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Magneto-luminescence of quasi-zero dimensional $In_{0.25}Ga_{0.75}As/GaAs$ quantum dots

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Abstract

We report photoluminescence measurements on $In_{0.25}Ga_{0.75}As/GaAs$ quantum well and dots grown on (1 1 1)B GaAs substrate in high magnetic fields up to 45 Tesla. A well-defined PL line with full width at half maximum of approximately 5.5 meV is observed. From an analysis of the zero field transition energy, we point out the importance of an internal piezoelectric field. By analyzing the diamagnetic shift of the PL in both Faraday and Voigt configurations, the optical characteristics of a quasi-zero dimensional exciton are discussed.

Keywords: Quantum well; Quantum dot; Megagauss; Photoluminescence

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As semiconductor growth techniques have progressed, work on light emitting structures has moved from two-dimensional quantum wells towards zero-dimensional quantum dots. This structure has attracted a great deal of attention not only for its potential application in laser devices but also from a fundamental physical point of view as a number of new properties occur when carriers are spatially confined by a three-dimensional potential [1,2].

In most of the previous studies, the dots are grown on a (1 0 0) oriented substrate. In this paper, we report photoluminescence (PL) measurements on $In_{0.25}Ga_{0.75}As/GaAs$ quantum wells (QW) and dots (QDs) grown on (1 1 1)B GaAs in magnetic fields up to 45 Tesla. A well-defined PL originating from the QDs is seen with a full width at half maximum (FWHM) of 5.5 meV. This is attributed to the effect of the large piezoelectric field which is caused by the strain. In magnetic field, there is a large quantitative difference of the energy shift of the QD between the Faraday and Voigt configurations.

PL was performed in pulsed magnetic fields at 4.2 K. The sample consists of (a) 3500 Å GaAs buffer, (b) $In_{0.25}Ga_{0.75}As$ QW, (c) 3500 Å GaAs, (d) $In_{0.25}Ga_{0.75}As$ QDs followed by a capping layer of 500 Å GaAs. The In concentration are determined by the calibrated flux rate and the nominal thickness of the QW and dots is 15 Å.

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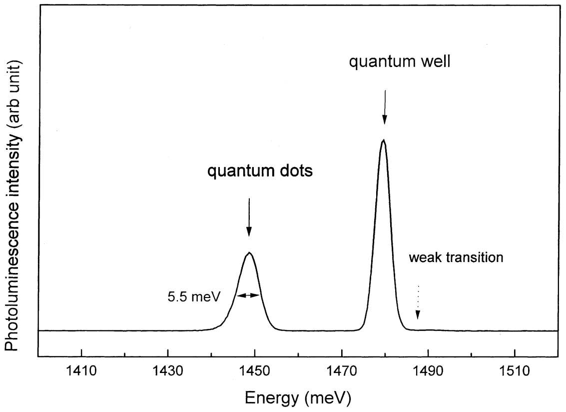

Fig. 1. PL spectrum at zero field showing the assignment of quantum well and quantum dots transitions.

The dots are formed due to the strain in the layer, and typically have a diameter of 500 Å with a density of 40 μm^{-2} as determined by atomic force microscopy [3].

The zero magnetic field PL spectrum is shown in Fig. 1 with two sharp lines at 1448.4 meV and 1479.5 meV. These transitions are far above the unstrained bulk $In_{0.25}Ga_{0.75}As$ band gap of 1152.8 meV [4] and originate from the confined states in the dots and quantum well. In comparison with previous reports, the two PL lines are extremely narrow with a FWHM of 4 and 5.5 meV for QW and QD respectively. This is unexpected due to the layer width fluctuations. We will discuss this later. First, the transition energy is analyzed. Using the excitonic model of Ref. [5], the energy of the QW is calculated. The mass parameters are taken from Refs. [6,7]. In the (1 1 1)B orientation, the band edge energy shift due to the strain is $\Delta E_c = a_c\epsilon_{xx}$ and $\Delta E_v = a_v\epsilon_{xx} + 2\sqrt{3}d\epsilon_{xy}$ [8], where ΔE_c, ΔE_v are the energy shift of conduction band and valence band respectively. a_c, a_v and d are taken from Ref. [9]. ϵ_{ii}, ϵ_{ij} are the diagonal and off-diagonal components of the strain tensors.

