Optical Spectroscopy of a Two-Dimensional Electron Gas near the Metal-Insulator Transition

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We report on optical measurements of a two-dimensional electron gas near the metal-insulator transition. We observe the appearance of excitons and negatively charged excitons, X^-, at the onset of the transition. The fact that these excitons appear at a relatively large average electron density shows that transition is induced by localization of single electrons in the electrostatic potential fluctuations of the remote ionized donors.

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Modulation-doped semiconductor quantum well is a heterostructure in which a layer of donors is introduced within the barrier region. The spatial separation between these donors and the two-dimensional electron gas (2DEG), formed in the well, strongly inhibits electron scattering. The flexibility in the choice of the structure parameters (spacer width, doping concentration, etc.) allows one to obtain a 2DEG with widely varying properties. Applying a gate voltage enables one to alter the 2DEG state from a high density mobile metallic state to a low density insulating one. While the metallic state of the 2DEG was intensively studied in recent years, there are only a few works which investigate the transition to an insulating state [1,2]. The change of the optical properties as the electron density is varied has also been studied [3,4]. It was shown that at large electron density the excitons are screened. When the electrons are removed from the well, an exciton line is gradually formed in the optical spectra. However, no detailed study of the optical properties was performed near the metal-insulator (M-I) transition.

The purpose of this work was to conduct a careful study of the optical properties near the M-I transition and to correlate them with transport measurements. We show that when the 2DEG density is decreased, an exciton line appears at a relatively high electron density, which can exceed 10^{11} cm^{-2} in thin spacer samples. We find that there is a strong correlation between the abrupt growth of the exciton and the onset of the M-I transition. As the exciton peak grows, no reminiscence of a 2DEG Fermi energy is observed in the optical spectra. Rather, a *new resonance* develops 1.2 meV below the exciton. We associate this resonance with a negatively charged exciton [5]. We interpret these observations as indicating that the M-I transition in our samples is due to a localization of single electrons. These localized electrons are not effective in screening the remote donors potential and the excitonic interaction.

We have studied a number of single side modulation-doped quantum well samples grown by molecular beam epitaxy. The structure of all samples was nominally identical except for the width of the well and the spacer. The structure was grown on a semi-insulating substrate. The buffer layer was composed of 0.5 μm undoped GaAs and a superlattice consisting of 50 periods of 30 Å GaAs and 100 Å $Al_{0.35}Ga_{0.65}As$. A single quantum well was followed by a spacer layer of undoped $Al_{0.35}Ga_{0.65}As$, a silicon δ-doped layer with 10^{12} cm^{-2}, 1000 Å of undoped $Al_{0.35}Ga_{0.65}As$, 200 Å of $Al_{0.35}Ga_{0.65}As$ doped with 2.5×10^{18} cm^{-3} silicon atoms, and a cup layer. The samples were grown in two batches: in the first we varied the well width (150, 200, and 300 Å) while keeping the spacer width constant (500 Å); in the second we varied the spacer width (150, 500, and 1500 Å) while keeping the well width constant (200 Å). Electron densities after illumination are 6×10^{10}, 2×10^{11}, and 6×10^{11} cm^{-2} for the 1500, 500, and 150 Å spacers, respectively. The samples are of a relatively high quality: the mobility is $\sim 10^6$cm^2/V sec for all samples.

The density of electrons in the well was varied by applying a negative voltage to a semitransparent gate with respect to the 2DEG. The samples were maintained at 4 K. The exciting photon energy was kept below the barrier energy gap, thus the illumination did not create carriers in the barrier, and therefore did not affect the built-in potential of the heterojunction [6]. The laser power density was about ~ 1 W/cm^2, which corresponds to a steady state electron-hole density of $\sim 10^8$ cm^{-2}.

The behavior of all samples was found to be qualitatively the same. We have chosen to present in the figures the data for the sample with 200 Å well and 150 Å spacer, where the findings are more significant. We specify the results for the other samples in the text. Figure 1 shows the photoluminescence (PL) spectra for various gate voltages V_g. The PL spectrum at the range $V_g > -3$ V starts as a broad and weak peak and gradually moves to higher energies, increasing in size and becoming narrower. This behavior was explained in Ref. [4] as being due to the reduction in both the band gap renormalization [7] and the built-in field with decreasing electron density. At $-3.05 > V_g > -3.1$ V the PL spectrum changes dramatically. Another peak (denoted by X) appears at an energy 1.2 meV above the main peak (denoted by Y). At $V_g = -3.1$ V the X and Y peaks are of comparable strength, and we

