

## One-Dimensional Band-Edge Absorption in a Doped Quantum Wire

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Low-temperature photoluminescence-excitation spectra are studied in an  $n$ -type modulation-doped  $T$ -shaped single quantum wire with a gate to tune electron densities. With a nondegenerate one-dimensional (1D) electron gas, the band-edge absorption exhibits a sharp peak structure induced by the 1D density of states. When the dense 1D electron gas is degenerate at a low temperature, we observe a Fermi-edge absorption onset without many-body modifications.

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Optical spectroscopy of the one-dimensional (1D) electron gas formed in  $n$ -type doped semiconductor quantum wires has been an exciting challenge in the past two decades [1,2]. Theories have pointed out some interesting phenomena inherent in the 1D electron gas, such as the appearance or disappearance of band-edge singularity induced by inverse square root 1D density of states (DOS) divergence, and also strong 1D many-body interaction effects [3–5]. Experimental investigations of Fermi-edge singularity (FES) effects [6–8] and 1D band-gap renormalization (BGR) effects [9–11] have been reported. However, no experiment has shown band-edge singularity induced by 1D-DOS divergence. Thus the question of whether the 1D band-edge singularity appears in optical spectra still remains unanswered.

To clarify such fundamental properties by optical spectroscopy, we need to measure both emission and absorption spectra at various temperatures and electron densities. This is because emission and absorption in doped systems selectively occur for occupied and unoccupied conduction-band states, respectively. However, it is difficult to measure absorption spectra of a quantum wire because of its small volume. Thus, there have been no systematic experimental studies of temperature-dependent absorption spectra of 1D electron systems at various densities. To investigate this unexplored subject, we developed a photoluminescence-excitation (PLE) measurement system that provides complete and clear line shapes of absorption spectra even for a single quantum wire.

This Letter reports the first observation of the sharp band-edge absorption peak structure induced by 1D DOS probed by low-temperature PLE measurements on an  $n$ -type doped single quantum wire with a gate to tune electron densities. The sharp band-edge absorption peaks appear in the PLE spectra when the 1D electron gas is not degenerate at high temperature, or at low electron density. In the presence of a dense electron gas at low temperature (5 K), we observe absorption onset at the Fermi edge of the degenerate 1D electron gas. Sharp excitonic peaks appear

in the spectra at very low densities of less than  $1 \times 10^5 \text{ cm}^{-1}$ , while no strong many-body effects appear in spectra at high densities.

The structure of the sample of  $n$ -type doped GaAs quantum wire is illustrated in Fig. 1. A single  $T$ -shaped quantum wire was formed in the cross section of a 14 nm-thick  $\text{Al}_{0.07}\text{Ga}_{0.93}\text{As}/\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$  quantum well (stem well) and 6 nm-thick GaAs/ $\text{Al}_{0.45}\text{Ga}_{0.55}\text{As}$  quantum well (arm well). Delta doping of Si at a distance of 100 nm from the stem well induced 2D electron gas with a density of  $1 \times 10^{11} \text{ cm}^{-2}$  in the stem well. By applying dc gate voltage ( $V_g$ ) to a gate layer on the top of the arm well relative to the 2D electron gas in the stem well, we tuned the electron densities ( $n_e$ ) in the 1D wire. The 1D electron density  $n_e$  for each  $V_g$  was determined via our model fitting of optical spectra shown later in this Letter. A more detailed description of the sample preparation is given elsewhere [9].

In our micro-PL and PLE measurements, excitation light from a continuous-wave titanium-sapphire laser with polarization parallel to the [001] direction (perpendicular to the wire axis) was focused into a  $1\text{-}\mu\text{m}$  spot by a 0.5 numerical aperture objective lens on the top (110) surface of the sample. The photoluminescence (PL) emission in the [001] direction was detected via a 0.5 numerical aperture

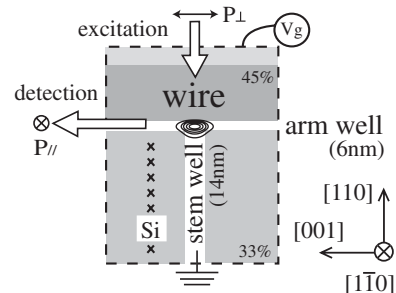


FIG. 1. Schematic view of  $n$ -type doped  $T$ -shaped quantum wire sample.

objective lens and a polarizer set in the  $[1\bar{1}0]$  polarization direction to reduce intense laser scattering.

