Electron–electron interaction effects in integer quantum-Hall photoluminescence

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Abstract

Photoluminescence in an integer quantum Hall regime $2 \leq v \leq 3$ is studied using a numerical diagonalization method. The spectra for left circularly polarized light show a double-peak structure while those for right circularly polarized light show a single-peak structure. The characteristic double-peak structure appears due to coupling with inter-Landau-level excitations of electrons with a different spin.

PACS: 78.66; 73.40.H

Keywords: Quantum Hall effect; Photoluminescence; Exciton; Quantum well

1. Introduction

Photoluminescence (PL) has been intensively studied both experimentally and theoretically in quantum Hall (QH) systems, i.e., in two-dimensional (2D) systems in a strong magnetic field. In this paper, we investigate effects of electron–electron interaction by calculating numerically exact PL spectra in finite-size systems characterized by the electron filling factor $2 \leq v \leq 3$.

When both electrons and a photo-excited hole are confined in a 2D layer, the electron–electron interaction $V_{ee}(r)$ and the electron–hole interaction $V_{eh}(r)$ satisfy $V_{ee} = -V_{eh}$. If only the lowest Landau level is occupied by electrons, this equation leads to a “hidden symmetry” [1,2] expressed by the commutation relation

$$[\hat{\mathcal{H}}, \hat{\mathcal{L}}_z] = -(E_z - E_0) \hat{\mathcal{L}}_z,$$

where $\hat{\mathcal{H}}$ is the Hamiltonian projected onto the lowest Landau level, $z = L$ and $R$ denotes left (LCP) and right circularly polarized (RCP) light, respectively, $\hat{\mathcal{L}}_z$ is the annihilation operator of a magnetoexciton with vanishing wave vector consisting of an electron and a hole in the lowest Landau level, $E_z$ denotes the PL energy in the absence of interaction, and $-E_0$ is the exchange self-energy of an electron in the lowest Landau level filled completely. Because of the commutation relation, PL spectra for the light polarization $z$ is given by a single $\delta$-function at $E_z - E_0$ independent of filling factor $v$. 

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PII: S1386-9477(99)00393-8
When the electron and the hole layers are separated from each other with a distance $d$, or when the Fermi level lies in excited Landau levels, PL spectra are directly modified by many-body effects in their energies and intensities. In the previous study effects of electron–electron interactions on PL were studied numerically in models systems without spins [3,4]. In this paper, we make similar calculations for more realistic systems with spins and demonstrate the importance of effects of the electron spin in PL spectra.

2. Model and method

We consider quantum well systems with an asymmetric shape caused by a one-side doping or an electric field applied normal to the interface, where the electron and the hole layers are separated with a distance $d$. Numerical calculations are performed in a square system with area $a^2 = 2\pi^2 N_\phi$, where $\ell$ is the magnetic length and $N_\phi$ is the number of flux quanta passing through the system. The electron–electron and electron–hole interactions are given by $V_{ee}(r) = V(r, 0)$ and $V_{eh}(r) = -V(r, d)$, respectively, where $V(r, d)$ is defined by

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

with the static dielectric constant $\epsilon$ and reciprocal lattice vector $q = (2\pi n/a, 2\pi m/a)$ ($n, m$: integer). Diagonalizing the Hamiltonian numerically, we obtain all of the initial and final states and calculate the PL spectra using Fermi’s golden rule.

We consider PL spectra at absolute zero temperature in the regime $2 \leq v \leq 3$, where the lowest Landau levels for both spins of electron are completely filled. It is assumed that the Zeeman splitting is large enough and the total spin of electrons in the first excited Landau level, which is partially filled, is maximally polarized at absolute zero temperature. When a pair of up-spin electron and “up-spin” heavy hole is recombined, LCP light is emitted. On the contrary, recombination of a down-spin electron and a “down-spin” hole induces RCP light.

It is important to take into account inter-Landau-level processes illustrated in Fig. 1, in which an electron in an excited Landau level drops down to fill the space created by photo-emission and an electron is excited to a higher Landau level. Because of these shake-up processes, the “hidden symmetry” is broken at $\nu \geq 2$ even at $d = 0$. Note that the processes shown in Fig. 1(c) exist only in the presence of electron spins. In fact, if such processes are neglected, PL spectra for LCP light at $2 \leq v \leq 3$ are exactly the same as those of spinless systems at $1 \leq v \leq 2$.

3. Results

The calculated spectra are shown by both histograms with a width $E_0/100$ (grey spikes) and their convolution with a Lorentzian with a half-width $E_0/5$ (solid lines). The photon energy $E$ is measured from $E_\nu$ in units of $E_0$ which is calculated in the finite-size system used for the calculation of PL spectra.