As the sample was grown on (1 1 1)B substrate, ϵ_{ij} give rise to a piezoelectric field pointing from A(cation) to B(anion). The strength of the field is $F = 2e_{14}\epsilon_{xy}/\epsilon\epsilon_0$ [6], where e_{14} is the piezoelectric constant, ϵ_0 the free space permittivity and ϵ is the dielectric constant. For In = 25% (1.8% lattice mismatch), the built-in field is 3.6×10^7 V/m. The interband transition energy is therefore reduced due to the Stark effect, and the wavefunctions of the electrons in particular can become very asymmetric with one interface acting as a barrier [10]. The results of the calculation are shown in Fig. 2. For In = 25% and well width of 15Å, the electron energy levels are confined very close to the GaAs CB edge with wavefunctions extended very far beyond the well, and the transition energy is mainly determined by the valence band potential

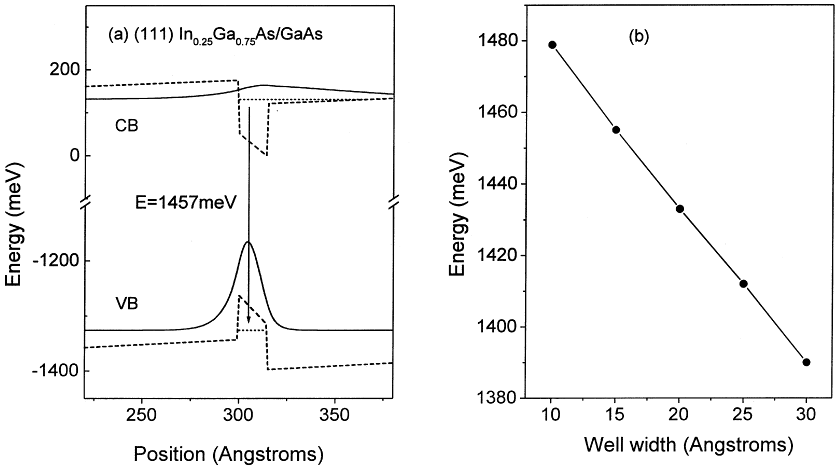

Fig. 2. (a) Calculated wavefunctions (solid lines) of a fully strained quantum well (15 Å). The band profile is deplicted as dash lines and the energy levels is indicated by dotted lines. (left plot). (b) Calculated transition energies as a function of well widths (right plot).

well. Theoretical calculation gives an energy of 1457 meV, below the observed value of 1479.5 meV. The disagreement can be understood by the segregation effect where a In atom exchanges its position with the top Ga atom during epitaxy growth [11]. As a result, the effective well width is thinner than the nominal growth parameters. Reducing the well width to 10 Å gives an energy of 1480 meV (Fig. 2(b)). A similar argument can also apply for the QDs system and the estimated width is ≈16 Å. As shown in Fig. 2, the energy levels of both electron and hole are located away from the bottom of the triangular well. In addition, the hole mass is large, as a result, the optical transition is thus less sensitive to size fluctuations. This leads to the rather narrow PL line width.

The field-dependent energies for both field geometries are summarized Fig. 3. In a magnetic field, the optical characteristics can be categorized into two regions: (a) Low magnetic fields: the Coulomb interaction dominates over the free carrier cyclotron energy ($\hbar eB_\perp$/m where $B_\perp$ is the perpendicular magnetic field component). The diamagnetic shift is $\Delta E_{\mathrm{dia}} = e^2\langle r^2\rangle B^2/8\mu c^2$ [12], where $\langle r^2\rangle$ is the wavefunction size, and μ is the reduced mass. (b) High magnetic fields: as the field increases the cyclotron energy dominates over the Coulomb energy. The optical transition therefore moves linearly with fields.

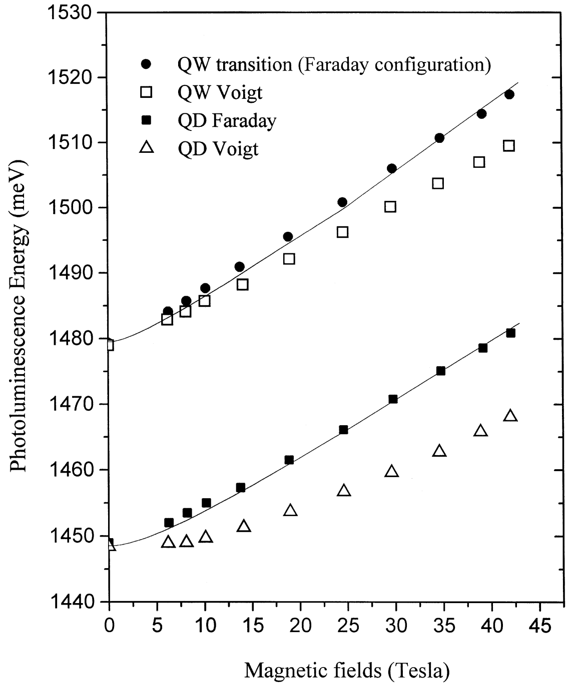

Fig. 3. The PL energy of quantum well and quantum dots in both Faraday and Voigt configurations. The solid line is the fitted energies.

