Fermi-edge singularities in photoluminescence spectra of *n*-type modulation-doped quantum wells with a lateral periodic potential

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We demonstrate that a many-body effect between electrons and a finite-mass hole can be modulated externally by lateral periodic potentials in a *n*-type modulation-doped GaAs-$Ga_{1-x}Al_xAs$ quantum-well structure. A peculiar asymmetric peak is observed in the photoluminescence spectra 2.5 meV below the Fermi energy when a weak lateral periodic potential is applied, whereas no significant feature is observed without any lateral potential. The asymmetric peak is shown to be due to the recombination of the electrons at the Fermi surface and a hole, by investigating the oscillations of the energy positions and the intensity of the emission spectrum as a function of the magnetic field.

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I. INTRODUCTION

The Fermi edge singularity (FES) has been one of the most attractive subjects of many-body effects in optical studies in condensed matter. The sudden appearance or disappearance of a valence-band hole by an optical transition gives rise to a power-law divergence in the energy dependence near the Fermi energy (E_F) in the absorption or the photoluminescence (PL) spectra due to many-body Coulomb interactions between electrons and a hole, which is called a FES. This effect was originally found to explain soft-x ray spectra of metals with an infinite-mass hole.[1–3]

The purpose of the present paper is to demonstrate that the Coulomb interaction between electrons and a hole, and hence the degree of the divergence of the FES in the PL, can be controlled by a tunable lateral periodic potential in a two-dimensional (2D) structure. As will be shown below, the hole mass in our system is finite. The exponent of the power-law divergence depends critically on two competing effects: the electron-hole attractive Coulomb interaction[1] and Anderson's orthogonality theorem,[4] which states that the overlap of the matrix element between an *N*-electron state vanishes in the limit $N\rightarrow\infty$. In an infinite-mass hole case, the FES is present in one-,[5] two-,[6] and three-dimensional[7] structures. In a finite-mass hole or a free-hole case, however, the dimensionality of the system significantly changes the many-body interactions between them. It has been well established theoretically that the FES disappears in a 3D structure,[8] but appears in a 1D structure independent of the hole mass.[5,9]

In quasi-2D systems with a finite-mass hole, the appearance of a FES has been discussed theoretically, where confining and artificial potentials must be taken into account by a 2D electron-hole attractive Coulomb interaction which is weakened by a form factor,[10] and the balance between the electron-hole Coulomb interaction and Anderson's orthogonality theorem is more subtle.[11] The disappearance of the FES was theoretically predicted by some,[12–14] while Bauer calculated a significant oscillator strength in PL near E_F below a critical electron density.[15] Experimentally, the FES was observed in absorption spectra,[16–18] but only a weak structure was observed near the Fermi energy (E_F) in the photoluminescence spectra.[19] This apparent diversity in published results may be attributed to the critical balance of the two competing effects in two dimensions.

One would expect, therefore, that the FES can be enhanced or suppressed by applying weak external potential in two dimensions in a finite-mass hole case. We employ a method utilizing a surface gate structure[20,21] to fabricate a lateral periodic potential. The coupling between unit cells can be controlled by applying a bias voltage (V_B) between the surface gate and the backgate. Self-consistently calculated electron densities are shown in Fig. 1. The calculation was carried out by self-consistently solving Schrödinger and Poisson's coupled equation numerically in real space,[22] with the exchange energy taken into account by a standard density-functional method.[23] Details of the calculation can be found elsewhere.[24,25] Figure 1 shows that the electron density is strongly coupled across unit cells of size L^2, and a global Fermi surface is present at $V_B=-0.1$ V ($V_{calc}=-0.3$ V). Electron states near the Fermi level show significant dispersion of about 0.5 meV due to the strong coupling between unit cells. The energy dispersion is significantly larger than the energy spacings of about 0.1 meV. The Fermi surface is thus well defined in this case, which is necessary to observe the FES. By contrast, the electron density is well isolated at $V_B=-0.5$ V ($V_{calc}=-0.7$ V), as shown in Fig. 1(b). The energy spacings near the Fermi energy are about 0.5 meV. The electron states are discrete, forming quantum dots at $V_B=-0.5$ V, and a global Fermi surface should not exist.