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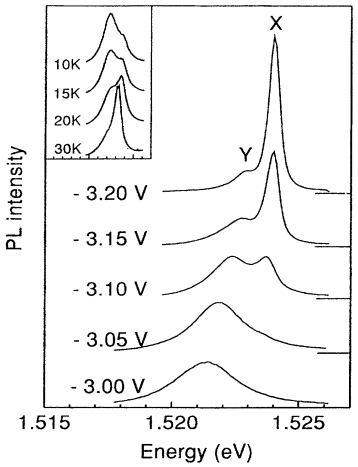

FIG. 1. PL spectra of the sample with 200 Å well and 150 Å spacer at 4 K for different gate voltages. The inset shows the PL spectra at different temperatures at $V_g = -3.075$ V.

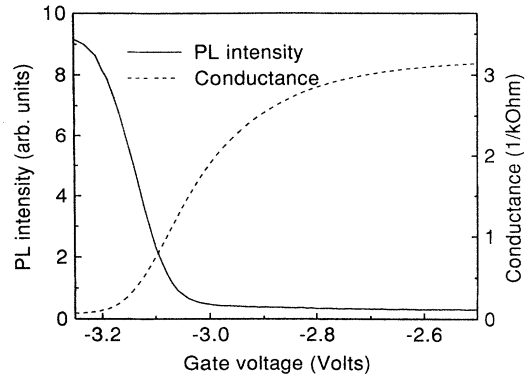

FIG. 2. PL intensity at the exciton energy position of 1.524 eV and conductance versus gate voltage for the sample with 200 Å well and 150 Å spacer. The upper value of the conductance is limited by the contact resistance, which is ~300 Ω. The leveling of the conductance curve for $V_g < -3.1$ V is caused by gate leakage of the large area device used for optical measurements.

observe a clear double peak structure. At $V_g = -3.2$ V the X peak clearly dominates the spectrum. This double peak structure was observed in all samples. The value of the energy gap between the X and Y peaks was found to be almost insensitive to the spacer and well width [8]. The inset of Fig. 1 describes the temperature dependence of the PL spectrum at $V_g = -3.075$ V. It can be seen that as the temperature is increased the ratio between the X and Y peaks changes in favor of X, and at 30 K only a small shoulder remains of Y.

The fact that the X peak becomes dominant as we lower the density in all samples indicates that it is a heavy-hole exciton line. To prove this assignment we should examine the spectra at the limit of an empty well. However, at low density the resistance of the 2DEG grows substantially and changes in the gate voltage do not affect the density of the 2DEG. To be able to empty the well we prepared a sample with both top and bottom gates, where the bottom gate was deposited after etching the substrate away. By applying a voltage between the top and the bottom gates we were able to totally deplete the floating 2D channel. We observed that under these conditions the X peak clearly dominated the PL spectrum. This observation unambiguously proves that the X peak is a heavy-hole exciton line.

To get an insight into the state of the 2DEG at the critical density, where excitions appear, measurements of the conductance of the sample as a function of V_g were performed (Fig. 2). The PL signal at the exciton energy was simultaneously measured. The rise of the exciton peak is strongly correlated with the decrease of the conductance. At lower gate voltages the exciton grows and saturates at $V_g = -3.25$ V. We can conclude that the exciton line appears at the onset of the M-I transition.

To determine the electron density at the transition we have conducted four probe Hall measurements at a low magnetic field of 0.1 T. These measurements were performed after continuous illumination, such that all DX centers are ionized, as in the optical experiment. Figure 3 shows the conductance per square (in units of e^2/h) versus the 2DEG density for two samples: one with 150 Å spacer width and the other with 500 Å. It can be seen that the critical density depends strongly on the spacer width, and it is $\sim 3 \times 10^{11}$ and 9×10^{10} cm^{-2} for the 150 and 500 Å samples, respectively. Thus, we conclude that excitons are formed when there is a large average electron density in the well.