We first discuss PL in Faraday configuration. At low magnetic fields, the PL from the QW and QD move quadratically with magnetic field as expected. Above 15 Tesla, both PL lines move linearly with field at a rate of 0.92 and 0.83 meV/T for the QW and QD respectively. The smaller diamagnetic shift of the QD reflects a larger excitonic Rydberg energy due to the greater thickness of the dots compared with the QW. (For a $\mathrm{In_{0.13}Ga_{0.87}As/GaAs}$ QW struture, the maximun binding energy is ≈8 meV at around 60 Å [13]) Since the diameter of the dots is wide (≈ 500 Å) in comparison with the Landau cyclotron diameter there will be little additional confinement energy due to the spatial extent of the dots.

To quantitatively interprete the transition energy, the Makado model is employed [14]. Using the same mass parameters mentioned above, the high field diamagnetic shift was fitted to deduce the exciton binding energy. The results of the fitting are shown as solid lines in Fig. 3 with a binding energy of 2.8 and 5.5 meV for the QW and QDs respectively. The fitted E_b for the QW is in good agreement with the theoretical calculation of 3.1 meV.

Voigt geometry provides further confirmation of the increased confinement of the electron wavefunction in the QDs. There is much more anisotropy in the behaviour of the QD PL than for the QW, which shows very similar shifts to those in the Faraday configuration, suggesting an almost 3-D electron wavefunction. For the QDs the diamagnetic shift is quadratic up to 10 T and above this has a nearly linear gradient of 0.37 meV/T, due to the stronger electron confinement. The linear region begins typically at a field where $\hbar\omega_c \approx E_b$, suggesting a binding energy of ≈14 meV for the dots. This is consistent with the Faraday PL data; the carriers in the QD are more strongly confined in the growth direction than the QW as we have discussed previously.

In summary, PL has been employed to study the InGaAs/GaAs quantum dots grown on (1 1 1)B. A very narrow line is observed due to the built-in piezoelectric field. The structures show a large magnetic shift of the energy levels, and measurements of the anisotropy of the shift allow us to conclude that there is enhanced confnement in the dots.

References

[1] H. Drex, D. Leonard, W. Hansen, J.P. Kotthas, P.M. Petroff, Phys. Rev. Lett 73 (1994) 2252.
[2] M. Sugawara, Y. Nakata, K. Mukai, H. Shoji, Phys. Rev. B 55 (1997) 13155.
[3] F.Y. Tsai, C.P. Lee, to be published.
[4] G. Arnaud, J. Allegre, P. Lefebvre, H. Mathieu, L.K. Howard, D.J. Dunstan, Phys. Rev. B 46 (1992) 15290.
[5] H.H. Cheng, R.J. Nicholas, M.J. Lawless, D.E. Asenford, B. Lunn, Phys Rev. B 52 (1995) 5269.
[6] C. Mailhiot, D.L. Smith, Phys. Rev. B 35 (1987) 1242.
[7] Landolt, Börnstein (Eds.), in: Physics of Group IV Elements and III-V Compounds, Spring, New York, 1982.
[8] E.L. Ivchenko, G. Pikus, Superlattices and Other Heterostructures, Springer, Berlin, 1995.
[9] C.G. Van de Walle, Phys. Rev. B 39 (1989) 1871.
[10] R. Andre, J. Cibert, L.S. Dang, Phys. Rev. B 52 (1995) 12013.
[11] D.J. Arent, Phys. Rev. B 41 (1990) 9843.
[12] C. López, R. Mayoral, F. Meseguer, J.A. Porto, J. Sáchez-Dehesa, M. Leroux, N. Grandjean, C. Deparis, J. Massies, J. Appl. Phys. 81 (1997) 3281.
[13] H.Q. Hou, Y. Segawa, Y. Aoyagi, S. Namba, J.M. Zhou, Phys. Rev. B 42 (1990) 1284.
[14] P.C. Makado, Physica 132B (1985); P.C. Makado, N.C. McGill, J. Phys.C 19 (1986) 873.