Photoluminescence on Low-Temperature grown InAs/GaAs Quantum Dots.

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Abstract: We study low temperature (LT, 250°C) grown Stranski-Krastanov InAs/GaAs quantum dots (QDs) to combine the large QD optical nonlinearity with an ultrafast response time. We observe a QD photoluminescence peak around 1200 nm on top of a background due to the As_{Ga}*-*V_{As} *center. The QD-emission line disappears with increasing temperature around 30K. The PL-efficiency increases with a factor of 45-280 as a function of excitation wavelength around the GaAs bandgap. Our observations point towards QDs with good optical quality, embedded in a LT-GaAs barrier in which the carriers are efficiently trapped at anti-site defects.*

Introduction

We have recently shown[1] that semiconductor quantum dots (QDs), provide strongly enhanced optical non-linearities due to the discrete density of states. The discrete density of states provides on the one hand a sharp absorption line with a high peak absorption. On the other hand, the discrete density of states implies that a single electron-hole pair is capable to completely bleach the sharp absorption line due of the ground-state exciton transition, while 2 electron-hole pairs even generate optical gain. We recently have embedded InAs/InP quantum dots in the core layer of an InGaAsP/InP waveguide which was subsequently processed into a Mach-Zehnder Interferometric switch. By illuminating one arm of the Mach-Zehnder switch from above, i.e. perpendicular to the wafer, we observed[1] all-optical switching of the 1550 nm probe beam. In this case, the switching energy was calculated to be as low as 6 fJ.

Nakamura et.al.[2] have also demonstrated that InAs QDs feature a small saturation energy density as low as 13 fJ/μm^2 under resonant conditions. Such a small saturation energy density also suggest the potential use of QDs in all optical switches. Nakamura[2] estimated a required excitation energy for π-switching of 240 fJ/μm^2.

Unfortunately, the time response of this nonlinearity is limited to the carrier lifetime within the QDs, which is at room temperature limited by carrier emission out of the quantum dot in combination with nonradiative carrier recombination. We recently observed[3] room temperature carrier lifetimes between 80 ps and 200ps in InAs/GaAs QDs. Low temperature grown InGaAs/InAlAs quantum wells have been reported with 230 fs recombination lifetime[4] due to nonradiative carrier trapping at As_{Ga} anti-site defects with a density as high as $10^{13}/cm^2$ per QW. In this report, we investigate whether similar femtosecond carrier recombination times can be achieved in low temperature grown quantum dots (LT-QDs).

Photoluminescence of LT-QDs

We study a set of low temperature (LT) grown[5] Stranski–Karastanov InAs/GaAs QDs. The samples R207, R200, R198, R191, R181 and R152 are all grown at a low temperature of 250°C. R152 was not annealed. All other samples are annealed directly after the QD-growth. R181, R191, R198 and R200 are annealed at 480°C. R191 and R198 received a second post-growth anneal at 480°C and 600°C, respectively. R207 was annealed at 580°C after the growth. In addition, in the R200 and R207 samples, the QDs are directly covered with 4nm GaAs grown at 480°C. Sample R228 consists of high temperature QDs grown at 480°C in a LT GaAs matrix.

The photoluminescence spectra were taken at liquid helium temperature for all the samples. The samples were excited with a Ti: Sapphire laser operating at a wavelength of 770nm. The excitation power was 250mW. The resulting photoluminescence was collected and was recorded by a cooled InGaAs photodiode array. We also performed temperature dependent measurements from 5K to 40K while keeping the excitation wavelength and power constant. We finally also measured the excitation wavelength dependence of the PL intensity at 5K.

