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Photoluminescence measurements under different excitation powers and time-resolved photoluminescence experiments were carried out at low temperature on tensile strained $In_{0.3}Ga_{0.7}As$ quantum wells with InGaAs barriers lattice matched to InP. Evidence of a type II recombination is found between carriers confined in the tensile strained layer and in the lattice matched one. This study allows us to propose a precise determination of the light holes band offset in the $In_{0.3}Ga_{0.7}As/In_{0.53}Ga_{0.47}As$ system.
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$In_xGa_{1-x}As$ based heterostructures grown on InP are very interesting for optoelectronic devices working in the 1.5–1.7 μm spectral range since the growth of both tensile and compressive strained layers is allowed. While compressive strained structures are now well known[1–4] few investigations have been done on tensile strained InGaAs layers, which can be used in insensitive polarization electroabsorption modulators[5,6] or amplifiers.[7]

$In_xGa_{1-x}As/In_{0.53}Ga_{0.47}As$ ($x<0.53$) structures grown on InP are expected to give type II band lineup for light holes.[4,8,9] This leads to a carrier type confinement: electrons and heavy holes are free in the lattice matched (LM) InGaAs layer, whereas the light holes are confined in the tensile strained layer. Type II heterostructures are expected to increase the performance of electro-optical modulators.[10,11] The spatial separation between electrons and light holes creates an electrical dipole that interacts with the electrical field. Therefore the Stark effect is linear in type II structures, whereas it is quadratic for those of type I. This allows a greater modulation at lower voltage bias and the possibility of both red and blue shifts. The band offset is an important parameter for modeling the optical properties of optoelectronic components using the type II band lineup.

In this letter we report results from photoluminescence (PL) and time-resolved PL experiments carried out on $In_{0.3}Ga_{0.7}As/In_{0.53}Ga_{0.47}As$ quantum wells (QWs) in order to determine the band alignment and an accurate evaluation of the valence band offset.

The samples were grown by molecular beam epitaxy, with a RIBER 2300 system, on (001) semi-insulating InP substrates. The structure consists of a tensile $In_{0.3}Ga_{0.7}As$ well inserted between two bulk layers of $In_{0.53}Ga_{0.47}As$ lattice matched to InP. Sample A was fabricated at 475 °C with a V/III beam equivalent-pressure (BEP) ratio of 6. The well width is 7.6 nm. Sample B was grown at 525 °C under a V/III BEP ratio of 25. The well width is 5.3 nm. In both cases the growth rate was 0.9 μm h^{-1}. Sample A was grown at lower temperature than sample B to avoid the three dimensional growth mode that occurs at 525 °C after growth of about 8 nm.[12] Lattice matched composition was checked by x-ray double diffraction (XDD). The PL measurements are carried out using the 514.5 nm emission line of a cw argon-ion laser focused on a 150-μm-diam spot. The PL signal is detected using a 0.64 m HRS2 Jobin–Yvon monochromator and a Ge photodetector cooled down to 77 K. For luminescence decay experiments the samples are excited by a mode locked Ti-sapphire laser whose pulse length is around 1.5 ps with a 82 MHz repetition frequency. The laser is focused on a 50-μm-diam spot. Excitation power on the sample is around 50 mW. The luminescence from the sample is spectrally selected by a 0.32 m monochromator and detected with a synchroscan Hamamatsu streak camera equiped with an S1 photocathode.

Figure 1(a) shows the 4 K PL spectra for sample A at different excitation powers ranging from 0.03 to 120 mW. Three peaks are observed at low excitation power. The first one around 0.79 eV, which remains practically unchanged with the excitation power, originates from the excitonic transition of the LM InGaAs layer. This value differs from the usually accepted 0.802 eV[13] excitonic transition in InGaAs layers lattice matched to InP. The difference could be associated with some ordering occurring in our samples leading to a smaller band gap. The second peak appears 17 meV below the LM InGaAs excitonic transition. This peak shows a 1–2 meV/decade blueshift when increasing the laser power and presents an intensity saturation at high laser power. This behavior allows us to attribute this peak to a donor–acceptor (D–A) transition in the LM InGaAs layer. Finally, a third peak strongly dependent on the excitation power, denoted (X), is detected in the lower energy range at 0.731 eV for a 0.03 mW laser power excitation and exhibits a 23 meV blueshift with a variation of the laser power over 4 decades.

