Grand canonical equilibrium of two-dimensional electrons confined in asymmetric $Al_xGa_{1-x}As/GaAs$ heterostructures in a quantizing magnetic field

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(Received 23 October 1998; revised manuscript received 22 March 1999)

The energy of electronic states of a two-dimensional electron gas (2DEG) confined in a one-sided *n*-doped $Al_xGa_{1-x}As/GaAs$ asymmetric quantum well (QW) in a perpendicular magnetic field B is studied using low-temperature photoluminescence experiments. The interband Landau-level energies show an oscillatory B dependence. This oscillatory behavior does not depend on QW width and is sensitive to the carrier concentration N_s of the 2DEG. These observations disagree with what one would expect from many-body theory. A theoretical model is developed assuming that, under continuous illumination, the 2DEG is in grand canonical equilibrium with the rest of the structure. Then, N_s may change from that at $B=0$ because of the B dependence of the density of states. In these semi-equilibrium conditions, the Fermi level should stay flat across the structure and should not depend on B. This study shows that, in asymmetric modulation doped quantum wells, the electronic transfer can be the main factor in the oscillatory behavior of interband transition energies as a function of B. [S0163-1829(99)01135-2]

Low-temperature photoluminescence (PL) experiments on $Al_xGa_{1-x}As/GaAs$ modulation doped quantum wells (MDQW's) have been of great interest for several years. In particular, PL studies in the presence of magnetic field have led to a wealth of very useful investigations on the two-dimensional (2D) character and on the physical properties of the two-dimensional electron gas (2DEG) confined at the $Al_xGa_{1-x}As/GaAs$ interface.[1] It has been, for example, experimentally revealed that the energy of interband Landau-level (LL) transitions oscillates as a function of B.[2–7] These oscillations do not exist in the magneto-optical spectra of undoped quantum wells (QW's).[8]

One reason invoked to interpret such an interesting feature was the Fermi-energy jumps between different LL's which may originate from different occupied electric subbands.[9] Since these have different spatial extents of their wave functions, different occupation implies different charge distribution. This gives rise to a deformation of the confinement potential causing a change of subband energies when B varies.

The phenomena commonly assumed for the steplike behavior of the PL energies with increasing B requires a correction involving the self-energy of electron and hole arising from many-body interactions.[10] This model was generally compared to experimental results in the case of *n*-doped symmetric QW's. In this case, the self-energy from electron-hole (e-h) interaction is the most important in explaining the magnetic oscillation of PL energy. These oscillations arise from the oscillation in the screening due to the discrete density of states (DOS). However, it was both theoretically[11] and experimentally[12] established that the contribution from e-h interactions to the spectral position of the luminescence line is strongly dependent on the spatial separation between the 2DEG and photogenerated holes. Therefore, it is interesting to perform magneto-luminescence measurement on a one-sided *n*-doped asymmetric QW. This structure has the advantage that one can control the strength of the e-h interaction by changing the well width. Consequently, in this system, the competition between electron-electron (e-e) interaction and e-h interaction is very sensitive to the QW's size. The amplitude and the phase of resulting magnetic oscillations are controlled by changing e-h separation when the well width changes.[13]

In this paper, we report on experimental observations of this oscillatory behavior of interband LL transitions in three different asymmetric QW's which we selected with different well widths, and (or) a different 2DEG density N_s. The main aim of this work is to compare the many-body approach with the experimental results obtained on these specific samples. A qualitative disagreement is clearly identified and discussed.

An attempt to describe the energy of interband LL transitions in increasing B is proposed here. We think that the

TABLE I. Characteristics of the investigated samples: L_w is the well width; d_0 is the spacer thickness; $N_d(\delta_0)$ is the surface density of Si donors for the closest plane from the $Al_xGa_{1-x}As/GaAs$ interface; N_s is the 2DEG density in the dark (I) and under illumination (II); μ is the 2D electron mobility under illumination.