Fig. 2 shows the PL spectra at $1 \leq v \leq 2$ calculated in spinless systems characterized by $N_\phi = 12$ [3,4]. The spectra consist of many discrete peaks but can be regarded as a single broadened peak when the broadening is introduced. The peak energy is shifted toward the low frequency side; as a function of $v$ the shift shows a convex curve at $d/\ell \ll 1$ but is almost linear at $d/\ell \gg 1$. These behaviors in energy shifts are consistent with the suggestion that the origin of the quantum oscillation of the PL energy is caused by screening effects [5,6]. In fact, accumulation of electrons in partially filled Landau levels around a positively charged photo-excited hole gives rise to a considerable lowering of the energy of the hole.

Fig. 3 shows PL spectra at $2 \leq v \leq 3$ calculated in spinful systems characterized by $N_\phi = 8$. They consist...
of a lot of $\delta$-functions but may be regarded as broadened double peaks when a sufficiently large broadening is introduced. This double-peak structure is consistent with recent experiments [7]. The first moment of the spectra is completely same as that of the spinless system at $1 \leq \nu \leq 2$ shown in Fig. 2, which shows that the averaged PL energy shifts are determined by screening effects also in the presence of electrons with different spins.

As has been mentioned, a single hole created in the lowest Landau level by photo-emission is coupled with the continuum consisting of inter-Landau-level excitations as shown in Fig. 1. The result of a numerical study at $\nu = 3$ has shown already that such coupling is much more important with excitations of electrons with different spins and the resulting strong hybridization leads to a double-peak structure [8]. This reason is that Pauli's exclusion principle tends to reduce considerably the interaction among electrons with the same spin in comparison with that between electrons with an opposite spin. The present numerical results show clearly that this situation prevails in the whole range of $\nu$, i.e., $2 \leq \nu \leq 3$.

In spinless systems, the coupling strength between the single-hole state created by photo-emission and the energy continuum is smaller than the characteristic broadening of energy continuum, because there is no interaction process between electrons with an opposite spin. As a result, the single-hole state is only broadened and the PL spectra show a single-peak structure. In spinful systems, on the contrary, the strong hybridization of the single-hole state and energy continuum form a kind of bonding and anti-bonding states and leads to a double-peak structure in PL spectra.

The PL spectra show an intriguing behavior near $\nu = 2$. In fact, in the system with small electron–hole distance $d/\ell \ll 1$, the single spectral line is suddenly split into two lines when the filling factor increases past $\nu = 2$ (the curve with $\nu = \frac{17}{8}$ in Fig. 3(a)). On the contrary, at large electron–hole distances $d/\ell \gg 1$, no such sudden splitting occurs but the PL-energy is shifted to the high-energy side (the curve with $\nu = \frac{17}{8}$ in Fig. 3(b)). These anomalous behaviors can be treated analytically and will be presented elsewhere.

We also investigated PL spectra for LCP light for small Zeeman splittings. At all parameters where calculations are performed, the ground state is still maximally spin-polarized even in the vanishing-Zeeman-splitting limit. In this case, temperature increase leads to increase of the concentration of down-spin electron in the first excited Landau level. Our calculation show that this spin-flipping effect enhance the high-energy peak.

On the other hand, broadened PL spectra for RCP light calculated in the same system exhibit only a
Fig. 4. PL spectra calculated for RCP light at $2 \leq v \leq 3$.

A single-peak structure as is shown in Fig. 4. The reason is that no inter-Landau-level excitations are possible after the emission of RCP light in the regime $2 \leq v \leq 3$. At $d/\ell = 0$, the absence of inter-Landau-level excitations restores the “hidden” symmetry mentioned above and the PL spectra consist of a single $\delta$-function located at $E = E_R - E_0$.

4. Conclusion

Photoluminescence spectra at $2 \leq v \leq 3$ have been studied by means of a numerical diagonalization method. The spectra for LCP light show a double-peak structure caused mainly by a strong hybridization with inter-Landau-level excitations of electrons with an opposite spin, while the shift of the average energy is understood in terms of screening effects. On the contrary, the spectra for RCP light consist of a single peak due to the absence of coupling with inter-Landau-level excitations.

Acknowledgements

This work is supported in part by the Japan Society for the Promotion of Science (“Research for the Future” Program JSPS-RFTF96P00103). One of the authors (KA) is supported by Research Fellowships of the Japan Society for the Promotion of Science for Young Scientists. Numerical calculations were performed in part on FACOM VPP500 in Supercomputer Center, Institute for Solid State Physics, University of Tokyo.

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