The effect of the external periodic potential is twofold. First, the FES is enhanced by a weak periodic potential, as shown in Fig. 1(a), due to an enhancement of the Coulomb interaction by the confinement, the relaxation of the optical selection rule by the admixture of the wave functions with different wave numbers, and a weakening of the hole recoil effect by the geometrical restriction. Second, the FES is suppressed by a strong periodic lateral potential, as shown in Fig. 1(b), by suppressing low-energy excitations of electron-hole pairs in the vicinity of E_F by a gap opening at E_F. In this aspect, our system is markedly different from the system

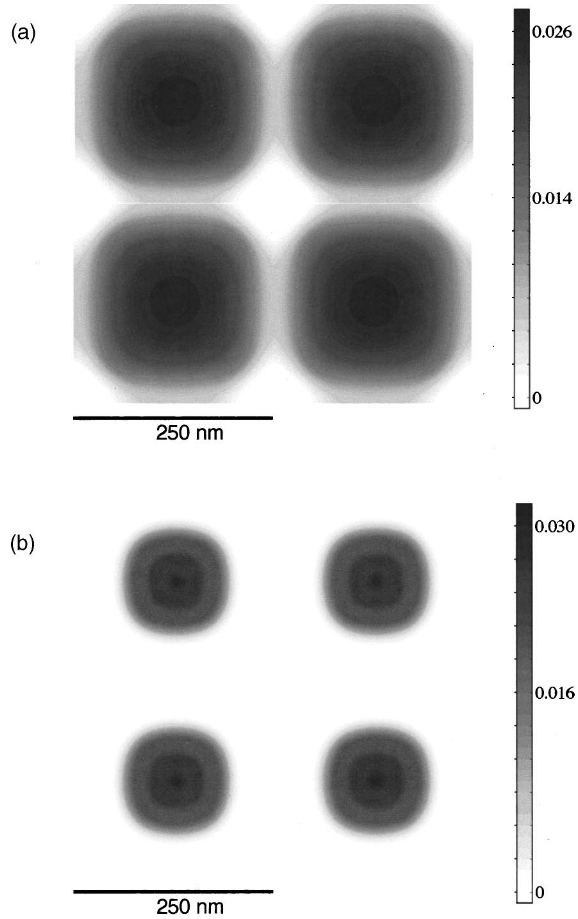

FIG. 1. Calculated electron densities (a) at $V_B = -0.1$ V ($V_{\rm calc} = -0.3$ V) and (b) at $V_B = -0.5$ V ($V_{\rm calc} = -0.7$ V) The unit-cell length ($L = 250$ nm) is shown by the horizontal line. The darker region shows higher electron density. The electron density is interconnected in (a), while it is isolated in (b).

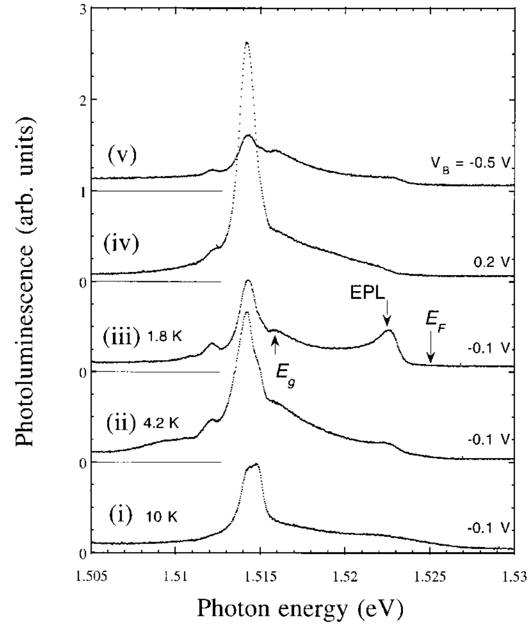

FIG. 2. PL spectra at temperatures 10 (*i*), 4.2 (*ii*), 1.8 and K (*iii*) at the bias voltages $V_B = -0.1$ V, and 1.8 K at $V_B = 0.2$ V (iv) and -0.5 V (v). The bandgap (E_g), the enhanced PL near the Fermi energy (EPL), and the Fermi energy (E_F) are indicated by the arrows. Zero points of the y axis are shifted.