Normalized PLE spectra at various temperatures in the presence of a dense 1D electron gas are shown by solid curves in Fig. 2(a). The gate voltage was fixed to 0.7 V, which corresponds to an electron density of about  $6 \times 10^5 \text{ cm}^{-1}$  in the quantum wire. At low temperature (5 K), we observed a single absorption onset at 1.575 eV with a long low-energy tail. We assigned this onset (FE) as the Fermi edge, which separates the occupied and unoccupied states in the conduction band. A large absorption by the arm well showed its low-energy tail at around 1.578 eV. As the temperature was increased, the FE onset became smeared and the low-energy tail increased in intensity. At 30 K, another absorption onset was formed at 1.565 eV. At higher temperatures, this onset increased in intensity and formed a sharp peak structure at 50 K. We assigned this structure to the 1D band-edge (BE) absorption peak induced by the inverse square root 1D DOS.

Dotted curves in Fig. 2(a) indicate PL spectra. We set photon energy of the laser between 1.57 and 1.575 eV so that excited carriers are formed only in the wire. At 5 K, we observed an asymmetrical PL peak at 1.565 eV. We assigned this PL peak to the band-edge emission. We observed a large energy gap of 10 meV between this peak and PLE onset at FE. As the temperature was increased, the PL peak shifted to lower energy without any remarkable change in its line shape. This redshift with increasing temperature also appears in bulk GaAs and is known as the Varshni shift [12]. At 50 K, we found that the PL and PLE peaks appeared at exactly the same energy of band edge, denoted by BE.

We calculated optical spectra with a free-particle model. This model includes the 1D joint DOS with the energy

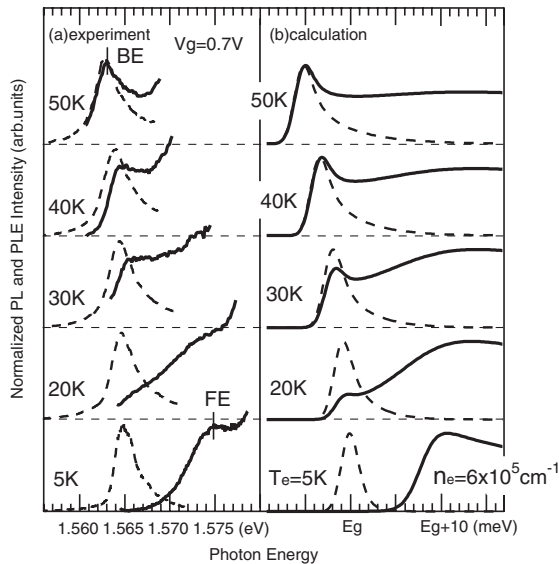


FIG. 2. Experimental (a) and calculated (b) spectra of PL (dotted line) and PLE (solid line) for 1D wire at various temperatures.

