Photoluminescence in asymmetric quantum wells at $v > 1$

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Abstract

Photoluminescence (PL) spectra in a two-dimensional (2D) electron system in strong magnetic fields are calculated by means of a numerical diagonalization method for various separations between the electron plane and the hole plane when the Fermi level lies in excited Landau levels. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Photoluminescence (PL) in two-dimensional (2D) systems in a quantum Hall (QH) regime has been intensively studied both experimentally and theoretically [1–10], most of which focus on the fractional quantum Hall regime [5,6]. In this paper, the PL spectrum is investigated using a numerical diagonalization method when the Fermi level lies in excited Landau levels.

In a narrow quantum well (QW) with a symmetric shape, electrons and a photo-excited hole can be regarded as being confined in the same 2D plane. In this case, the matrix element for the electron–electron interaction, $V_{ee}$, and the electron–hole interaction, $V_{eh}$, satisfy the relation $V_{ee} = -V_{eh}$. This relation leads to a ‘hidden’ symmetry [1] when the Fermi level lies in the lowest Landau level. This symmetry is mathematically expressed as

$$[L, \hat{H}] = (E_g - E_0) L,$$

where $\hat{H}$ is the Hamiltonian projected onto the lowest Landau level, $L$ the annihilation operator for a single magnetoexciton with zero wave vector consisting of an electron and a hole in the lowest Landau level. The energy of this magnetoexciton is $E_{ex} = E_g - E_0$, where $E_g$ is the effective band gap in the presence of a magnetic field and $-E_0$ is the exchange self-energy for an electron in the lowest Landau level filled completely. Because of this hidden symmetry, the PL spectra become a $\delta$-function at $E_{ex}$ independent of the filling factor, although the intensity changes sensitively at low temperatures depending on the symmetry of the ground state of the electron–hole system [9].

When the plane of electrons and that of a hole are separated with a distance $d$ by an electric field normal to the interface or by a one-side doping, the hidden symmetry is destroyed. It is also broken when the Fermi level lies in higher Landau levels because the full Hamiltonian $\hat{H}$ does not satisfy Eq. (1). In these cases, PL spectra are directly modified by interactions among electrons and holes in their positions and structures.

2. Method

For simplicity, the spins of the electrons and the hole are neglected although they play an important role in the PL spectra.
role in some cases [7,8]. Periodic boundary conditions are applied to square systems with area $a \times a$ penetrated by $N_\phi$ magnetic flux quanta ($N_\phi$: integer). The filling factor for electrons is defined by $v = N_e/N_\phi$, where $N_e$ is the number of electrons. The electron–electron and electron–hole interaction are given by $V_{ee}(r) = V(r,0)$ and $V_{eh} = -V(r,d)$, respectively, where $V(r,d)$ is defined as

$$V(r,d) = \frac{1}{a^2} \sum_{\mathbf{q} \neq 0} \frac{e^2}{2\epsilon q} \exp(-qd - i\mathbf{q} \cdot \mathbf{r}),$$

(2)

with the static dielectric constant $\epsilon$ and the reciprocal vector $\mathbf{q} = (2\pi n/a, 2\pi m/a)$ ($n, m$: integer).

The PL spectra are calculated using Fermi’s golden rule as

$$P(E) = \frac{1}{Z} \sum_{\beta} \exp \left( -\frac{E}{k_B T} \right) |\langle \beta | L | \alpha \rangle|^2 \times \delta(E - E_\beta - E_\alpha),$$

(3)

where $Z$ is the partition function, $k_B$ the Boltzmann constant, $T$ the temperature, $E$ the photon energy, $|\alpha\rangle$ and $|\beta\rangle$ are the initial and final states, and $E_\alpha$ and $E_\beta$ their energies. It can be shown that the total intensity of PL spectra is always unity at $v \geq 1$. All of the initial and final states are obtained by means of the numerical diagonalization of the Hamiltonian.

In the following, the calculated spectra at $T = 0$ are shown by both histograms with width $E_0/100$ (grey spikes) and their convolution with a Lorentzian with half width $E_0/20$ (solid lines). The photon energy $E$ is measured from $E_\alpha$ and in units of $E_0$. This unit energy $E_0$ is calculated in each finite-size system using previously defined $V_{ee}(r)$. The system size is fixed as $N_\phi = 12$ for $1 \leq v \leq 2$ and 10 for $2 \leq v \leq 3$.

3. Results

The spectra for $d/\ell = 0$ are shown in Fig. 1. Except at $v = 1$ and 13/12, the PL spectra consist of a lot of $\delta$-functions and therefore are broadened considerably. The broadening is larger for higher electron concentrations $v \geq 2$. The actual energy dependence of the lineshape varies with $v$ in an irregular manner. This is presumably due to a subtle change in the ground state of the electron–hole system and is likely to be sensitive also to the system size. The average PL energy shows a smooth downward convex curve in the region $1 < v < 2$ and $2 < v < 3$ except for the presence of irregular structures associated with the change of the lineshape.

Fig. 2 shows the PL spectra for $d/\ell = 0.5$. The irregularity in the change of the lineshape with $v$ has been slightly enhanced. Fig. 3 shows the results for $d/\ell = 2$. In addition to the further enhancement of the irregularity of the line shape, the PL peak exhibits a blueshift when the filling factor is increased slightly from $v = 1$ and from $v = 2$. Fig. 4 gives the results for $d/\ell = 5$. They are qualitatively very similar to those for $d/\ell = 2$. This is to be expected because for sufficiently large $d/\ell$ the ground state becomes independent of the presence of a photo-excited hole.

With the increase of $d/\ell$, the redshift of the PL energy for $1 < v < 2$ and $2 < v < 3$ tends to be reduced and approaches a linear dependence on $v$. Such behavior is consistent with the suggestion that origin of the quantum oscillation of the PL energy is caused by screening effects [2,3]. Because of the large broadening and the irregular lineshape,
however, the phase reversal with increasing $d/\ell$ [3] cannot be clearly identified in the present results.

At $v = 1$ and 13/12, the PL spectra consist of a single $\delta$-function and exhibit a discrete jump from $v = 1$ to 13/12 in the energy. The discrete jump changes its direction when the distance between the electron plane and the hole plane increases. The jump for large $d/\ell$ originates from the same mechanism as that predicted previously [7,10], but the jump in the opposite direction for small $d/\ell$ has not been pointed out so far. An analytic treatment of this discontinuous jump will be presented elsewhere.

4. Summary

PL spectra in 2D systems in the QH regime $v > 1$ has been calculated using a numerical diagonalization method for varying electron–hole separation $d$. When $d/\ell \ll 1$, the PL energy shows a discontinuous redshift just at $v = 1$ when an extra electron is added and exhibits a downward convex curve in the region $1 \leq v \leq 2$ and $2 \leq v \leq 3$. When $d/\ell \gtrsim 1$, it shows a discontinuously blueshift just at $v = 1$ and almost linear $v$ dependence in the region $1 \leq v \leq 2$ and $2 \leq v \leq 3$.

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References