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Spin-Splitting Reversal in InGaAs/InP Quantum-Wires in High Magnetic Field

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We report on interband circular polarized magneto-photoluminescence results on differently wide $In_{0.53}Ga_{0.47}As$ quantum wires in magnetic fields up to 28 T. The experimental results reveal a highly wire width dependent spin splitting and even reversal of the left and right circular polarized light arising from the lowest conduction and valence states in the quantum wires. Our results indicate a highly wire width dependent total $g=g_e+g_h$ factor for these wire structures.

1. INTRODUCTION

Quantum wires made from different semiconductor material systems have in the past years received a considerable attention due to their intriguing physical properties and large potential for optical devices. One efficient way to investigate quantum wire structures and lateral quantum confinement effects is to apply a transverse magnetic field. A transverse magnetic field is coupled in two ways to the electronic structure in the wires. Firstly the magnetic field interacts with the magnetic moments arising from the quasi angular momenta and spins of the periodic Bloch functions. This so called spin term induces an energy split $\Delta E_{e,h}=g_{e,h}\mu_0 B$ of the spin up and down states (which normally are degenerate at zero magnetic field). g_e and g_h are the electron and the hole g-factor respectively, μ_0 is the Bohr magneton and B the magnetic field. Secondly, the lateral harmonic potential generated by the transverse magnetic field will couple with the lateral wire confinement potential. The lateral carrier motion will be subjected to a lateral confinement potential consisting of both the lateral and magnetic potential.

There have been a number of magneto-luminescence studies of the electronic structures in quantum wires published in the literature up to this date. They have all shown that a sufficiently strong transverse magnetic field quenches the lateral wire subband structure observed in the luminescence spectra.[1] The quantized states induced by the wire lateral potential merge into Landau level states at sufficiently high magnetic fields. However, strong lateral quantum wire confinement will also increase the admixture between the light- and heavy-hole bands ($j_z=\pm 1/2$ and $\pm 3/2$ respectively) in the valence band, besides reducing the subband energy shifts at low fields. The admixture will increase with increasing subband or Landau level quantum number and also with the magnetic field strength.[2] To study the detailed electronic structure in quantum wires we have performed polarized magneto-luminescence experiments. Transitions between pure conduction band states ($s=\pm 1/2$) and valence band states ($j_z=\pm 1/2$ or $\pm 3/2$) can be expressed in terms of angular momentum conservation, i.e. the angular momentum will change by $\Delta j_z=\pm 1$ if the photon angular momentum of circular polarized light is considered to be ± 1. This allows us to study the magnetic field induced spin splitting by circular polarized luminescence measurements. Previously there have been reports on an anisotropic spin splitting when the magnetic field is applied in different orientations with respect to the quantum wire.[3,4] As far as we know there have been no reports that have dealt with spin splitting as a function of magnetic field and wire width. We have therefore performed a series of high magnetic field experiments to study the circular polarized light arising from inter band transitions of lattice matched InGaAs quantum wires. The quantum wire structures are fabricated with a combination of CBE-growth, high resolution electron beam lithography, selective wet etching and MOCVD overgrowth.[5] This system is very convenient considering that the fabrication technique allows us to vary the lateral wire width without changing the composition of the wire region, nor the vertical width of the wire. We can therefore study the effects induced by the lateral quantum confinement systematically as a function of wire width.

2. EXPERIMENTAL DETAILS

The original quantum well structure used in the fabrication process of the quantum wires contains a 150 Å wide $In_{0.53}Ga_{0.47}As/InP$ quantum well. The wires were formed by writing a 170 nm pitch and line space pattern in the (110) direction and there after selectively etching the InGaAs cap layer, InP barrier, and the InGaAs quantum well. Finally the etched wires were embedded in InP by MOCVD overgrowth. The wires used in the experiments span a lateral width from 450 Å to 250 Å. We define the growth direction to be the z-direction, the wire axis to the y-direction and the lateral direction perpendicular to the wire axis to be the x-direction.

