Evaluation of Carrier Capture Times for Very Thin InGaAs/InP Quantum-Wells

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Conventional and time-resolved photoluininescence measurements were conducted on an InGaAs/InP quantum-well structure with six quantum-wells, each grown for a different period of time varying between 1 ancl 20 seconds. Calculations of the lowest transition energy were carried out assuming several types of interfaces with varying compositions and thicknesses showing that tlie barrier for emission of an electron is always smaller than that of a hole. The experimentally observed photoluminescence peaks are within tlie small energy range predicted by theory. Combining then the calculated electron barriers with the measured lifetimes, one was able to determine the capture times of electrons into the quantum-wells using the Principle of Detailed Balance for capture and emission. The capture times ohtained range from 2 to 14ps.

The fast cevelopment of devices based on quantum-well structures has greatly raised the interest on the evaluation of carrier capture times ill quantum-wells of different materials and widths. Lasers based on such structures depend on an efficient carrier capture process[1-3] while photodetectors rely on long capture times in order to efficiently collect the current[4].

On tlie theoretical point of view, the interest lies both on the approach taken to tackle tlie capture process which is intermediated by LO phonons and on tlie prediction of capture times for different systems. The classical picture aclopted in the late 70's ancl early 80's resulted in rather fast capture times for quantum-wells thicker than the mean-free-path of the carriers[5,6]. In the mid 80's a quantum-mechanical approach was introduced which predicted oscillations on the capture times with quantum-well (QW) thicknesses[7,8].

Experimentally, capture times are obtained indirectly, often through the measurement of either the decay of tlie barrier photoluminescence (PL) signal or tlie rise of the QW PL. In the literature one can find capture times varying from 0.1 to 20 ps depending on the sample configuration and experimental technique used[9-11]. In any case, frequently the theoretical results do not agree with the measured data. However, the oscillations in the capture times with QW thickness has been experimentally observed for the

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$Al_xGa_{1-x}As/GaAs$ system[1].

In this letter we present a simple approach using tlie Principle of Detailed Balance between capture and emission processes to determine capture times in extremely thin quantum-wells of an $In_{0.53}Ga_{0.48}As/InP$ multiple-quantum-well (MQW) structure consisting of a series of quantum-wells of thicknesses varying from 3 to 50 Å. The Detailed Balance analysis not only clearly demonstrates tliat the emission of carriers oiit of a well or in other words, the transfer of carriers frorii one well to a. neighboring one, takes place via the least bound particle and not via excitons, but also provides capture times which are in excellent agreement with other recent published results for the $GaAs/Al_xGa_{1-x}As$ system[11].

The sample used was grown at 600°C and 50 mbar oii a Sn-doped InP substrate usiiig 2 seconds growth interruption on both interfaces. First, an InP buffer layer of 250nm was deposited, followed by an $In_{0.53}Ga_{0.47}As$ lattice-matched thick reference layer. Then, a series of six $In_{0.53}Ga_{0.47}As$ quantum-wells separated by 200 Å InP barriers was grown. Finally, a. 350 Å thick InP cap layer was deposited. Further details about the sample structure can be found in Ref. 12.

Conventional PL was performed between 2 and 450 K using the 5145 Å line of the Ar^+ laser. A nitrogen-cooled germanium photodiode was used with lock-in detection. For tlie time-resolved PL experiments a pulsed Ti:sapphire laser was used with excitation wavelength of 9600 Å. The signal was detected by a. Hamamatsu streak camera. The temporal resolution of the experiment was limited by the 6 ps laser pulse width. Tlie excitation poiver used on both PL experiments was around 100 W/cm^2.

Fig. 1 shows a. 2K PL spectrum of the sample where several PL peaks originatirig in different quantum-wells can be observed. The associated number of monolayers (ML) is iiidicated ill the figure. One can distinguish, for iiistance, two PL peaks coming from the QW grown for five seconds, each one corresponding to a different number of ML's, tlie so-called extended monolayer flat-islands. Excitons under certain circunstances are allowed to move froni one of these islands to another within the same QW (intra-well transfer). This type of migration has already been extensively discussed in a previous publication[13]. This communication will be concentrated on the emissioii out of a QW towards a. neighboring one.

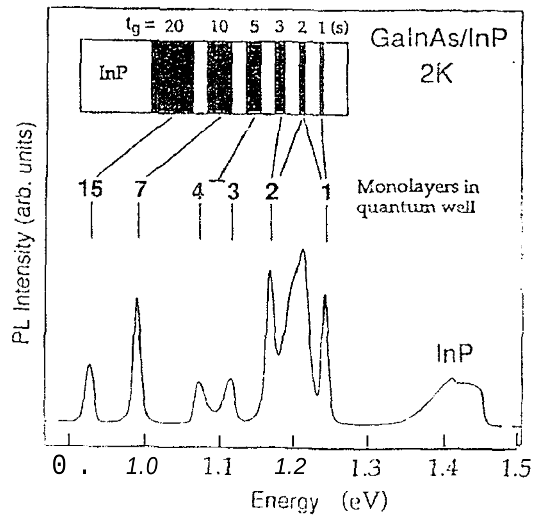

Figure 1: Photoluminescence spectra at 2K of the investigated $In_{0.53}Ga_{0.47}As/InP$ multiple-quantum-well structure. For each nominal quantum-well grown according to the growth sequence, the spectra consists of PL emission lines which are split into multiplets. The sample structure and thickness of the quantum-well corresponding to each of tlie luminescence lines are shown in the insert.

