Magneto-optics of narrow GaAs/Al_xGa_{1-x}As quantum wells grown on vicinal substrates

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Magnetoluminescence measurements performed on GaAs/Al_xGa_{1-x}As quantum wells grown on a vicinal substrate show a blueshift of the excitonic transitions compared with those obtained on a reference sample grown on nominal substrates. This blueshift is interpreted in terms of the lateral modulation induced by the steps array resulting from the use of vicinal surfaces.

One of the main goals in semiconductor physics is to obtain reliable two- and three-dimensional confinement because of both their potential application in semiconductor devices,[1,2] and the intrinsic physical phenomena involved.[3] Lithographical methods by electron beam or holographic chemical etching has been successfully used in order to get one- (1D) and zero-dimensional (0D) systems.[4,5] However the methods suffer the increased influence of interfaces that induces a large broadening in the subband levels and small lateral confinement.[5] Recently, GaAs quantum-well wires with lateral confinement in the nanometer scale have been obtained, by growing tilted superlattices (TSL) on vicinal substrates.[6,7] Through this method one obtains large dimensional confinement although the lateral confinement is not yet well defined because of segregation processes.[8]

A periodic distribution of steps like it appears in TSL or quantum wells (QW's) grown on vicinal substrates which would induce additional quantum effects that could influence their electronic states.[9,10] Nevertheless, to the best of our knowledge, little attention has been paid to the electronic properties of QW's grown on vicinal surfaces.

Photoluminescence (PL) and photoluminescence excitation (PLE) spectroscopy under magnetic fields are very good techniques in order to study the electronic properties of QW's, like subband energy spacing, heavy-hole–light-hole mixing effects, exciton binding energy, etc.

In this paper we report on PL and PLE experiments as a function of the magnetic field for GaAs QW's grown on a vicinal substrate. The results obtained by PLE show a blueshift with respect to those corresponding to the reference sample grown on a nominal substrate with the same well width. This result is accounted for by a simple model, which takes into account the periodic distribution of steps present in the QW (see Fig. 1). The samples used in the experiments include two single GaAs QW's with well widths $L=19$ and 38 Å, respectively. These QW's were grown by molecular-beam epitaxy on both a nominal GaAs(001) substrate (sample 1) and a vicinal GaAs substrate misoriented from (001) by 4° toward $(111)_A$ (sample 2). The QW's are isolated by 500-Å Al_xGa_{1-x}As barriers. To be strictly comparable, both samples have been grown simultaneously. To improve the interface smoothness of the nominal sample, a 60-s growth interruption has been performed at each interface.[11] In order to obtain an ordered step array on the vicinal substrate, the growth parameters were chosen to achieve a step flow growth mode, avoiding nucleation on the terraces.[12,13] The following growth conditions were used: 0.31 ML/s (where ML represents monolayer) for the GaAs growth rate, 0.45 ML/s for Al_xGa_{1-x}As with $x=0.30$, [As]/[Ga] ratio $\simeq 3$, and growth temperature 610 °C. the growth rates have been precisely measured using intensity oscillations of the reflection of the high-energy electron

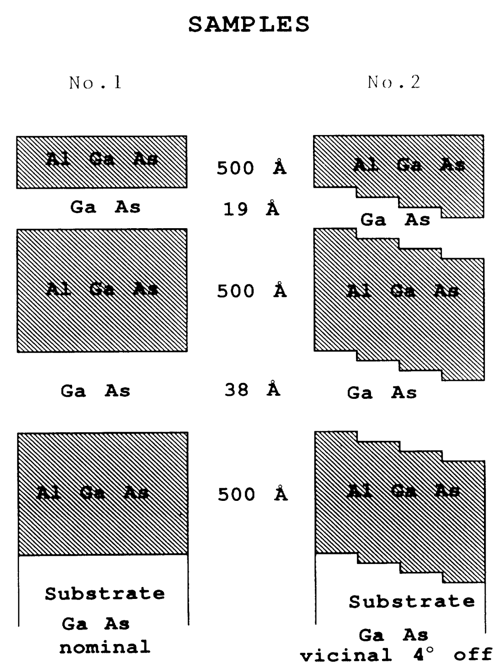

FIG. 1. Quantum well grown on a vicinal substrate, showing the periodic distribution of the terraces. The reference sample, grown on a nominal substrate, is also shown for comparison.

diffraction.[14] Narrow QW's like those studied here would have small hole mixing effects and the fan charts for magnetoexcitonic transitions are much simpler than those of thick QW's.[15,16] Therefore, it should be easier to study by magneto-optical measurements the perturbation resulting from the step-induced lateral modulation.

