Solid State Communications, Vol.59,No.9, pp.613-617, 1986.
Printed in Great Britain.

0038-1098/86 $3.00 + .00
Pergamon Journals Ltd.

BAND GAP RENORMALIZATION IN A GaAs-$Ga_{1-x}Al_xAs$ MODULATION DOPED QUANTUM WELL

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(Received May 1986 by M. Balkanski)

The electron density of a high-mobility 150 Å thick GaAs-$Ga_{1-x}Al_xAs$ one-side modulation doped quantum well can be monitored by illumination with energetic photons or by applying a weak in-plane electric field. The energy of the band to band transition and the carrier density are measured simultaneously by low temperature photoluminescence and photoluminescence excitation spectroscopy experiments. The comparison with the results of a self-consistent calculation in the Hartree approximation gives the density dependence of the band gap renormalization.

High quality quasi two-dimensional Fermi systems are now easily achieved in simple GaAs-$Ga_{1-x}Al_xAs$ heterojunctions by molecular beam epitaxy. Many experimental and theoretical studies of transport properties have been performed in these structures, leading to exciting discoveries like the Quantum Hall effect. Unfortunately, except for the Raman effect [1] ,the simple heterostructures do not allow optical studies as the built-in electric field prevents the photocreated holes to recombine with an electron of the Fermi sea. Such optical studies are possible in modulation doped quantum wells (MDQW) [2], which have been less studied up to now owing to the low carrier mobility associated with the poor quality of the inverted interface (i.e. GaAs grown on the top of GaAlAs). The recent growth of one-side MDQW's leads to an important improvement of the mobility of the carriers [3], partly due to the increased spatial separation achieved between the electron gas and the inverted interface.

One of the fundamental interests of these structures is the study of many body effects in the 2D electron gas. A great amount of work has been done in the 3D case either in metals or in electron-hole plasmas photocreated in semiconductors [4]. The MDQW offers a unique system of a low temperature 2D one-type carrier plasma where the mobility of electrons is high because of the spatial separation between the 2D gas and the donor impurities in the doped part of $Ga_{1-x}Al_xAs$. Recent experiments were performed on nominally symetrically doped QW's of n type [2] or p type [5] with relatively low mobilities or thick GaAs layers, at a given carrier concentration for each sample. Several authors [5,6,7,8] have explained the experimental results in terms of band gap renormalization (BGR), where the effect of exchange and correlation processes is regarded as a rigid shift of the electron and hole bands in the region of band edges towards each other.

In this paper, the photoluminescence and absorption edge energies (obtained by excitation spectroscopy) are measured as a function of the electron density n_s on the same sample. The electron density is varied either by applying a weak in-plane electric field or by illuminating the sample by energetic photons [9] . Using a self-consistent Hartree approximation and the Luttinger Hamiltonian for the valence band, a calculation of the energy levels is obtained and checked both by the assignement of high energy transitions as well as by the zero extrapolation at vanishing n_s where the excitonic effect occurs. The difference between the calculated and experimental energies of the recombination line provides the determination of the density dependence of the BGR.

The experiments described here are performed on a sample consisting in a semi insulating GaAs substrate followed by a 2.5 μm thick GaAs buffer layer, a GaAs-$Ga_{0.61}Al_{0.39}As$ superlattice (7x35Å, 8x100Å), a 15 nm thick

