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Suppression of molecular anyon states in the magneto-photoluminescence spectra of $InP/GaInP_2$ quantum dots at a temperature of 30 K

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Abstract. We used the photoluminescence spectra of a single $InP/GaInP_2$ quantum dot with a Wigner-Seitz radius of about 3.4, doped with 4 electrons, to measure the magnetic field dispersion of single quantum states in a range between 0 and 10 T at 30 K. The measurements show the formation of a molecular structure at high temperature and its transition to a puddle-like structure with a decrease of localization size from 110 nm to 70 nm. Fock-Darwin spectrum fitting shows a decrease in the cyclotron frequency and magnetic field shift, that are interpreted as the formation of an anyon structure in a QD with fractional charge 1/5, 2/3, 1/2 and a built-in magnetic field of −3T.

Keywords: single quantum dots, anyon, Wigner localization, Fock-Darwin spectrum, magneto-photoluminescence

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Материалы конференции
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Подавление молекулярных энионных состояний в спектрах магнито-фотолюминесценции квантовых точек $InP/GaInP_2$ при температуре 30 K

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Аннотация. Спектры фотолюминесценции легированной 4 электронами одиночной квантовой точки $InP/GaInP_2$ с радиусом Вигнера-Зейтца около 3,4 использовались в работе для измерения дисперсии одиночных квантовых состояний в диапазоне магнитного поля в 0–10 Т при температуре 30 К. Результаты измерений указывают на формирование молекулярной структуры при высокой температуре с переходом в «лужную» структуру при уменьшении размера локализации с 110 нм до 70 нм во внешнем магнитном поле.

В результате подгонки спектра Фока-Дарвина обнаружено уменьшение циклотронной частоты и сдвиг магнитного поля, что может быть связано с формированием в квантовой точке энионной структуры с дробным зарядом 1/5, 2/3, 1/2 и встроенным магнитным полем величиной в −3Т.

Ключевые слова: одиночные квантовые точки, энионы, вигнеровская локализация, спектр Фока − Дарвина, магнето-фотолюминесценция

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Introduction

The study considers atom-like single-particle quantum states of electrons (electron shells) in two-dimensional quantum dots (QDs) with a Wigner localization regime, i.e., Wigner-Seitz radius $r_s > 1$, where $r_s = 1/[a^*_B(\pi \cdot n)^{0.5}]$ (n is the electron density and a^*_B is the Bohr radius). These states generate magnetic flux quanta (i.e., vortices), producing anyon (magneto-electron) states that have a fractional charge of ~$1/k$ (k is the number of vortices). The resulting built-in (B_{in}) magnetic field corresponds to the filling factor $\nu = N/K$, where N is the number of electrons in the dot and K is the total number of vortexes. This is confirmed by measurements of magneto-photoluminescence spectra (magneto-PL) of self-organized $InP/GaInP_2$ QDs [1]. Molecular or composite ('puddle') anyon state structures were observed in these measurements at 10 K with the external magnetic field B_e ranging from 0 to 10 T for QDs with $N > 5$ and $r_s \sim 2.3$ and 1.3, respectively, and $\nu \sim 1/3$ and 5/2, respectively. In this paper, we present the measurement results for magneto-PL spectra of QDs for $r_s \sim 3.4$ and $N = 4$, allowing to observe the molecule-puddle transition, i.e., suppression of the molecular state corresponding to a change from $\nu \sim 1/5$ to 3/2. The transition was observed at a temperature $T = 30$ K, which indicates high temperature stability of the anyon state in $InP/GaInP_2$.

Materials and Methods

We studied $InP/GaInP_2$ QD samples grown on a GaAs [001] substrate by MOS-hydride epitaxy at 725 °C. The QDs were formed by the Stranski-Krastanov mechanism by depositing 3 monolayers of InP on a $GaInP_2$ $Ga_{0.48}In_{0.52}P$ ($GaInP_2$) layer, lattice-matched to the substrate and covered with a 40 nm $GaInP_2$ layer.