Magneto-optical spectra were measured using LD700 and DCM dye lasers pumped by Kr^+- and Ar^+-ion lasers, respectively. The emission light was detected with a Jarrell-Ash 1-m double monochromator and a photon counting system. The experiments were performed in a Faraday configuration with the magnetic field parallel to the growth direction. In order to obtain circular polarization, achromatic $\lambda/4$ plates were used. Table I shows the energy and the full width at half maximum (FWHM) of the luminescence signals for the 19- and 38-Å GaAs QW's in samples 1 and 2, respectively. The small values of the FWHM in both samples are a good test for the QW's quality.

Figure 2 shows the PLE spectra of the 38-Å-thick GaAs QW's at $B=12$ T for samples 1 and 2. The $\sigma^+\sigma^-$ indicate the helicity for the incident and the scattered circular polarizations, respectively. The different peaks correspond to the magnetoexciton transitions H_0, H_1, H_2, ... coming from the E_0 electronic subband and the $E_{(\mathrm{HH})_0}$ hole states. One observes a blueshift in the PLE peaks of sample 2 when compared with those of sample 1. This blueshift is also observed in the PL and PLE spectra of the 19-Å-thick QW's.

Figure 3 shows the PLE energy peak position as a function of the applied magnetic field for the 19-Å-thick QW in samples 1 (circles) and 2 (stars). Only the $E_{(\mathrm{HH})_0}$ exciton is observed because only one state for holes has an energy smaller than the hole barrier energy. The PLE peaks correspond to magnetoexcitons H_0, H_1, H_2, etc. We would like to stress here the systematic blueshift of ~ 1.7 meV in the PLE peaks of sample 2 with respect to those of sample 1. The lines drawn through the H_0 to the H_3 states correspond to the best fit of the experiments of sample 1, following a two-dimensional hydrogeniclike exciton model.[17,16] From the simultaneous fit of the ground and excited states we obtain $E_0 - E_{(\mathrm{HH})_0} = 1807.5$ meV, and $m_r = 0.078$ for the reduced effective mass of the heavy-hole exciton, its binding energy being $E_b = 10$ meV. The same model can fit the data of sample 2, only by increasing the $E_0 - E_{(\mathrm{HH})_0}$ energy transition obtained for sample 1 by 1.7 meV.

Figure 4 shows the results for the 38-Å GaAs well on samples 1 (circles) and 2 (stars). The results obtained on sample 1 are similar to those reported by other authors on narrow GaAs QW's.[15,16] Sample 2 shows also here a blueshift of the PLE signals whose value is ~ 1 meV. From the fit of the experimental data of sample 1 we obtain $E_0 - E_{(\mathrm{HH})_0} = 1685.5$ meV, $m_r = 0.063$, and $E_b = 13.5$ meV. Here also the magneto-optical data of sample 2 can be well fitted by increasing the $E_0 - E_{(\mathrm{HH})_0}$ transition energy obtained for sample 1 by 1 meV. The electronic transitions obtained at 0 T for both QW's on sample 1 coincide with theoretical calculations with the

TABLE I. Luminescence energy ($\hbar\omega_L$) and full width at half maximum (FWHM) of the 19- and 38-Å QW width in samples 1 and 2 at 2 K.