in the literature with a localized hole.[6]

In this paper, magneto-optical measurements are reported to clarify the many-body nature of the enhanced PL near E_F, which is a function of the bias voltage. For a higher electron density sample at 0 T, it was shown in earlier results that the enhancement of the PL is observed only for a bias voltage at which the electron density is strongly coupled.[26] However, it was left to be answered whether the enhanced PL is due to the FES or not. It is also important to investigate samples with different carrier densities to identify the FES.

The presence of a higher conduction subband state in the vicinity of E_F gives additional complexity to the FES in two dimensions. The enhancement of the FES was observed depending on the energy separation between E_F and the higher conduction subband,[27] and there are theoretical accounts for the role of the higher conduction subband.[14,28,29] We restrict ourselves to the case where the second subband state is far from E_F.

II. EXPERIMENT

The sample studied was a molecular-beam-epitaxy-grown GaAs-$Ga_{1-x}Al_xAs$ ($x \approx 0.3$) modulation-doped quantum-well structure with a 20-nm-thick undoped GaAs quantum-well (QW) layer embedded at 55 nm from the surface on an n-type GaAs substrate which was used as a back contact. The 2D electron density (n_s), without modulation by the external bias voltage, was estimated to be $2.4 \times 10^{11}\ {\rm cm}^{-2}$ at 1.8 K from an optical Shubnikov–de Haas measurement. The second subband of the vertical confinement, which is located about 45 meV above E_F, as estimated from an excitation PL measurement at 0 T, is unoccupied. A semitransparent Ti/Au Schottky gate structure was fabricated on the surface, with a square mesh of a period of 250 nm and a width of 25 nm, by electron-beam lithography. The size of the active area of the mesh structure was $1 \times 1\ {\rm mm}^2$. A bias voltage was applied between the mesh gate structure and a AuGe/Ni/Au Ohmic back contact.

The PL measurement was performed by exciting the sample with a 488-nm line of a continuous wave Ar-ion laser at an incident power density of 1.6 ${\rm mW/cm}^2$ at 1.8 K in magnetic fields (B) between 0 and 4 T perpendicular to the QW layer. The PL from the sample was dispersed through a 75-cm monochromator, and detected by a liquid-nitrogen-cooled charge-coupled-device detector.

III. RESULTS AND DISCUSSION

A. Zero-magnetic-field case

The PL spectra of the sample at 0 T is shown in Fig. 2 for temperatures between 1.8 and 10 K, and a bias voltage between 0.2 and -0.5 V. The band gaps (E_g) and E_F are located at 1.5155 and 1.525 eV, respectively, at 0 T. The PL intensity decreases monotonously between E_g and E_F at $V_B = 0.2$ V. This is a typical PL spectrum for a high-quality

MDQW with free holes. The bandwidth E_F-E_g is evidence of a finite hole dispersion. This can be seen by the relation $E_F = E_g + (1 + m_e/m_h)\varepsilon_F$, where ε_F is the Fermi energy measured from the bottom of the conduction band in the one-particle picture, m_e and m_h are the effective masses of an electron and a hole, respectively. By taking $\varepsilon_F = 8.6$ meV and $m_e = 0.0667$, corresponding to $n_s = 2.4\times10^{11}$ cm^2, m_h is estimated to be 0.67 of the free-electron mass. The PL intensity at E_F is very weak compared to that at E_g. The strong peak at 1.514 eV is due to a bulk exciton in the GaAs buffer layer below the QW, and will not be discussed hereafter. The electrons below the Schottky gate were slightly depleted at $V_B = 0$ V. The PL spectrum at $V_B = 0.2$ V is found to be identical to the PL without a mesh gate structure. The zero point of the bias voltage is shifted, probably due to a photovoltaic effect in the MDQW structure under illumination, and possibly due to the strain induced in the QW layer by the surface metal structure.[30]