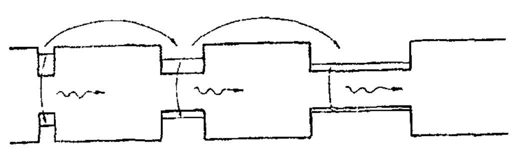

Figure 2 Scheme of the emissioii, radiative reccmbination and inter-well transfer processes occuring in the investigated $In_{0.53}Ga_{0.47}As/InP$ multiple-quantum-well structure.

Tlie thinner tlie QW is the closer the electron and the hole energy levels are to the corresponding InP barrier ones. Therefore, the energy barrier for carriers to be emitted out of the QW is smaller for tlie tliinner wells. This description is schematically pictured in figure 2.

As one increases the temperature, the PL starts to quench. The temperature for which the quenching of tlie PL sets ıı will be higher tlie thiclter tlie mell. Tliese characteristic temperatures T' can be determined from an Arrhenius plot for eacli QW and should indirectly correspond to tlie emission rate of a particular QW. At T = T', one can then say tliat the emission and recombination rates are equal. Putting it in another way, at $T = T'$

$$e_n = \tau_{\text{rec}}^{-1} \tag{1}$$

where e,, is t.ie einission rate and T_{rec} tlie recombination time.

Simultaneously with the decrease of tlie PL intensity of one QW the PL signal of tlie thiclter neighboring QW increases. This implies tliat tlie PL quencliiiig process is essentially clue to emission of carriers out of tlie QW and their subsequent capture in a neighboring QW. Since the emission out of a QW is evidenced by both the quenchirg of tlie PL signal and by the capture of carriers hy a.ıother QW, compiling these characteristic temperatures with tlie activation energy for emission, one should be able to easily correlate the emission and capture rates. Using the Principie of Detailed Balance one can write:

$$e_{,,} = c_n \exp(-\Delta E/kT) \,, \tag{2}$$

where c, is tlie capture rate. At $T = T'$ Eq. (2) can be rewritten as:

$$r_{,,,} = \tau_{\text{cap}} \exp(-\Delta E/kT) \,. \tag{3}$$

Tlie emission rates can he determined by measuring the reconibination time $r_{,,,}$ at T'. Tlie activation energy A E can be calculated from the confinement energies for electrons and holes. Consequently, it should be possible to extract capture times for these QW's.

So far one has completely neglected recapture. Carriers emitted out of a. QW can move eitlier towards a thiniier or a thicker well. In case tliey migrate in tlie direction of tlie thinner QW, they will be immeadiately reemitted, be:ause tlie temperature is high enough, and recaptured by the original QW. Therefore, in order to take recapturr into accoiint and still use tlie Principle of Detailed Balance, one should introduce a factor of 2 on equation (3). The argument to understand this is as follows. Since there are two emission paths, one needs two emitted carriers for one captured carrier. In this way,

$$2\tau_{\text{rec}}^{-1} = r_{,,,} \quad \exp(-\Delta E/kT') \,. \tag{4}$$

Next step is to determine the activation energy ΔE. If one assumes that the carriers are transferred as an exciton, then ΔE is the sum of the barriers for the electron and for the hole, C barriers. Plotting kT' as a function of C barriers one obtains a linear relationship: $kT' = 0.053$ C barriers. Substituting it in Eq. (4),

$$2\tau_{\text{rec}} = \tau_{\text{cap}}^{-1} \exp(-1/0.053) \,. \tag{5}$$

In order to verify whether the inter-well carrier transfer takes place via excitons or not one can simply use values of τ_{rec} from the literature to evaluate τ_{cap}. Using $\tau_{\text{rec}} = 10$ ns[14] one obtains r,,, < fs which is totally unrealistic. This demonstrates that the interwell migration occurs via free carriers. Certainly the first particle to move is tlie least bound one, which has not beeii determined yet.

Defining ξ, as an energy fraction of the C barriers one can write barriers. Then, Eq. (4) becomes: one can write $\xi = \Delta E/\Sigma$ barriers

$$2\tau_{\text{cap}} = \tau_{\text{rec}} \exp(-\xi/0.053) \,. \tag{6}$$

In calculating ξ, using the envelope function approach several types of interfaces were tested. In addition to the ideal interface, five different plausible structural perturbations were also checked. One of them was tlie introduction of lialf a monolayer of InAs on eacli side of the QW. Others also included different $InAs_xP_{1-x}$ monolayer configurations with compositions varying from $x = 0.25$ to $x = 0.75$.