The high magnetic field photoluminescence measurements were performed at Grenoble High Magnetic Field Laboratory using a hybrid magnet at fields up to 28 T. The sample was mounted in a liquid He bath cryostat and cooled down to 2 K. The magnetic field was applied in the growth direction of the original single quantum well structure and the propagation direction of the excited and the detected light were parallel with the applied magnetic field, i.e. Faraday configuration. The samples were excited by using the 514 nm line from an Ar^+ ion laser, with the light coupled to the sample via an optical fiber. The luminescence from the sample was collected with the same optical fiber and thereafter dispersed by a single grating spectrometer. The circular polarization of the light was measured in-situ in the cryostat, i.e. a quarter wave plate and a linear polarizer were mounted in close proximity to the sample. Emission arising from either $\Delta j_z=+1$ or -1 transitions were selectively measured by changing the magnetic field direction, i.e. by changing the light propagation direction relative to the magnetic field direction.[6]

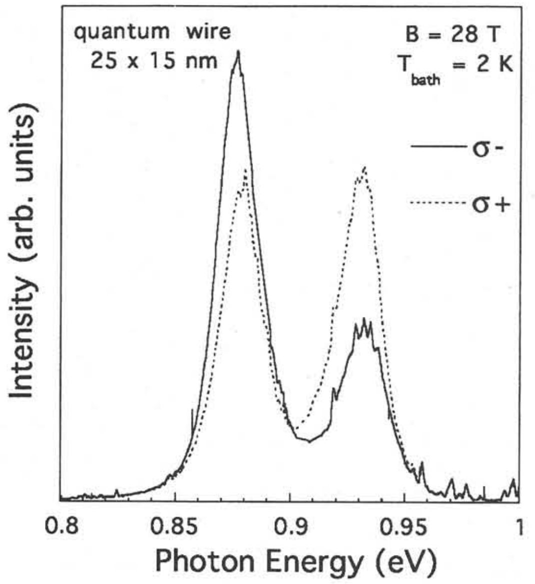

FIG. 1 (a). The emission spectra of a $In_{0.53}Ga_{0.47}As/InP$ quantum wire at 28 T. The cross section is approximately 150 Å x 250 Å. The excitation density is ~10 W/cm^2.

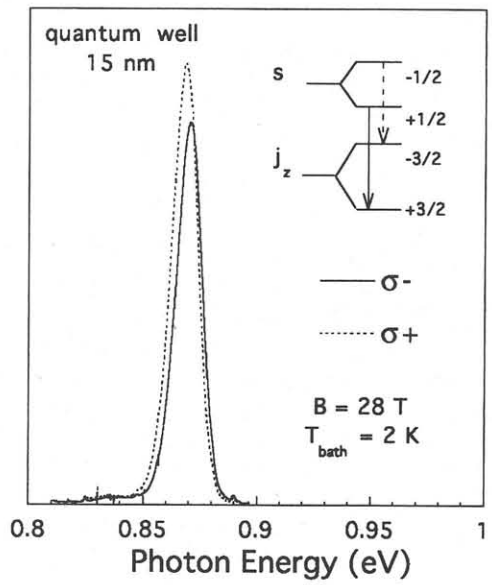

FIG. 1 (b). The emission spectra of a 150 Å wide $In_{0.53}Ga_{0.47}As/InP$ quantum well at 28 T. The excitation density is ~10 W/cm^2. The inset is showing the spin splitting structure[7,8] and the transition rules near the band edge.[9]