The PL results for sample B [Fig. 1(b)] are quite similar

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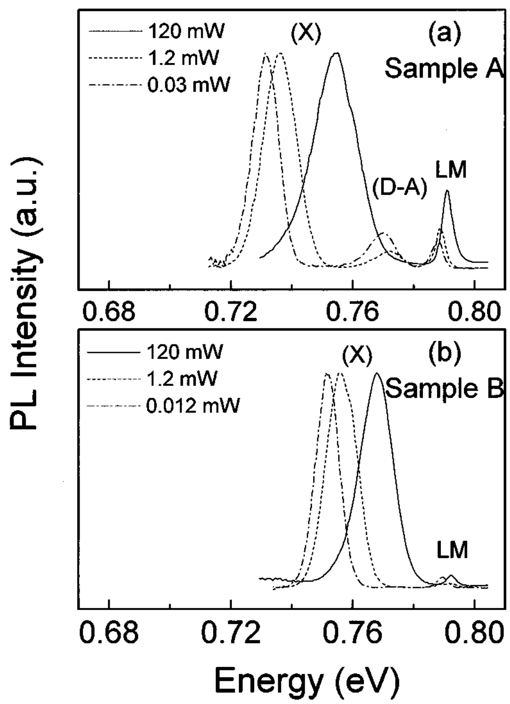

FIG. 1. Normalized photoluminescence spectra under different excitation powers for sample A (a) and sample B (b).

to those of sample A. The LM InGaAs excitonic peak is found around 0.792 eV, whereas the D–A transition is not visible in this sample. A peak is detected at 0.751 eV for 0.012 mW laser power excitation with a blueshift of 16 meV for a variation of the laser power over 5 decades. This later transition seems to have the same behavior as peak (X) for sample A.

Now we focus on the so-called (X) transition. Since the (X) PL intensity does not show any intensity saturation for high power laser excitation, it cannot be assigned to some impurity incorporation. Moreover the shift observed with increasing excitation power is too large to be attributed to a D–A transition and it is well known that a D–A transition becomes narrower at high excitation powers. The opposite behavior is observed for the peak (X) which broadens when the excitation power increases. We notice also that the peak (X) does not correspond to any referenced transition in LM InGaAs layer.

Furthermore, we can observe a 20 meV increase of the (X)–PL transition energy as the well width decreases from 7.6 nm (sample A) to 5.3 nm (sample B). The peak (X) seems to be very sensitive to quantum confinement effects. We therefore assign the peak (X) to an intrinsic transition that originates from the InGaAs tensile strained layer. In a type I quantum well the optical transition energies are expected to occur between the band gap energies of the well and the barriers. For both samples, LM InGaAs and $In_{0.3}Ga_{0.7}As$ band gaps (0.79 and 0.863 eV, respectively) are larger than the energy position of the peak (X). All the above results lead us to attribute the (X) transition to a type II recombination, noted ELH_1, between electrons in the LM InGaAs layer and light holes confined in the InGaAs tensile strained layer, as shown in Fig. 2. Such transition is expected to appear below the well and barrier band gap and to be very sensitive to the excitation power. This kind of transition has been widely studied in the InP/InAlAs heterostructures.[14–17]

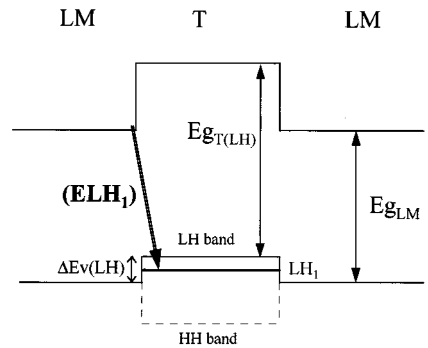

FIG. 2. Band alignment for $In_{0.3}Ga_{0.7}As/In_{0.53}Ga_{0.47}As$ quantum well, where layer LM is the LM InGaAS layer and layer T is the $In_{0.3}Ga_{0.7}As$ tensile strained layer. Eg_{LM} and $Eg_{T(LH)}$ are the band gaps for layer LM and T, respectively. ELH_1 represents the type II transition between electrons and the first confined light holes level. Dashed and full lines represent respectively the HH and LH valence band.

The PL lifetime in a type I quantum well is expected to be lower than in bulk material because of the enhancement of the excitonic effects in confined structures. Therefore, one should expects a faster decay of the QW PL as compared to the decay of the barrier PL. The oscillator strength of a type II transition is expected to be a few percents of those of type I transitions[18] leading to a longer lifetime. Time-resolved PL was carried out and we first measured a carrier lifetime related to the excitonic transition in the LM InGaAs layer of 850 ps. For the (X) transition a lifetime of 15 ns is determined. This value is about 20 times larger than the excitonic LM InGaAs one. It indicates that it could not be a type I transition. Indeed the lifetime measured in InGaAs/InAlAs or InGaAs/InP type I QWs is about 1 ns.[19,20] All these results confirm the type II nature of the (X) transition. Therefore, band filling could occur at high excitation power. This explains the observed blue-shift and the broadening of the (X)–PL transition as the excitation power increases. Similar behavior has also been observed in the AlInAs/InP type II heterostructure.[21]

