Many-Body Effects in a Modulation-Doped Semiconductor Quantum Well

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(Received 3 August 1987)

The electron areal concentration n_s of a one-sided 130-Å-thick GaAs-Ga(Al)As modulation-doped quantum well is continuously varied from 0 to 6.6×10^{11} cm^{-2} by use of a Schottky gate. This allows one to study the precise evolution of the luminescence and excitation spectra with increasing n_s. From a comparison between the measured peak positions and Hartree calculations of the energy levels, a measurement of the band-gap renormalization is obtained.

PACS numbers: 73.20.Dx, 71.35.+z, 71.45.−d

On account of improved quality, it has become possible to perform accurate optical studies of modulation-doped quantum wells (MDQW).[1,2] Clear experimental answers can thus be given to such issues as the manifestation (and magnitude) of many-body effects (i.e., exchange and correlation effects) in high-mobility one-type carrier plasmas. Such answers are obscured in bulk materials by the interplay between many-body and heavy-doping effects. On the other hand, neutral two-component plasmas can be studied by line-shape fittings of photoluminescence lines in the high-excitation regime.[3] The carrier concentration n_S of a MDQW has already been varied by illumination.[4] The purpose of this Letter is to present what we believe to be the first experimental study of the precise evolution from optical spectra totally dominated by excitonic effects to those characterizing the one-component plasmas in which the excitons have disappeared because of screening and phase-filling effects. We have performed photoluminescence (PL) and photoluminescence excitation (PLE) spectroscopy measurements in the low-excitation regime ($\simeq 0.1$ W/cm^2) on a sample where n_S is controlled via a Schottky gate[5] from 0 to 6.6×10^{11} cm^{-2} at $T=2$ K. We were able to cover a $k_F a_0$ range between 0 and $\simeq 2.5$, where k_F is the Fermi wave vector $[k_F=(2\pi n_S)^{1/2}]$, and $a_0 \simeq 138$ Å is the three-dimensional effective Bohr radius.[6] These experiments thus permit us to test the validity of recent calculations of many-body effects in quasi-2D systems.[7-9]

The investigated sample consists of a semi-insulating GaAs substrate followed by a 1.3-μm buffer layer, a GaAs-$Ga_{0.61}Al_{0.39}As$ superlattice (nominally 5×420 Å $+6\times680$ Å, followed by 7×35 Å$+8\times115$ Å) used to improve the quality of the inverted Ga(Al)As-GaAs interface, and by the nominally 150-Å-thick MDQW; all these layers are nominally undoped. The electrons transfer into the one-sided MDQW through a 480-Å-thick undoped $Ga_{0.61}Al_{0.39}As$ spacer from a 330-Å Si-doped ($N_D=3.5\times10^{18}$ cm^{-3}) $Ga_{0.61}Al_{0.39}As$ layer. A 20-Å doped ($N_D=5\times10^{18}$ cm^{-3}) $Ga_{0.61}Al_{0.39}As$ layer and a 240-Å undoped layer cap the structure. Two Ge-Au Ohmic contacts to the channel, separated by 4 mm, allow the determination of n_S at 2 K by Shubnikov–de Haas measurements. Without a Schottky gate and under the same illumination conditions as those in optical experiments we measured $n_S=3.2\times10^{11}$ cm^{-2}. The PL line peak position was found to be Stokes shifted from

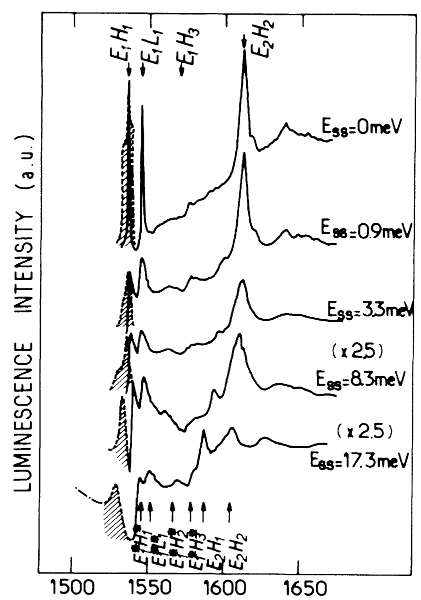

FIG. 1. PLE (full curve) and PL (shaded area) of the investigated structure at various Stokes shifts E_{SS} induced by various voltages on the Schottky gate. E_{SS} is the Stokes shift occurring between the luminescence peak and the first excitation peak. The assignment of the lines is explained in the text. The transitions marked by an asterisk occur at $k=k_F$.

the first PLE peak by $E_{SS}=13$ meV.

