Excitonic emission in the presence of a two dimensional electron gas: 
a microscopic understanding

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The near- and far-field photoluminescence spectra of a gated two-dimensional electron gas have been measured. Spatial fluctuations in the electron density are found to be manifested as spatial fluctuations in the emission amplitude of the negatively charged exciton ($X^-$) and in the peak energy of the neutral exciton ($X$). Consequently, the far-field $X^-$ spectrum is a homogeneously broadened Lorentzian, while the $X$ lineshape exhibits substantial inhomogeneous broadening. We present a novel and simple technique to extract the electron density from the $X^-$ spectrum. We show that width of the far-field $X$ line is proportional to the electron density fluctuations; hence it can be used to characterize the inhomogeneity in the electron density.

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The photoluminescence (PL) spectrum of a low density two dimensional electron gas (2DEG) has been the subject of considerable interest in recent years. It is observed that at a certain critical density, which depends on sample parameters but is typically between $10^{10} - 10^{11}$ cm$^{-2}$, the spectrum abruptly changes, from a broad line at high densities to two narrow peaks at low densities. A number of spectroscopy experiments at zero and high magnetic fields have clearly shown that the two peaks are associated with the neutral ($X$) and negatively charged ($X^-$) excitons. The $X^-$ is formed by the binding of a photoexcited electron-hole pair to an electron of the 2DEG. When the electron density is decreased its relative intensity decreases, and the spectrum becomes dominated by the $X$ line. It was found that the appearance of this excitonic spectrum is correlated with a rapid decrease in the 2DEG conductivity. This drop in conductivity was theoretically predicted to mark the onset of strong localization: As the 2DEG density is decreased, it becomes ineffective in screening the potential fluctuations due to the remote ionized donors, and they grow substantially. Consequently, the electrons become localized in those potential fluctuations, and their ability to screen is further reduced. It was suggested that this reduction in screening and the subsequent strong localization of the electrons, allowed the observation of excitons in the presence of the 2DEG. This conclusion was corroborated by a near-field optical study, which has shown that the $X^-$ intensity exhibits strong spatial fluctuations: regions with high (low) electron density give rise to a strong (weak) $X^-$ signal.

Our goal in the present work is to establish a quantitative relation between the optical spectrum at low electron density and the properties of the 2DEG. We measure and carefully analyze both the near- and far-field PL spectra of a gated 2DEG. We find that the near-field $X^-$ lineshape is a Lorentzian, with an amplitude that varies strongly between different points in the sample, but with a very narrow distribution of peak energies and widths. Consequently, the far-field $X^-$ lineshape is a homogeneously broadened Lorentzian, with a numerator that is proportional to the average density. We show that one can easily determine the average electron density in this low density regime from the PL spectrum. The near-field spectra of the $X$, on the other hand, exhibit a broad distribution of peak energies. We show that there is a clear correlation between the 2DEG density fluctuations and those of the $X$ peak energies: regions with high (low) electron density give rise to a high (low) $X$ peak energy. Hence, we conclude that the electron density fluctuations are the origin of the inhomogeneous broadening of the far-field $X$ peak. Thus, the far-field $X$ width is a measure for the electron density fluctuations in the sample.

The sample we studied is a 20 nm GaAs quantum well (QW). A 3.6 nm Si doped donor layer with a density of $4 \times 10^{18}$ cm$^{-3}$ is separated from the QW by a 50 nm Al$_{0.36}$Ga$_{0.64}$As spacer layer. The distance between the QW and the sample surface is 107 nm. A $2 \times 2$ mm$^2$ mesa was etched, and ohmic contacts were alloyed to the 2DEG layer. A 4.5 nm PdAu semitransparent gate was evaporated on top of the sample. The ungated 2DEG density and mobility (after illumination) at 4 K are $2.2 \times 10^{11}$ cm$^{-2}$, and $3 \times 10^6$ cm$^2$/V sec, respectively.

