Near-Field Spectroscopy of a Gated Electron Gas: A Direct Evidence for Electron Localization

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(Received 20 January 1998)

The near-field photoluminescence of a gated two-dimensional electron gas is measured. We use the negatively charged exciton, formed by binding an electron to a photoexcited electron-hole pair, as an indicator for the local presence of charge. Large spatial fluctuations in the luminescence intensity of the negatively charged exciton are observed. These fluctuations are shown to be due to electrons localized in the random potential of the remote ionized donors. We use these fluctuations to image the electron and the donor distribution in the plane. [S0031-9007(98)06953-1]

PACS numbers: 71.35.Cc, 73.20.Dx, 78.55.Cr

The two-dimensional electron gas (2DEG) which is formed in semiconductor heterostructures has been a subject of intense research in the past two decades. The electrons in these heterostructures are provided by a remote layer of donors and are confined in a two-dimensional potential. Applying a gate voltage enables one to affect the conductivity of the 2DEG in a profound way: At low temperatures a drop of several orders of magnitude can be observed over a small range of gate voltage [1]. This large change in conductivity is accompanied by a relatively small change in the electron density, typically less than an order of magnitude. The microscopic understanding of this behavior is the focus of this paper.

It has been realized that the remote ionized donors, which provide the electrons to the 2DEG, play an important role in this drop of conductivity [1,2]. Spatial variations in the density of these donors are manifested as random potential fluctuations in the plane of the 2DEG. At small negative gate voltages, when the conductivity is high, these fluctuations are effectively screened by the 2DEG. As the electron density is decreased at larger negative gate voltages, the screening becomes less effective and the fluctuations grow, giving rise to a large drop in the electron conductivity.

The photoluminescence (PL) of a gated 2DEG was intensively studied in recent years [3,4]. It was found that at small negative gate voltage the PL spectrum is a broad line, with a width of approximately the Fermi energy (Fig. 1). As the gate voltage becomes more negative and the electron density is reduced, the PL spectrum narrows. An important finding was that at a certain gate voltage the spectrum changes abruptly into two exciton peaks. Decreasing the gate voltage further changes the relative strength of the two peaks. It was shown [3,4] that the high energy peak is due to a recombination of a neutral exciton (X), a bound complex of an electron, and a hole. The low energy peak was found to be associated with the negatively charged exciton (X^-), which consists of two electrons and a hole and is a semiconductor analog of the hydrogen ion H^- [5,6]. The appearance of the excitonic peaks is an indication that the screening of the electron-hole interaction by the 2DEG is suppressed and a bound complex can be formed [7]. Indeed, a correlation was found between the growth of the X peak and the drop of conductivity [3].

It has been shown that X^- is formed in a gated 2DEG by binding a photoexcited electron-hole pair to an electron from the 2DEG [3,4]. X^- can therefore be used as *a probe for the presence of electrons*, and, by mapping its intensity across the area of the sample, one can identify the regions where electrons are located.

In this work we use the X^- luminescence to image the distribution of electrons in the 2DEG in the range of gate voltages where the conductivity drops. We show that in this regime the electrons are localized in the potential fluctuations of the remote ionized donors. This is done using near-field spectroscopy, which provides subwavelength spatial resolution [8,9]. The underlying idea is rather simple: The spectral signature of a region filled with electrons is very different from that of an empty region. Thus, by collecting the PL through a

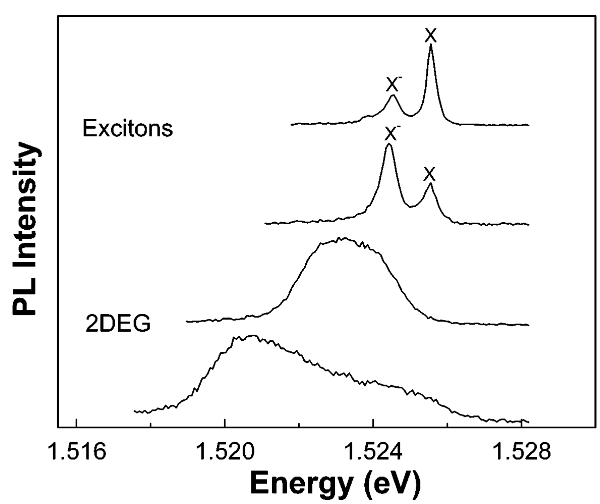

FIG. 1. The evolution of the far-field PL of a 2DEG with gate voltage (upper curves correspond to more negative gate voltage).