Magneto-PL spectra were measured using a near-field scanning optical microscope (NSOM) in illumination-collection mode at a temperature of 30 K and an external magnetic field B_e in the range from 0 to 10 T. The NSOM probes were tapered Al-coated fiber with an aperture of 50 − 100 nm. The spectra were excited by an Ar laser line with a wavelength of 514.5 nm.

Considering the anti-Stokes components (ASCs) of the PL spectra at minimum pumping, we determined that the QD has four electrons in the photo-excited state, i.e., three in the initial state, (see Fig. 1, *a*) forming an anyon Wigner molecule in both states [2, 3, 4].

Experimental results of magneto-PL

Fig. 1, *a* shows the PL spectra using the Stokes shift energy scale, where the zero peak denoted as the *s*-peak is e_0 (energy emission of the s-peak is 1.715 eV), with B_e increasing in the range from 0 to 10 T. Fig. 1, *b* shows the Stokes region of the spectra, and Fig. 1, *c* shows the shift of the Stokes component (SC) peak.

According to the experimental data, the magneto-PL spectra of the QD anyon state are divided into 3 regions, denoted as I, II, III, differing in the fractional charge and the configuration of the Wigner molecule.

Region I (B_e = 0–3 T). The system was in the molecular state, this state in the PL spectrum is characterized by the separation of ASCs peaks, which are anyons e_0, e_1, e_2, e_3, with the average $\Delta E \approx 2.5$ meV. The Wigner molecule configuration is determined by the SC emission of the vibrational mode (ω_0 = 3.75 meV) of the molecule (this issue is discussed in detail in [2]).

Region II (B_e = 3–6 T). The molecular state is destroyed and passes into the puddle state. We define the puddle state by the characteristic blurring of the emission peaks (e_0, e_1) and the jump-like change in the emission energy of the Wigner molecule SC with $\Delta\omega_0$ = 0.7 meV. The size of the Wigner molecule localization in this state is 110 nm, like in the I state.

Region III (B_e = 6–10 T). The puddle state is rearranged into a different configuration with mixing of ASCs emission peaks (e_0, e_1) and (e_2, e_3) and a second jump in the emission energy of the Wigner molecule SC ($\Delta\omega_0$ = 1.5 meV) with a decrease in the localization size from 110 nm (States I, II) to 70 nm.

