Room-Temperature Photoluminescence Measurements in InP-InGaAs Single Asymmetric Quantum Well

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A single asymmetric quantum well (AQW) of InGaAs lattice matched to InP grown by Vapor Levitation Epitaxy (VLE) has been investigated using room-temperature photoluminescence (PL) measurements. The experiment was performed under different optical excitation using a 6328 Å line from a Helium-Neon laser. By increasing the incident laser power a 28.8 meV blue shift in recombination energy is observed to occur in a very narrow range of excitation intensity. The observed energy upshift is claimed to be related to a pronounced reduction of the 2D electron gas density in the InGaAs AQW.

Optical investigations on one-side modulation-doped or single asymmetric quantum wells of GaAs-AlGaAs grown by epitaxial techniques have been reported for over a decade[1,2]. A typical growth sequence used in such structures includes a GaAs-AlGaAs short-period superlattice on top of the GaAs substrate, the GaAs quantum well, an undoped AlGaAs spacer layer, a p-doped or n-doped AlGaAs layer followed by a GaAs cap layer. The n-doped structures has a 2D electron gas in the quantum well which accounts for their very high mobility at low temperatures. Particularly interesting is the possibility to control the 2D electron gas density ($\mathbf{n}_s$) located in the asymmetric quantum well by optically pumping the sample at different optical excitation intensities ($\mathbf{I}$)[2]. As far as PL experiments are concerned the signature of the optical control of the 2D electron gas is a shift in recombination energy in the PL spectrum as a function of the incident laser power. The low-temperature PL under consideration have been interpreted in terms of electron- hole pair photogenerated at the spacer layer. The photogenerated electron-hole pair is spatially pulled apart due to the built-in electric field in the spacer region. The photogenerated electrons are drifted out of the large gap layer into the remote layer containing the ionized donors and the photogenerated holes are drifted into the AQW. The PL spectra are identified as intrinsic band-to-band recombination involving the photogenerated holes and electrons from the 2D gas. The reduction of the 2D electron gas due to electron-hole recombination at the AQW is stabilized by electron tunneling back from the ionized donors into the quantum well through a potential barrier represented by the spacer layer[2]. The same charge transfer mechanism was recently used to explain negative photoconductivity in modulation-doped GaAs-AlGaAs and undoped InAs-AlGaSb quantum wells[3].

In this paper we report for the first time room-temperature PL data obtained with a single asymmetric n-doped quantum well of InGaAs lattice matched to InP. Our sample was grown by vapor levitation epitaxy, a dual chamber, atmospheric pressure, chloride transport vapor phase epitaxial growth technique[4]. A 2400 Å buffer layer of InP was first grown on top of a semi-insulating InP substrate followed by a 100 Å InGaAs quantum well lattice matched to InP, a 240 Å InP undoped spacer layer, a 600 Å n-doped InP layer with nominal 2×10^{18} cm^{-3} donors. The whole structure is then terminated by an InP cap layer. The growth profile in our case is very similar to the growth profile used in AQW's of GaAs-AlGaAs except for the absence of a short-period InP-InGaAs superlattice. Despite of a much more simplified growth scheme used here for single AQW's of InGaAs lattice matched to InP our PL measurements indicate that good quality interfaces are indeed obtained. Our sample has a 2D electron gas in the AQW estimated to be of the order of 3.7×10^{11} cm^{-2}. A conventional lock-in detection technique was used to take the PL spectra. The laser line was chopped and focused to a spot of the order of 60 μm in diameter to give excitation intensities in the range of 10 to 103 W/cm^2. A calibrated set of neutral density filters was used to change optical excitation intensities. The sample was mounted in a vertical sample holder and kept at room temperature. The PL spectra were recorded using a liquid-nitrogen-cooled Ge detector. Fig. 1 shows typical PL spectra under low-excitation as well as under high-excitation intensities. The recombination energy as a function of the optical excitation intensity is represented by full circles in Fig. 2. As shown in Fig. 2 around 102 W/cm^2 in optical excitation intensity a sharp shift in recombination energy is observed at room temperature. As mentioned above such a shift in recombination energy has been taken as the signature of the optical control of the 2D electron gas in AQW's of GaAs-AlGaAs at low temperature. However, from the experimental point of view there are remarkable differences between our room-temperature measurements with InP-InGaAs AQW and low-temperature measurements reported for GaAs-AlGaAs AQW. In our case the PL peak shifts by 28.8 meV, from 767.7 meV at an optical intensity of the order of 100 W/cm^2 towards saturation around 200 W/cm^2 at 796.5 meV. Typical values for the energy upshift obtained from low-temperature PL measurements with AQW's of GaAs-AlGaAs are of the order of 15 meV. In addition, the overall energy upshift as observed from low- temperature PL measurements occurs within a wide range of optical excitation, being the ratio of the excitation intensity at the high side (I_h) to the excitation intensity at the low side (I_l) of the order of $Q_1 = I_h/I_l = 10^3$. By excitation intensity at the low side and at the high side we mean respectively the minimum value of optical excitation one needs to start the energy upshift and the minimum value of optical excitation one needs to saturate the shift in energy. In our case however the total energy upshift occurs within a much narrow optical excitation range of the order of $Q_2 = I_h/I_l = 2$, despite of the structural similarities between our InGaAs-InP sample and the GaAs-AlGaAs samples used elsewhere[1–3].

