Near-field scanning magneto-photoluminescence of composite fermions in In(Ga)P/GaInP quantum dots

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Abstract. We measured spatial and magnetic field dependence of photoluminescence (PL) spectrum of In(Ga)P/GaInP quantum dots (QDs) having up to 8 electrons and quantum confinement $\hbar\omega_0$ down to 2 meV using low temperature (10K) near-field scanning optical microscope (NSOM) providing spatial resolution ~20 nm and external magnetic field up to $B_0=10$ T. Using these measurements we identified QDs having Wigner-Seitz radius up to 2 and internal magnetic field $B_{\text{int}}$ up to 15 T, corresponding to Landau level filling factor $\nu_0$ 3, 5/2, 2/5 and 1/5. In magneto-PL spectra we observed features related to integer and fractional quantum Hall states and identified composite fermion (CF) states corresponding to Wigner molecule isomers (1, 5) and (0, 6). Our results demonstrate perspectives of using In(Ga)P/GaInP QD structures, providing deterministic localization of CFs in zero external magnetic field, in “magnetic-field-free” topological quantum gates.

1. Introduction

Strongly correlated states of two dimensional (2D) electrons of fractional quantum Hall effect (FQHE) can be described as the states of integer quantum Hall effect (IQHE) of non-interacting quasi particles called composite fermions (CFs) [1]. CFs have fractional charge and consist of single electrons bound to even number of magnetic flux quanta $\phi_0 = h/e_0$, and in which Coulomb interaction and external magnetic field are screened by quantized vortexes. More than 100 FQHE states were observed [2] and most of them are formed in the lowest Landau level (LL) having odd denominator filling factors $\nu=n/(2pn\pm1)$, with $p=1$ or 2, where $2p$ is the number of vortices attached. Also the FQHE states having even denominators, which formed in the first excited LL, were observed [2], among which 5/2 CF state can be formed from non-Abelian anyons, which can be explored for topological quantum computation (TQC) [3]. The use of 2D quantum Hall (QH) structures for TPC, however, have difficulties arising from intrinsic disorder, preventing deterministic localization of CFs and q-bit initialization. Here we demonstrate such localization using self-organized In(Ga)P/GaInP QD structures, providing deterministic localization of CFs in zero external magnetic field.

2. Experimental details

The In(Ga)P/GaInP QDs are flat lens-shape islands having diameter and height 120 and 15 nm and they represent natural 2D Wigner molecules having up 20 electrons and Wigner-Seitz radius up to 5 as was established from high-spatial-resolution cryo-magnetic near-field scanning optical microscopy (NSOM) measurements [4]. In some of these QDs strong internal magnetic field is generated producing quantum
Hall effect in zero external magnetic field. Below we present magneto-PL measurements of QD having \( N = 5 \), \( \hbar \omega_0 = 2 \text{ meV} \) and \( B_{\text{int}} = 6 \). The details of measurement techniques described in Ref. [4].

\( B_{\text{int}} \) was estimated using FD functions [5] in the form \( E_{k,l}(B) = E_{k,l}(B_0 + B_{\text{int}}) \).

3. Experimental results

Measured magneto-PL spectra at external magnetic field \( B_0 = 0, 1, \ldots, 10 \) T (see Fig.1(a)) reveal 6 anti-Stokes peaks having separation 0.5-1.5 meV. The shifts of these peaks, denoted as \( 1^*-6^* \), over entire \( B_0 \) range are very close to \( E_{k,l}(B) \) for \( B_{\text{int}} = 6 \) T and fractional electron charge \( 1/3e_0 \), indicating formation of CFs. Thus total magnetic field in the dot, \( B_{\text{tot}} = B_0 + B_{\text{int}} \), changes from 6 to 16 T, which corresponds to \( \nu \) range from 2/5 to 1/5, including \( \nu = 1/3, 1/4 \) and 2/9.