3. EXPERIMENTAL RESULTS

The zero field luminescence spectra of the samples contains a broad peak near 0.85 eV. The shape of the spectra are however substantially changed when we apply a transverse magnetic field (z-direction). Fig. 1 shows the emission spectra of 250 Å wide $In_{0.53}Ga_{0.47}As/InP$ quantum wires (a) and the quantum well reference (b) at a magnetic field of 28 T. Note that the change of the quantum wire spectrum appears at considerably lower fields, near the field strength where the magnetic length $l_c=(h/2\pi eB)^{1/2}$ becomes smaller than half the wire width. Above this field strength classical closed Landau orbits can be formed in the center of the wires. By using a simple classical analogy, we can say that the new wire states formed at high fields are similar to the Landau levels states in the quantum well reference, as they do not see the lateral interfaces. The formation of classical Landau level states has a profound effect on the density-of-states in the wires and thereby on the luminescence spectrum. Sharp peaks appear in the spectrum when the magnetic field is increased, as the wire density-of-states slowly approaches the more discrete quasi-zero-dimensional density-of-states. The band filling effect is although lager in the quantum wires compared to the quantum well reference in spite of the use of the same excitation density in the experiments, see figure 1. This is due to an overall lower density-of-states in the wire structures. One Landau level are therefore observed at 28 T in the quantum well reference whereas two Landau levels are observed in the quantum wires. The dashed and solid lines are representing the σ- (left) and σ+ (right) polarization spectrum, respectively. The spin splitting of σ- and σ+ lines (Δ=E(σ-)-E(σ+)) is negative in the 250 Å wide quantum wires whereas it is positive in the quantum well. Furthermore, the spin splitting of the spectrum is almost absent in the wider wires even at as high magnetic fields as 28 T, i.e. the splitting between the σ- and σ+ lines seems to smoothly vary as a function of the wire width, see Fig. 2. In addition, also the second subband/Landau level in the 250 Å wide wires is reversed in polarization compared to the wider wires. There is also a tendency to a slight polarization reversal effect in the first and the second (not shown) Landau level in the 400 Å wide wires at very high magnetic fields, as seen in Fig. 2.

4. DISCUSSION

Spin splitting of the Landau levels in the wires occurs in both the conduction and the valence band. The electrons are split into two sublevels with spin projection s=+1/2 and s=-1/2, where +1/2 is the lower level.[7] In the same manner the valence band states split into sublevels. Near the band edge in a quantum well, the valence band states consist mainly of the heavy hole states j_z=+3/2 and -3/2, see inset of Fig. 1 (b).[8,10] The quantum well spin splitting is quite large in both the conduction band and the valence band but of opposite sign in sense of the transition scheme and with a slightly larger splitting in the valence band.[11] The electron g-factor in $In_{0.53}Ga_{0.47}As/InP$ quantum wells (150 Å wide) have been found to be $|g_e|=5.6$ from electron spin resonance measurements[12] and $g_e=-6$ from magneto-luminescence measurements.[11] Assuming that g_e is independent of energy we obtain a linearly increasing spin split with the magnetic field in the conduction band. $\Delta E_e \approx -2.8$ meV at 8 T and -9.7 meV at 28 T for $g_e=-6$. Analyzing our experimental values for the quantum well reference we then obtain a spin splitting in the valence band equal to: $\Delta E_h \approx 3.9$ meV at 8 T and 12 meV at 28 T. If we express the spin splitting in the valence band in terms of a hole g-factor we obtain: $g_h \approx 8.4$ at 8 T and 7.4 at 28 T. The observed split experiences a slight saturation at high magnetic fields which thereby indicate a reduction of g_h and $g=g_e+g_h$, see Fig. 2. This can be due to an increased heavy-light-hole band intermixing at high magnetic fields, which has been found to induce saturation and even reversal of the spin splitting in the case of $In_xGa_{1-x}As/GaAs$ quantum wells.[8] The heavy- light-hole subband separation at zero field is approximately 25 meV for a 150 Å wide InGaAs/InP quantum well. Such valence band admixture effect could in fact also explain, or at least contribute to, the reversal we observe in the quantum wires. Especially when one considers the delicate balance that exists between the conduction and valence band spin splitting in the quantum well reference. The spin split structure has been calculated for GaAs quantum wires and it was found that the lateral confinement and the magnetic field induce a additional intermixing in the valence band.[2] The calculations showed that magnetic field need to reach above 20 - 25 T until the 1000 Å wide GaAs wire obtains the same degree of admixture of spin states in the valence band as the narrower 300 Å wide wire,[2] i.e. far above the point where the magnetic length becomes smaller than half the wire width. In our case the total g-factor ($g=g_e+g_h$) needs to change from approximately 1.4 to -1.4 at 28 T to explain the reversal we observe between the quantum well and the 250 Å wide quantum wire. (Assuming this interpretation is correct, the negative sign indicates a slightly larger spin splitting in the conduction band than in the valence band for the narrowest wires).

