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Evidence of a Transition from Nonlinear to Linear Screening of a Two-Dimensional Electron System Detected by Photoluminescence Spectroscopy

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We clearly identify single-electron-localization (SEL), nonlinear screening (NLS), and linear screening (LS) regimes of gate induced electrons in a GaAs quantum well from photoluminescence spectra and intergate capacitance. Neutral and charged excitons observed in the SEL regime rapidly lose their oscillator strength when electron puddles are formed, which mark the onset of NLS. A further increase in the density of the electrons induces the transition from the NLS to LS, where the emission of a charged exciton changes to the recombination of two-dimensional electron gas and a hole.

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When a two-dimensional electron system (2DES) is formed at a semiconductor interface with a disorder potential, the screening of the potential fluctuation by the accumulated electrons plays an essential role in keeping the electron density homogeneous. At a high electron density the screening greatly reduces the random potential by a few hundred nanometers, which is much larger than that in a modulation-doped GaAs QW. It is very important to study the properties of the dilute 2DES in an undoped QW with such a long-range random fluctuation.

In this Letter, on the basis of the results of low-temperature (100 mK) intergate capacitance and photoluminescence (PL) measurements, we study the transition of electron states in an undoped GaAs QW with changing electron density. From the intergate capacitance, which directly reflects the electron screening length $d_w$ [15], we deduce two characteristic voltages: one at which electrons begin to accumulate in the QW, and the other at which $d_w$ has the minimum. These characteristic voltages consistently match the change in the bias voltage dependence of the PL intensity and the linewidth of charged excitons, which clearly reveal three different electron states: a single-electron-localization (SEL) regime, an NLS regime, and an LS regime.

The sample was an $0.08\times1\,\text{mm}^2$ 20-nm GaAs QW sandwiched by undoped Al$_{0.2}$Ga$_{0.8}$As barriers grown by molecular beam epitaxy, as shown in Fig. 1(b). The background impurity was $p$-type and below $1\times10^{14}$ cm$^{-3}$. A semitransparent Ti/Au film deposited on the surface and a heavily $n$-doped GaAs wafer worked as front and back gates, respectively, which were separated by $d_1 = 250$ nm and $d_2 = 620$ nm from the QW, respectively. AuGeNi was
theory predicts that $d_w$ were supplied from this contact when the gate bias $V_{fb}$ applied. The laser light was introduced to the sample (b) and detected with a 1-m monochromat-

cial fluctuation without screening by electrons as expected fluctuation without screening by electrons as $\varepsilon$.

The electron density $n_e$ is given as $n_e = V_{fb} - V_0$. The experimental data for $d_w$ in Fig. 1(c) are plotted so that the actual density is $n_e$ in the bias voltage $V_{fb}$.

The wave packets are filled by degenerate electrons. The electron density $n_e$ can be estimated as $n_e = 1.0 \times 10^{11} \text{cm}^{-2}$, which corresponds to the minimum value of $d_w$.

The capacitance bridge is measured with a capacitance-bridge circuit. The solid curve is the relation between the screening length at 0.12–1 kHz and at 30-mV excitation. The offset constant $d_w$ could not be accurately determined because of a stray capacitance of $\sim 15 \text{pF}$. The experimental data for $d_w$ in Fig. 1(c) are plotted so that they coincide with the theoretical value of $d_w$.

A laser was introduced to the sample (b) with the same fiber and detected with a 1-m monochromat-
alloyed to provide an Ohmic contact to the QW. The Ohmic contact was kept at $V_w = -0.3 \text{V}$, and electrons were supplied from this contact when the gate bias $V_{fb}$ was applied. The laser light was introduced to the sample surface through an optical fiber with an excitation power density $<1 \text{mW/cm}^2$ at 800 nm. The PL was collected with the same fiber and detected with a 1-m monochromat-

density in the QW, $\nu$ is the chemical potential and the electron density in the QW, $S \sim 1 \text{mm}^2$ is the sample area, and $C_{fb} = \varepsilon S/(d_1 + d_2)$ is the geometric capacitance between the gates at $n_e = 0$. The NLS theory predicts that $d_w(n_e)$ is represented by the sum of the contribution of the single-particle density of states $a_B/4 (a_B$: the effective Bohr radius), exchange correction $\Delta d_{ax}(n_e)$, correlation effect $\Delta d_{cor}(n_e)$, and disorder potential $\Delta d_{dis}(n_e)$ [6].

The $V_{fb}$ dependence of intergate capacitance for $B = 0 \text{T}$ and 1.5 T is plotted in Fig. 1(a). The capacitance, which is almost constant at low $V_{fb}$, suddenly drops around $V_{fb} = V_0^C = 0.3 \text{V}$, where the electrons start to accumulate. An asymmetric minimum appears at $V_{fb} = V_0^C = 0.72 \text{V}$, which corresponds to the minimum value of $d_w$ shown in Fig. 1(c). The solid curve is the theoretical fit to the NLS theory; here, the $n_e = 2.0 \times 10^{12} \text{cm}^{-2}$ is only the fitting parameter used to adjust the position of the minimum. The offset constant $d_w$ could not be accurately determined because of a stray capacitance of $\sim 15 \text{pF}$. The experimental data for $d_w$ in Fig. 1(c) are plotted so that they coincide with the theoretical value of $d_w$.

