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Recombination in Deep Etched CdZnSe/ZnSe Quantum Wires (*).

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Summary. — Picosecond photoluminescence spectroscopy was used to investigate the recombination dynamics of excitons in deep etched CdZnSe/ZnSe quantum wires with lateral extensions down to 20 nm. In the low-temperature regime ($T \leqslant 10$ K), no significant reduction of the exciton lifetime was found down to a wire width of 20 nm, indicating a negligible influence of carrier loss at the wire sidewalls. At higher temperatures, the lifetime decreases for decreasing wire width, *e.g.*, from 330 ps in the mesa structure to 21 ps in the 28 nm wide wires at room temperature. Simple model calculations indicate that this drop of the lifetime is due to diffusive carrier transport to the wire sidewalls and subsequent non-radiative surface recombination.

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1. – Introduction.

While a lot of work has been done to analyse the recombination dynamics in quantum wires based on III-V semiconductors [1-3], in II-VI materials only two-dimensional systems [4-6] or dots embedded in glass matrices [7] have been investigated due to the lack of an appropriate low-damage fabrication process. It has been shown recently that electron beam lithography and wet chemical etching is suitable to realize quantum wires in the ZnSe system with lateral extensions below

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20 nm [8]. Although wet etching avoids the problem of optical inactive «dead» layers, as observed, *e.g.*, in dry etched structures [2], the question of non-radiative surface recombination in the wire sidewalls still arises. Compared to common GaAs- or InP-based III-VI materials, wide-band-gap II-VI semiconductors are characterized by an enhanced exciton binding energy [9], thus implying a reduction of the radiative recombination time. From this point of view it can be expected that the influence of non-radiative recombination, as *e.g.*, at open surfaces of deep etched nanostructures may be reduced.

In the present work time-resolved photoluminescence (PL) spectroscopy was used to investigate the recombination dynamics in wet chemically etched CdZnSe/ZnSe quantum wires. We have focussed our attention on the wire width and the temperature dependence of the exciton lifetime, especially to study the influence of non-radiative carrier loss at the wire sidewalls.

2. – Experimental details.

The CdZnSe/ZnSe quantum wires under investigation were fabricated based on a MBE-grown single quantum well with $L_z = 5.5$ nm and a Cd content of 35% in order to avoid carrier loss due to thermal emission of excitons into the barrier at elevated temperatures. The wire pattern was defined by electron beam lithography in polymethylmethacrylate resist and transferred into the semiconductor by a deep wet chemically etch process [8]. This technique ensures wire sidewalls of high optical quality, *i.e.* without any dead layer and enables the continuous variation of the lateral structure size down to the sub-20 nm range.

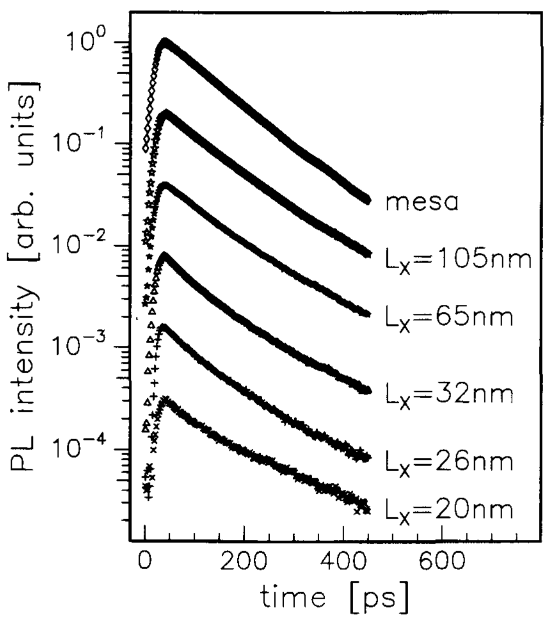

Fig. 1. – Time dependence of the PL intensity of CdZnSe/ZnSe quantum wires with varying width L_x at $T = 2$ K in comparison to a 2D reference (mesa).