It was previously observed that a shoulder or a bump in the PL spectra appeared a few meV below the Fermi energy when a negative bias voltage between 0 and -0.5 V was applied in a sample with larger 2D density than that of the present sample.[26] The bump was largest and narrowest at $V_B = -0.5$ V, and decreased by changing V_B from -0.5 to -1.0 V. A similar behavior is observed in the present sample, with a smaller density of 2.4×10^{11} cm^{-2}. The enhancement of the PL (EPL) near the Fermi energy is largest at $V_B = -0.1$ V at the transition energy $E_{\mathrm{EPL}} = 1.5225$ eV, and disappears at $V_B = -0.5$ V, as shown in Fig. 2(a). The optimum V_B for the observation of the EPL is smaller in the sample with smaller density. This is in agreement with one of the requirements for the observation of the EPL in the PL, namely, that the electron density has to be interconnected, and the Fermi surface should be well defined.

The strong temperature dependence clearly shows evidence from the FES that the EPL is due to the many-body Coulomb interaction between the electrons and a hole, as shown in Fig. 2 at $V_B = -0.1$ V. With an increase in the temperature, the bump in the PL at 1.8 K becomes a shoulder at 4.2 K, which completely disappears at 10 K.

The line shape of the PL at 1.8 K at $V_B = -0.1$ V shows a peculiar feature for a Fermi-surface effect, being asymmetric with a very sharp rise in the higher-energy side and a gradual decay in the lower-energy side. This feature is similar to the FES observed in MDQWs (Ref. 27) and *n*-type quantum wires,[31,32] and to the calculated doublet structure in PL for a MDQW with a finite-mass hole.[15] A many-body enhancement was observed in the PL from MDQW structures;[19] however, the PL intensity at the position of the FES was less than 1% of that at E_g.

The EPL at 1.5225 eV is not due to the resonance coupling with the second vertical conduction subband state,[14,28,29] for the following reasons. First, the energy difference between E_F and the second vertical subband state is larger than 45 meV. Second, the asymmetric spectral line shape is insensitive to the 2D density, as seen by comparing Fig. 2 and the spectrum for a higher-density sample.[26] Third, the temperature dependence of the PL in Fig. 2 is different from the case of Chen *et al.*, who observed a buildup of n_z $=2$ exciton states in the PL associated with a quenching of the FES emission with an increase in the temperature.[27] In our case, however, a smooth quenching of the PL near E_F is observed without any signature of a PL from $n_z = 2$ subband. This behavior is qualitatively similar to the FES observed by Brown *et al.*, for samples with free holes.[19]

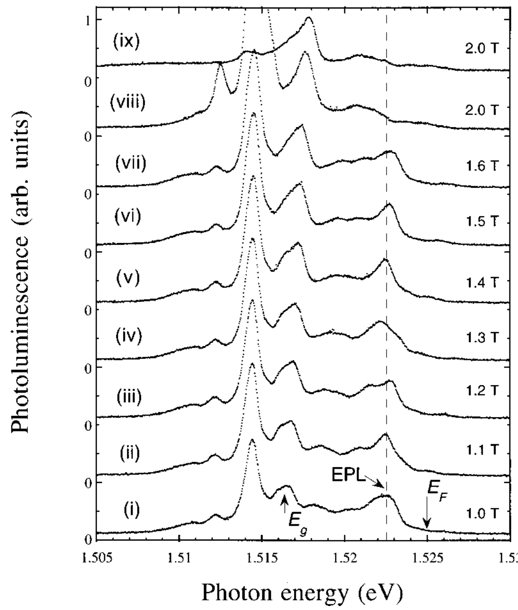

FIG. 3. Magnetic-field dependence of the PL spectra at 1.0 (*i*), 1.1 (*ii*), 1.2 (*iii*), 1.3 (*iv*), 1.4 (*v*), 1.5 (*vi*), and 1.6 T (*vii*) at $V_B = -0.1$ V, and 2.0 T at $V_B = 0.2$ V (*viii*) and -1.0 V (*ix*). Zero points of the *y* axis are shifted.