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small aperture which is scanned in close proximity to the surface, one can map the charge distribution in the plane.

We have built a low temperature near-field scanning optical microscope (NSOM), which collects the emitted PL through a tapered optical fiber tip. The tip, which is manufactured by Nanonics, is coated on the sides with aluminum and has a clear aperture of $\sim$250 nm and a transmission of 10^{-3}. We have verified the continuity of the metallic coating using scanning electron microscopy (SEM) imaging. The tip is glued to a commercial tuning fork, having a resonance frequency of 32 768 Hz. The piezoelectric signal from the tuning fork is used to control the height of the tip above the sample surface at $\sim$10 nm and to measure the sample topography [10]. The sample is mounted on a 2 in. piezoelectric tube, giving a scan range of $11 \times 11\ \mu\mathrm{m}^2$ at 4 K. A coarse *X*-*Y* movement assembly enables movement to different regions of the sample within an area of $2 \times 2\ \mathrm{mm}^2$, with 1 μm steps. The microscope is inserted into a sealed tube filled with He exchange gas, and the tube is immersed in a storage Dewar. Further details on the NSOM are given elsewhere [11].

The photoexcitation is done using a second single mode fiber which is oriented such that the light comes out nearly parallel to the surface, thus illuminating a broad region of $\sim 1\ \mathrm{mm}^2$. This mode of operation, which does not use the tip for illumination [12,13], ensures uniform excitation of the scanned region while maintaining a good spatial resolution. The excitation intensity is typically 50 $\mathrm{mW/cm}^2$ at a wavelength of 632.8 nm. The collected PL is dispersed in a 0.5 m spectrometer and detected in a thermoelectrically cooled, back-illuminated charge-coupled device (CCD) detector. The system spectral resolution is 0.04 nm. The typical signal at that excitation condition is 30–40 counts/sec at the exciton peak. Scanning is performed with a typical integration time of 5 sec per point and a step size of 100 nm. These scanning parameters translate to a measurement time of several hours for a two-dimensional scan. We have verified that the system is stable during this measurement time. To determine the spatial resolution of the system, we deposited an array of opaque gold lines (1.5 μm width and 3.5 μm period) on a sample of GaAs quantum well and measured the collected PL as the tip is scanned across the pattern. The spatial resolution is obtained by the distance over which the integrated PL intensity changes from 0.1 to 0.9 of its maximum value. The value which is obtained is $\sim$250 nm, in a very good agreement with the results of the SEM imaging, ensuring there are no leaks in the metallic coating of the tip.

The sample consists of a 20 nm GaAs quantum well followed by 37.5 nm $Al_{0.37}Ga_{0.63}As$ spacer layer and a 10 nm $Al_{0.37}Ga_{0.63}As$ layer doped with silicon at a concentration of $3.5 \times 10^{18}\ \mathrm{cm}^{-3}$. The structure is capped by a 20 nm undoped $Al_{0.37}Ga_{0.63}As$ and 10 nm GaAs. A $2 \times 2\ \mathrm{mm}^2$ mesa was etched, and Ohmic contacts were alloyed into the 2DEG layer. A 4 nm Pd/Au semitransparent gate was evaporated on top. We have verified the continuity and uniformity of the gate by SEM imaging. The 2DEG concentration was $4 \times 10^{11}\ \mathrm{cm}^{-2}$, and the mobility was $1.3 \times 10^6\ \mathrm{cm}^2/\mathrm{V\,sec}$, both measured at 4.2 K. The laser energy is below the AlGaAs band gap; hence, no photoexcited carriers are created in the high band gap region. Nevertheless, upon excitation with the laser, the electron density is reduced by an amount which depends on the laser intensity. Consequently, the gate voltage needed to deplete the sample is intensity dependent.

Let us now turn to the experimental results. Figure 2(a) shows four near-field spectra measured at different locations at the same gate voltage, $V_g = -0.135$ V. At this gate voltage the spectrum is excitonic: The high and low energy peaks are X and X^-, respectively. It can be seen that the near-field spectrum is different from one location to another. While the height of the X peak is very similar in the four spectra, the height of the X^- peak varies substantially. Since X^- is an indicator for the presence of electrons, these variations in its intensity show that the *electrons are nonuniformly distributed*.