Near-field PL measurements were performed using a system, which is described in detail in Ref. [5]. It is a low temperature near-field scanning optical microscope (NSOM) that operates in the collection mode: the sample is illuminated uniformly by a single-mode fiber and the emitted PL is collected through a tapered Al-coated optical fiber tip. The tip clear aperture diameter and transmission were measured to be 200 nm and $10^{-3}$, respectively. The spatial resolution was determined using a grating mask to be 180 nm. The tip is glued to a quartz tuning fork, and its piezoelectric signal is used to control the height of the tip above the sample surface at $\sim 10$ nm. For the excitation we used a He:Ne laser at 632.8 nm. The collected PL was dispersed by a 0.5 m spectrometer and detected using a cooled CCD camera. The overall system spectral resolution is 0.038 nm.

Figure 1a shows two near-field PL spectra (thin lines)
measured at a fixed gate voltage at two points in the sample, 0.25 \mu m apart. Both spectra consist of two peaks, X and X\textsuperscript{−}. It is seen that there are large differences between the two spectra over this small distance. The differences are manifested in the relative heights, widths and peak energies of each spectral line. The strong spatial fluctuations in the X\textsuperscript{−} intensity were already reported by us in a previous work [9]. We have significantly improved the signal to noise in the present measurements, and were thus able to better resolve the properties of the emission spectra. In extracting these properties we performed line fitting at more than 3000 points for each excitonic line. This summation results in a far-field lineshape that is also a Lorentzian. The near-field X peak histogram, on the other hand, exhibits significantly greater scatter in its peak energies. This scatter is larger than the X homogeneous linewidth (Lorentzian width) and gives rise to inhomogeneous broadening of the X far-field spectrum. Indeed, we observe in Fig. 4b that the far-field X width is comparable to the X peak energy distribution. We find that the X peak is inhomogeneously broadened already in the near-field measurements. This implies that the broadening mechanism occurs on a length scale smaller than our spatial resolution, and the width of the X peak energy histogram measured at higher spatial resolution would be even larger. We shall address this point later when we discuss the origin of the inhomogeneous broadening.

To check this assignment of broadening types we have conducted a set of far-field PL measurements at various gate voltages and illumination intensities (six laser intensities and 50 gate voltages per laser intensity), and fitted the measured spectra with the double Voigt function discussed above. We have found that throughout the gate voltage range the X\textsuperscript{−} is well fitted by a Lorentzian (convolved with a Gaussian, which is much narrower than the Lorentzian) while the X lineshape has substantial inhomogeneous Gaussian broadening. These findings are consistent with the results of the near-field measurements. Let us address the X\textsuperscript{−} Lorentzian lineshape, which we express as

\[ I_{X^-}(E) = \frac{\rho}{(E - E_{\text{peak}})^2 + \Gamma^2}, \]  

where \(E_{\text{peak}}\) and \(\Gamma\) are the X\textsuperscript{−} peak energy and half width at half maximum, respectively. In general, a Lorentzian line is obtained by Fourier transforming an exponentially decaying state, \(\Psi(r)\exp(- \frac{IE_{\text{peak}}}{\hbar}t - \frac{\Gamma}{2}t)\), and taking its absolute value squared. Thus, the numerator of the Lorentzian \(\rho = \hbar^2 |\Psi(r)|^2\) should depend linearly on the probability density of the state \(\Psi\), and in this particular case, on the X\textsuperscript{−} density. Since the X\textsuperscript{−} density should depend linearly on the electron density \(n_e\), we expect...
I and the 2DEG (the agreement is better than 5%). The sec-
capacitance per unit area between the Shottkey gate and
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The results are shown in the inset of Fig. 2b. Two ob-
served the conductance using the van der Pauw (VdP)
technique [10], under different illumination intensities.