FIG. 1 (color online). (a) The capacitance spectra between the gates at 0 T (black circles) and 1.5 T (blue or dark gray squares). (b) The layer structure of the sample and a diagram of the intercapacitance measurement using a capacitance bridge (C.B.). (c) The screening length $d_w^{\text{ex}}$, plotted as a function of the estimated electron density (open circles). The solid curve is the fit to the nonlinear screening theory $d_w^{\text{exp}} = a_B/4 + \Delta d_{dis} + \Delta d_{ex} + \Delta d_{cor}$. (See text for details.)
To investigate the above transition, we performed PL measurements. Figure 2(a) shows typical PL spectra measured in the three regimes described above and Fig. 2(b) shows color plots of the spectral evolution. In regime I, PL emissions for \( X^0 \) and \( X^- \) are observed. \( X^- \) is created by combining a photoexcited electron-hole pair and a single localized electron at the bottom of the disorder potential. In the middle of regime II at around \( V_{fb} = 0.5 \) V, the \( X^0 \) signal disappears and a single broad peak remains. In this regime, electron puddles are formed, and the accumulated electrons in the puddles weaken the binding energy between the electron and hole of a neutral and charged exciton. The long tail observed in Fig. 2(a) (indicated by arrows) is presumably due to the localization effect of the electrons and holes [16]. On the other hand, in regime III, where the electron density is higher than \( 3 \times 10^{10} \) cm\(^{-2}\), the line shape becomes even wider and more asymmetric. This is attributed to the formation of a 2DES extending over the entire region where the 2DES-hole recombination emission is dominant. In this regime, the localization-induced tail disappears, which suggests that the potential fluctuation is reduced by screening. As we have seen in Fig. 2(b), the \( X^- \) peak transits smoothly to the 2DES-hole peak as \( n_e \) is increased, and we hereafter tentatively name this series of peaks the \( Y \) band.

The peak intensity and the linewidth obtained by fitting this series of peaks the \( Y \) band. The unchanged linewidth indicates that the \( X^- \) in this regime does not interact with the third electron.

There is a sharp transition at \( V_{fb}^{PL} \approx 0.36 \) V where both the \( X^- \) and \( X^0 \) intensities suddenly decrease. As mentioned before, this is caused by the screening of the Coulomb interaction between the electron and hole by degenerate-electron puddles. The first PL transition at \( V_{fb}^{PL} \) is consistently located between \( V_C^e \) and \( V_C^p \), where degenerate electrons begin to accumulate, as we have argued previously. We can also see the increase in the linewidth with \( n_e \). With the free \( X^- \), which is moving in the QW, the increase in the linewidth due to the \( (X^-, e) \) scattering is discussed in [17].

We should note, however, that \( X^- \) observed in regime II is probably the localized one since the line shape of \( X^- \) in regime II is rather symmetric, while the free \( X^- \) has an asymmetric line shape due to the energy distribution of the recoil electron after the \( X^- \) recombination [18].

FIG. 2 (color). Typical PL spectra (a) in plots for different biases \( (V_{fb}) \) and (b) in a color plot at 0 T. The solid lines represent critical voltages \( V_{fb}^C \) and \( V_{fb}^{PL} \) deduced from the capacitance measurement in Fig. 1. The \( V_{fb} \)-independent backgrounds are subtracted in the color plot.

FIG. 3 (color). The PL peak intensity of the \( Y \) band (i.e., \( X^- \) or 2DES-hole recombination peak) (red circles) and neutral exciton (\( X^0 \)) (blue circles) depending on \( V_{fb} \). Open circles represent the linewidth of the \( Y \) band. The electron states of each regime (I, II, III), determined by the capacitance measurement, are shown schematically.
without forming puddles, because the short range potential fluctuation cannot contain multiple electrons. In our undoped GaAs sample, \( s \approx 250 \text{ nm} \) (corresponding potential valley density \( \sim 1.6 \times 10^{10} \text{ cm}^{-2} \)) is sufficiently large for the formation of electron puddles [20]. In addition, it is known that metal gate deposition causes interface roughness [21], which enhances the random potential amplitude. Electrical transport measurements in undoped samples have revealed only one kind of transition, i.e., the percolation transition [3], because it cannot cover the nonconducting regime.

In summary, we have clearly identified for the first time two transitions between three different electron regimes, i.e., the SEL regime, NLS regime, and LS regime by measuring both PL and capacitance. The result will provide an important contribution to our understanding of the microscopic mechanisms of the metal-insulator transition in the presence of the electronic screening effect in two dimensions.

We have found further clear evidence for the transition from the NLS regime to the LS regime. The peak energies of the \( Y \) band at both 100 mK and 4 K, which are plotted in the upper panel of Fig. 4, deviate only above \( V_0^c \). We believe that the energy deviation arises from the thermal excitation of the weakly localized holes at a weakly fluctuating potential. As shown in the lower panel of Fig. 4, the energy difference of the peaks between 100 mK and 4 K is 0.4 meV, which is comparable to the thermal energy of 4 K. In regime III, the original potential fluctuation of about 30 meV in regime I is screened and significantly reduced by the factor \( 1/2q_0s \sim 1/100 \) for \( s = 250 \text{ nm} \), which results in a potential fluctuation amplitude below 0.3 meV.

To the best of our knowledge, most previous optical experiments have found only one kind of transition near the MIT [10,11,19]. As we have pointed out previously, this may be related to differences in the sample structure. For the electron puddle state to appear, the potential amplitude as well as the length scale of the potential fluctuation should be large. With a modulation-doped sample, the localized-electron state transits directly to the dilute 2DES