These PL intensity variations disappear at the far field when the PL is collected far from the surface. To substantiate the fact that the far-field spectrum is a superposition of different local spectra, we performed the following procedure. We first scanned a square of $1 \times 1\ \mu\mathrm{m}^2$ and summed up the PL spectra from all the

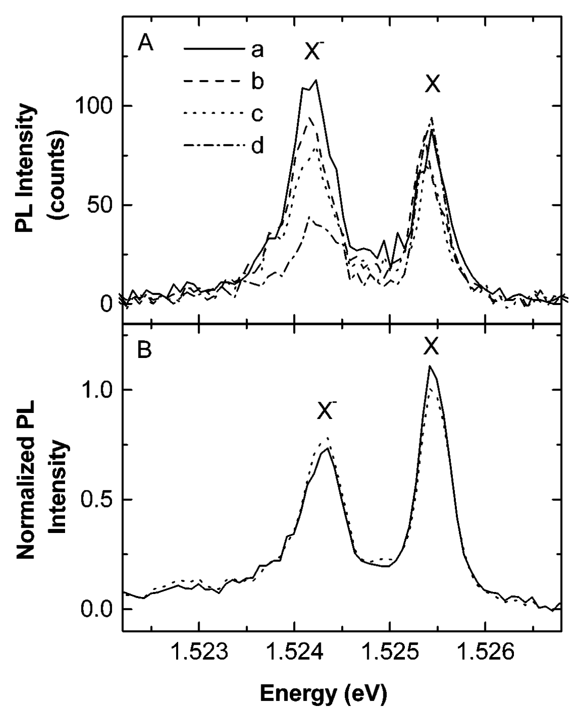

FIG. 2. (a) Four near-field spectra taken at $V_g = -0.135$ V and at different tip locations. (b) A sum of near-field spectra from a $1 \times 1\ \mu\mathrm{m}^2$ region (solid) and a far-field spectrum taken at 1 μm above this region (dotted).

points [Fig. 2(b) solid line]. We then withdrew the tip to a distance of 1 μm from the sample and measured the PL above the center of this square [Fig. 2(b) dashed line]. It can be seen that the two curves nearly coincide.

To quantify the fluctuations of the X^- intensity we measured the PL along 11-μm-long line, with 100 nm steps between subsequent measurements, and integrated the intensity under the X^- peak at each point. For comparison, we performed the same procedure for the X peak. The results are shown in Fig. 3(a) [the four points at which the spectra of Fig. 2(a) were taken are denoted in the figure]. It is evident that there are large fluctuations in the X^- intensity, which occur throughout the scanned region and on any length scale, down to the resolution limit. The X peak exhibits much smaller fluctuations. It should be emphasized that these fluctuations are stable over time: the line scan is reproduced by repeating the measurement over and over again. We found no correlation between these fluctuations of the X^- intensity and the shear-force signal, which exhibits a ± 1.5 nm noise.

Figure 3(b) shows a comparison between the integrated intensity under the X^- peak for three line scans [over the same line as in Fig. 3(a)], each scan was done at a different gate voltage: $V_g = -0.105$, -0.135, and -0.155 V. We normalize the curves by dividing the value at each point along the line by the average value of that curve. Comparing the different line scans, one can clearly see that the relative fluctuation amplitude increases with the gate voltage. The positions of the maxima and minima, however, are fixed in space and are almost unaffected by the gate voltage. Figure 4 summarizes the dependence of the fluctuation amplitude on gate voltage (note that this measurement is taken at a smaller illumination intensity than the measurements of Fig. 3; hence, the gate voltages are more negative). The graph describes the dependence of the normalized standard deviation of the X^- fluctuation amplitude on gate voltage. It can be clearly seen that the fluctuation amplitude is constant over a large range of gate voltages and starts to increase at the voltage at which the spectrum becomes excitonic. This correlation between the appearance of the excitonic spectrum and the rise of the fluctuation amplitude is very significant. The excitons appearance is an indication of a change in the screening properties of the 2DEG: It becomes ineffective in screening the electron-hole interaction. It follows that the 2DEG is also ineffective in screening the random potential induced by the ionized donors in the doped AlGaAs layer, and the fluctuations in this potential grow. These donors are randomly distributed, with an average distance between them of a few nm. They give rise to a random electrostatic potential in the 2DEG plane, with the smallest spatial period being the spacer width (37.5 nm in our sample) [2]. The high spatial frequencies of the observed fluctuations and the fixed positions of the minima and maxima are consistent with this explanation.