The geometrical capacitance between the Shottkey gate
parallel plate capacitor model for the gated 2DEG we can
express the 2DEG density as
$
\rho
$ can write
\[ n_c = \rho \frac{C}{a}, \] (2)
and $a$ is simply the slope of the $\rho$ versus $V_g$ curve at some
arbitrary laser intensity. This is a new method to extract
$n_c$ in the low density regime from the PL data and the
geometrical capacitance, without having to measure $V_0$
and $I_L$.

To verify the linear dependence of $n_c$ on $V_g$ we mea-
sured the conductance using the van der Pauw (VdP)
technique [14], under different illumination intensities.
The results are shown in the inset of Fig. 2b. Two ob-
servations can be made: First, the density does change
linearly with gate voltage with a slope $C$, which is the
capacitance per unit area between the Shottkey gate and
the 2DEG (the agreement is better than 5%). The sec-
ond observation is the shift of $V_0$ to more positive val-
ues with increasing laser intensity. The implication of
this behavior is that the electron density in the well is
depleted under illumination by an amount that is pro-
portional to the laser intensity, but is independent of the
gate voltage. The probable mechanism of this depletion
process is tunneling of photo-excited electrons to the sur-
face, leaving the photo-excited holes trapped in the well
[12]. The recombination of these holes with the 2DEG
electrons results in the reduction of the 2DEG density. In
Fig. 2b we apply Eq. (2) to calculate the electron
density $n_c$ from the measured values of $\rho$ of Fig. 2a. We
get a set of parallel lines similar to those obtained by the
VdP measurements. Earlier reports have attempted to
extract the electron density from the ratio between the X
and X$^-$ intensities [12]. We have found that this
method does not give an electron density that is linear
in $V_g$. Furthermore, the resulting electron densities are
substantially lower than the actual ones.

![Figure 2](image2.png)

**FIG. 2.** a) The numerator, $\rho$, of the X$^-$ Lorentzian as a function of $V_g$ for six laser intensities. b) The electron density $n_e$ as a function of $V_g$, obtained by applying Eq. (2) to the data of (a). Inset: $n_e$ as a function of $V_g$ obtained from VdP measurements.

![Figure 3](image3.png)

**FIG. 3.** a) The fluctuations in $\rho$ and in the X peak energy $E_{\text{peak}}$, along a line scan of 5.5 $\mu$m at $n_e = 3.1 \times 10^{10}$
cm$^{-2}$. Note the correlation between the two curves. b) A two-dimensional histogram of $\rho$ and $E_{\text{peak}}$ for the whole
scoped area ($\sim$ 3000 points).

Let us try now to understand the origin of the inhomoge-
neous broadening of the X line. We have shown above
that the neutral exciton peak energy, denoted as $E_{\text{peak}}$, exhibits large spatial fluctuations (Fig. 3b). Examining
these fluctuations in the near-field spectra, we find
that they are strongly correlated with the fluctuations
in the X$^-$ intensity, and hence with the local electron
density. Figure 3b shows the results of a line scan over
5.5 $\mu$m with steps of 0.05 $\mu$m. At each spatial point
we extract the values of the parameters $E_{\text{peak}}$ and $\rho$. It
is clearly seen that the fluctuations in $\rho$ are in phase
with those of $E_{\text{peak}}$: Their minima and maxima occur at nearly the same spatial locations. To determine the relation between the fluctuations in the local density and in the peak energy we plot in Fig. 3 a two-dimensional histogram of the energy difference $\Delta E = E_{\text{peak}} - E_{-\text{peak}}$ and $\rho$ for all $\sim 3000$ points in the scanned area at one gate voltage (we normalize $\rho$ by dividing it by its average value). Using Eq. 2 we can relate $\rho$ and $n_e$, and hence express the horizontal scale in units of electron density (upper axis). The correlation between $\Delta E$ and $n_e$ is clearly visible, and emphasized by the line, which is a linear fit for the measured $\sim 3000$ points. It is important to emphasize that the relation between $\Delta E$ and $n_e$ holds locally, regions with high (low) electron density giving rise to large (small) $\Delta E$. Since $E_{-\text{peak}}$ is nearly constant (Fig. 3) the major contribution to the fluctuations in $\Delta E$ comes from fluctuations in $E_{\text{peak}}$ [4]. We can therefore conclude that the dominant cause of the X inhomogeneous broadening is local density fluctuations. These fluctuations occur on a length scale of the order of the spacer width [5], which is smaller than our spatial resolution. Hence, each near-field point unavoidably measures a distribution of electron densities, giving rise to inhomogeneous broadening of the X line already in the near-field spectrum. We note that the broadening of the two-dimensional histogram is independent of $n_e$, and we believe that it is due to exciton diffusion, characterized by a diffusion length of $\sim 1 \mu$m: Excitons that are created in a low electron density region may diffuse to a high density region and recombine there.