A 100-Å-thick semitransparent (2×2 mm^2) Cr Schottky contact was evaporated between the two Ohmic contacts, thus realizing a quantum well (QW) based field-effect transistor. The Schottky gate was biased by V_S with respect to the grounded Ohmic contacts. For $V_S \le 0.3$ V, the QW channel was completely empty of electrons. Figure 1 (upper curve) shows the characteristic PL (dashed areas) and PLE spectra of the empty QW. Very sharp excitonic peaks corresponding to the E_1H_1 (fundamental conduction and heavy-hole subbands) and E_1L_1 (light-hole subband) transitions are observed in PLE, as well as the weakly allowed E_1H_3 line and the sharp E_2H_2 excitonic peak. The structures in the PL can be accounted for by well-width fluctuations. There was essentially no Stokes shift between PL and PLE. As V_S increased, the channel was filled with electrons and a Stokes shift E_{SS} between PL and PLE appeared. Also, the sharpness of the two first excitonic peaks dramatically decreased because of screening and occupancy effects: PL involves E_1H_1 band-to-band transitions at in-plane wave vector $k=0$, while the first two peaks of PLE, $E_1^*H_1^*$ and $E_1^*L_1^*$ involve band-to-band transitions at $k=k_F$ (marked by an asterisk). Note in Fig. 1 ($E_{SS}=0.9$ meV) that the sharpness of the E_2H_2 peak, which involves an empty conduction subband, is much less affected than that of the $E_1^*H_1^*$ or $E_1^*L_1^*$ transitions. When V_S was further increased, E_{SS} increased and the PLE structures were reduced. In addition, the PLE spectra increasingly displayed the $\Delta n \neq 0$ transitions, including Δn odd lines. This result is expected since with increasing n_S, the QW becomes more and more asymmetric, because of the band bending induced by the 2D electron gas located near the spacer layer. Finally, Fig. 1 shows a striking red shift of the PL peak position with increasing n_S. This red shift is accompanied by a broadening of the PL line: The half width at half maximum is $\simeq 1$ meV at $E_{SS}=0$ and reaches 7 meV at $E_{SS}=17.3$ meV where a high-energy tail develops (apparent temperature $\simeq 17$ K).

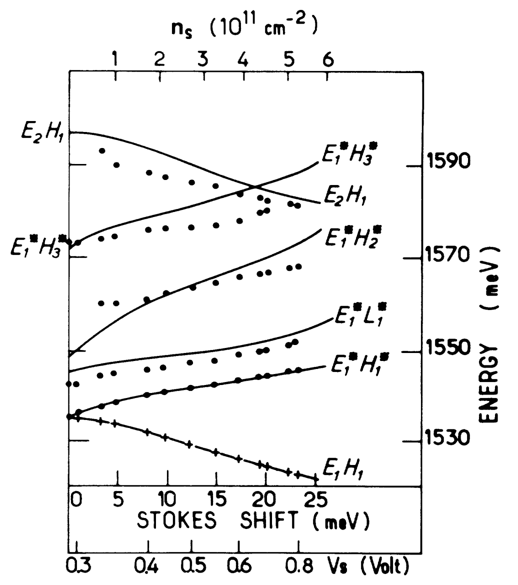

FIG. 2. Fit between the experimental PL (crosses) and PLE (circles) measurements and calculated Hartree energies corrected by a n_S-dependent but subband-independent renormalization energy, as explained in the text. The data are plotted as functions of the experimental applied Schottky voltage V_S and the theoretical carrier density n_S corresponding to the same Stokes shift E_{SS}. The transitions marked by an asterisk occur at $k=k_F$.

The subband-edge energies as well as the valence-band dispersion relations have been calculated by our self-consistently solving the Poisson and Schrödinger equations at different n_S using the envelope function approximation and the Luttinger Hamiltonian for the valence band.[2] In the empty QW, the best fit for the PL peak position was found for a well width of 130 Å and a E_1H_1 exciton binding energy of 7.5 meV.[10] A 14.5-meV Stokes shift was then calculated for $n_S=3.2\times10^{11}$ cm^{-2}, which corresponds to the ungated structure. This compares favorably with the experimental results (13 meV). Thus in the gated structure, the n_S values can be confidently extracted from the E_{SS} measurements. This allows a comparison between the measured PLE peak positions and Hartree calculations performed at the same n_S. Although predicting a red shift due to band bending, the calculations are unable to quantitatively account for the actual PL variation with n_S: It is necessary to use a band gap smaller than the bulk GaAs one to obtain good agreement between the absolute positions of the calculated and observed transitions. The comparison between the experimental points and the theoretical curves for several transitions is shown in Fig. 2. These