Figure 4 describes a set of photoluminescence excitation (PLE) and the corresponding PL spectra for various gate voltages. The PLE spectrum at -2.8 V exhibits a steplike behavior, typical for absorption in the presence of a 2DEG. There is a clear Stokes shift, which arises from

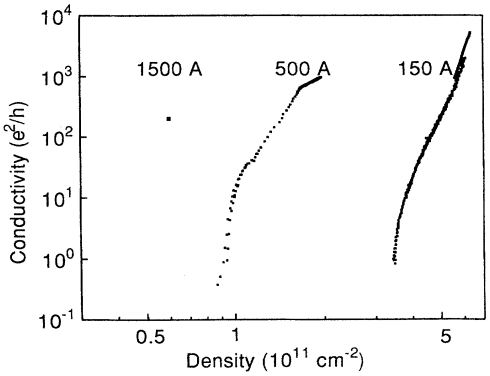

FIG. 3. The conductivity (in units of e^2/h) versus the 2DEG density for the 150 and 500 Å spacer samples. The curves are obtained by a four probe Hall measurement with $B = 0.1$ T. The result of a measurement at $V_g = 0$ for the 1500 Å spacer sample is also shown.

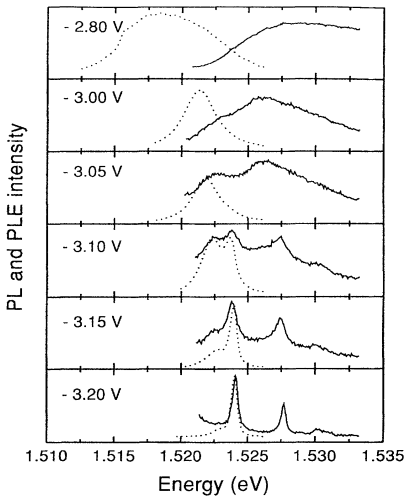

FIG. 4. PLE (solid) and the corresponding PL (dots) spectra for the sample with 200 Å well and 150 Å spacer at different gate voltages. The detection energy is 1.5187 eV.

the relatively large 2DEG density, of $\sim 4 \times 10^{11}$ cm^{-2}. At $V_g = -3.0$ V and especially at $V_g = -3.05$ V, we notice the formation of a broad absorption peak at lower energies. As the density is further reduced ($V_g = -3.1$ V), we can clearly identify the X and Y peaks and the light-hole exciton (1.5275 eV). Despite the presence of a relatively large electron density in the well ($\sim 3 \times 10^{11}$ cm^{-2}) there is a negligible Stokes shift between the PL and the PLE. At $V_g = -3.15$ and -3.2 V the Y peak gradually decreases, and the X peak dominates. These spectra clearly prove that both the X and Y peaks are intrinsic lines and provide another support for the association of the X peak with the heavy-hole exciton.

Let us now turn to a discussion of the experimental results. We have shown that excitons appear at the onset of the M-I transition. However, the electron density at which it occurs, $n_c \sim 3 \times 10^{11}$ cm^{-2}, is surprisingly large. The mean distance between electrons at such density is of the order of the exciton diameter. If the 2DEG would be uniformly distributed, the exciton should be screened [9]. Thus, we can conclude that the electrons become less effective in screening at the onset of the M-I transition. If the 2DEG is separated into regions, which are full or empty of electrons, excitons can be formed in the empty regions. Such a phase separation model for the behavior of 2DEG as its density is reduced was proposed by Efros [2]. In this model the remote ionized donors, randomly distributed in the doped region, create an electrostatic potential at the 2DEG plane, with a typical length scale which is approximately given by s, the spacer width. As the 2DEG density is reduced, the Fermi level becomes lower than the bottom of the conduction band in some regions of the 2DEG, and these regions become empty.

Following the derivation by Efros we can estimate the potential fluctuations induced by the remote ionized donors [2]. The mean square value of the potential fluctuations is $\langle U^2(r)\rangle \approx 2\pi e^4 N_{d^+}(2\epsilon q_0 s)^{-2}$, assuming a linear screening by the 2DEG. In our case the spacer $s = 150$ Å, the sheet donor concentration is $N_{d^+} \approx 10^{12}$ cm^{-2}, and the inverse screening length $q_0 \approx 1/(50$ Å), so that $\langle U^2(r)\rangle^{-1/2} \approx 4$ meV. These fluctuations are not strong enough to cause phase separation of a 2DEG with a Fermi energy of ~ 10 meV. It should be noted, however, that this expression is valid only in the metal phase, when linear screening can be used. Screening may become less effective as we approach the transition, and the linear screening approximation may not be used after the transition. Assuming as a rough estimate that the 2DEG in the insulator phase is not effective at all in screening the donors potential, i.e., $q_0 = 0$, we obtain $\langle U^2(r)\rangle \approx 2\pi e^4 \epsilon^{-2} N_{d^+} \ln(l/2s)$, where l is a long length cutoff. Since the metal gate screen fluctuates with a length scale larger than the distance from the donors to the gate, it is natural to associate l with that distance. This gives an estimate of $\langle U^2(r)\rangle^{-1/2} \approx 30$ meV for the potential fluctuations. This rough estimate can explain the origin of the abrupt appearance of the exciton line as a positive feedback process. As we reduce the density, electron localization starts to take place, and screening becomes less effective. This causes the potential fluctuations to grow appreciably, which in turn gives rise to a stronger localization of the electrons. Such a feedback mechanism of nonlinear screening can sharpen the transition and result in a development of electron localization in a small range of densities. This is consistent with our observation that $\Delta n \ll n_c$.

