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Journal of Luminescence 60&61 (1994) 400–403

JOURNAL OF LUMINESCENCE

Transient photoluminescence of GaAs/AlGaAs quantum wires

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Abstract

We have studied the temperature dependence of exciton decay and rise times in a strain confined quantum wire and its host quantum well. The decay time in the wire increases as $T^{1.7}$ rather than the predicted $T^{0.5}$. At high temperature, the radiative decay time in the wire is longer than in the well.

It has been shown that by applying an inhomogeneous strain laterally to a GaAs/AlGaAs quantum well (QW) by strain patterning, we can get a quasi one-dimensional (1D) structure, the so called "quantum wire" [1]. By steady-state measurement, we found that at low temperature the wire has approximately the same quantum efficiency of exciton emission as its host QW structure; however, the wire retains this high efficiency to higher temperature than the host QW [2]. This suggests that non-radiative recombination in the wire is efficiently inhibited. We have also found that energy transfer from the QW to the wire is temperature dependent due to thermal activation of excitons in the QW over a potential barrier created by the strain [2].

In this work, we have measured the picosecond transient photoluminescence (TPL) of the excitons in quantum wires as well as in the host QW. TPL can supply valuable information on, for instance, carrier relaxation and radiative decay time in the wire, and energy transfer between QW and wire. The specific quantum wire structure is an array of 350 nm wide wires with 1.650 μm spacing patterned on a 9 nm wide QW. The details of the structure, its strain tensor and strain potential were described in Ref. [3]. A mode-locked Ar^+ laser (5145 Å) was used as excitation source. The detection system is a standard time-resolved single photon counting set-up, resolution 47 ps/channel. The measured laser pulse (including the system response) has a 200 ps FWHM. The measured TPL data have been deconvolved from the measured laser pulse on the assumption of linear response. The excitation intensity was about 3.5×10^{-7} J/cm^2/pulse.

In the patterned region, we can simultaneously observe the exciton emission from the wire and the QW between the wires. Fig. 1 shows TPL of the QW and wire as well as the unpatterned QW (UQW) at two typical temperatures. They were measured at the peaks of the emission bands, 1.558 eV for the QW and 1.526 eV for the wire at 5.2 K. After the laser pulse, excitons in both QW and wire decay exponentially, apart from an

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SSDI 0022-2313(94)E0468-D

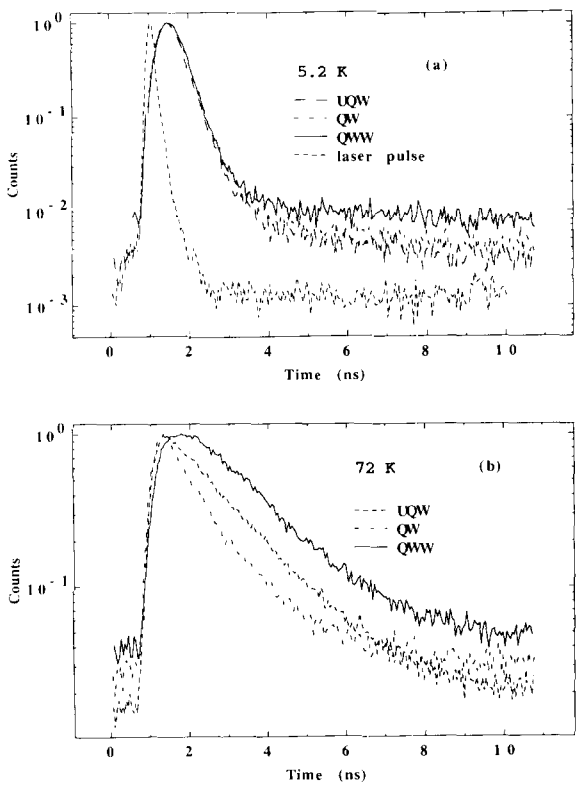

Fig. 1. Transient photoluminescence of excitons in UQW (unpatterned quantum well), QW (quantum well between wires) and QWW (quantum wire).

additional slow component at low temperature presumably due to impurities or defects. In a simplified model [4] in which electron–hole pairs are created in the barrier and transfer to the QW, which is too thin to contribute appreciably to the absorption, the TPL of a QW can be described by

$$I(t) = I_0 \frac{\tau_d}{\tau_d - \tau_b}(-e^{-t/\tau_b} + e^{-t/\tau_d}). \quad (1)$$

Here τ_b is the lifetime of the electrons in the barriers, and is the rise time if $\tau_d > \tau_b$, τ_d is the exciton decay time in the QW, $I_0 = (\tau_d/\tau_r)m_0/\tau_c$, τ_r is the radiative decay time in the QW, τ_c is the carrier capture time from the barrier to the well and is the major contribution to τ_b, and m_0 is the carrier number in quasi steady state after each excitation pulse. We have assumed that the hot carriers have a very fast relaxation time and the laser profile is a delta function. For the patterned structure, considering the transfer from the QW to wire, we have two kinetic equations for the exciton populations in the QW and wire:

$$\frac{dn_1}{dt} = \frac{m_1}{\tau_{c1}} - \frac{n_1}{\tau_{d1}}, \quad (2)$$

$$\frac{dn_2}{dt} = \frac{m_2}{\tau_{c2}} + \frac{n_1}{\tau_t} - \frac{n_2}{\tau_{d2}}, \quad (3)$$