Samples	LW (Å)	$N_d(\delta_0)$ [$\times 10^{11}$ cm^{-2}]	d_0 [Å]	N_s [$\times 10^{11}$ cm^{-2}] I	II	μ [$\times 10^5$ cm^2/Vs]
A	130	10	110	5.3	7.8	2.5
B	250	3.3	110	3.6	7.6	4.6
C	250	5	100	6.3	8.5	4.5

oscillating B dependence is a signature of the existence of gaps in the LL energy spectrum as well as of the linear B dependence of bidimensional DOS. Consequently, when B varies, the 2DEG system has to exchange electrons with a large reservoir made of the whole of the structure, so that the grand canonical equilibrium condition is satisfied. This condition requires that the Fermi energy should stay flat across the sample and should be magnetic field independent. The hypothesis of an external reservoir was first proposed by Baraff and Tsui to explain quantum Hall plateaus.[14] Using the reservoir hypothesis one can describe not only the quantum Hall effect and the Shubnikov–de Haas effect,[15] but also the oscillations of magnetization and thermoelectric power.[16] In our experimental conditions, namely under continuous illumination, one can certainly assume that the 2DEG is not isolated but in contact with the whole of the structure which represents the grand canonical reservoir.

Our investigations are based on magnetoluminescence measurements performed on $Al_xGa_{1-x}As/GaAs$ single QW structures, grown by molecular beam epitaxy (MBE), with well widths L_w of 130 and 250 Å. The value of N_s under optical excitation was measured using magnetotransport experiments and varied from sample to sample between 7.6×10^{11} cm^{-2} and 8.5×10^{11} cm^{-2} (see Table I). Details on the investigated samples and on the experiments are given in Ref. 17. At zero field, we observed an asymmetric broad line with a spectral weight shifted towards higher energies. The position of this line depends on N_s and on QW width. When B is applied, the broad line splits into separate peaks, related, in the first approach, to the transition between conduction-band and valence-band LL's. Note that we have not observed any difference between the spectra measured on samples with contacts and the spectra measured on samples without contacts. A typical fan chart of the observed magnetoluminescence peaks related to LL transitions is shown in Fig. 1 (sample A). As shown in Fig. 1, the LL transitions present a nontrivial oscillatory behavior as a function of B.

It is clear that the observed energy oscillations cannot be explained by the assumption of a possible electronic redistribution between different occupied electric subbands when B varies, since only one subband is populated for sample A with L_w=130 Å.

In symmetric QW structures, Uenoyama and Sham[10] as well as Katayama and Ando,[10] attributed the oscillatory behavior of LL transitions to the self-energy correction of electrons and holes. The conduction e-e screened interaction term and the electron exchange term tend to cancel each other out. Such cancellation does not occur for holes since only the e-h screened interaction term is present and gives then the dominant term in the oscillatory behavior of the total energy. This term depends on electron occupation through the dielectric screening. When the filling factor ν is an even integer, the screening effect is minimum, and consequently the e-h interaction term shows an anomalous shift from the linear B dependence. Note that the amplitude of this shift is very sensitive to the LL's broadening parameter Γ and that the period of the experimental oscillations does not coincide with the period of the many-body oscillations: experimentally the shift is observed for values of ν smaller than the even values (see Ref. 10). Recently,[13] the authors of this model theoretically predicted that, in asymmetric QW structures, the phase and the amplitude of the induced many-body effect oscillations are strongly dependent on QW width. This is due to the competition between e-h and e-e interactions. In the narrow-well limit, the e-h interaction dominates and shows oscillations with blue-shift peaks. In the large-well limit, the e-h interaction vanishes because of spatial separation between the 2DEG and the photogenerated holes and the dominating term is then the e-e interaction which shows oscillations with red-shift peaks. In Ref. 13, the calculation was

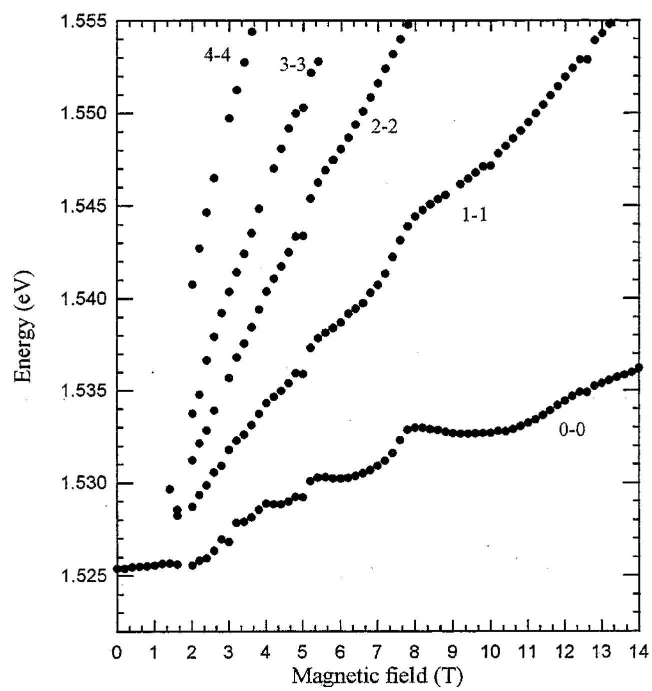

FIG. 1. A representative fan chart of the magnetoluminescence peaks at T=4.2 K for sample A.