	Sample 1 Nominal Substrate		Sample 2 Vicinal Substrate	
QW width (Å)	19	38	19	38
$\hbar\omega_L$ (meV)	1780	1666	1782	1668
FWHM (meV)	9.0	6.0	8.0	5.0

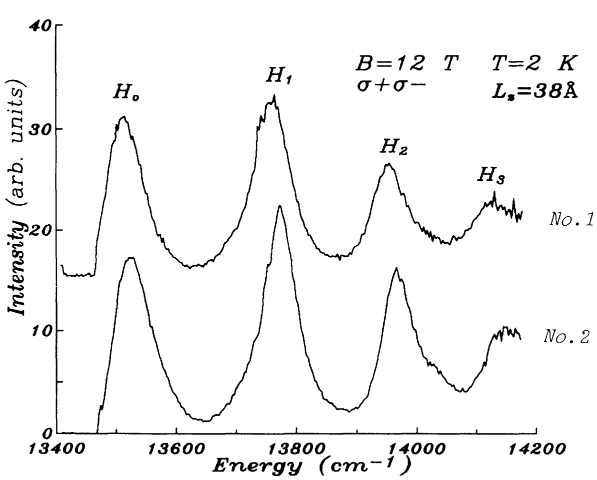

FIG. 2. Photoluminescence excitation spectra of the $L_z = 38$ Å QW's for samples 1 and 2 at a magnetic field $B = 12$ T. The different peaks H_0, H_1, H_2, ... correspond to the magnetoexciton transitions. Observe the blueshift of the PLE peaks in sample 2 compared to that in sample 1.

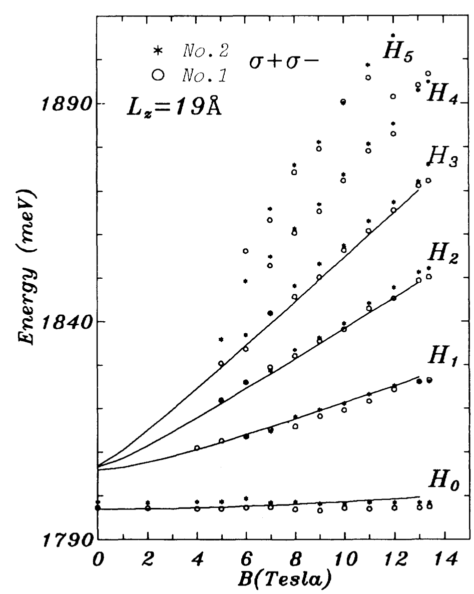

FIG. 3. Magnetoluminescence transitions of the $L_z = 19$ Å thick QW's for samples 1 (circles) and 2 (stars) as a function of the applied magnetic field B. Solid lines are a fit of the experimental data for sample 1, by using a two-dimensional excitonic model.

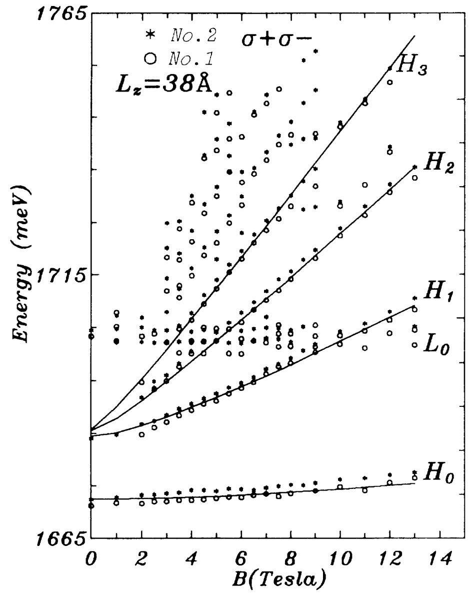

FIG. 4. Magnetoluminescence transitions of the $L_z = 38$ Å thick QW's for samples 1 (circles) and 2 (stars) as a function of the applied magnetic field B. Solid lines are a fit of the experimental data for sample 1, by using a two-dimensional excitonic model.

70:30 band offset rule.[18]

In order to understand the blueshift obtained, one should calculate the electronic energy levels for electrons and holes of a two-dimensional potential $V(x,z)$ under a magnetic field $\mathbf{B}=(0,0,B)$. However, we will restrict ourselves to the problem of electrons in a two-dimensional potential. Using the gauge $\mathbf{A}=(0,Bx,0)$, the Schrödinger equation to be solved is

$$\left[-\frac{\hbar^2}{2m}\left[\frac{\partial^2}{\partial x'^2} + \frac{\partial^2}{\partial z^2} \right] + \frac{e^2B^2}{2m}x'^2 + V(x,z) \right] \psi(x,z) = E\psi(x,z) , \quad (1)$$