where the indices 1 and 2 are for parameters in the QW and QWW, respectively. τ_t is the transfer time from QW to QWW. Note that τ_{d1} now includes the effect of the carrier transfer. $m_i = m_{i0}\exp(-t/\tau_{bi})$, and m_{10}/m_{20} can be approximated by the ratio of unpatterned area to patterned area. Reverse transfer from the wire to QW is not included, since the depth of the potential well is about 30 meV. The solution of Eqs. (2) and (3) gives for the wire luminescence:

$$I_2(t) = \frac{n_2(t)}{\tau_{r2}} = c_1 e^{-t/\tau_{b2}} + c_2 e^{-t/\tau_{d1}} + c_3 e^{-t/\tau_{b1}} + c_4 e^{-t/\tau_{d2}}, \quad (4)$$

where c_1–c_4 are complicated functions of the τ's. The first term corresponds to an increase due to the direct excitation into the wire barrier ($c_1 < 0$); the second and third terms are from the transfer from the QW to wire ($c_2 < 0$ if $\tau_{d2} > \tau_{d1}$, $c_3 > 0$); and the fourth is the major decay term ($c_4 > 0$) which gives the intrinsic exciton decay time in the wire. From Fig. 1(a) we can see that at low temperature, all three curves have similar decay times. It shows that the exciton decay times τ_{d1}, τ_{d2} and τ_d are approximately equal, and the QW to wire transfer time τ_t is much longer than the exciton decay time. We expect that with increasing temperature, the second term will be relatively more important than at low temperature and be a rising term, since the transfer rate increases with temperature while the total decay time becomes longer and $\tau_{d2} > \tau_{d1}$, as shown in Fig. 1(b). The first and third terms are relatively fast processes, especially at high temperature.

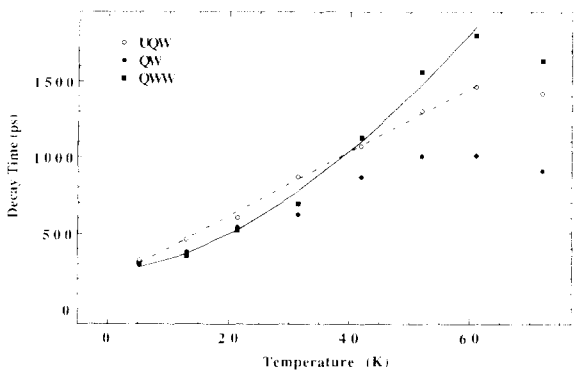

Fig. 2. Temperature dependences of exciton decay times in the UQW, QW and QWW.

In practice, for simplicity, we fit the TPL curves to a biexponential for both the QW and the wire. For the wire, this fit yields effective rise and decay times. However, the effective decay time should be reasonably close to τ_{d2}, the intrinsic decay time of the wire excitons. The temperature dependences of these fitted decay times are shown in Fig. 2. In general, at low temperature, the decay times of wire and QW excitons are approximately equal to the decay time of the UQW, ~ 300 ps; the rise time of the wire is slightly longer than in the UQW, ~ 230 ps in the wire compared to ~ 150 ps in the UQW due to the contribution of the relatively slow transfer process from the QW to wire. In disagreement with Ref. [5], the carrier relaxation, characterized by τ_{c2}, in the wire is not significantly slowed by reduced dimensionality. With increasing temperature, the rise time of UQW shortens to ~ 10 ps at 72 K, while the rise time of the wire initially decreases, then increases to about 400 ps at 72 K. At first the transfer from the wire barrier is dominant, thus τ_{b2} decreases; then transfer from the QW becomes dominant.

All decay times increase with increasing temperature until above 60 K, where non-radiative processes become significant. However, the temperature dependences are quite different for the QWW and UQW. With the following assumptions: free excitons, well separated quantized levels, no non-radiative recombination, and rapid thermalization, the temperature dependence of the radiative decay time at low temperature should be determined by the density of states, that is, $\tau_r \propto T^{3/2}$ for 3D [6], $\tau_r \propto T$ for 2D [7], $\tau_r \propto T^{1/2}$ for 1D [8]. Our $\tau_d(T)$ for UQW does show a linear T-dependence as $T < 60$ K, $\tau_d(T) = 200 + 21T$ (ps), in agreement with Ref. [6]. The non-zero intercept at zero temperature is commonly seen and is due to exciton localization. Deviation from linearity at higher temperature is due to non-radiative recombination. However, for the wire, we can fit the decay time by $\tau_d(T) = 250 + 1.42T^{1.71}$ (ps) in disagreement with theory. To explain the discrepancy between the theory and our experimental result, one obvious factor is that in this specific structure the splittings of the electron subbands are only around 1 meV which is comparable to or smaller than kT. However, this effect would give a linear T-dependence like the quasi 2D case. Incomplete thermalization should give a slower T-dependence. We attribute the more rapid T-dependence to the larger exciton localization energy in the wire due to the fluctuation of the wire width. Note that at high temperature, the radiative decay time of the wire excitons is longer than that of the UQW.

In principle, we can get the temperature dependence of the transfer time from the decay times of the UQW and QW, but our data is not accurate enough to draw any quantitative conclusion. By selectively exciting to the exciton states in the QW, we could get a more accurate transfer time from the rise time of the wire excitons.

In summary, we have evidence that the carrier relaxation in this quasi 1D system is not effectively slowed due to reduced dimensionality, and the T-dependence of the wire exciton decay has been shown not to agree with the existing theory. At higher temperature, the wire exciton has a longer radiative decay time than the UQW. The temperature dependence of the energy transfer from QW to wire is consistent with out previous steady-state results.

Acknowledgement

This work is supported by the Office of Naval Research under grant #N001491J1429.

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