dependence of  $1/\sqrt{E}$ , Fermi distribution functions for electrons and holes, and a broadening function of Gaussian line shape, but does not take into account many-body Coulomb interactions. Figure 2(b) shows normalized emission (dotted curves) and absorption (solid curves) spectra calculated for various temperatures for electrons and holes,  $T_e (= T_h)$ , with the following parameters: broadening ( $\Gamma$ ) of 1.0 meV, the effective masses for electrons and holes of  $0.067m_0$  and  $0.105m_0$ , respectively [13], where  $m_0$  is electron mass in vacuum, and electron density ( $n_e$ ) of  $6 \times 10^5 \text{ cm}^{-1}$ . The band-gap energies with shifts at various temperatures,  $E_g(T)$ , were estimated from those for bulk GaAs [12,14]. The absorption spectrum at 5 K, shown as the bottom solid line in Fig. 2(b), exhibits an onset at the energy of  $E_g + 10 \text{ meV}$ , which corresponds to the Fermi edge of the degenerate 1D electron gas. The emission spectrum exhibits a peak at the energy of  $E_g$ , which corresponds to the band edge. At higher temperature, the Fermi-edge absorption onset disappears while another low-energy absorption onset of the band edge appears at the same energy as the emission peak ( $E_g$ ). At 40 or 50 K, the absorption spectra exhibit a sharp asymmetrical peak at the band edge of the nondegenerate 1D electron gas. This peak originates from the 1D-DOS divergence with broadening of 1.0 meV. We found that the experimental results agree well with these free-particle-model calculations. This supports our assignment that the sharp PLE peak at 50 K originates from the 1D band-edge singularity induced by 1D DOS.

We also studied the electron density dependence of PLE spectra at low temperature (5 K) using the same sample of doped quantum wire. The solid curves in Fig. 3(a) indicate the normalized PLE spectra at various  $V_g$ . The top line at  $V_g = 0.7 \text{ V}$  shows the single Fermi-edge absorption onset (FE), which is the same as the bottom line in Fig. 2(a). As the density was decreased, the FE onset shifted to lower energy. The photon energies of the FE onset are plotted by filled inverted triangles in Fig. 4(a). At  $V_g = 0.4 \text{ V}$ , band-edge absorption onset appeared at the low-energy side (1.566 eV). At  $V_g = 0.35 \text{ V}$ , this onset increased in intensity, and a characteristic double peak structure was formed.

As the density was further decreased, the Fermi-edge peak merged into the tail of the low-energy peak and formed a single asymmetrical absorption peak structure at  $V_g = 0.2 \text{ V}$ . This asymmetrical peak became a symmetrical peak ( $X^-$ ) at  $V_g = 0.15 \text{ V}$ . This  $X^-$  peak lost its intensity as the density approached zero. Instead, another peak appeared at higher energy (1.569 eV), which became a sharp symmetrical peak ( $X$ ) at 1.5685 eV at  $V_g = 0 \text{ V}$ . The full width at half maximum (FWHM) of the  $X$  peak was 0.9 meV. The splitting of the  $X$  peak is probably due to monolayer thickness fluctuations in the stem well. In Fig. 4(a), we plot peak energies of  $X^-$  (filled triangles) and  $X$  (filled circles).

Dotted curves in Fig. 3(a) indicate PL spectra, which are almost the same as those we reported in detail in a previous

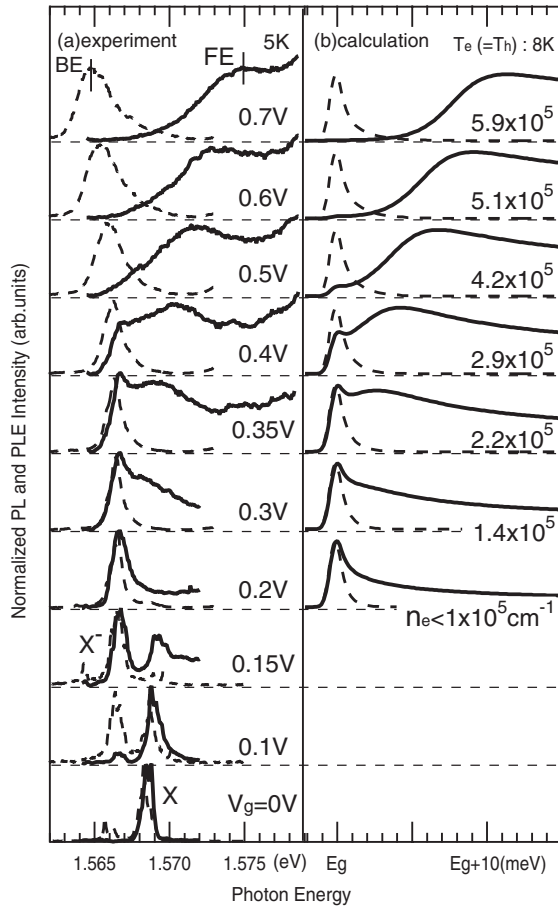


FIG. 3. Normalized experimental (a) and theoretical (b) spectra of PL (dotted lines) and PLE (solid lines) for 1D quantum wire at various electron densities.  $X$  was assigned to excitons and  $X^-$  to trions.

