Electrically Pumped InAs Quantum Dot Mid-IR Emitters

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Motivation—Quantum Cascade Lasers (QCLs), the product of *Band Gap Engineering*, have been revolutionary in transforming the mid-infrared (mid-IR, 3µm - 12µm) into an accessible region for semiconductor based sources. These have seen continuous improvement in power, wavelength coverage, and operating temperature. One way to further expand the capabilities of semiconductor mid-IR semiconductor sources is to use self assembled quantum dots (SAQDs) as the active region in place of the quantum wells. The possible advantages of doing so are increased efficiency and the potential for devices that can naturally emit light normal to the growth direction.

Background—For many years, InAs SAQDs have been noted to have desirable optical properties due to their atomic-like quantum states (0D density of states). However, in the mid-IR, we have yet to see useful light emitters utilizing SAQDs even though quantum well (2D density of states) QCL technology has progressed rapidly. The primary reason for this gap is the lack of knowledge pertaining to engineering SAQD electronic states in a manner analogous to that employed in QCLs.

In QCLs, injector and collector filter stages are used to pump conduction electrons into custom designed active regions where photons are emitted. Engineering of an injector stage can provide current injection into an upper (p) SAQD state; however, to increase the likelihood of an optical transition, the lower (s) SAQD states must be depopulated faster than p-states. This situation is readily achieved in QCLs, however, the key difference between QCL and SAQD based devices is the nature of electronic tunneling (2D-2D as opposed to 0D-2D). To succeed in creating electrically pumped SAQD active material, the understanding of this 0D-2D tunneling must be developed.

Accomplishment—Our initial approach to creating mid-IR SAQD devices was to tunnel electrons into bulk semiconductor material (3D density of states). We had hoped to use the matrix of semiconductor material surrounding the dots and wavefunction distributions of excited and ground SAQD states to control the tunneling times. Theory determined that this situation was untenable using any reasonable combination of materials. As a result, the 0D-2D tunneling problem was reopened. We found that, by properly designing injector and filter stages and understanding the momentum selection rules introduced by using SAQDs, it was possible to create the condition where the s-state of the dot could be depopulated faster than the p-state (simplified and shown in Fig. 1). Light emission tests of the materials based on these principles showed significantly improved characteristics over previous designs, and one iteration emitted mid-IR light at room temperature (Fig. 2).

Significance—By varying the injector and collector stages in electrically injected SAQD material, and seeing significant changes in both I-V characteristics and light emission, it is now known that we are controlling the tunneling in and out of SAQDs. Once useful mid-IR SAQD material has been developed, through improved understanding of the processes involved, we see a path towards efficient, arrayable, wavelength tunable surface emitting devices.

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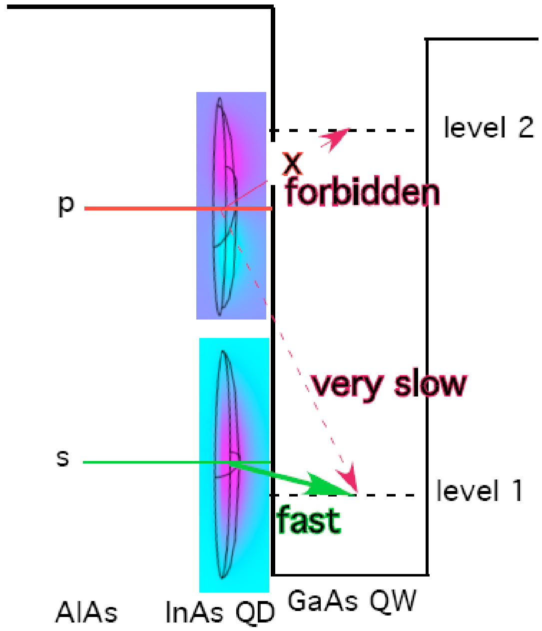

Figure 1. Conceptual diagram of the energy level structure desired for efficient depopulation of the s-state and tunneling blockage from the p-state. The energy level of the s-state should be slightly higher than the tunneling state (level 1), while the p-state should be energetically below level 2. For s-tunneling, the excess "vertical" energy is dissipated into the lateral 2D motion in the QW with the 2D momentum less than the momentum uncertainty determined by the QD size. Energy conservation prohibits p-tunneling. This differs from the approach of QCL engineering where an envelope approximation and energy level alignment are primarily considered.

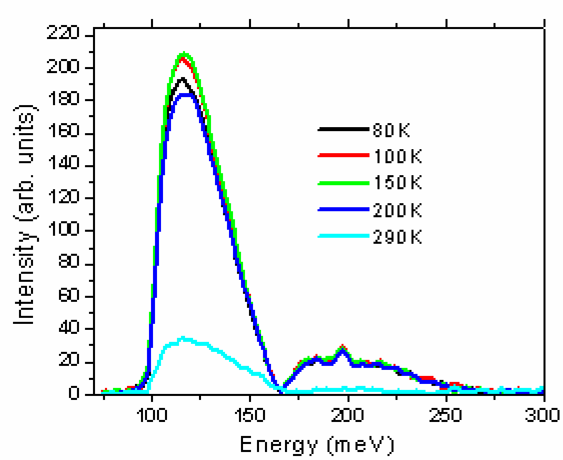

Figure 2. Electrically pumped emission from newly designed SAQD material. The conduction electron excited (p) to ground (s) state transition is centered around 10µm wavelength (120meV). Relatively strong emission is observed up to a temperature of 200K, and emission persists to room temperature.