GaAs quantum well, a 30 nm thick $Ga_{0.61}Al_{0.39}As$ spacer layer followed by a 33 nm thick Si-doped ($N_d \simeq 10^{18} cm^{-3}$) $Ga_{0.61}Al_{0.39}As$ layer grown before a 25 nm thick top layer. The mobility was determined by Hall measurements to be higher than $2\ 10^5$ $cm^2/V.s$ in the dark at T=4.2 K. In another experimental set-up, electron density has been measured in an optical cryostat at 2 K in the ambient light by Shubnikov-de-Haas measurements to be in the range of $n_s = 4.5\ 10^{11} cm^{-2}$. This is twice larger than the density measured in the dark, as previously noted by Chaves et al. [9]. It is worth noticing that a calculation of this optical persistent photoconductivity effect performed by adapting Stern's approach to our heterostructure [10] gives the same result. The 2 K luminescence spectrum under weak excitation is reported (in dashed line) in part *a* of fig.1; the onset of the excitation spectrum of the MDQW (continuous line) is also shown. The luminescence peak of the MDQW, indicated by the arrow in figure 1 (the other features are related to the bulk GaAs buffer layer), is attributed to band-to-band transitions near k=0 between the first electron and heavy hole subbands E_1 and HH_1, whereas the two excitation peaks refer to an excitation transition between the heavy (HH_1) and light (LH_1) valence levels towards the E_1 electronic level near $k=k_F$, the Fermi wavevector (see figure 2). The details of the theoretical calculation have been reported elsewhere [11]. The energy of the lowest E_1 level and the built-in potential have been determined using a self-consistent Hartree approximation. Only the first electronic subband is populated. Once the built-in potential is known, the valence-band levels are calculated using the Luttinger Hamiltonian. The results, including the in-plane dispersion curves of the valence band, are schematized in fig.2. The calculated in-plane dispersion of HH_1 is nearly parabolic corresponding to a in-plane heavy hole mass of the order of $m_h \simeq 0.2 m_0$, in good agreement with magnetooptical experiments [12]. Taking a mean value $m_e = 0.07 m_0$ for the electron mass, the Stokes shift between the luminescence and the first excitation peak is calculated to be $E_F(1+m_e/m_h) = 21$ meV for $n_S = 4.5\ 10^{11} cm^{-2}$. This is in excellent agreement with the experimental value. This shows that, conversely, a value of the electronic density can be deduced from the measurement of the Stokes shift with an accuracy of 10%.

An increase of the luminescence energy has been observed [9] under intense illumination by energetic photons. It has been proposed that the holes photocreated in the $Ga_{1-x}Al_xAs$ barrier (the effect does not occur when the carriers are created only in the MDQW) move into the MDQW

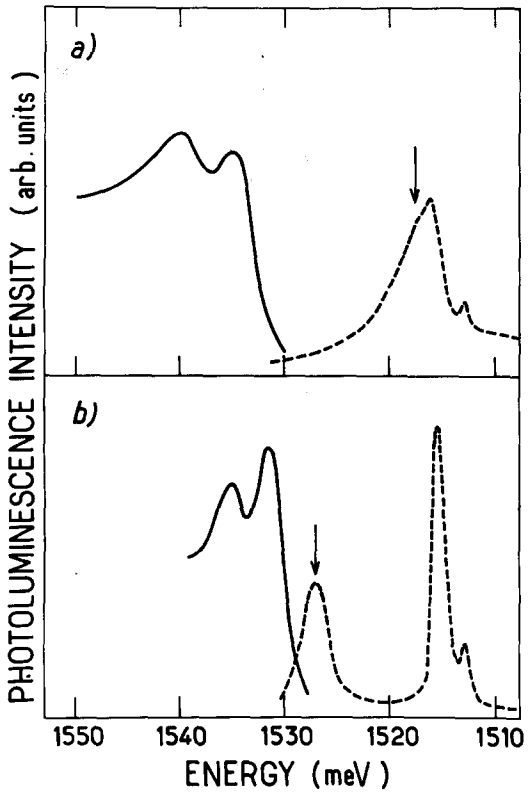

Fig.1 Low temperature Photoluminescence (dashed line) and onset of the excitation spectrum (full line) obtained with a 30 mwatt/cm^2 LD700 dye laser operating at 1650 meV, (*a*) without illumination by an Argon laser, (*b*) under an illumination of the order of 3 watt/cm^2. The excitation spectra are obtained by observing the MDQW luminescence, indicated by an arrow in each figure.