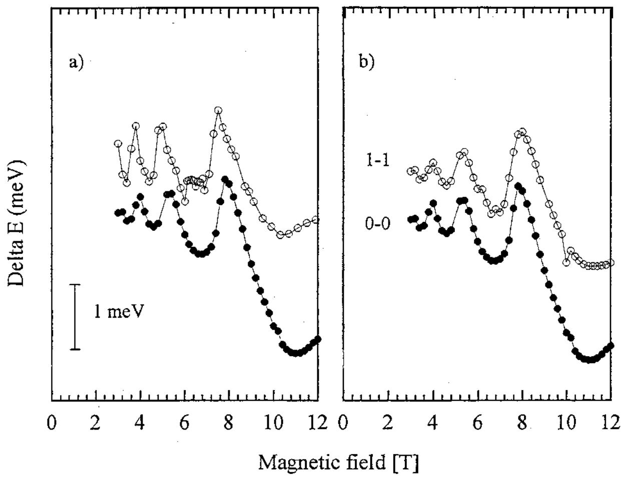

FIG. 2. (a) Low temperature ($T=4.2$ K) magnetoluminescence oscillation of the ground state energy transition 0-0, after subtracting the linear B dependence, for sample A with $L_w=130$ Å (closed circles) and for sample B with $L_w=250$ Å (open circles). The two samples have approximately the same carrier concentration $Ns \approx 7.7\times 10^{11}$ cm^{-2}. (b) The magnetoluminescence oscillations taken from sample A with $L_w=130$ Å. The closed circles represent oscillations of transition energy 0-0, the open circles represent the oscillations of transition energy 1-1. The linear dependence on B has been subtracted.

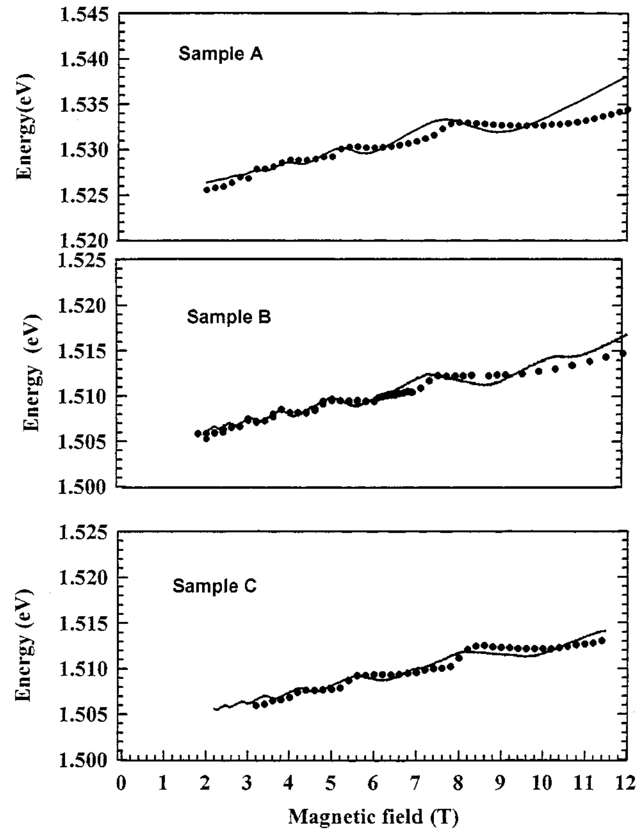

FIG. 3. Experimental (circles) and calculated (solid lines) transition energy 0-0 at 4.2 K, as a function of B for the three investigated samples.

performed in one-sided n-doped $Al_xGa_{1-x}As$/GaAs sample with $N_s=2.2\times 10^{11}$ cm^{-2}. The transition from blue-shift to red-shift occurs for widths between 200 and 300 Å. Furthermore, in this case of asymmetric QW, higher carrier concentration induces more e-h separation and consequently, the critical well width to this change of phase should be achieved at $L_w<200$ Å. In any case, this phase change is a crucial test to identify the clear mechanism of the experimentally observed magnetic oscillations of PL energy.