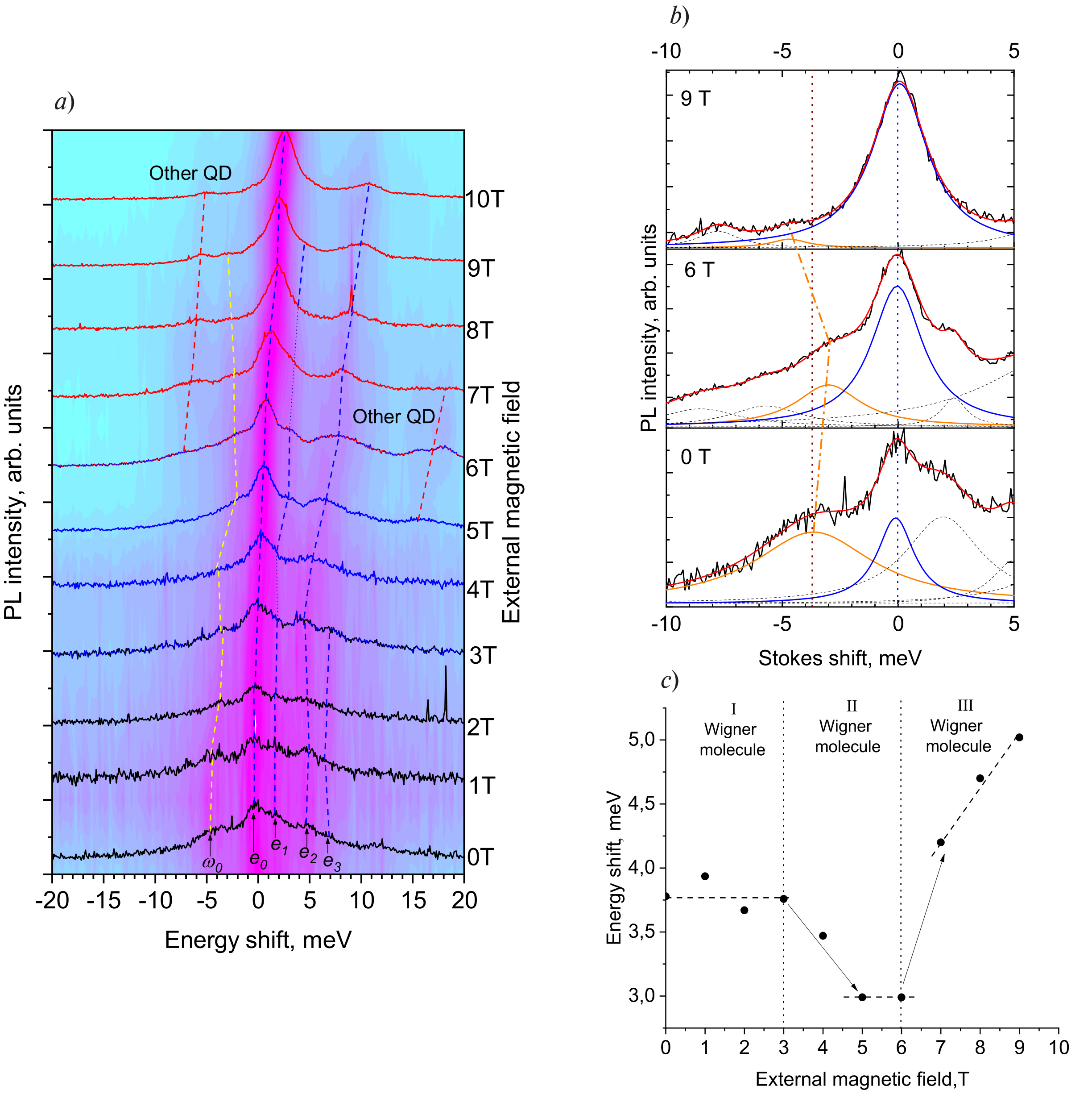

Fig. 1. PL spectrum of a single QD measured at B_e in the range from 0 to 10 T (*a*) (the black lines indicate the spectrum of State I, the blue lines that of State II, the red lines that of State III); PL spectrum in the Wigner molecule SC (orange line) for B_e = 0,6 and 9 T (*b*); position of the SC Wigner molecule peaks in the entire Be range (*c*)

Fock-Darwin spectrum

To analyze the shift of quantum levels of InP/$GaInP_2$ QDs in the magnetic field, we use the single-particle Fock-Darwin (FD) theoretical spectrum of electrons in a parabolic potential ($\hbar\omega_0$) [2, 5, 6] using adjustment of the cyclotron frequency to determine fractional charge, i.e., anyon state, for individual FD states, as described in [7,8].

In Fig.2, *a* on top of the experimental spectrum we plotted the FD spectrum calculated for $\hbar\omega_0$ = 2.5 meV and the *s*, *p*, *d*, and *f* levels. We can see that this fit poorly describes the experimental shift of the QD levels in the magnetic field, and clearly there is a strong deviation of the *s* and *d* peaks from the FD spectrum. The FD spectrum with a fit accounting for the electrons in the QD as anyon states with a fractional charge is plotted in Fig. 2, *b* on top of the experimental spectrum. Due to the built-in magnetic field (B_{in}), the total magnetic field of the system (B_{tot}) is characterized by the sum of the external field B_e and B_{in}, i.e., $B_{tot} = B_e + B_{in}$.