B. Magnetic-field dependence

It remains to be clarified whether the EPL at 1.5225 eV, which is 2.5 meV lower than E_F, is due to the Fermi-surface effect, even though both the temperature dependence and the asymmetric line shape of the structure in PL indicate that the structure is due to the FES. Magnetic-field measurements unambiguously show that the EPL at 1.5225 eV is due to the Fermi-surface effect, and that the difference in the transition energies is due to the difference in the hole energies.

The PL spectra at $V_B = -0.1$ V and at 1.8 K are shown in Fig. 3 for a magnetic field perpendicular to the sample varied from 1.0 T ($\nu \sim 10$) to 1.6 T ($\nu \sim 6$) and at 2.0 T. Structures due to the Landau levels (LL's) and EPL are observed between 1.516 and 1.525 eV. The fourth Landau level, which is observed at $V_B = 0.2$ V, is less clear at $V_B = -0.1$ V due to overlapping with the EPL with higher intensity.

One of the most significant features in Fig. 3 is the oscillation of the peak position of the EPL. The peak shifts to lower energy between 1.6 and 1.3 T, and to higher energy at 1.2 T, with decreasing *B* and increasing ν. Figure 4 shows the magnetic-field dependence of the peak energies of the EPL and the LL's at $V_B = -0.1$ V. The oscillation of the peak energy of the EPL shows a correlation with even filling factors. The peak shifts to lower energy correlate with the discontinuous jump of the Fermi energy to a lower LL energy when the higher LL is depleted with increasing mag-

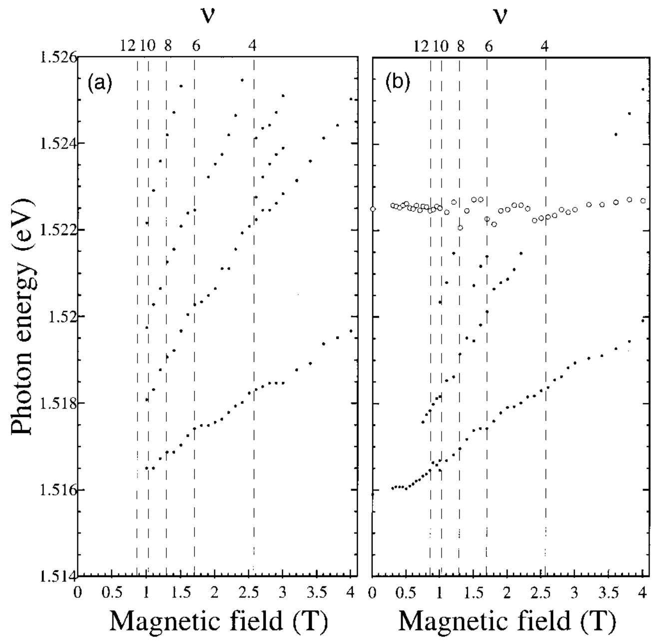

FIG. 4. PL peak positions as functions of the magnetic field at (a) $V_B = 0.2$ V and (b) -0.1 V for Landau levels (closed circles) and EPL (open circles).