The dependence of $\Delta E$ on $n_e$ was recently a subject of intensive interest. Theoretical analysis predicts that this energy difference should depend on the density as $\Delta E = \mu(n_e) + E_B$, where $\mu$ is the 2DEG chemical potential and $E_B$ is the X$^-$ binding energy [6]. This dependence should be understood as follows: When an X$^-$ is neutralized to form an X, the released electron is placed at the chemical potential energy. Hence, the cost in energy of this process is the sum of the binding energy and the chemical potential. This relation was recently studied experimentally [7, 13]. It was shown that while it holds at high densities, a weaker dependence of $\Delta E$ on $n_e$ is measured in the low density regime [17]. Indeed, the slope of the histogram is smaller by more than a factor of three than that expected from theory. The fact that the far-field inhomogeneous exciton lineshape is directly related to the electron density fluctuations gives a powerful and simple tool for determining these fluctuations.

In conclusion, we have shown that the PL spectrum of a low density 2DEG can be quantitatively understood in terms of the underlying microscopic properties of the 2DEG. We have presented simple and novel methods to extract the average electron density and its fluctuations from the far-field PL spectrum.

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[1] K. Kheng et al., Phys. Rev. Lett. 71, 1752 (1993).
[2] G. Finkelstein, H. Shtrikman and I. Bar-Joseph, Phys. Rev. Lett. 74, 976 (1995).
[3] A. J. Shields et al., Phys. Rev. B51, 18049 (1995).
[4] A.L. Efros, Solid State Commun. 65, 1281(1988) and 70, 253 (1989); A.L. Efros, F.G. Pikus, and V.G. Burnett, Phys. Rev. B47, 2233 (1993).
[5] J.A. Nixon and J.H. Davies, Phys. Rev. B41, 7929 (1990).
[6] G. Eytan et al., Phys. Rev. Lett. 81, 1666 (1998).
[7] G. Eytan, et al., Ultramicroscopy 83, 25 (2000).
[8] K. Karrai and R. D. Grober, Appl. Phys. Lett. 66, 1842 (1995).
[9] A. Menassen et al., Phys. Rev. B54, 10609 (1996).
[10] L.J. van der Pauw, Phillips Res. Rep. 13, 1 (1958).
[11] The VdP measurements were performed on a different device, processed from the same wafer. Hence, $V_0$ is different.
[12] S. Glasberg et al., Phys. Rev. B59, R10425 (1999).
[13] A. Ron et al., Solid State Commun. 97, 741 (1996).
[14] The width of the distribution of $\Delta E$ in smaller than that of $E_{\text{peak}}$. This implies that some fluctuations, which are common to X and X$^-$ and do not depend on electron density, were subtracted. The most likely source of these common fluctuations is well width fluctuations.
[15] P. Hawrylak, Phys. Rev. B 44, 3821 (1991); J. Brum and P. Hawrylak, Comments on Cond. Matt. Phys. 18, 135 (1997)
[16] V. Huard et al., Phys. Rev. Lett. 84, 187 (2000).
[17] G. Yusa, H. Shtrikman, I. Bar-Joseph, to be published in Phys. Rev. B (2000).