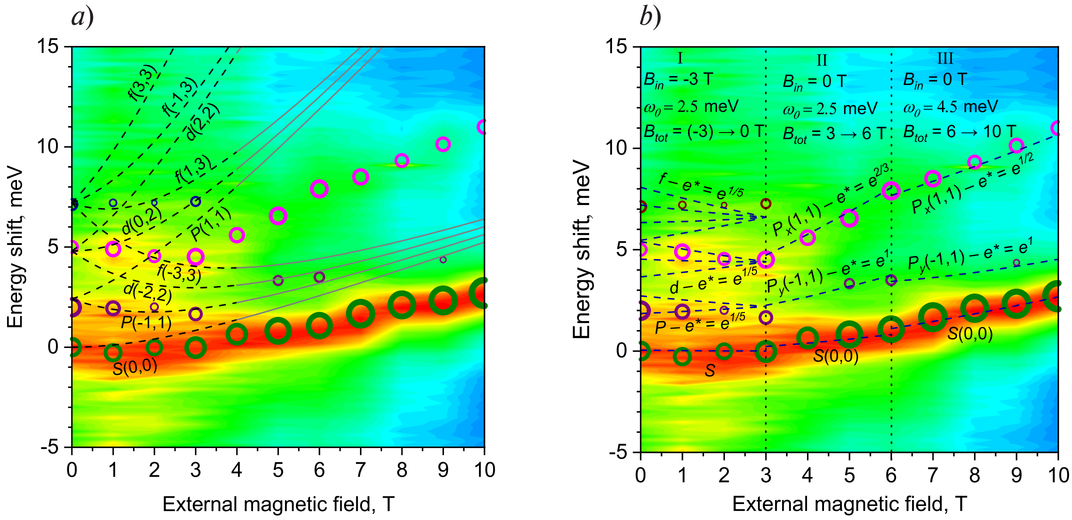

Fig.2. Contour maps of the ASC PL and FD spectrum (*a*) classical theory, with adjustment of the confinement. In the interpretation of the anyon state in the fractional quantum Hall effect mode with adjustment of the built-in magnetic field B_{in} and fractional charge, where $B_{tot} = B_e + B_{in}$ we are showing range of change $B_{tot} \in [-3,0]$ like B_{tot} (−3) → 0 T (*b*). We use an atom-like formalism to denote FD levels, in which quantization levels n = 0,1,2 is denoted as $s(m,0)$, $p(m,1)$, $d(m,2)$, respectively, where m is the magnetic number. To separate p levels with different magnetic number we use indices – $p_x = p(1,1)$ and $p_y = p(-1,1)$

For fitting, we divided the spectrum into 3 regions as in Fig. 1, *a*, *b*, *c*:

Region I (B_e = 0–3 T). This is the state of spontaneous anyon with B_{in} = −3 T, a quantum confinement of 2.5 meV, and the fractional charge $e^* = e^{1/5}$ for each level. In this case, B_{tot} varies between −3 T and 0 T, i.e., the FD spectrum is reversed. The filling of the *s*, *p*, *d* and *f* levels with single electrons is observed, which can be attributed to the total spin polarization of the system due to the high temperature of 30 K.

Region II (B_e = 3–6 T). There is a transition of spontaneous anyons to induced ones with a quantum confinement of 2.5 meV and B_{in} = 0 T, due to which a jump of B_e to 3 T is observed. In this state, the *f* peak disappears and only the *s*, p_x, and p_y levels remain filled. For induced anyons, each line is described by their own fractional charge, for p_x the fractional charge is $e^* = e^{2/3}$, and for py the charge is $e^* = e^1$. The B_{tot} jump and redistribution of the fractional charge leads to the destruction of the molecular state and rearrangement of the Wigner molecule.

Region III (B_e = 6–10 T). The system remains in the state with induced anyons with fractional charge $e^* = e^{1/2}$ for p_x and charge $e^* = e^1$ for p_y. We observe a jump in the Wigner molecule SC, which we interpret as a reverse rearrangement to the molecular state, which is accompanied by a redistribution of the fractional charge and a change of Wigner molecule isomer. For FD fitting, we describe this transition by changing the quantum confinement to 4.5 meV, which is interpreted as a reduction of the Wigner molecule size to 70 nm.

Conclusion

We used the magneto-PL method of a single $InP/GaInP_2$ QD with 4 doped electrons to demonstrate anyon state formation in a zero external magnetic field. We observed the molecular state disintegration and the transition of the puddle state of the anyon state in a QD by the shift of the Wigner molecule Stokes component. Analysis of the QD based on the theoretical spectrum of one-electron Fock-Darwin points to the formation of induced and spontaneous anyon states with different values of the fractional charge and the built-in magnetic field.

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