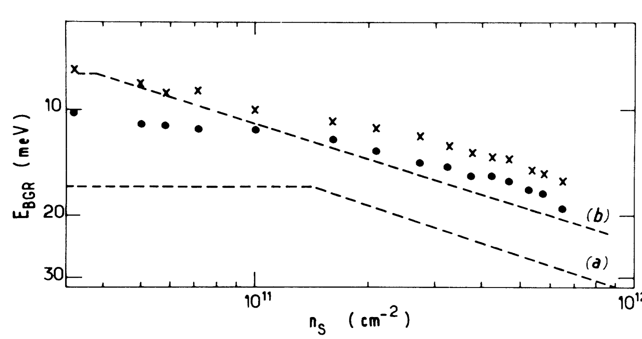

FIG. 3. Measured band-gap renormalization (BGR) for E_1H_1 transition (crosses) and $E_1^*L_1^*$ transition (circles) as a function of n_S. The theoretical results are as follows: a, taken from Ref. 7, $E_{BGR}=-3.1(n_S a_{2D}^2/2)^{1/3}E_{2D}$, in a pure 2D gas, with $E_{2D}=16.8$ meV, $a_{2D}=69$ Å, and with a factor $\frac{1}{2}$ to take into account the one-component character of the plasma investigated here; and b, from Ref. 8 in a symmetric n-type MDQW of thickness 217 Å.

theoretical curves were obtained by our subtracting from the Hartree calculation a n_S-dependent, but subband-independent, renormalization energy chosen to ensure a good fit of the E_1H_1 PL line. The overall agreement is fairly good, demonstrating that the Hartree calculations provide a correct assignment of the observed lines.

At zero density, this renormalization energy is the binding energy of the E_1H_1 exciton due to electron-hole correlation. Note that a portion of the discrepancies in Fig. 2 can be attributed at $n_S = 0$ to the subband dependence of the exciton binding energy. At large density, this renormalization energy is the band-gap renormalization (BGR) due to the many-body exchange and correlation effects. We now turn our attention to the n_S dependence of the BGR energy. The crosses of Fig. 3 show the BGR energy deduced from the E_1H_1 line. This energy is equal to 12.5 (15.5) meV at $n_S = 3.2 \times 10^{11}$ (6×10^{11}) cm^{-2}. At high density the slope of the BGR curve versus n_S in a double-logarithmic plot is consistent with a $n_S^{1/3}$ functional dependence. This scaling law was predicted to occur in the $10^{11}-10^{12}$ $\text{cm}^{-2} n_S$ range due to exchange and correlation effects.[7,8] Quantitatively, however, our findings are smaller than the theoretical predictions (dashed lines in Fig. 3) which are derived for structures different from our own: *a*, two-component idealized 2D plasmas[7] or *b*, symmetrically doped quantum wells.[8] In particular, the correlation effects between the photocreated hole and the electrons, which are a significant fraction of the BGR, ought to be smaller in our asymmetrical well than in symmetrical ones because of the spatial separation between the electrons and holes induced by the band bending. The transition between an excitonic PL, at low n_S (constant PL energy that we have schematized in theoretical curves of Fig. 3), and a PL involving band-to-band luminescence is difficult to determine from our experiments. Nevertheless, it is constant with a 5×10^{10} cm^{-2} order of magnitude found by space-filling considerations.[7,11,12] Finally, a check of the validity of a k- and subband-independent rigid shift of the one-particle states can be attempted. In Fig. 3, the dots refer to the BGR deduced from the calculated and measured $E_1^*L_1^*$ excitation peaks. The larger value of the BGR scales well to the larger value of the binding energy of the excitation found at low n_S (10 meV). It is clear that nothing can be asserted on higher energy transitions, because of the uncertainties of the Hartree calculation (in particular, a parabolic conduction band was assumed) and the lack of an exact theory of BGR in the asymmetric finite-thickness case. Nevertheless, the delay in the disappearance of the sharp E_2H_2 exciton peak, with respect to the $E_1^*H_1^*$ one, shows clearly the importance of the occupied and unoccupied character of the subband in the behavior of the excitation resonance.

In conclusion, the carrier density in a GaAs-Ga(Al)As MDQW has been controlled by a Schottky gate. PL and PLE spectroscopy measurements have been performed, at low temperature and low-excitation regime, in a quasi-2D one-component plasma, from 0 to 6.6×10^{11}-cm^{-2} areal density. The transition from an excitonic to a plasma behavior is observed. By comparison with the results of a Hartree calculation of the transition energies, quantitative information is obtained on the BGR, yielding a probe of many-body theories.

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