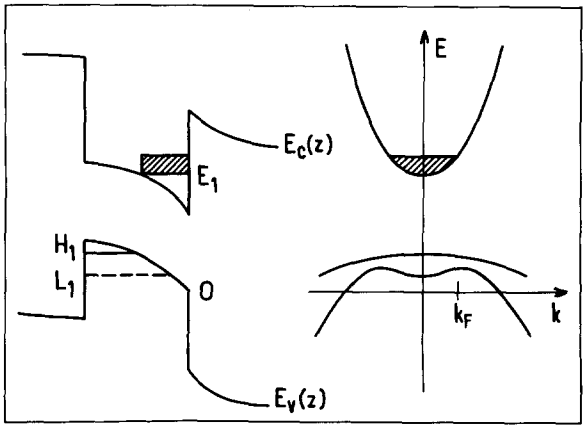

Fig.2 Profiles of the conduction- and valence-band edges in the vicinity of the MDQW (left panel); schematic in-plane dispersion relations (right panel).

and recombine there with the electrons of the Fermi sea, inducing a decrease of the charge density in the MDQW.The steady state process is controlled by tunnelling of electrons from the doped part of GaAlAs towards the QW. The experiment described here consists in exciting the sample with photons from a continuous Argon laser,i.e. of energy higher than the $Ga_{1-x}Al_xAs$ gap energy, and in probing simultaneously the luminescence and excitation spectra by focusing a low power chopped LD700 dye laser of energy close to the DQW band-gap and by measuring the chopped luminescence signal. As shown in part *b* of fig.1, the energy of the luminescence line increases (towards the left of the figure) without apparition of a high- energy tail; moreover, the photoluminescence linewidth decreases by a factor of 2. On the contrary, the first two excitation peaks are shifted towards low energy. The energy positions of the luminescence and excitation peaks as a function of the power of the Argon laser are plotted in part *a* of fig.3. The Stokes shift actually decreases, evidencing a diminution of n_S. Taking for the carrier masses $m_e=0.07m_0$ and $m_h=0.2m_0$, as discussed earlier, a quantitative determination of n_S is made and the crosses in fig.4 show the experimental values of the luminescence energy as a function of this optically-controlled n_S.

It is also possible to control n_S by applying a steady and weak in-plane electric field. A 3 mm length-300 μm width Hall bridge has been processed. Here also, the electronic structure is tested by 2 K luminescence and excitation spectroscopy in the center of the structure. The luminescence energy is found to increase and the energy of the excitation peaks to decrease. At 10V/cm, the Stokes shift between the luminescence and the first excitation peak is reduced to 1meV. These energy shifts are not accompanied by any dramatic heating of the electron gas. The luminescence lines do not develop high energy tails in contrast with other reports [13].The positions of the luminescence and excitation peaks as a function of the applied voltage are reported in part *b* of fig.3. The small features which occur near V=0 may be

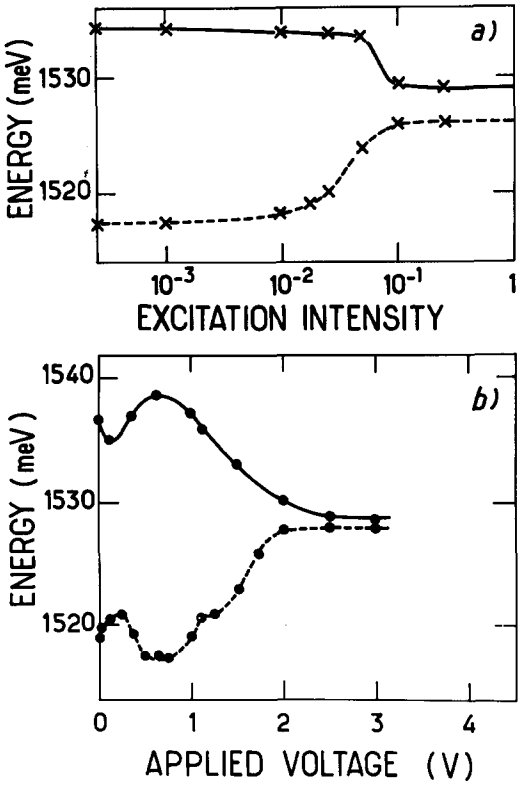

Fig.3 Energy of the photoluminescence peak (dashed lines) and of the first excitation peak (full lines) as a function (*a*) of the intensity of the Argon illumination, (*b*) of the applied in-plane voltage. In case *a* the full scale intensity is of the order of 30 W/cm^2. In case *b* , the length of the Hall bridge is 3mm.