To go deeper in the investigation of this type II band lineup we try to determine the valence band offset value using the PL results. The general expression for the ELH_1 transition is

$$ELH_{1(th)} = Eg_{(In_{0.53}Ga_{0.47}As)} - \Delta E_v(LH) + LH_1, \tag{1}$$

where (see Fig. 2) $Eg(In_{0.53}Ga_{0.47}As)$ is the band gap energy of the LM InGaAs layer whose value is extracted from our measurements: 0.79 eV for sample A and 0.792 eV for sample B, $\Delta E_v(LH)$ is the light holes band discontinuity, and LH_1 is the light hole confinement energy in the well. It appears that the optical transition ELH_1 depends linearly on the band offset, whereas for type I QW the fundamental transition is not very sensitive to band discontinuities. This allows an accurate determination of $\Delta E_v(LH)$. To do this we used a χ^2 test taking the minimum of

$$\chi^2(\Delta E_v) = (ELH1^B_{th} - ELH1^B_{exp})^2 + (ELH1^A_{th} - ELH1^A_{exp})^2, \tag{2}$$

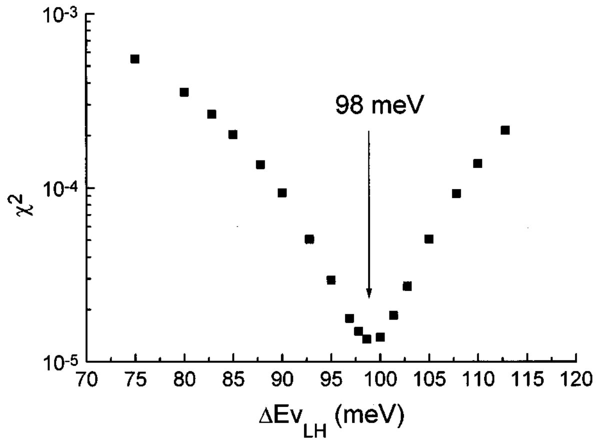

FIG. 3. χ^2 function vs $\Delta E_{v_{LH}}$, the valence band discontinuity for light holes. χ^2 is defined as follows: $\chi^2(\Delta E_v) = (ELH1^B_{th} - ELH1^B_{exp})^2 + (ELH1^A_{th} - ELH1^A_{exp})^2$, where $ELH1^B_{th}$ and $ELH1^A_{th}$ stand for the theoretical values for the type II transition of samples B (5.3 nm) and A (7.6 nm) and $ELH1^B_{exp}$ and $ELH1^A_{exp}$ the experimental data.

where $ELH1^B_{th}$ and $ELH1^A_{th}$ are the theoretical values for the type II transition of samples B (5.3 nm) and A (7.6 nm) and $ELH1^B_{exp}$ and $ELH1^A_{exp}$ the experimental data.

Theoretical calculations of LH_1 confinement energy are carried out with a numerical treatment of the Schrödinger equation within the envelope function approximation parabolic band. Parameters used in the calculation such as effective masses of the tensile strained layer are extracted from a calculation performed with an 8 band k.p model adapted for strained materials.[22] The effective masses are as follows: $m_e/m = 0.0363$, $m_{hh}/m_0 = 0.37$, and $m_{lh}/m_0 = 0.039$ for the tensile layer. Note that the tensile layer gap value does not have any effect on the calculation of $ELH1_{th}$. For the experimental data we have to consider the lowest excitation power measurements because of the band filling effect described above.

Figure 3 reports data for the χ^2 expression versus plotted ΔE_v(LH) in log scale. The curve exhibits a sharp minimum around 98 ± 4 meV. This corresponds to a conduction band discontinuity $\Delta E_c / \Delta E_{g(HH)}$ (where ΔE_c stands for the conduction band offset and $\Delta E_{g(HH)}$ for the heavy holes band gaps difference) of 75%. The uncertainty is estimated to be ± 4 meV by determining the experimental results dispersion range over four different samples (not reported here).

Previous works on $In_xGa_{1-x}As/In_yGa_{1-y}As$ quantum wells[4] and superlattices[8,23,24] (SLs) lead to a great variety of band offset values. For $In_{0.4}Ga_{0.6}As/In_{0.53}Ga_{0.47}As$ SLs Quillec *et al.*[8] assumed a conduction band discontinuity of 90%, as for InGaAs/GaAs. This was in agreement with the theoretical results of Priester *et al.*[23] Unfortunately, they were not able to observe the type II (LH) transition because of the layer thickness, which was not thin enough to allow a sufficient wave function overlap. Zucker *et al.*[4] also report only type I recombination results for the same reasons. Later, the theoretical works of Godefroy[24] gave a conduction band discontinuity of 45% for an $In_{0.38}Ga_{0.62}As/In_{0.53}Ga_{0.47}As$ SLs. No experimental measurement confirmed this calculation. In our case the light hole transition is observed in the 4 K PL spectra. To our knowledge, this is the first direct observation of type II LH transition in the InGaAs system. It allows a more reliable determination of the valence band offset which is found to be 98 ± 4 meV for $In_{0.3}Ga_{0.7}As/In_{0.53}Ga_{0.47}As$.