In the range \( \nu = 2/5-1/5 \) the intensity of the lowest energy peak \( 1^* \) is few times larger than intensity of the other 5 peaks, while for \( \nu < 1/5 \) the intensity of all peaks is nearly equal, corresponding to \((1,5)\) and \((0,6)\) WMs, respectively. For \((1,5)\) WM peak \( 1^* \) is strongest due to strong overlap of corresponding CF with photoexcited hole at the center, while for \((0,6)\) WM all CFs have nearly equal separation from the center leading to their equal intensity in PL spectrum. Another, weaker change in the intensity distribution is observed at \( B_0 = 4 \) T, i.e. \( \nu = 1/4 \), and it is related to a contribution peak \( 2^{**} \), split from peak \( 2^* \). The change in the intensity distribution for \( \nu = 1/4 \) and \( 1/5 \) is accompanied with the shifts kinks. The shift kinks are also observed at \( \nu = 1/3 \) and 2/9. Thus, the kinks indicate changes in total angular momenta \( (L) \) of the ground state by magic numbers [6, 7], which are \( \Delta L = 6 \) and 5 for \((0,6)\) and \((1,5)\) WM, respectively. According to calculations, presented for similar dot parameters in Refs. [8, 9], \( L = 39 \) and 45 for \( \nu = 2/5 \) and 1/3, respectively. Using relation \( \nu = L_0/L \), where \( L_0 = N(N-1)/2 \) [9], we can assign, \( L = 63, 69 \) and 74 for \( \nu = 1/4, 2/9 \) and 1/5, respectively. Using CF description [10] the FQHE states having \( \nu = 2/5 \) and 1/3 can be assigned to \( \nu = 2 \) of IQHE states of \( 3\) CFs, while the FQHE states \( \nu = 1/4 \) and 2/9 and 1/5 to zero field Fermi liquid state, and \( \nu = 2 \) of IQHE states of \( 4\) CFs, respectively. The total angular momenta of CFs is \( L_{\text{CF}} = L - 2pL_0 \).

For \((1,5)\) WM Stokes or shake up (SU) modes \( \omega_{\text{ex}}, \omega_0, 2\omega_0 \) and \( \omega_0 \) have much weaker intensity, which results from weak distortion of \((0,5)\) in initial state by photoexcited electron loaded at the center of \((1,5)\) WM.

FIG. 1 Low-temperature (10K) PL spectra (a) and energy shift of their fine structure peaks (b, empty circles) of In(Ga)P/GaInP QD at external magnetic field \( B_0 = 0, 1, \ldots, 10 \) T. In (a) fine structure peaks were separated using Lorentz contour decomposition (not shown) and lines connecting peak maxima are drawn to outline their \( B_0 \) shift. In (b) the size of the circles is proportional to peak intensity; thin solid (dashed) curves are FD levels \( E_{k,l}(\Omega) \) for \( B_{\text{tot}} = 6(0)\) T and electron charge \( 1/3e_0 \).
The formation of $B_{int}$ induced by spin polarized state at $B_0=0$ T in initial state having $N=5$. We can suggest that $B_{int}$ is generated by locking of the electron spin orientation by 2D nature of electron state in combination with axial anisotropy, induced by $<111>$ CuPt-type In-Ga atomic ordering [11], and alignment of nuclei’s spin via hyper-fine interaction.

In Fig.2 we show PL spectra of 3 more dots in which the structure related to 6 CFs is appeared. These dots are CFP1, CFP2 and CFP3 at $B_0=0$ and we compare it with CFP0 for $B_0=0$ and 8 T presented in Fig.1. It is seen from Fig.2 that CFP3 has intensity distribution of (1,5) WM similar to CFP0 and thus in has $B_{int} \sim 6$ T. The CFP1 and CFP2 show (0,6) WM intensity distribution, similar to that for CFP0 at $B_0 = 8$ T. Thus they have $B_{int} \sim 14$ T. The SU components of CFP0 and CFP2 are molecular-like translational ($\omega_0$) and stretching ($\omega_s = 1.9\omega_0$) vibrational excitations [12], while of CFP1 they are droplet-like magneto-roton excitations. Activation of vibrational modes manifests radial distortion of CD by photoexcited electron, which can arise from ear-like CD shape in initial stat and larger lateral asymmetry.

In conclusion we used cryo-magneto-PL NSOM measurements to demonstrate FQHE in In(Ga)P/GaInP QDs having $N=5$ electrons and quantum confinement $\hbar\omega_0=2$ meV. We also demonstrate the existence and localization of CFs having $n=2/5$ and $1/5$ at zero external magnetic field. Our results demonstrate perspectives of using In(Ga)P/GaInP QHP structures, providing deterministic localization of CFs in zero external magnetic field, in “magnetic-field-free” topological quantum gates.

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