Carrier Dynamics in Quantum Dots and Their Application to Lasers and Microcavity Light Emitters

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The topic of carrier dynamics in self-organized III-V quantum dots (QDs) has emerged as an important area of research for their application to semiconductor lasers and other light emitters. Because the 3-dimensional confinement leads to discrete energy levels, the QD dynamic response is strongly influenced by its 0-dimensional energy levels. When these levels have energy spacings that correspond to an optical phonon energy the carrier relaxation is expected to be fast. However, when the energy level separation is significantly greater than the optical phonon energy, the relaxation is expected to be much slower. The electronic structure is furthermore unique in that the 0-dimensional energy levels are connected to a 2-dimensional density of levels associated with the QDs' wetting layer. Entropy effects can be important when electrons and holes relax from the wetting layer into the QDs' 0-dimensional levels, because of the large disparity in the effective density of states. The result of both entropy effects and slowed relaxation between the 0-dimensional energy levels is that the QDs' dynamic response can show strikingly different temperature dependencies [1], [2], becoming either faster or slower with increasing temperature, depending on which effect may dominate.

The 0–dimensional energy levels also establish the temperature dependence of the QD light emission. The fast carrier relaxation between the electron levels relative to the radiative light emission approximately establishes quasi-equilibrium in the QDs. Thus, for steady-state excitation, the carriers take thermal occupations among the 0-dimensional energy levels that depend on level degeneracies, temperature, and the 0-dimensional energy spacings. More widely spaced energy levels lead to a smaller temperature dependence of the QD's light emission characteristics. This has been shown to have a significant impact on the temperature dependence of a QD laser's threshold current [3]. For application to microcavity light sources, the QDs' 0-dimensional energy spectra set the relative amount of diffusion that occurs in a QD ensemble, and also establishes the surface and edge loss of carriers in these small volume devices [4].

In this paper we discuss recent experiments performed to characterize the energy relaxation of charge carriers in self-organized QDs [5]. We find several interesting phenomena in these QDs, including a QD size dependence in the relaxation time. While large InGaAs QDs with closely spaced energy levels show relaxation times from the QD wetting layer to the 0-dimensional ground state of ~1 psec, smaller InAs QDs with more widely spaced energy levels show relaxation times of ~7 psec. In addition, an interesting pump dependence exists for the relaxation time (as measured by the radiative emission) to the first excited radiative transition to the ground state transition.