In conclusion we have performed PL and time-resolved PL measurements on $In_{0.3}Ga_{0.7}As/In_{0.53}Ga_{0.47}As$ structures; we find a new transition at 0.731 eV for sample A (7.6 nm) and at 0.751 eV for sample B (5.3 nm) very sensitive to the excitation power and with a long carrier life time of 15 ns assigned to the type II transition between the free electrons in the LM InGaAs layer and the confined light holes in the $In_{0.3}Ga_{0.7}As$ tensile strained layer. We have deduced a LH band discontinuity equal to 98 ± 4 meV.

[1] M. H. Meynadier, J-L. de Miguel, M. C. Tamargo, and R. E. Nahory, Appl. Phys. Lett. **52**, 302 (1988).
[2] E. Tournié and K. H. Ploog, Appl. Phys. Lett. **62**, 858 (1993).
[3] S. Monéger, Y. Baltagi, T. Benyattou, A. Tabata, B. Ragot, G. Guillot, A. Georgakilas, K. Zekentes, and G. Halkias, J. Appl. Phys. **74**, 1437 (1993).
[4] J. E. Zucker, C. H. Joyner, and A. G. Dentai, IEEE Photonics Technol. Lett. **4**, 432 (1992).
[5] S. Chelles, R. Ferreira, P. Voisin, A. Ougazzaden, M. Allovon, and A. Carenco, Appl. Phys. Lett. **64**, 3530 (1994).
[6] H. W. Wan, T. C. Chong, and S. J. Chua, IEEE Photonics Technol. Lett. **6**, 92 (1994).
[7] K. Magari, M. Okamoto, H. Yasaka, K. Sato, Y. Noguchi, and O. Mikami, IEEE Photonics Technol. Lett. **2**, 556 (1990).
[8] M. Quillec, J. Y. Marzin, J. Primot, G. LeRoux, J. L. Benchimol, and J. Burgeat, J. Appl. Phys. **59**, (1986).
[9] R. Schwedler, F. Brüggemann, A. Kohl, K. Wolter, K. Leo, and H. Kurz, Appl. Phys. A **57**, 199 (1993).
[10] C. Lugand, T. Benyattou, and G. Guillot, Proc. SPIE **2397**, 710 (1995).
[11] P. N. Stavrinou, S. K. Haywood, and G. Parry, Appl. Phys. Lett. **64**, 1251 (1994).
[12] T. Venet, M. Gendry, G. Hollinger, M. Ambri, M. Pitaval, C. Lugand, T. Benyattou, and F. Cadete Santos Aires, Proceedings of ICSH, Montpellier, France, 1995, p. 648.
[13] D. K. Gaskill, N. Bottka, L. Aina, and M. Mattingly, Appl. Phys. Lett. **56**, 1269 (1990).
[14] L. Aina, M. Mattingly, and L. Stecker, Appl. Phys. Lett. **53**, 1620 (1988).
[15] H. Kobayashi, T. Kawamura, and H. Iwamura, Jpn. J. Appl. Phys. 1 **32**, 548 (1993).
[16] E. Lugagne Delpon, P. Voisin, J. P. Vieren, M. Voos, J. P. André, and J. N. Patillon, Semicond. Sci. Technol. **7**, 524 (1992).
[17] J. Böhrer, A. Krost, T. Wolf, and D. Bimberg, Phys. Rev. B **47**, 6439 (1993).
[18] G. Bastard, *Wave Mechanics Applied to Semiconductor Heterostructures* (Editions de Physique, Paris, 1988).
[19] S. Gupta, P. K. Bhattacharya, J. Pamulapati, and G. Mourou, J. Appl. Phys. **69**, 3219 (1991).
[20] U. Cebulla, G. Bacher, A. Forchel, G. Mayer, and W. T. Tsang, Phys. Rev. B **39**, 6257 (1989).
[21] T. Benyattou, M. A. Garcia Perez, S. Moneger, A. Tabata, M. Sacilotti, P. Abraham, Y. Monteil, and J. Tardy, Appl. Surf. Sci. **63**, 197 (1993).
[22] T. B. Bahder, Phys. Rev. B **41**, 11992 (1990).
[23] C. Priester, G. Allan, and M. Lannoo, Phys. Rev. B **38**, 9870 (1988).
[24] A. Godefroy, PhD thesis, $n°$1118, University of Rennes, 1994.