where the electrons are free along the y direction, and $x' = x + \hbar ky/eB$ is the Landau orbit center. The solution of Eq. (1) with a realistic potential $V(x,z)$ is a cumbersome calculation. Instead of that we will assume that the potential $V(x,z)$ can be written as

$$V(xz) = V(x) + V(z) , \quad (2)$$

where $V(z)$ is the quantum-well potential with a fixed width L_z and $V(x)$ is a periodic potential with periodicity a. $V(x)$ simulates the well width modulation induced by the periodic distribution of steps present in the QW's grown on vicinal substrates. The drastic assumption of Eq. (2) is justified as long as the perturbation produced by the steps on the electronic levels is much smaller than the eigenenergies of the potential $V(z)$, as in our case. Using this model we can factorize the wave function $\psi_{an}(x,z) = \phi_a(x)\zeta_n(z)$, where $\zeta_n(z)$ are the eigenfunctions of the equation

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial z^2} + V(z) \right] \zeta_n(z) = \varepsilon_n \zeta_n(z) . \quad (3)$$

Finally, the equation of interest to be solved is

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x'^2} + \frac{e^2B^2}{2m}x'^2 + V(x) \right] \phi_\alpha(x) = (E - \varepsilon_n)_\alpha \phi_\alpha(x) . \quad (4)$$

We have used an array of harmonic potentials to represent the periodic perturbation $V(x)$,

$$V(x) = \sum_{n=0}^{+\infty} A(x \pm x_n)^2 , \quad n - a/2 \le x \le n + a/2 , \quad (5)$$

where $x_n = na$ (n integer), a being the length of the terrace. In our case, the mean value for the terrace length in sample 2 is ~40 Å. Parameter A determines the amplitude of the modulation potential in the x direction. Figure 5 shows the Landau fan chart for two different values of A that could simulate the two samples studied here. The origin of energies in Fig. 5 has been taken at the energy value of the fundamental state of $V(z)$ at zero magnetic field. As expected, for $A=0$, i.e., no $V(x)$ modulation, the Landau fan converges to $E=0$ for zero magnetic field (broken lines). However, for $V(x) \neq 0$ (continuous lines), the Landau fan converges at $B=0$ T to an energy value $E>0$, and the shift observed is smaller (by a few meV) than the QW eigenenergies. This result would qualitatively explain the blueshift experimentally observed.

Let us point out that the miniband formation expected in a periodic potential $V(x)$ is not present in our case due to the rather small period ($X_{n+1} - X_n = 40$ Å) and also due to the small potential modulation assumed for the value of parameter A in Fig. 5 [$V_{max}(x) = 5.2$ meV for

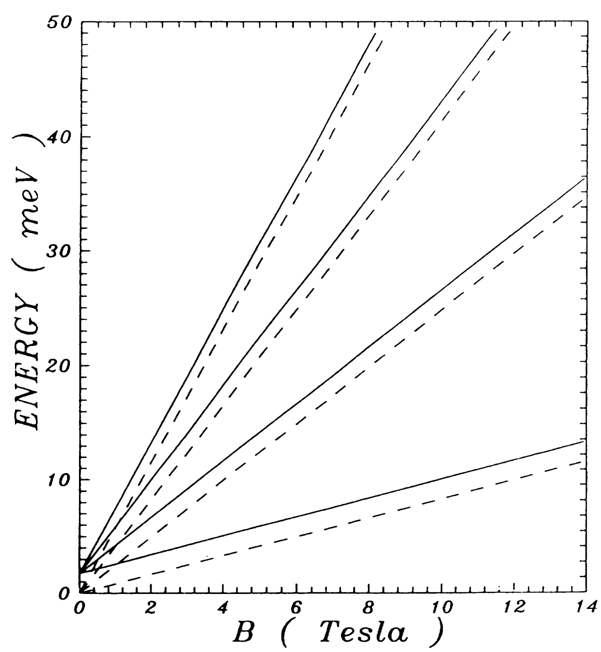

FIG. 5. Energy of the electronic Landau levels as a function of the magnetic field for two different values of parameter A in formula (5) (see text). $A=0$, broken lines; $A=1.3\times10^{-2}$ meV/Å^2, continuous lines.

$A = 1.3 \times 10^{-2}$ meV/Å^2].