Considering the length scale of the potential fluctuations, which is of the order of the spacer width [2], we can easily see that for $s = 150$ Å and a critical transition density $n_c = 3 \times 10^{11}$ cm^{-2} the average number of electrons per fluctuation is ~ 1. This conclusion is valid also for the larger spacer sample, where $s = 500$ Å and $n_c \sim 9 \times 10^{10}$ cm^{-2}. Thus, the phase separation model seems inappropriate. Furthermore, such a model leads to a percolation transition [2]. If that would be the case, the appearance and growth of the exciton line would be insensitive to the percolation threshold. Our experiment, however, shows a strong correlation between the onset of the transition and the appearance of excitons (Fig. 2). We can therefore conclude that rather than a phase separation we get *localization of single electrons.*

Since the electrons become ineffective in screening the excitons at the M-I transition, we can conclude that it is not of an Anderson type [10]. In such transition the electrons would still be effective in screening even at the insulator phase. On the other hand, our situation is similar to the Mott-Hubbard transition, in which the screening is sharply decreased at the transition [11]. Indeed, the on-site repulsive interaction between electrons in the same potential fluctuation would favor a situation in which each electron is localized at a different site. This single

electron localization picture of the transition can help us understand the origin of the Y peak and the 1.2 meV splitting between the X and Y peaks. Examining the PL and PLE spectra it is evident that the Y peak changes its nature near the M-I transition. Before the onset of the transition ($V_g > -3$ V) this peak exists only in the PL and corresponds to a recombination of a hole with an electron from the Fermi sea. The Pauli exclusion principle inhibits transition into occupied electron states, thus there is no absorption at this energy (zero PLE signal). On the other hand, when the electrons localize ($V_g < -3$ V), an absorption appears at the energy position of the Y peak. Clearly, it cannot originate from regions which contain an appreciable number of electrons and large average density. Such regions would give rise to a Stokes shift between the PL and PLE. The resonant nature of the Y peak makes it natural to assume that it corresponds to some discrete state. We can rule out the possibility that Y is a localized exciton. If that would be the case, the Y peak would remain at the limit of zero 2DEG density. The experiment with both top and bottom gates shows the opposite. Furthermore, there is no reason to expect a constant localization energy of 1.2 meV for different regions within the same sample and for different spacer widths. The fact that this line is strong in the PLE spectra and the relatively high mobility of the samples also rules out the possibility that it is an impurity line.

We attribute the Y peak to a negatively charged exciton, X^-. Such an object, consisting of a hole and two electrons, was recently observed in CdTe quantum wells [12]. In our case, the localized electrons and the photoexcited electron-hole pairs can form an X^-. The unique situation, of excess electrons which are not effective in screening, can enable X^- to be stable. The energy difference between the exciton line and the X^- should be equal to the binding energy of the second electron in X^- [12]. The value of the energy splitting between X and Y, $\Delta = 1.2$ meV, is consistent with the expected value for this binding energy in GaAs quantum wells [5]. Recent measurements of the polarization properties and the behavior in a magnetic field strongly support this assignment and will be reported elsewhere. Following this interpretation the temperature dependence of the PL spectrum (inset of Fig. 1) is understood as representing thermal activation of X^- to an exciton and an electron. The fact that the energy of the PL peak just before the M-I transition ($V_g = -3.05$ V in Fig. 1) merges into the X^- transition energy has a clear physical meaning. At the metallic phase the PL peak position is determined by the correlation of the 2DEG with the hole (band gap renormalization). A limiting case of such correlation is that of two electrons with a hole, namely, X^-.

In conclusion, we have used optical spectroscopy and its correlation with transport measurements to show that the M-I transition of a 2DEG in modulation-doped heterostructures may occur due to the localization of single electrons in the electrostatic potential fluctuations of the remote ionized donors. The signature of this state was shown to be the existence of regular and negatively charged excitons in high average electron density.

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