One way of checking the results is to calculate the transition energies as well and compare them with the measured PL peak energies. The result of this procedure is plotted in figure **3.** By this method one should

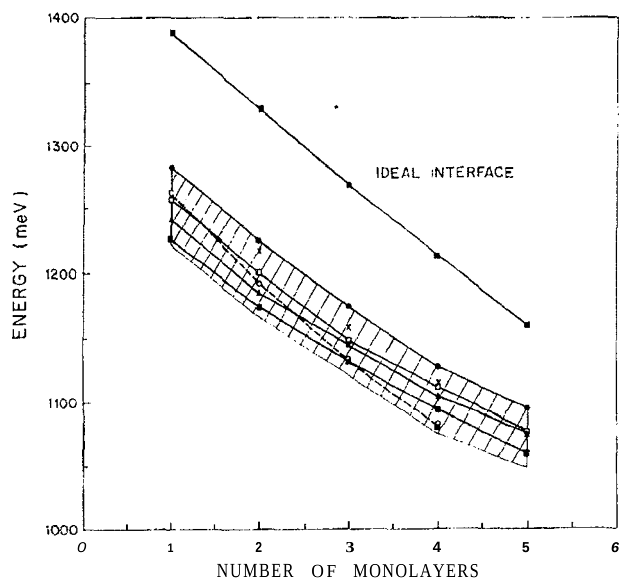

Figure 3: Transition energies vs. the number of monolayers for the iiivestigatetl $In_{0.53}Ga_{0.47}As/InP$ multiple-quantum-well structure. The lines are just a guide for tlie eyes. The solid ones connect calculated points for tlie same interface perturbation introduced while the dashed line links tlie experimental points. The crosses refer to a different sample described in tlie text. The shadowed rectangle ernbraces tlie tlieoretically obtainerl energy values except for tlie case of tlie ideal interface.

be able to know which interface structure approaches the most the one encountered in the sample and to eventually choose the most adequate ξ

In figure 3, the straight solid lines connect the values obtained for the same type of interface and are just a guide for tlie eyes. The dashed line connects the experimental points obtained from the 2K PL spectra. Also included iii the figure, represented by crosses, are the experimental points for another sample grown under similar conditions but containing a stack of 10 QW grown for 6 secorids. Tlic QW's contain islands with 2, 3 and 4 ML's.

Two features are striking in tliis figure. First, the values calculated for the ideal interface are more than 100 meV higher than the experimental data. Second, the exact interface perturbation introduced is not crucial since they all provide transition energies that follow the same trend and do not differ by much. Also, the perturbation that best simulates tlie sainple structure depends on the number of ML's. The liighlight of the figure is that the experiinenal data for both samples fall within the shadowed rectangle depicted on the figure 3 which embraces all the calculated data.

Table I. Calculated range of fraction of energy barrier ξ, for the electrons between the InP barrier and the $In_{0.53}Ga_{0.47}As$ yuantum-wells consisting of 1 to 5 monolayers.

	ξ
1ML	(0.19,0.23)
2ML	(0.22,0.25)
3ML	(0.23,0.27)
4ML	(0.26,0.31)
5ML	(0.28,0.33)

In additioii, the calculations showed that the electron is always tlie least bound particle, its fraction of the total barrier ξ, ranging from 0.19 to 0.33 for QW's between 1 to 5 monolayers as shown in Table I.

The recomination tiines were measured from 10K to 210K. At higher temperatures the PL signal was too weak. In tliis temperature range the recombination time varied between 1 and 4 ns which is in complete accord with recently reported values[15]. However, to determine $r_{,,,,}$ from Eq. (S), one is only interested in $r_{,,,}$ at $T = T'$. Since T' for QW's of more than 4 monolayers exceeds 210K, τ_{rec} was only measured for QW's of 1 to 4 monolayers. At $T = T'$, $r_{r,,}$ was found to equal to 2.0 ± 0.3 ns. Introducing the calculated range of ξ, and measured values of $r_{,,,}$ into Eq. (8), one obtains capture times varying from 2 to 14ps.

Tliese values are in excellent agreement with the results published by Blom et al[14] where they obtairied a capture time of 20 ps for a 30 Å thick $Al_xGa_{1-x}As/GaAs$ QW and 3 ps for a 50 Å thick QW corresponding to the predicted capture time oscillations. Their results were extracted froin the rise time differences of the QW luminescence after direct excitation into the QW and indirect excitation into the $Al_xGa_{1-x}As$ barrier. Deveaud et al.[10] claimed that capture times ought to be shorter than **3** ps, which at first sight may disagree with our results. However, it is in fact the decay time of the barrier PL signal that they say has an upper limit of 3 ps. Those authors extracted the capture time from the decay of the barrier PL signal for an $Al_xGa_{1-x}As/GaAs$ QW. The PL decay time refers to the time the carriers take to leave tlie barrier while the capture time determined here is the time for the carrier to be captured by the lowest QW energy level.

In conclusion, capture times of electrons into $In_{0.53}Ga_{0.47}As/InP$ QW of thicknesses varying from 3 to 12 Å have been determined to be between 2 and 14 ps. This evaluation was done using the straight forward Principle of Detailed Balance between emission and capture which only requires knowledge of recombination time:; and band-offsets between tlie InP barrier and the QW's.

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