So far we have ignored any anisotropy or 1D effects in the conduction band. Anisotropy of g_e have been reported in case of quantum wells and explained by conduction-valence band coupling effects.[13] The anisotropy of g_e is given by $g_{e\perp}-g_{e//}=2p_{cv}^2/m_0(1/E_{e1hh1}-1/E_{e1lh1})$, where $g_{e\perp}$ and $g_{e//}$ are the g-factor parallel and perpendicular to the growth axis. $2p_{cv}^2/m_0$ is the interband matrix element, E_{e1hh1} and E_{e1lh1} are the transition energies for the heavy- and light-hole band, respectively. By using this model to estimate maximum variation of g_e due to a confinement potential perpendicular to the field[4] we obtain a variation of approximately 0.75 for our wires, assuming a light-hole heavy-hole subband separation of 25 meV (which is a slight overestimation for the wires). This is a little bit too small to explain the reversal but an anisotropy in g_e should be considered in a more accurate model. Furthermore, it is known that exchange effects can renormalize the spin splitting in quantum wells.[11] This was investigated by varying the excitation density at 20 T. No substantial renormalization was found in the lowest Landau level within the accuracy of the experiments. This is in line with the size of the spin split renormalization previously found for $In_{0.53}Ga_{0.47}As$/InP quantum wells.[11]

5. CONCLUSION

We have performed a series of circular polarized magneto-luminescence experiments to resolve the electronic structure in quantum wires. The energy shift and spectral shape of the wire luminescence peaks at high fields indicate that the field strength used has reached the high magnetic field limit. However, the circular polarized measurements reveal more detailed information which indicate that the magnetic field not completely quenched the electronic structure induced by the lateral wire confinement, even at as high fields as 28 T. Several aspects should be considered in a more detailed theoretical model to explain the experimental results, although the most important effect should be the valence band structure. Lateral confinement will besides reducing the level energy shift at low field also enhance the admixture of the light- and heavy-hole band states. The admixture reduces the spin splitting in the valence band. Our experimental results should thereby be in line with theoretical predictions.

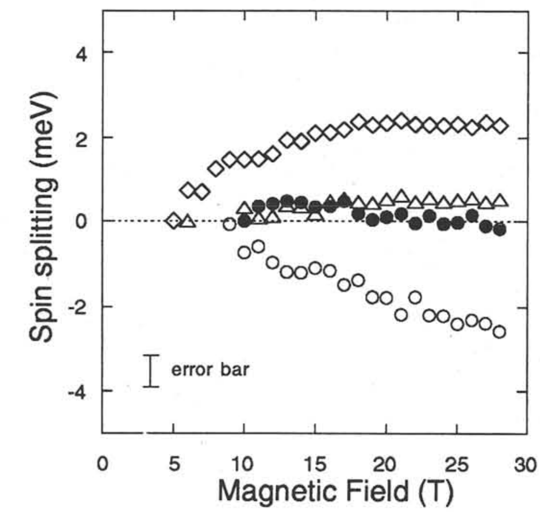

FIG. 2. Spin splitting of the lowest σ+ and σ- polarization emission peaks in the quantum well reference (◊), the approximately 450 Å (Δ), 400 Å (•), and 250 Å (o) wide wires.

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