

Temperature-dependent Saturation Fluence in InGaAs Quantum Dots Based on Direct Absorption Measurements

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Direct measurement of the absorption of an ensemble of InGaAs quantum dots using a heterodyne multibounce technique reveals that the saturation fluence decreases dramatically with decreasing temperature. The dependence is attributed to homogeneous linewidth narrowing.

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An important consideration in many experiments on self-assembled quantum dots is the interaction strength between the dots and a laser pulse. This information is useful in low temperature as well as room temperature regimes and in non-linear as well as linear absorption regimes. Quantum computing experiments, for example, deal with π pulses in order to make qubit flips and lower temperatures in order to take advantage of long dephasing times. We report interaction strength information as a function of power and temperature in the form of the absorption coefficient. Straightforward absorption measurements have proven difficult to perform on dots, primarily due to the small net absorbance of a layer of dots at normal incidence. One way around this problem is to embed quantum dots in a waveguide, where the interaction length is increased. However, this introduces a new problem, in that the input and output coupling are difficult to determine with any accuracy. Multibounce absorption measurements have the advantage of removing the coupling efficiency of the light into the absorbing region from the calculation [1], but these measurements have only been made at room temperature. Our temperature-dependent multibounce measurements provide information on the saturation behavior of an ensemble of dots. We see a change of over an order of magnitude in the saturation onset due to changes in the homogeneous linewidth, which we verify using heterodyne-detected four-wave mixing.

The sample consists of self-assembled $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$ quantum dots, grown by molecular beam epitaxy in an AlGaAs waveguide. Using a waveguide means a laser pulse can interact with large numbers of dots, allowing us to make ensemble measurements as well as increasing the signal strength. The dot density is approximately 10^{10} cm^{-2} , and the sample is about 1.5 mm long. Variation in dot size means the sample is inhomogeneously broadened, with a linewidth of 70 nm for the ground state transition. The ground state photoluminescence peak shifts from 1215 nm at room temperature to 1125 nm at 10 K.

Absorption of the dots is directly obtained by multibounce measurements [1], modified to measure the pulse field by heterodyne detection rather than upconversion. Since the end facets of the sample are flat-cleaved, a significant portion of the exciting pulse, about 35%, is reflected back into the waveguide. This reflected part travels through the sample an additional two times. Although it loses most of its power when it reaches the initial facet, the reflected pulse can still be detected after it leaves the waveguide. The original pulse and the first reflected pulse are time-resolved using a reference pulse. Comparison of the areas of the first and second peaks gives the absorption without needing to know the coupling into or out of the waveguide. It is necessary to know the field reflection at the facets, but this is more easily calculated. In the low power regime, the ratio between the areas of the first and second peaks is given simply by $P_1/P_2 = R^2 e^{-2\alpha L}$, where R is the facet reflectivity, α is the absorption coefficient, and L is the length of the sample. This equation reflects the fact that the second pulse makes two additional passes through the absorbing medium.

Although the dots do not show a significant difference in low-power absorption with temperature, they do exhibit a strong temperature dependence in the saturation fluence. At room temperature our results agree in general with previous measurements [1], with saturation of the absorption beginning at similar powers. Our larger low-power absorption may be attributed to sample differences. As we lower the

temperature, we find that the power at which saturation begins drops by over an order of magnitude between room temperature and 10 K. Figure 1 shows the saturation behavior for four temperatures, where the power is determined from the input power and an estimated coupling efficiency of 0.3 percent. As mentioned, the coupling is a difficult value to determine, but this uncertainty does not prevent us from making accurate saturation comparisons between different temperatures.

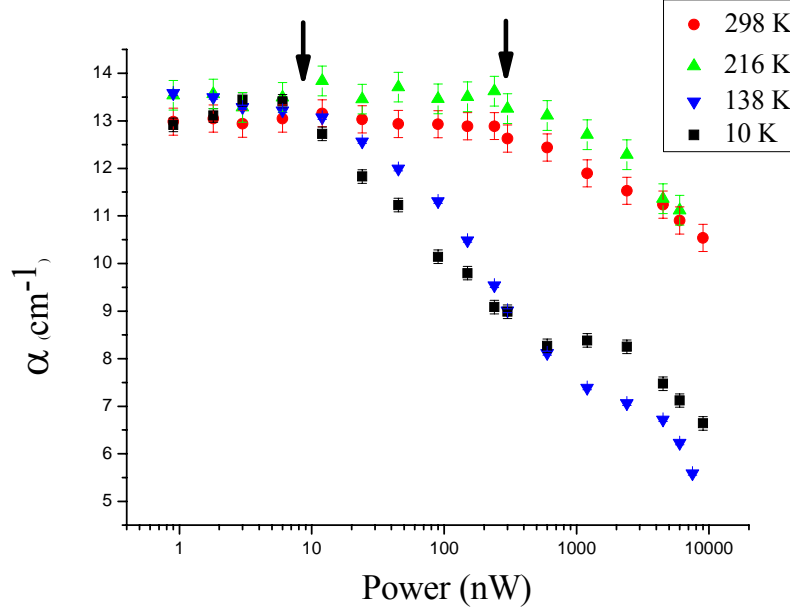


Fig. 1. The quantum dot absorption coefficient as a function of exciting pulse power. At lower temperatures, the dots begin to saturate much earlier, as indicated by the arrows.

The temperature-dependent saturation behavior can be understood in terms of the decrease in the dots' homogeneous linewidth, $\Delta\nu_h$, with decreasing temperature. The saturation fluence, F_s , is inversely proportional to the absorption cross-section, σ , which is in turn proportional to the homogeneous lineshape $g(\nu)$. As $\Delta\nu_h$ narrows, the peak of the lineshape increases. So from $F_s \propto 1/\sigma \propto 1/g(\nu) \propto \Delta\nu_h$ [3],

the saturation fluence decreases with decreasing homogeneous linewidth. We might expect the low-power absorption to increase at low temperatures, since it also depends on the absorption cross-section as $\alpha_0 = \sigma N$, where N is the dot density [3]. However, the homogeneous linewidth affects the dot density as well as the absorption cross-section. At room temperature, $\Delta\nu_h$ is large enough that dots with center frequencies outside of the bandwidth of the exciting pulse still interact with the field. Between room temperature and 10 K, however, the homogeneous linewidth narrows considerably. At low temperature, therefore, the exciting pulse has access to a much smaller dot distribution, since it effectively interacts only with those dots within the pulse bandwidth. The smaller number of contributing absorbers appears to offset the increase in absorption cross-section, keeping the low-power absorption constant.

We have measured $\Delta\nu_h$ for this sample using four-wave mixing, again with heterodyne detection [2], which will enable us to quantify our results. At room temperature the dephasing time is within the pulse width, putting the homogeneous linewidth at 3 nm or greater. At 10 K, the dephasing time is 572 ps, corresponding to a linewidth of 2.3×10^{-3} nm. With our measured $\Delta\nu_h$ values, we intend to model the absorption in order to explain more quantitatively the saturation behavior. The shape of absorption versus power and the transition from high temperature saturation behavior to low temperature behavior are of particular interest for future calculations.

[1] K.L. Silverman, R.P. Mirin, et.al, "Direct measurement of polarization resolved transition dipole moment in InGaAs/GaAs quantum dots," *Applied Physics Letters* **82**, 4552-4554 (2003).

[2] P. Borri et al., "Ultralong dephasing time in InGaAs quantum dots," *Physical Review B* **87**, 157401(R) (2001).

[3] Richard L. Sutherland, *Handbook of Nonlinear Optics* (Marcel Dekker, Inc., 1996), Chap. 9.