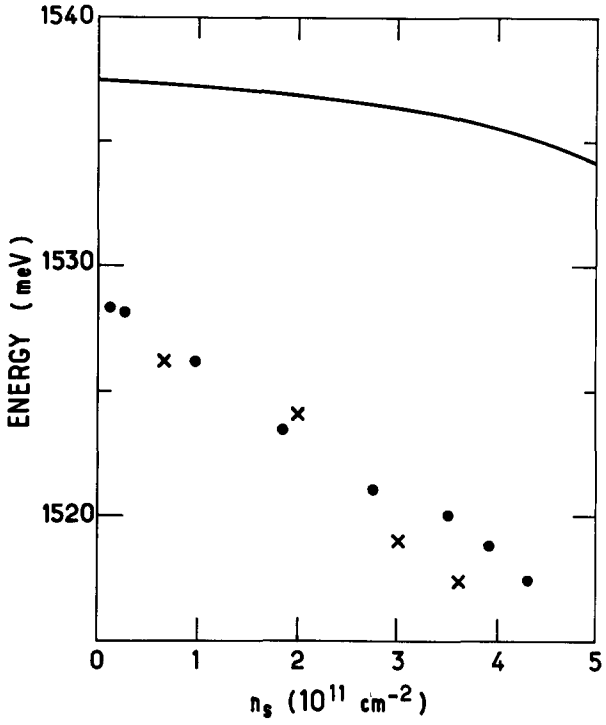

Fig.4 Line: n_S dependence of the band-to-band transition energy calculated in the Hartree approximation as described in the text. Crosses: experimental data obtained by optical control of n_S. Points: experimental data obtained by voltage control.

due to contact problems. Although the physical process responsible for the decreasing of n_S with the applied voltage (or the current which is of the order of 5mA for V=10 Volts) is not clearly understood, it is possible to plot the energy of the luminescence as a function of n_S deduced from the Stokes shift (points in fig.4). The good agreement between the two experimental ways of controlling n_S is striking.

The energy levels and the transition energies of the actual 150Å QW can be calculated as a function of n_S taking into account in a self consistent way the built-in potential as described earlier. The calculated transition energy of the band - to-band luminescence is given by the curve of fig.4. It is always larger than the measured data. We attribute the difference between experiments and calculations to the band-gap renormalization effects, i.e. exchange and correlation effects between the electrons and correlation effects between the photocreated holes and the electrons. Fig.5 gives a measurement of the BGR as a function of the electron density n_S for a one-side MDQW of 150 Å. It varies from 9 meV at n_S=0.5 $10^{11}cm^{-2}$ to 20 meV at 4.5 $10^{11}cm^{-2}$. When $n_S \to 0$, the electron-hole correlation amounts to the exciton binding energy. In fact, this exciton binding energy in a 150 Å GaAs undoped well is = 8 meV [14]. We consider our experimental finding (E_{BGR}=9 meV at $n_S \to 0$) to be reasonably described by exciton effect. At low n_S, there is a compensation between the decrease of the exciton binding energy and the increase of the exchange and correlation effects when n_S increases [15]. For $n_S > 10^{11}cm^{-2}$, the excitons have no longer any bound state [16]. No calculation of the BGR in this peculiar geometry has been performed. Nevertheless, we can attempt, in a first approximation, to compare our experimental results with theoretical ones obtained under various assumptions in symmetrical wells of different widthes. We have reproduced these theoretical results in fig.5. Any serious comparison is outside of the scope of this paper, as the calculations are not related to the actual sample. We simply want to point out the relatively good agreement between our experimental findings and theoretical models.

In conclusion, we have shown that the electron density of a one-side MDQW can be controlled either optically or electrically. By a simultaneous determination of the luminescence and excitation spectra by a low-power dye laser, the luminescence energy and the Stokes shift between excitation and luminescence (and thus the electron density) have been measured. By using a self-consistent calculation, we have determined the band-to-band energy in the Hartree approximation. The difference with experiment, checked at $n_S \to 0$, has provided the fist direct measurement of the density dependence of the band-gap renormalization in a high quality 2D system. A more detailed comparison between our experiments and theoretical models requires the peculiar shape and width of the well to be taken onto account into the calculations.