It is evident from Fig. 4 that fluctuations in the PL intensity are observed throughout the gate voltage range. At the range where the PL is 2DEG-like, namely, broad and shifted to lower energies, the electrons are free. The weak fluctuations in this range are independent of the gate voltage and are due to localization of the photoexcited

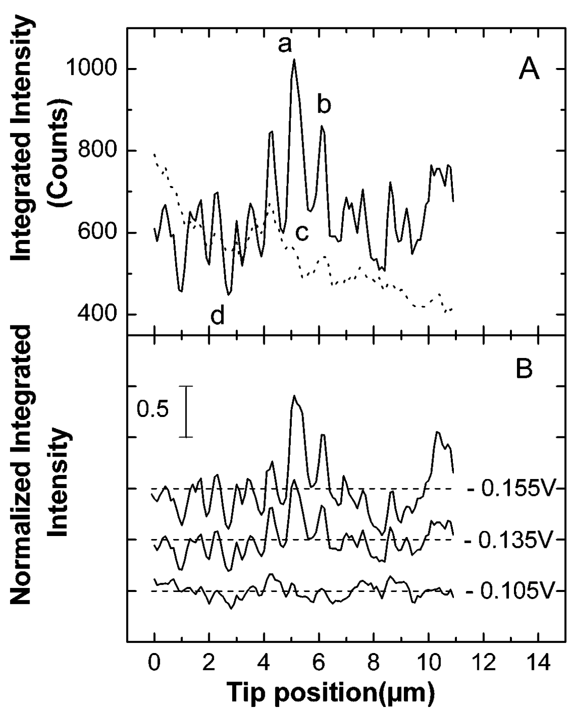

FIG. 3. (a) The integrated X^- (solid line) and X (dotted line) intensity along an 11–μm-long line scan. The letters denote the location of the spectra shown in Fig. 2(a). (b) The normalized X^- integrated intensity along an 11-μm-long line at three gate voltages. The curves are normalized by dividing the value at each point by the average (dashed line) of the whole line. The -0.135 V and -0.155 V curves are shifted up by 0.5 for clarity.

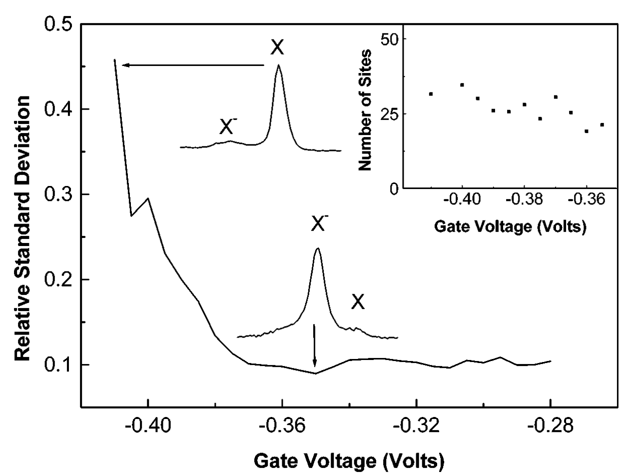

FIG. 4. The standard deviation of the relative fluctuation amplitude of the X^- intensity along an 11-μm-long line, as a function of gate voltage. The averaged spectra at $V_g = -0.35$ V and $V_g = -0.41$ V are also shown. Inset: The number of sites under the tip, calculated for various gate voltages. The calculation method is explained in the text.

holes in the donor potential. The observed increase in the fluctuation amplitude as the spectrum becomes excitonic is *the onset of the electron localization*.