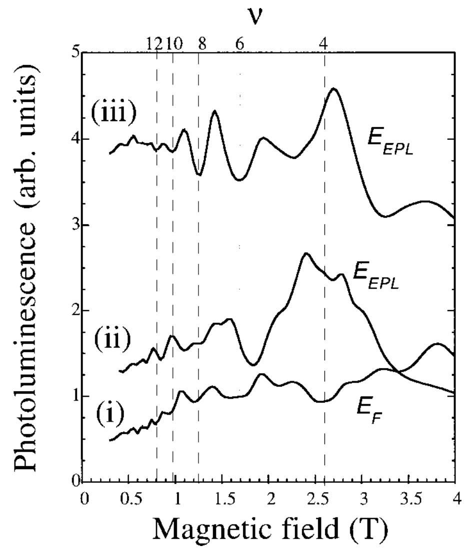

FIG. 5. PL intensities as functions of the magnetic field at $V_B = -0.1$ V and at $E_F = 1.5250$ eV (*i*), at $V_B = 0.2$ V and at $E_{\mathrm{EPL}} = 1.5225$ eV (*ii*), and at $V_B = -0.1$ V and at $E_{\mathrm{EPL}} = 1.5225$ eV (*iii*). The intensity minima correlate with even ν (shown by the vertical dashed lines) for curves (*i*) and (*iii*), while they do not for curve (ii).

netic field. This oscillation in the energy shows that the EPL originates from the Fermi surface, in agreement with theories.[15,33] A discrepancy is seen for the cusp near $\nu = 4$ in the peak position of EPL. This will be discussed below.

The LL's also show steplike oscillations in energy with magnetic fields. The peak energy maxima at $V_B = 0.2$ V correlate with even filling factors, showing that the hole is free in our sample. It was shown theoretically that the peak energy maxima correlate with even filling factors for a free-hole case, while the peak energy minima correlate with even filling factors for an infinite-mass hole case.[14,34–37] The oscillation at $V_B = -0.1$ V is distorted from that at $V_B = 0.2$ V, which is considered to be due to the change in the self-energies of a free-hole and electrons by the change in the static potential by V_B.

Figure 5 shows the PL intensity as a function of magnetic field at $E_F = 1.5250$ eV at $V_B = -0.1$ V, and at $E_{\mathrm{EPL}} = 1.5225$ eV at $V_B = 0.2$ and -0.1 V. The PL intensity at E_F shows intensity minima at even filling factors ν. This oscillation in the PL intensity as a function of magnetic field is called an optical Shubnikov–de Haas oscillation, which was shown to be identical with the oscillation measured by magnetotransport for a wide range of magnetic fields.[38,39]

A remarkable feature in Fig. 5 is that the oscillation periods and the positions of the minima are sensitive to V_B for the PL intensity at E_{EPL}. At $V_B = 0.2$ V, the oscillation correlates with the crossings of the LL's at the observed transition energy of E_{EPL} in sweeping the magnetic field,[33] showing that a 2D electron system is formed at $V_B = 0.2$ V. The oscillation in this case correlates with $D(E_{\mathrm{EPL}})$, where $D(E)$ is the density of states of electrons at E. By contrast, the intensity minima correlate with the even filling factors at $V_B = -0.1$ V at E_{EPL}. This oscillation is understood as an optical Shubnikov–de Haas oscillation, and correlates with $D(E_F)$. This is direct evidence that electrons at the Fermi surface are involved in the initial state of the optical recombination[33,40] in the EPL at $V_B = -0.1$ V. The correlation of the intensity with the even filling factors is clear for ν between 6 and 12, but the position of the minima at 2.3 T is lower than the magnetic field corresponding to $\nu = 4$, as in the case of the oscillation in the peak position. A similar discrepancy was observed between a Hall measurement and an optical Shubnikov–de Haas oscillation for high magnetic fields.[39] The reason for the discrepancy is not clear, but is probably due to the complex interaction between the EPL and the LL, and to the lifting of the spin degeneracy.

The hole state plays an important role in the PL spectra in the presence of a periodic potential. The self-consistently obtained potential shows nearly flat regions at the center of the quantum dots, as shown in Fig. 1. The hole associated with LL's in Fig. 4(b) is considered to be in this flat region. The hole associated with the EPL is relaxed by $E_F - E_{\mathrm{EPL}} = 2.5$ meV, relative to the hole associated with LL's. This relaxation in the hole energy is partly explained by the attractive Coulomb energy between the hole and the electrons; however, we cannot totally exclude the possibility of the relaxation of the hole position from the maximum point of the electron density where the Hartree potential of the hole is highest. Paasen *et al.* found that the holes optically generated at the center of the Hall bar are trapped at the edge where the electron density vanishes by a spatially resolved PL measurement and a theoretical analysis.[41] Similar weak trapping of a hole at the edge of the electron density may explain the relaxation of the hole in our case.

