

# Advances in Lasing from Colloidal Quantum Dots

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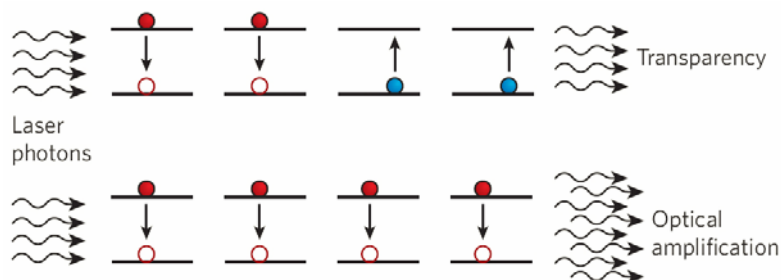
Literature Seminar

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Quantum dots are small particles with sizes on the order of 1-20 nm. Their physical properties are extremely size dependent: for example, the melting points, ionization potentials, and band gap energies are all controllable variables.<sup>1</sup> Research involving quantum dots has exploded since wet chemistry techniques were developed to produce colloidal nanoparticles of a desired radius with a narrow size distribution.<sup>2-4</sup> The surfaces of the particles are passivated with organic molecules to prevent aggregation and also increase solubility. The tunable physical properties and solubilities make colloidal quantum dots particularly attractive for a number of applications including lasers.

Although bulk semiconductors have fixed band gaps, semiconductor quantum dots have band gaps that can be engineered through size control. The phenomenon of band gap tuning is possible through an effect called quantum confinement. Irradiation of a semiconductor with sufficient energetic light produces an electron-hole pair, known as an exciton. These two charged entities have a natural physical separation in the material referred to as the Bohr exciton radius. For semiconductor quantum dots, that physical separation is constrained to be less than the size of the crystal, which causes the exciton to increase in kinetic energy due to quantum mechanical effects. This increase in kinetic energy causes the band gap of the material to increase.<sup>5</sup> A smaller particle causes more confinement leading to a larger band gap. The ability to manipulate the band gap through synthesis makes quantum dots attractive choices for lasing media. The use of quantum dots may lead to reduced lasing thresholds, narrower emission lines, decreased sensitivity of temperature, and access to wavelengths not characteristic of current lasers.<sup>6</sup>

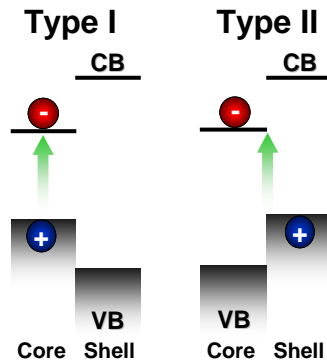
The phenomenon of population inversion, in which there is a larger occupation of high energy excited states than lower energy states, is critical for lasing. Spontaneous emission, the creation of a photon from an exciton due to the presence of another photon of the same frequency, takes advantage of the excited state population inversion and results in more photons being emitted from a material than was incident (Figure 1). This increase in overall photon count is called optical gain.



**Figure 1:** A balance of emission and absorbance producing optical transparency (top) and emission only producing optical gain (bottom).<sup>7</sup>

Only recently has the phenomenon of optical gain from colloidal quantum dots been achieved.<sup>6</sup> Optical gain has been demonstrated using close packed films of CdSe nanocrystals, but the relaxation rates of the excited state limit the lifetime of population inversion. Auger recombination, a nonradiative process, results in an emitted electron due to energy transfer from another excited state. It has been shown that Auger recombination is very efficient when the pump intensity incident on the quantum dots is high enough to induce multiple excitons per quantum dot.<sup>8</sup> Auger recombination uses excitons that would otherwise produce photons through stimulated emission, thus reducing optical gain.

Quantum dots do not have to be made of a single material. They can have core/shell designs that incorporate different materials into the same particle. Type I nanocrystals have a shell made of a wider band gap material over a smaller band gap core. In such quantum dots, the exciton is contained within the core because the electron prefers to populate the lowest energy conduction band and the hole prefers the highest energy valence band available. This design reduces energy transfer between quantum dots because the electron and hole are not near the surface. Type II nanocrystals, however, have two materials with similar band gaps, but the gaps are offset, causing the electron and hole to be separated into the core and shell individually. The band gap offsets for both types of nanocrystals can be seen in Figure 2. Type II architectures allow for a greater tuning of the band gap because both the core diameter and the shell thickness affect the electronic structure of the particle. Core/shell nanocrystals with Type II construction may offer a solution to the issue of Auger recombination.<sup>9,10</sup>



**Figure 2:** Electronic structures of Type I and Type II quantum dot architectures.

In Type II quantum dots consisting of a CdS core with a shell of ZnSe, the exciton-exciton interaction is affected by the energy gradients at the core/shell interface, causing a decrease in Auger recombination.<sup>11,12</sup> In these CdS/ZnSe quantum dots, the excited states have lifetimes of 1.7 ns versus only 30 ps for traditional CdSe quantum dots. In comparison, bulk semiconductor diodes used in current lasers have excited state lifetimes of ~10 ns.<sup>7</sup> The use of Type II structures increase the lasing efficiency of quantum dots, but improvements still need to be made to compete with present day technology.

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