Since our spatial resolution is 250 nm, we are unable to collect light from a single localization site which has a typical size of $\sim$40 nm, the spacer width. Thus, at each tip location, we collect light from several sites. The changes in the X^- intensity from one tip location to another originate from a nonuniform occupation of these localization sites. To model the localized system let us assume for simplicity that it consists of a periodic potential in the plane, in which the electrons are randomly distributed. In such a model the tip samples a subregion, in which there are N sites with a probability p to be occupied by electrons. The average number of electrons is $n_{\mathrm{av}} = pN$, and the corresponding standard deviation is $\sigma_n = \sqrt{pN(1 - p)}$. The average PL intensity can be written as $I_{\mathrm{av}} = \alpha n_{\mathrm{av}}$, where α is a proportionality factor. In this model the measured standard deviation in the X^- intensity is given by $\sigma = \alpha\sigma_n$. Taking the maximum intensity when all the sites are occupied to be $I_{\max}$, one can show that $N = (I_{\max}I_{\mathrm{av}}/\sigma^2)(1 - I_{\mathrm{av}}/I_{\max})$. Since I_{av} and σ depend on the gate voltage, we can check the consistency of this model by calculating N for each gate voltage. The inset of Fig. 4 describes N as a function of the gate voltage. We can see that, indeed, we get a relatively small scatter around an average value of $N \approx 30$. Since our tip diameter is 250 nm this implies an average fluctuation size of 40–50 nm. This is in a very good agreement with the expected size, which is the spacer width (37.5 nm). It is important to note that we have not found in the gate voltage range when the spectrum is excitonic any area of the sample where the signal is 2DEG-like, which would represent puddles of free electrons. This indicates that there are no large clusters of free electrons and the localization is of *single electrons*.

The behavior of a two-dimensional carriers gas at zero magnetic field is the subject of large current interest: It was recently shown that in some material systems the conductivity undergoes a metal-insulator transition [14]. We wish to emphasize that the question of whether the system is initially weakly localized or metallic cannot be answered by this optical experiment. It should be noted, however, that this metal-insulator transition has not been found in GaAs 2DEG, and it is likely that the 2DEG in our sample is initially weakly localized.

Finally, we use the fact that the location of the fluctuations is independent of the gate voltage to image the donor distribution in the plane. This is done by fixing the gate voltage at a convenient value and scanning the probe to obtain a two-dimensional map of the X^- intensity. Figure 5 shows such a map for a region of $6 \times 6\ \mu\mathrm{m}^2$. Regions with large amplitudes of the X^- intensity correspond to areas with large donor density. We examine the statistical distribution of the X^- intensities and find a nice Gaussian distribution. An analysis of this type can,

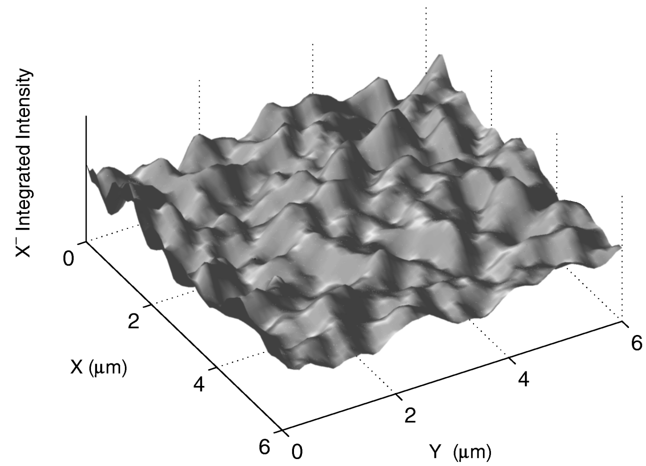

FIG. 5. A two-dimensional image of the X^- integrated intensity for a $6 \times 6\ \mu\mathrm{m}^2$ region.

in principle, reveal the existence of correlation in this distribution. In such a case, a deviation from a Gaussian distribution is expected.

In conclusion, we have demonstrated the use of NSOM for the imaging of charge distribution. Our near-field PL measurements of a gated 2DEG detect the random potential induced by the remote ionized donors and determine the electron distribution in this potential. The correlation between the appearance of the excitonic spectrum and the rise of the fluctuation amplitude of the X^- intensity shows that the electrons are singly localized in that potential.

This research was supported by the Minerva foundation and the Israel Academy of Science. We thank G. Finkelstein, M. Heiblum, A. Stern, and A. Yacoby for fruitful discussions.

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