For the time-resolved PL experiments, we have used a frequency-doubled mode-locked Ti-sapphire laser providing pulses with a pulse width of 2 ps at a repetition rate of 82 MHz. The laser wavelength was tuned to 460 nm, thus exciting carriers only in the CdZnSe quantum well. The peak excitation density was about 100 kW/cm^2. The luminescence signal was detected by a synchroscan streak camera followed by a CCD array with an overall time resolution of about 5 ps.

3. – Results and discussion.

In fig. 1 the PL intensity of $Cd_{0.35}Zn_{0.65}Se$/ZnSe quantum wires is plotted *vs.* time for different wire widths at a temperature of 2 K.

For all wires, the PL intensity rises to a maximum within about 40 ps after the exciting laser pulse due to carrier relaxation to the band edges and subsequent exciton formation. The decay of the PL signal is correlated to the exciton lifetime. While at low temperatures in the mesa a monoexponential decay is observed, an additional longer component, possibly due to exciton localization, occurs in narrow wires. As can be seen from fig. 1, we observe no reduction of the excitonic lifetime in narrow wires as is expected in the presence of open wire sidewalls [2]. This can be explained on the one hand by a small exciton diffusion length, which is the consequence of both the high carrier masses and the small radiative lifetime as well as localization effects in the CdZnSe/ZnSe system. On the other hand, a small surface recombination velocity may cause a reduced non-radiative sidewall recombination rate.

In fig. 2, the exciton lifetime as extracted from the fast component of the biexponential decay is shown as a function of temperature for different quantum wires compared to the 2D reference. For the two-dimensional reference an increase of

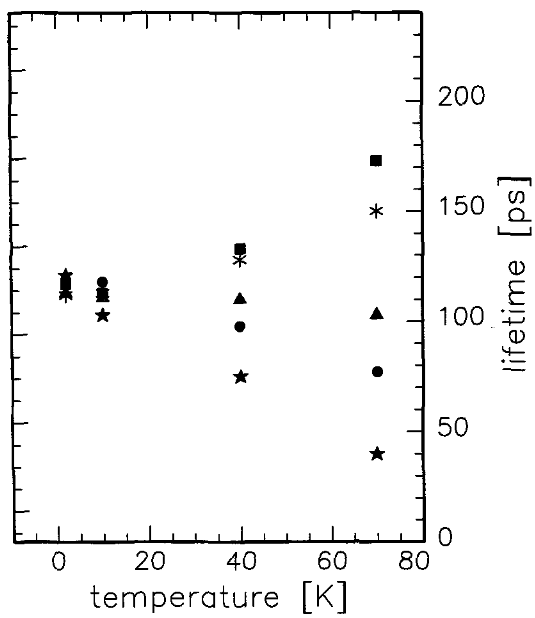

Fig. 2. – Temperature dependence of the exciton lifetime in deep etched CdZnSe/ZnSe quantum wires. ■ 2D reference, $*$ $L_x = 800\,\mathrm{nm}$, ▲ $L_x = 350\,\mathrm{nm}$, ● $L_x = 55\,\mathrm{nm}$, ★ $L_x = 56\,\mathrm{nm}$.

the lifetime from 120 ps at $T = 2$ K to 170 ps at $T = 70$ K was found. In this temperature range, no significant decrease of the time-integrated PL intensity is found, indicating that the emission is mainly dominated by radiative excitonic recombination. The non-linear increase of the lifetime with temperature indicates the influence of exciton localization even in the 2D reference at low temperatures. For wires non-radiative recombination channels become activated for increasing temperatures. While for 350 nm wide wires the lifetime is almost constant up to a temperature of 70 K, a reduction of the lifetime with increasing temperature is observed for smaller wire widths. This is most significant in extremely narrow wires, where, *e.g.*, the lifetime of the 26 nm wide wires drops from about 120 ps at $T = 2$ K to about 40 ps at $T = 70$ K. This is consistent with a model describing the carrier loss in deep etched wires by a carrier diffusion to the wire sidewalls and non-radiative sidewall recombination [2]. Increasing the temperature, both the diffusion length [10] as well as the surface recombination velocity [2] are expected to increase, causing an enhancement of the non-radiative recombination rate at the wire sidewalls.