The periodic potential at $V_B = -0.1$ V enhances the FES for the following reasons. First, the confinement enhances the many-body Coulomb interaction between the electrons and the hole as in the case of quantum wires.[5] Second, the periodic potential induces an admixture of the wave functions for electrons and holes with components with different wave numbers, which relaxes the selection rule for the optical recombination process. Third, the periodic potential induces a geometrical restriction of the hole. This weakens the recoil and the temperature distribution of the hole, which were shown to obscure the observation of the FES for the finite-mass hole.[13] The argument by Brown *et al.* for the FES observation with a finite-mass hole[19] should also be applicable here; the holes at $k=k_F$ have too small an excess energy to thermalize by LO-photon scattering; thus the thermalization time for a hole is long enough to recombine with electrons at E_F. Fourth, the screening of the attractive Coulomb interaction becomes less effective due to the inhomogeneous electron-density distribution and smaller electron density of states near E_F in the presence of the periodic potential, as compared to 2D electron systems.[42] It should be stressed here that the geometrical restriction of the hole by the periodic potential with a period of 250 nm is orders of magnitude weaker than the localization of a hole by alloy fluctuations.[6]

Spatially indirect gap formation was considered by Weiner *et al.*[43] to explain the PL spectra of a periodic array of *n*-type modulation-doped quantum wire structure. They observed weaker PL at the band-gap energy than at E_F, and assigned it to the confinement of electrons and holes to laterally separate regions of the sample, thus forming a spatial type-II indirect gap. The difference in the PL intensity at the band gap and at E_F was explained to be due to the difference in the overlap of the wave functions of electrons and holes. In our case, the peak at the PL spectra of the band gap or the lowest LL is ascribed to a direct optical transition between the electrons and holes, because the observed peak position is insensitive to V_B. The spatially indirect gap is formed in our sample, however, which is observed as a tail in the lower-energy side of the PL peak. The peak in the PL of the lowest LL at 2.0 T at $V_B=-1.0$ V is broader on the lower-energy side than that at $V_B=0.2$ V, as shown in Fig. 3. This broad spectrum of the lower-energy side is a signature of the spatially indirect gap formation under the negative bias voltage in our sample.

IV. CONCLUSION

We have demonstrated that the many-body interaction between electrons and a hole is modified by an externally applied periodic potential, which leads to the observation of the FES for a hole with a finite mass. The degree of divergence of the FES is investigated experimentally in a system with dimensionality swept continuously from two to zero dimensions. An enhanced PL near the Fermi energy is observed when a weak lateral periodic potential is applied. The enhanced PL near the Fermi energy is shown to be due to the recombination of the electrons at the Fermi level and a hole, by observation of the filling-factor-dependent energy shift and the PL intensity oscillation. Currently there is no theoretical account of the FES in two dimensions with a lateral periodic potential in a finite-mass hole case, and we hope that our results will stimulate theorists to work on this subject.

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[22] Schrödinger and Poisson's coupled equation was solved numerically in real space with the higher-order finite-difference method on a 3D mesh of $50\times50\times8$ and $50\times50\times30$ per unit cell for Schrödinger and Poisson's equations, respectively. Four special points in **k** space $(\frac{1}{8},\frac{1}{8})$, $(\frac{1}{8},\frac{3}{8})$, $(\frac{3}{8},\frac{1}{8})$, and $(\frac{3}{8},\frac{3}{8})$ in units of $2\pi/L$, where $L=250$ nm, were used to calculate the electron density. The bias voltage in the calculation was taken to be $V_{\rm calc}=V_B-\Delta V$ with $\Delta V=0.2$ V, phenomenologically taking into account the experimentally observed shift of the zero point of the bias

voltage. The sample geometry and the surface gate pattern were realistically taken into account. The Fermi energy ε_F is fixed to be 8.6 meV. Parameters used are $m_e = 0.0665$, and $\varepsilon = 12.53$.
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