High-resolution continuous-wave absorption measurements on InGaAs/GaAs self-assembled quantum dots

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Self-assembled quantum dots (QDs) are semiconductor nanostructures of high material quality and true 3-dimensional confinement of electrons and holes. At low temperatures they have a density of states reminiscent of atomic transitions and are therefore sometimes referred to as 'artificial atoms'. We have applied two sensitive techniques long used in atomic physics, spectral hole burning and cavity-ringdown spectroscopy (CRDS), to investigate the absorptive properties of self-assembled quantum dots.

The QDs used in these experiments are composed of InGaAs/GaAs and grown by molecular beam epitaxy (MBE). For the spectral hole burning measurements, the QDs are embedded in a typical semiconductor waveguide structure to increase the interaction length with the laser. For the CRDS measurements, the QDs are grown on top of an AlAs/GaAs high-reflectivity quarter-wave stack.

The spectral-hole burning was carried out with two tunable diode lasers with a mutual bandwidth of approximately 10 MHz. One laser is kept fixed in frequency while the other laser is scanned across the Bennet-hole burned in the inhomogeneous absorption profile. At low excitation levels the width of this hole is equal to twice the homogeneous linewidth of the QD transition.

Displayed in Figure 1 is the width of the transition as a function of pump laser intensity with the probe laser intensity kept fixed well below saturation. To fit this data we used a function predictive of the power broadening of a simple two-level system. The model fits the data rather well, and we obtain a low-excitation value

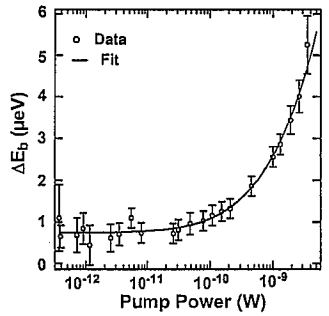

Fig. 1: Power dependence of the QD transition full-width at half-maximum.

of 0.74 μeV for the QD transition full-width at half-maximum (FWHM). This corresponds to a dephasing time $T2 = 1/\gamma$ of 1.7 ns. We also measured the spontaneous emission lifetime of the QDs at the wavelength probed in the above experiment to be ~ 970 ps by non-resonant, time-resolved photoluminescence. If the QDs were purely radiatively broadened at this temperature, the measured spontaneous emission lifetime would correspond to a 1.94 ns dephasing time in our spectral-hole-burning measurement. This is indeed very similar to our measured value and indicates that our QDs are almost purely radiatively broadened at 10 K. Other measurements of the dephasing time of InGaAs/GaAs QDs at low temperature have yielded results not quite at the radiative limit. We attribute these discrepancies to the difference in the experimental technique. Ultrafast four-wave mixing measurements (1) necessarily sample a broad spectral window of QDs and are therefore sensitive to variations in the dipole moment over that range, and single dot photoluminescence measurements (2) suffer from the effects of spectral diffusion.

It is also desirable to investigate absorptive properties of a QD ensemble with excitation parallel to the growth direction. The small absorption coefficient of these structures makes this difficult to accomplish without wavelength modulation or bleaching of this transition by some additional mechanism (3). We can overcome these difficulties by employing CRDS. CRDS is especially sensitive to small values of absorption because the excitation photons interact with the absorber many times before exiting the cavity.

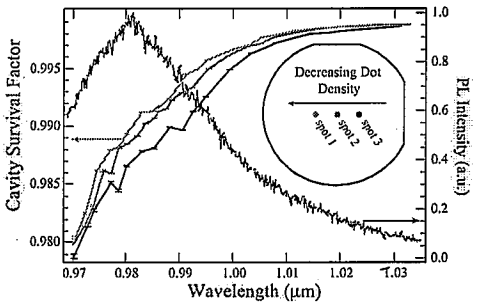

Fig. 2: CSF of resonant cavity with excitation on different parts of the wafer. Emission spectrum from the QDs is included.

The cavity is formed on one side with a high-reflectivity dielectric concave mirror and on the other by a AlAs/GaAs quarter-wave stack with QDs embedded in the top layer. A cavity-stabilized Ti:sapphire laser is used to load the cavity, and the ring-down signal is recorded with a photodiode and oscilloscope. Figure 2 shows the cavity survival factor (CSF) as a function of position of the laser spot on the sample studied. This sample has a strong variation of the QD density across it, and this evidenced as a change in CSF at different locations. From this data we can see that CRDS is indeed sensitive to the QD absorption. The true utility of this technique lies in the detection of single QD absorption and is a future research direction.

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