As a consequence of the huge difference between Q_1 and $Q_2(Q_1/Q_2 = 500)$, any attempt to fit our room-temperature PL data, i.e., the shift in recombination energy ($\Delta \mathbf{E_r}$) as a function of the optical excitation intensity, based on the model proposed by Chaves et al.[2], had little success.

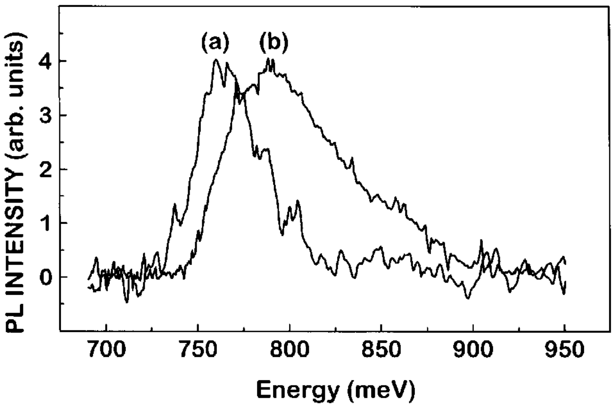

Figure 1. Room-temperature PL spectra ofthe InP-InGaAs AQW (nominal 100 A wide) under low-excitation intensity (a) and high-excitation intensity (b).

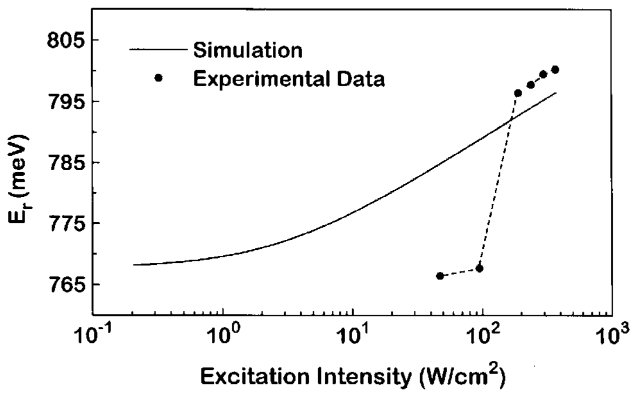

Figure 2. Photoluminescence recombination energy versus excitation intensity. The points are experimental results and the full line represents a simulation according to eqs. (1) and (2).

The solid line in Fig. 2 represents the behavior of our sample as simulated by the model proposed by Chaves et al.[2]. According to that model at equilibrium condition, the majority carrier concentration in the quantum well depends upon the optical excitation intensity as

$$I = C(n_s^0 - n_s)\exp(-D\sqrt{n_s}) \ , \qquad (1)$$

where C, n_s^0 and D are respectively a constant related to the tunneling attempt frequency of the carrier back into the quantum well, the 2D charge density in the dark and a geometric factor related to the height and thickness of the spacer region. The exponential in eq. (1) describes the tunneling of carriers from the ionized donors back into the AQW. A second equation connecting changes in recombination energy and 2D charge density at equilibrium, has to be written to explain the PL measurements. This is accounted for

$$\Delta \mathbf{E}_r = \mathbf{A}(n_s) + \mathbf{B}(n_s)^{1/2} , \qquad (2)$$

where **A** and **B** are constants. The linear term in eq. (2) represents the effect of the band bending to the shift of the PL line. The square root term in eq. (2) represents the effect of the band gap renormalization to the shift of the PL line. By increasing the optical excitation intensity a blue shift in the PL spectrum is therefore expected as described by coupling together eqs. (1) and (2). Within the model proposed by Chaves et al.[2] the estimated values of A, B and D in case of our sample, taking into account its geometrical parameters, are $A = 2 \times 10^{-11}$ meV $\times$ cm^2, $B = 3.5 \times 10^{-5}$ meV$\times$cm and $D = 6.3 \times 10^{-6}$ cm. A typical value for C considering the thickness of the spacer layer of our sample is of the order of $C = 10^{-9}$ W. Estimation of the parameter $D = 6.3 \times 10^{-6}$ cm involves calculation of the electron tunneling current through a triangular barrier of height $V = e^2 L_s n_s / K\epsilon_0$, being K the dielectric constant of InP, L_s the thickness of the undoped InP spacer and n_s the 2D electron gas density in the InGaAs quantum well. The calculation is usually done within the WKB approximation. As predicted by eqs. (1) and (2) the full line in Fig. 2 tends to the dashed line as D tends to zero. The dashed line in Fig. 2 is drawn as an aid to the eye and is not related to any theoretical model. Smaller D values represent faster carrier tunneling through the spacer layer. Abnormally small D value has been reported for GaAs-AlGaAs AQW's and has been associated with the presence of impurity states in the spacer layer[2].

To conclude, room-temperature PL peak position taken from InP-InGaAs AQW is shown to be sensitive to the optical excitation intensity similar to what has been previously observed in GaAs-AlGaAs AQW at low temperatures. Qualitatively our data indicate that an optical-assisted charge transfer mechanism could takes place at room temperature as it does at low temperature. However a tunneling mechanism through the spacer layer, as proposed by Chaves et al.[2] to explain low-temperature PL measurements, do not account by itself for the experimental results at room temperature. A much faster charge transfer mechanism, probably thermal activated, should be taken into consideration to explain the experimental results presented here. A deeper analysis of this new effect is presently in progress and will be published latter on. Indeed, such a sharp optical-induced change in the majority carrier density at room temperature, as indicated by our PL measurements, could be an interesting feature to design new devices.

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