Letter [9]. We set the photon energy of the laser between 1.568 and 1.575 eV to form carriers in the wire. At  $V_g$  from 0.7 to 0.2 V, we observed a broad PL peak that shifted to higher energy with decreasing electron density, which represents the BGR shift. The energies of the PL peak at BE are plotted by filled squares in Fig. 4(a). At 0–0.15 V, PL spectra also showed sharp peaks of  $X^-$  and  $X$ .

In 2D systems, very similar crossover from band-to-band transition to  $X^-$  and  $X$  with decreasing electron density has been well studied experimentally [15,16] and theoretically [17,18]. Thus, we analogously assigned [9] the present  $X^-$  and  $X$  peaks to trions (a bound state of two electrons and a hole) and neutral excitons (a bound state of an electron and a hole), respectively. Furthermore, we confirmed the assignment of  $X$  by additionally measuring PLE features near and above the  $X$  peak at 0 V that were the same as those of excitons and continuum states identified in nondoped quantum wires [19,20].

Figure 3(b) shows calculated normalized emission (dotted curves) and absorption (solid curves) spectra with the free-particle model assuming various electron densities ( $n_e$ ). We assumed a slightly high carrier temperature of  $T_e (= T_h) = 8$  K and a broadening of  $\Gamma = 0.4$  meV to

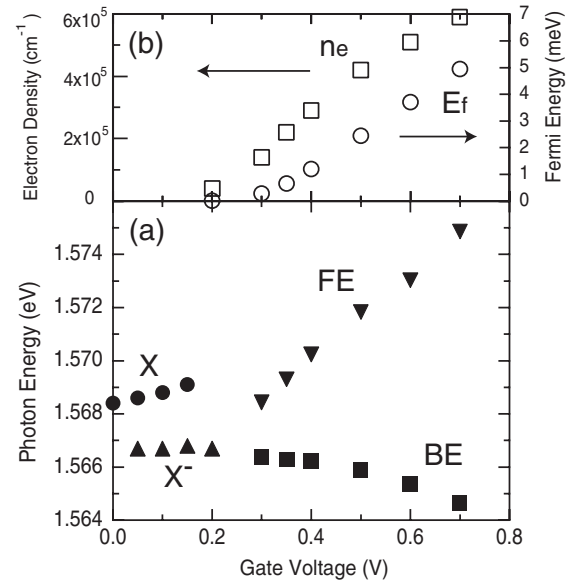


FIG. 4. (a) Peak positions and (b) estimated electron density and corresponding Fermi energy plotted as a function of gate voltage.

obtain the best fit to the PLE spectra. The assumed electron density ( $n_e$ ) in the calculations and corresponding Fermi energy,  $E_f = \frac{\pi^2 \hbar^2 n_e^2}{8m_e}$ , are plotted as a function of  $V_g$  in Fig. 4(b) as open squares and open circles, respectively.

The calculated absorption spectra for  $n_e > 1 \times 10^5 \text{ cm}^{-1}$  show good agreement with the experimental PLE spectra at  $V_g > 0.2$  V. In particular, the characteristic double peak structures of the band-edge and Fermi-edge absorptions at  $V_g = 0.35\text{--}0.4$  V are almost completely reproduced by the calculations. The sharp band-edge absorption originates from 1D DOS, and it appears in the PLE spectra when the 1D electron gas is not degenerate at low density. We have already demonstrated, in Fig. 2(a), the appearance of 1D band-edge absorption peak in the PLE spectra at high temperature (50 K). These results prove that the singularity of 1D DOS appears in the PLE spectra in the presence of nondegenerate electron gas at low density, or at high temperature.