For the three investigated samples (A,B,C), the period and the amplitude of the observed oscillations do not depend on the electron and hole LL index. Also, they seem to be sensitive to N_s but quasi-independent on L_w. Figure 2(a) shows a comparison of the fundamental energy transition line referred to as 0-0, with respect to the reference energy of $E(B)=1.524$ eV$+0.705$ meV/T for the 130 Å well width (sample A) and $E(B)=1.502$ eV$+0.950$ meV/T for 250 Å well width (sample B). The two samples have nearly the same N_s but two different QW widths. It can be seen that both results are very similar and no phase change was observed unlike predictions of the many-body effect model. Moreover, the observed oscillations are quasi-independent of QW width. An other interesting point is that the amplitude of the observed oscillations increases with N_s. Figure 3 shows such comparison measured from sample B and sample C having the same well width and different N_s. Again, this result disagrees with what one would expect from the many-body effect model. It is also remarkable from Fig. 2(b) that these oscillations are LL index independent. Thus, we conclude that the observed oscillations cannot be explained by the oscillatory behavior of the many-body interactions.

Our approach in interpreting such features is based on two considerations. On the one hand, under continuous illumination, the 2DEG system is in grand canonical equilibrium with the whole surrounding structure which plays the role of the reservoir. This result was experimentally established by Haynes *et al.*,[18] by Kukuskin *et al.*,[19] as well as by Plentz *et al.*[12] who showed that, at $B=0$, the Fermi energy remained constant when the 2D density N_s increased while, in the same conditions, the bottom of the first electronic subband decreased. On the other hand, when B varies, the 2DEG exchanges electrons with the reservoir as a consequence of the DOS dependence on B and because of the existence of gaps in the energy spectrum of the 2DEG. Then N_s varies according to the electron distribution equation:

$$N_s(B)=\frac{eB}{h}\sum_{n,s}\sqrt{\frac{2}{\pi}}\frac{1}{\Gamma}\int\frac{\exp\left(-2\left(\frac{E-E_{0,n,s}}{\Gamma}\right)^2\right)}{1+\exp\left(\frac{E-E_F}{KT}\right)}dE, \tag{1}$$

where Γ is the electron LL broadening parameter and $E_{0,n,s}$ is the ns^{th} LL energy related to the lowest electrical subband.

In the following, we concentrate on the fundamental transition energy 0-0. To calculate this energy at fixed B, we use a self-consistent procedure to solve the Schrödinger equation for the eigenfunctions and eigenvalues, the Poisson equation for the confinement potential, and the electron distribution Eq. (1) for the carrier concentration. In our calculation, we take into account the spin-splitting enhancement by the exchange interaction of electrons.[20] We assumed a pinned Fermi energy across the sample. The results obtained from our calculation show an oscillating shape of N_s vs B. In the quantum-Hall plateau regimes, N_s follows the variation of the DOS and increases linearly with B. In the quantum-Hall uphill regimes N_s falls, following the total number of states in the 2DEG. The variations of N_s induce oscillations of the energy profile and consequently of the electron and hole LL energies. According to this model, the anomalous blue-shift from linear B dependence occurs for values of the filling factor smaller than the even values predicted by the many-body effect model. The corresponding data are presented in the insets of Fig. 3, together with the dependence of the 0-0 transition energy on B. It can be seen from this plot that the charge transfer approach reproduces remarkably well the observed oscillations of interband LL transitions measured for different samples. The most remarkable observation is that the amplitude of these oscillations depends neither on QW width nor on LL index as observed experimentally. Indeed, in the asymmetric QW case, the degenerate 2DEG system is confined at the interface between the $Al_xGa_{1-x}As$ doped barrier and the GaAs well. In the region of spatial confinement of electrons, the band-bending profile is more sensitive to carrier-concentration change than in the region of spatial confinement of holes. Consequently, the oscillations of the energy profile as well as the oscillations of the energy of the electron and hole ground subbands are quasi-insensitive to QW width and depend only on 2DEG carrier density N_s.