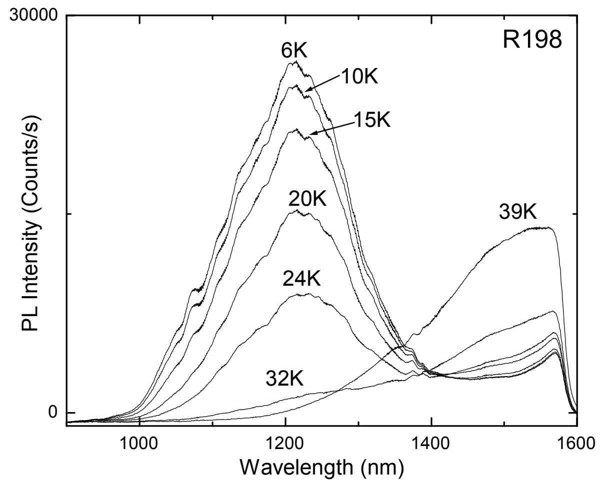

Fig. 1:
Temperature dependent PL measurements from low temperature grown quantum dots (R198), showing QD-emission at 1200 nm on top of a background which increases with wavelength and which is most clearly observed at 32 and 39 K.

In the photoluminescence spectra as shown in Fig. 1, we observe a background, which increases with wavelength up to 1600 nm. This background is most easily observed at sample temperatures between 30K and room temperature were the QD-related PL around 1200 nm disappears. We attribute the background due the semi-insulating GaAs substrate. The most well-known defect emissions are the EL2 emission bands due to the As_{Ga} center, which are centered at 0.68 and 1.1 eV (1820 and 1126 nm). Our background however seems to increase with wavelength up to at least the edge of the detector sensitivity at 1600 nm, indicating that the background is most probable due to the As_i-V_{Ga} center[6], which is centered at 0.8 eV (1549 nm)

In addition to the background, we observe a photoluminescence peak around 1200 nm, which we attribute to the LT-QDs. The slight wavelength variations of the PL-peak between the different samples, as shown in Fig. 2, indicates that the peak is due to QD

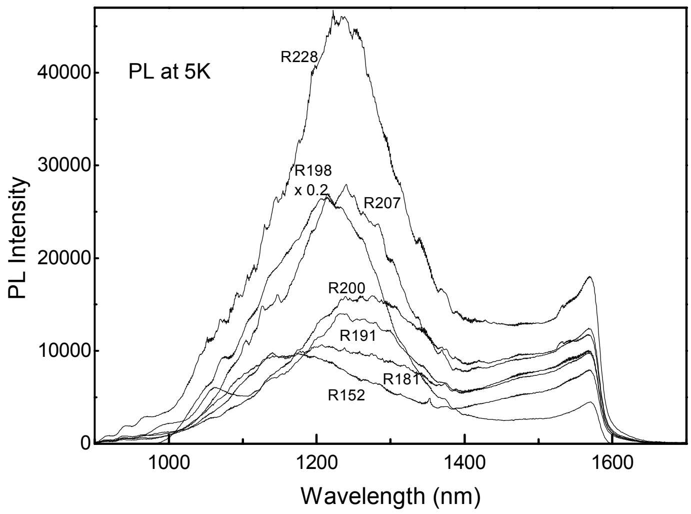

*Fig. 2: Photoluminescence spectra for a set of low-temperature (250°*C*) grown InAs quantum dots on GaAs measured at 5K and excited with 250 mW from a Ti:Sapphire laser at 770 nm.*

photoluminescence and not due to a deep level emission. We also observe that the PL-intensity is lower for sample R152, which is not annealed, or R181 and R191, which were only annealed at 480°C, as compared to samples R198 and R228 which were annealed at 600°C or grown at 480°C respectively. A surprising result is the very strong temperature dependence of the LT-QD emission as shown in Fig. 1 We observe that the QD-emission line disappears with increasing temperature around 30K, indicating strong nonradiative recombination which is already activated between 10K and 30K. The temperature dependence of the QD photoluminescence points towards QDs with a good optical quality, embedded in a LT-GaAs barrier in which the carriers recombine nonradiatively with an ultrashort time response.