The characteristic double peak structures in the PLE spectra at  $V_g = 0.35\text{--}0.4$  V is unique to 1D systems, which have never been observed for 2D systems [15,16]. In previous studies of FES including microscopic theories [17,18], the effect of Coulomb interaction, or Coulomb enhancement, appeared at the Fermi edge while the band edge reflected the shape of single particle DOS. Following these studies, we ascribed the origin of the sharp band-edge peak in the double peak at  $V_g = 0.35\text{--}0.4$  V to the 1D-DOS singularity instead of Coulomb interaction. As for the single asymmetric PLE peak in the crossover region of  $V_g = 0.2\text{--}0.3$  V, it is difficult to distinguish the two contributions of 1D-DOS singularity and Coulomb interaction. The sharp symmetrical absorption peaks at  $V_g = 0\text{--}0.15$  V, where very low densities below  $1 \times 10^5 \text{ cm}^{-1}$

are estimated from extrapolation in Fig. 4(b), are caused by trions and excitons, which originate from the Coulomb interaction.

We remark here that nondoped quantum wires [19–22] show absorption spectra without 1D band-edge singularity due to strong 1D Coulomb interaction. Thus, doping was essential in the present first observation of 1D band-edge singularity. Moreover, PLE measurements were also indispensable, because PL spectra at low temperature are dominated by the lowest energy transitions and by themselves do not represent 1D DOS [9].

Let us now discuss the 1D many-body effects in PL and PLE spectra at high electron densities. As we have mentioned, previous reports predicted theoretically or investigated experimentally several interesting many-body effects, such as the FES and BGR effects. The theories of FES [3–5] predicted a sharp FES peak, or a power-law singularity, at a low-energy (high-energy) shoulder in absorption (emission) spectra. This effect results from multiple scattering processes involving electrons near the Fermi level. The theories of BGR [1,23,24] predicted a redshift of the band-edge emission peak with increasing electron density, which results from the electronic correlation effects. In our experiments, as shown in Fig. 3(a) or Fig. 4(a), the BGR effect was observed as redshifts of the band-edge PL peak (BE) with increasing density.

However, the FES effect in the PLE spectra was negligible. No sharp peak nor power-law singularity was observed at the Fermi edge of the PLE spectra. Note that the wire size was small (14 nm  $\times$  6 nm), the inhomogeneous broadening was small (0.9 meV), and the temperature was low (5 K), which are favorable conditions for studying 1D FES effects. Even under these conditions, the FES effect was found to be weak.

Similar experimental results [6] were reported by Oberli *et al.* They observed weak FES effects in PLE spectra for 1D electron systems formed in *V*-groove quantum wires. They pointed out that the existence of a strong FES effect is related to the hole localization effect and a resonance with a partially empty higher subband. In other words, the strong FES effect was not attributed to the character of the 1D electron gas formed in a high-quality 1D limit quantum wire. In fact, the quantum wires used in the earlier experiments showing strong FES effects [7,8] had large sizes and large wire width fluctuations, and the electrons and holes were not in the same positions in the structure.

Theories have shown that optical spectra exhibit a strong peak at the Fermi edge with extrinsic origins, such as impurities [3], Fano resonance [25], empty higher subband near the Fermi edge, and a type II structure [4]. These calculations indeed explain the earlier experimental results [6–8].

As for intrinsic FES effects in clean 1D systems, theoretical calculations have been used to investigate the values and characteristics of the power-law critical exponents as a function of electronic correlation and finite effective mass

of the valence hole [5,26]. However, the strength and robustness of intrinsic FES under finite temperature and damping due to scatterings with phonons and carriers remain to be investigated. We hope that our experimental results will inspire further theoretical investigations of the optical responses of 1D electron systems at various densities including the effect of finite temperature and finite damping.

In conclusion, we performed low-temperature PLE measurements on an *n*-type doped quantum wire and achieved the first observation of sharp band-edge absorption peaks induced by 1D DOS. In the presence of a dense electron gas at low temperature (5 K), the PLE spectra showed a Fermi-edge absorption onset without FES enhancements.

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