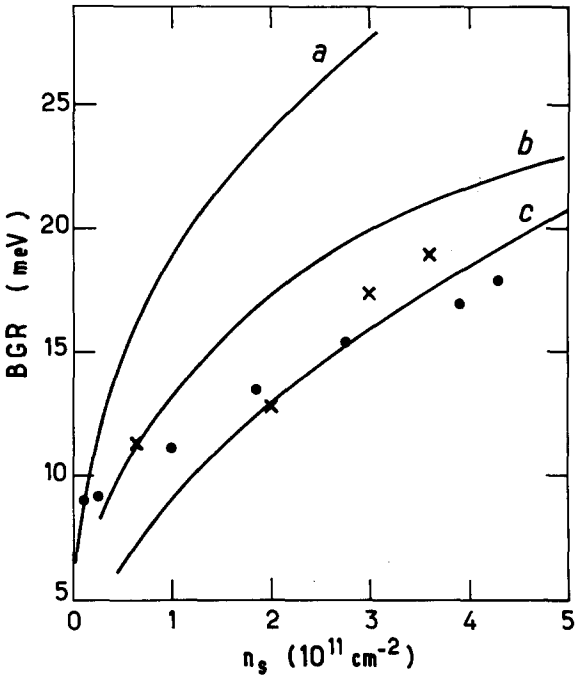

Fig5 Crosses and points: experimental n_S dependence of the band gap renormalization obtained from fig.4 as described in the text. Theoretical curves: (a) ref.[8], in a idealized 2D system; (b) ref.[5], by interpollation between calculations performed on a 81Å thick QW and on a 217Å thick QW; (c) ref.[7], in a idealized 2D system, taking for the BGR the electronic exchange energy e^2k_F/ε, where ε=12.4 is taken for the dielectric constant of GaAs.

One of us (J.A.B.) would like to express his gratitude to the Conselho Nacional de Desenvolvimento Cientifico e Tecnologico (CNPq) for financial support.

References

[1] G. Abstreiter and K. Ploog, Phys. Rev. Lett. 42, 1308 (1979).

[2] A. Pinczuk, J. Shah, R.C. Miller, A.C. Gossard and W. Wiegmann, Solid State Commun. 50, 735, 1984.

[3] H. Burkhard, W. Schlapp and G. Weimann, to appear in Suface Science.

[4] T.M. Rice, in *Solid State Physics* , edited by H. Ehrenreich, F. Seitz and D. Turnbull (Academic, New York, 1977), Vol. 32, pp. 1-86.

[5] D.A. Kleimann and R.C. Miller, Phys. Rev. B 32, 2266 (1985).

[6] G. Bauer and T.Ando, Phys. Rev. B 31, 8321 (1985).

[7] Yia-Chung Chang and G.D. Sanders, Phys. Rev. B 32, 5521 (1985).

[8] S. Schmitt-Rink, C. Ell , S.W. Koch, H.E. Schmidt and H. Haug, Solid State Commun. 52, 123 (1984).

[9] A.S. Chaves, A.F.S. Penna, J.M. Worlock, G. Weimann and W. Schlapp,
to appear in Surface Science.

[10] F. Stern, to appear in Surface Science.

[11] M.H. Meynadier, J. Orgonasi, C. Delalande, J.A. Brum, G. Bastard,M. Voos, G. Weimann and W. Schlapp, to appear in Phys. Rev. B.

[12] J. Orgonasi, J.A. Brum, M.H. Meynadier, G. Bastard, C. Delalande, J.C. Maan, G.Weimann and W. Sclapp, submitted to publication.

[13] J. Shah, A. Pinczuk, H.L. Störmer, A.C. Gossard and W. Wiegmann, Appl. Phys. Lett. 44, 322 (1984).

[14] R.L. Greene, K.K. Bajaj and D.E. Phelps, Phys. Rev. B 29, 1807 (1984).

[15] S. Schmitt-Rink and C. Ell in *High excitation and short pulse phenomena* edited by M.H. Pilkuhn (North Holland, Amsterdam, 1984), p. 585.

[16] D.A. Kleimann, Phys. Rev. B 32, 3766 (1985).