In fig. 3 the decay curves for different wire widths are shown at room temperature. The two-dimensional reference shows a lifetime of about 330 ps. For decreasing wire width, the decay time decreases resulting in a lifetime of about 21 ps in the case of the 28 nm wide wires. At $T = 400$ K, the excitons are able to diffuse to the open wire surfaces, where they can recombine non-radiatively.

Describing the non-radiative sidewall recombination with the classical diffusion model as discussed above, the experimental data give access to the surface recombination velocity S. From the fit we obtain $S = 7 \cdot 10^4$ cm/s. Compared to GaAs/AlGaAs systems [2] which show at $T = 50$ K a surface recombination velocity

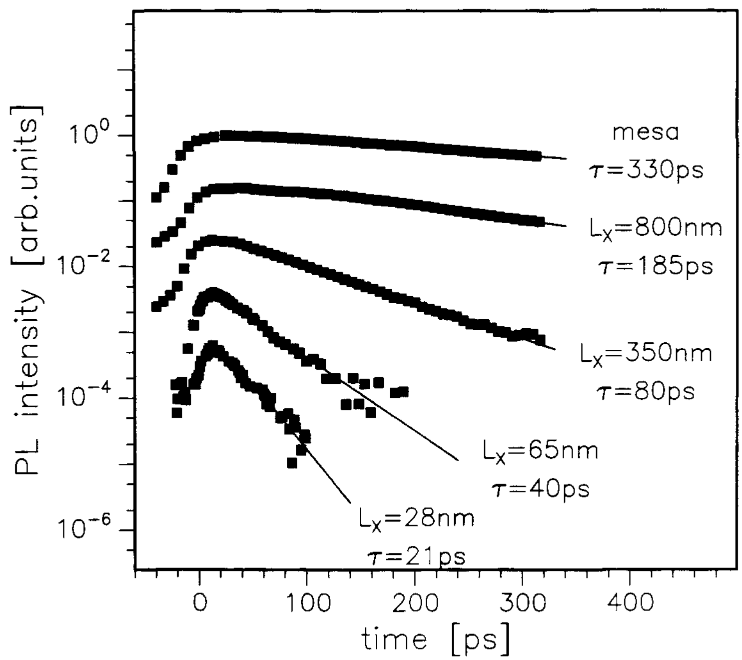

Fig. 3. – Normalized PL intensity at $T = 300$ K as a function of time from deep etched CdZnSe/ZnSe quantum wires with varying wire width.

$S = 2 \cdot 10^6$ cm/s, the value derived in the CdZnSe/ZnSe system is much lower, even at room temperature. This small value for S is responsible for the high quantum efficiency of the narrowest wires even at room temperature.

4. – Conclusions.

In summary, we have investigated the exciton recombination dynamics in deep etched CdZnSe/ZnSe quantum wires by time-resolved PL spectroscopy. At low temperatures ($T \leqslant 10$ K), no significant reduction of the exciton lifetime with decreasing wire width could be observed, indicating a strongly reduced influence of non-radiative sidewall recombination. Increasing the temperature both the diffusion length and the surface recombination velocity increase, resulting in a diffusive transport of excitons to the open wire sidewalls and a subsequent non-radiative surface recombination. *E.g.* at room temperature, the lifetime of the 2D reference is about 330 ps, while for the 28 nm wide quantum wires, a decay time of about 21 ps was found. From simple model calculations a surface recombination velocity of about $7 \cdot 10^4$ cm/s at room temperature could be derived.

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