We finally measured the PL-spectrum as a function of the excitation wavelength between 760 and 900 nm as shown in Fig. 3. In high-temperature grown QDs, the PL-efficiency is usually much higher for excitation in the GaAs barrier ($\lambda < 816$ nm at 5K) where the absorption length is large, than for excitation below the GaAs bandgap in the wetting layer and the thin QD-layer ($\lambda > 816$ nm). In our low-temperature grown QDs, the PL-efficiency on the contrary surprisingly *increases* for excitation inside the wetting layer and the QD-layer at 900 nm as compared to excitation in the GaAs barrier at 760 nm. The increase of the PL-efficiency at 900 nm as compared to 760 nm amounts to a factor of 45 for R198 and a factor of 280 for R152, and thus seems to be dependent on the annealing conditions.

We assume that the probability for carrier generation into the QD is unity for excitation above 816 nm. For excitation below 816 nm, the photo-generated carriers in the LT-barrier have a very small probability for diffusing towards the QD before being trapped by an anti-site defect. The small diffusion probability towards the QDs is even more surprising since we generate much more carriers in the thick GaAs barrier as compared to direct excitation in the thin QD-layer. In Fig. 3 we therefore normalize the PL-efficiency to unity at 890 nm where we excite directly into the QDs. The step-height at 816 nm is thus proportional to the trapping probability in the GaAs-barrier at arsenic anti-site defects. Even when the carriers are excited energetically above the GaAs bandgap, but spatially within the QD, the trapping probability at anti-site defects seems to exceed the capture probability into the QD. Since the step-height is proportional to the ratio of the trapping and capture probability, the step height is expected to be largest for R152, which is not annealed. The step-height at 816 nm is not expected to be proportional to the radiative recombination efficiency within the QD, since this quantity is expected to have the same effect for excitation above or below the GaAs bandgap.

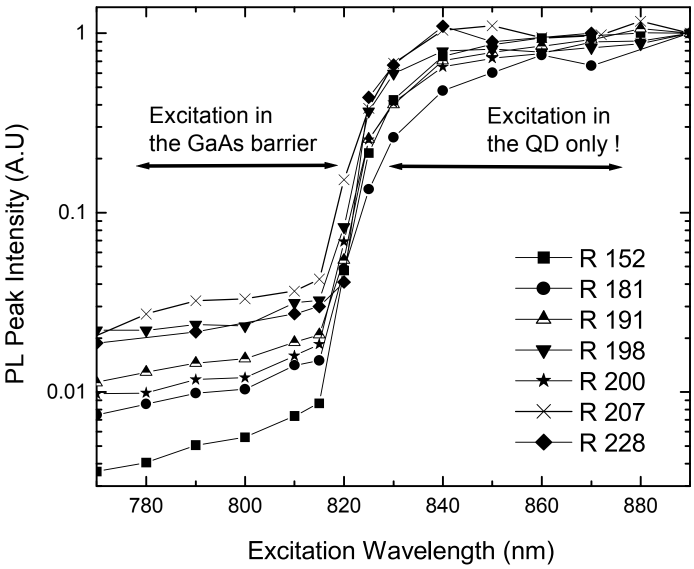

Fig. 3:
Excitation wavelength dependence of the at 5K photoluminescence peak intensity, showing a remarkable increase of the PL-efficiency at the GaAs bandgap.

In conclusion, both the temperature dependence and the excitation wavelength dependence point towards QDs with a reasonable radiative recombination efficiency embedded in a LT-GaAs barrier with a very high trapping efficiency due to a high concentration of arsenic anti-site defects. While direct excitation into the QDs results in a measurable PL-efficiency, excitation within the thick LT-GaAs barrier results in much more photo-generated carriers which are however mainly trapped at anti-site defects before getting the chance to get captured into the QDs. When the temperature is increased, carrier emission out of the QDs into the LT-GaAs barrier seems to quench the QD-photoluminescence efficiency already at 30K.

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