Besides this, if one uses a simple parabolic approximation, the electron-hole LL transition takes the form

$$E_{\mathrm{PL}}(n,B)=E_e(B)-E_h(B)+\left(n+\frac{1}{2}\right)\frac{\hbar eB}{m^*_{\mathrm{red}}}, \qquad (2)$$

where $E_e(B)$ and $E_h(B)$ are, respectively, magnetic-field dependent electron and hole ground subband energies, n labels Landau levels, and m^*_{red} is the e-h reduced effective mass. As can be seen from Eq. (2), all interband LL transitions oscillate in the same way as $[E_e(B)-E_h(B)]$ and are LL index independent.

In conclusion, we have shown that the interband LL recombinations exhibit an oscillatory behavior with, always, blue-shift from linear B dependence when the well width increases. No phase change was experimentally observed and the amplitude of these oscillations is independent of both QW width and LL index but increase with 2DEG carrier concentration. These observations disagree with the predicted oscillations from self-energy correction of electrons and holes. Our experimental results are in good agreement with the assumption that under continuous illumination, the 2DEG system is in grand canonical equilibrium with a reservoir represented by the rest of the structure. In these conditions the Fermi energy is a constant throughout the whole structure and does not depend on B. The present model gives both period, phase, and oscillation amplitudes in the overall feature of experiments and agrees very well with recent observations of Kerridge *et al.*[21]

[1] D. Heiman, in *Semiconductors and Semimetals*, Vol. 36, edited by D. G. Seiler and C. L. Littler (Academic Press, New York, 1992), Chap. 1, p. 1.

[2] M. C. Smith *et al.*, *Seventeenth International Conference on the Physics of Semiconductors*, edited by J. D. Chadi and W. A. Harrison (Springer-Verlag, New York, 1984), p. 547.

[3] M. S. Skolnick *et al.*, Solid State Commun. **67**, 637 (1988).

[4] B. B. Goldberg *et al.*, Phys. Rev. Lett. **65**, 641 (1990).

[5] S. Adams *et al.*, Phys. Rev. B **46**, 13 611 (1992).

[6] P. Vicente *et al.*, Solid State Commun. **96**, 901 (1995).

[7] M. Kamal-Saadi *et al.*, *Proceedings of the Twelfth International Conference on High Magnetic Fields in the Physics of Semiconductors* (Springer, Berlin, 1996), p. 597.

[8] J. C. Maan *et al.*, Phys. Rev. B **30**, 2253 (1984).

[9] D. G. Hayes *et al.*, Phys. Rev. B **44**, 3436 (1991).

[10] T. Uenoyama and L. J. Sham, Phys. Rev. B **39**, 11 044 (1989); S. Katayama and T. Ando, Solid State Commun. **70**, 97 (1989).

[11] T. Rötger *et al.*, J. Phys. (France) **48**, 389 (1987); V. M. Apal'cov and E. I. Rashba, Pis'ma Zh. Eksp. Teor. Fiz. **53**, 420 (1991) [JETP Lett. **53**, 442 (1991)]; A. H. MacDonald, E. H. Rezai, and D. Keller, Phys. Rev. Lett. **68**, 1939 (1992); P. Hawrylak, N. Pulsford, and K. Ploog, Phys. Rev. B **46**, 15 193 (1992).

[12] F. Plentz *et al.*, Solid State Commun. **101**, 103 (1997).

[13] T. Tsuchiya, S. Katayama, and T. Ando, Jpn. J. Appl. Phys., Part 1 **34**, 4544 (1995); and Surf. Sci. **361/362**, 376 (1996).

[14] G. A. Baraff and D. C. Tsui, Phys. Rev. B **24**, 2274 (1981).

[15] A. Raymond and H. Sibari, Phys. Status Solidi **183**, 159 (1994), and references therein.

[16] W. Zawadzki and M. Kubisa, in *High Magnetic Fields in Semiconductors Physics III*, edited by G. Landwehr (Springer, Berlin, 1992), p. 187.

[17] A. Raymond *et al.*, Europhys. Lett. **43**, 337 (1998).

[18] M. Haynes, A. Usher, A. S. Plaut and K. Ploog, Phys. Rev. B **50**, 17 208 (1994).

[19] I. V. Kukushkin, K. von Klizing, K. Ploog and V. B. Timofeev, Phys. Rev. B **40**, 7788 (1989).

[20] T. Ando and Y. Uemura, J. Phys. Soc. Jpn. **37**, 1044 (1974).

[21] G. Kerridge *et al.*, Solid State Commun. **109**, 267 (1999).