The theoretical results shown here are not in contradiction with those obtained by Kaplan and Warren[19] because they consider a single parabolic potential and not a lateral modulation like ours. In fact our model would predict the coupling between Landau levels and 1D bands for larger lateral modulation and periodicity.[20] In this sense, it would be very interesting to analyze with a more realistic calculation the critical parameters in QW's grown on vicinal surfaces in order to have 2D confinement induced only by the presence of the terraces, like those recently discovered by Colas *et al.*[21] Finally, we have not included the effect of holes in our theory. Although it could play an important role in the electronic properties of QW's grown on vicinal surfaces like it does in TSL's,[22] it is beyond the scope of the present paper.

In conclusion we have observed a blueshift in magnetoluminescence experiments of GaAs QW's grown on vicinal substrates. The results obtained are explained in terms of the modulation induced by the presence of the step array at the QW interfaces. The effect of the steps periodically distributed in the x direction is to shift the electronic levels of the QW at larger energy values.

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[1] H. Sakaki, Jpn. J. Appl. Phys. **19**, 94 (1980).
[2] Y. Arakawa and H. Sakaki, Appl. Phys. Lett. **40**, 939 (1982).
[3] T. J. Thornton, M. Pepper, H. Ahmed, D. Andrews, and G. J. Davis, Phys. Rev. Lett. **56**, 1198 (1986).
[4] K. Ensslin and P. M. Petroff, Phys. Rev. B **41**, 12 307 (1990).
[5] M. Kohl, D. Heitmann, P. Grambow, and K. Ploog, Phys. Rev. B **37**, 10 927 (1988).
[6] M. Tanaka and H. Sakaki, Appl. Phys. Lett. **54**, 1326 (1989).
[7] M. Tsuchiya, J. M. Gaines, R. H. Yan, R. J. Simes, P. O. Hotlz, L. A. Coldren, and P. M. Petroff, Phys. Rev. Lett. **62**, 466 (1989).
[8] M. S. Miller, C. E. Pryor, H. Weman, L. A. Samoska, M. Kroemer, and P. M. Petroff, in *Proceedings of the 20th ICPS Conference,* edited by E. M. Anastassakis and J. D. Joannopoulos (World Scientific, Singapore, 1990), p. 1717.
[9] K. Kanamoto, K. Fujiwara, Y. Tukuda, M. Tsukada, M. Ishii, and T. Nakayama, Appl. Surf. Sci. **41/42**, 526 (1989).
[10] H. Sakaki, W. Wagatsuma, J. Hamasaki, and S. Saito, Thin Solid Films **36**, 497 (1976).
[11] H. Sakaki, M. Tanaka, and J. Yoshino, Jpn. J. Appl. Phys. **24**, L417 (1985).
[12] J. H. Neave, P. J. Dobson, B. A. Joyce, and J. Zhang, Appl. Phys. Lett. **47**, 100 (1985).
[13] J. Massies, C. Deparis, C. Neri, G. Neu, Y. Chen, B. Gil, P. Auvray, and A. Regreny, Appl. Phys. Lett. **55**, 2605 (1989).
[14] J. H. Neave, B. A. Joyce, P. J. Dobson, and N. Norton, Appl. Phys. A **31**, 1 (1983).
[15] D. C. Rogers, J. Singleton, R. J. Nicholas, C. T. Foxon, and K. Woodbridge, Phys. Rev. B **34**, 4002 (1986).
[16] M. Potemski, L. Viña, J. C. Maan, K. Ploog, and G. Weiman, Phys. Rev. B **43**, 14 707 (1991).
[17] A. H. MacDonald and D. S. Ritchie, Phys. Rev. B **33**, 8336 (1986).
[18] G. Bastard, *Wave Mechanics Applied to Semiconductor Heterostructures* (Les Editions de Physique, Paris, 1988).
[19] S. B. Kaplan and A. C. Warren, Phys. Rev. B **34**, 1346 (1986).
[20] J. Sánchez-Dehesa and F. Meseguer (unpublished).
[21] E. Colas, E. Kapon, S. Simhony, H. M. Cox, R. Baht, K. Kash, and P. S. D. Lyn, Appl. Phys. Lett. **55**, 867 (1989).
[22] D. S. Citrin and Yia-Chung Chang, J. Appl. Phys. **69**, 2685 (1991).