Materials Science and Technology
Nanoscience

Mid-infrared Electroluminescent Quantum Dots

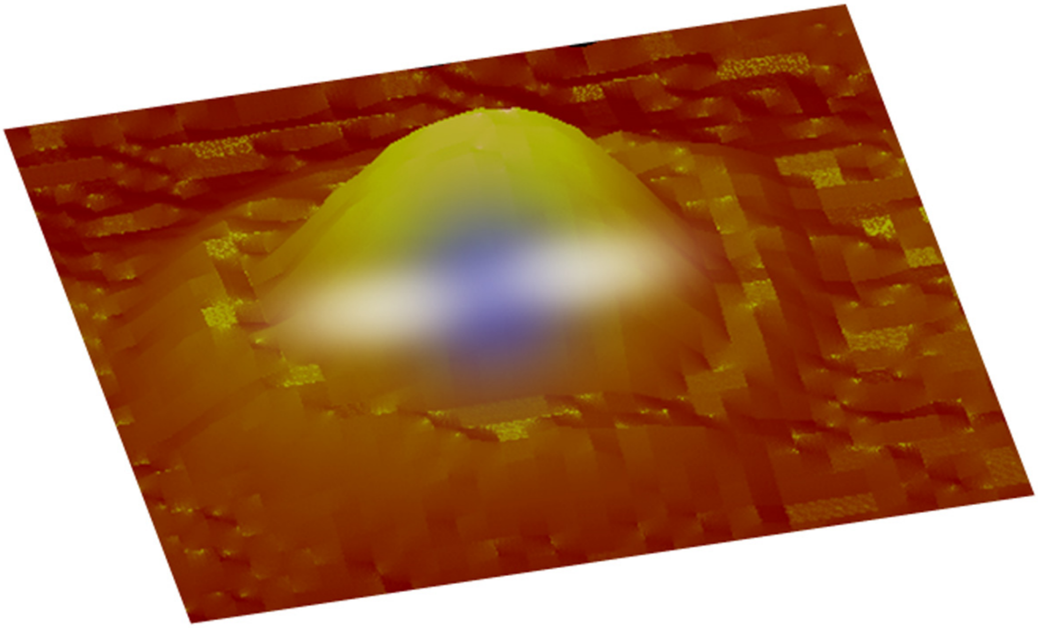

Figure 1: InAs quantum dots can be grown on the surface of GaAs, and then imaged using atomic force microscopy microscopy (AFM). This technique can be used both for verifying the size of the dots (about 20 nm), as well as the density of dots per unit area. For illustrative purposes, the ground (blue) and excited state (white) electron wave functions are drawn schematically within the quantum dot AFM image.

Engineering the layers around quantum dots can greatly impact performance

Compact sources of mid-infrared (mid-IR, 3 µm -12 µm) radiation are important to defense, health monitoring, and environmental sensing. While quantum cascade lasers (QCLs) have been revolutionary over the past decade in covering the mid-IR, there is still considerable room for improvement in terms of wall-plug efficiency. One path to improve conversion of electrical power into light is to reduce non-radiative losses by utilizing three-dimensional nanostructures such as InAs quantum dots.

While the semiconductor quantum dot approach is still in its relative infancy compared to the mature quantum well based QCLs, recent progress has been made by researchers at Sandia, in collaboration with the University of Massachussetts Lowell, that demonstrates the potential of this technology. InAs quantum dots are grown in the GaAs material system through a process known as 'self-assembly.' These lens-shaped 'artificial atoms' (figure 1) are approximately 2 nm tall with a 20 nm base. It turns out that the energy separation between the ground (s) and first excited (p) electron state in these structures corresponds to wavelengths ranging from roughly 8 µm (155 meV) to 14 µm (90 meV), depending on size. In order to electrically pump the dots, electrons need to first be injected into the upper p-state through a quantum tunneling process. Once an electron is in the excited state of the dot, it can either transition to the lower energy s-state and tunnel out of the dot, emitting a photon along the way, or tunnel directly out of the dot without emitting a photon. It is the control of this process, through properly designed electron filtering, that primarily determines the efficiency of quantum dot based emitters.

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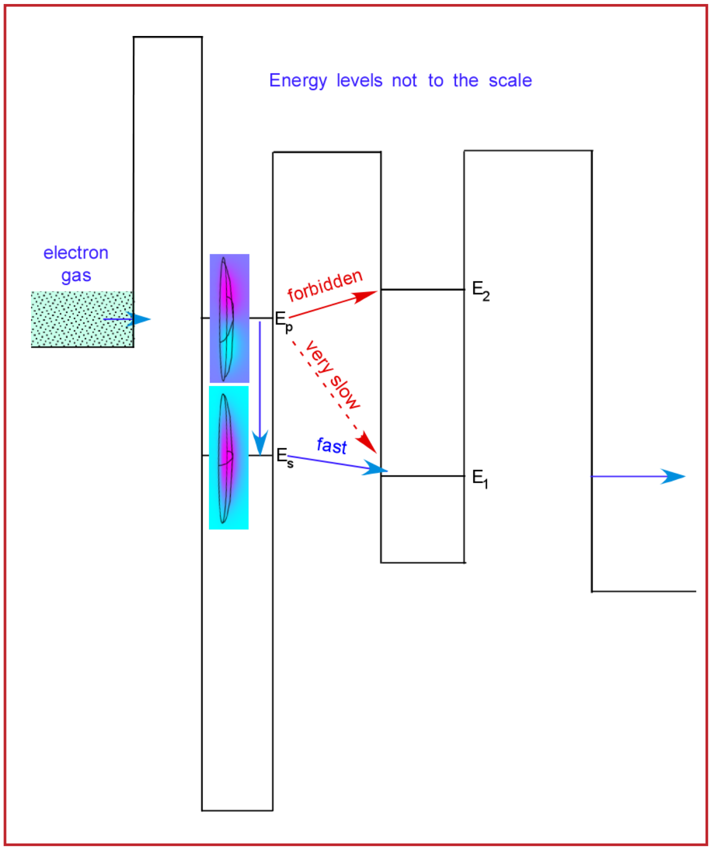

Figure 2: Basic description of the quantum dot design rule implemented in this work. The quantum well filter is designed in such a way that the upper p-state in the dot is positioned energetically below the second quantum well level, while the low s-state in the dot is positioned slightly above the first quantum well state.

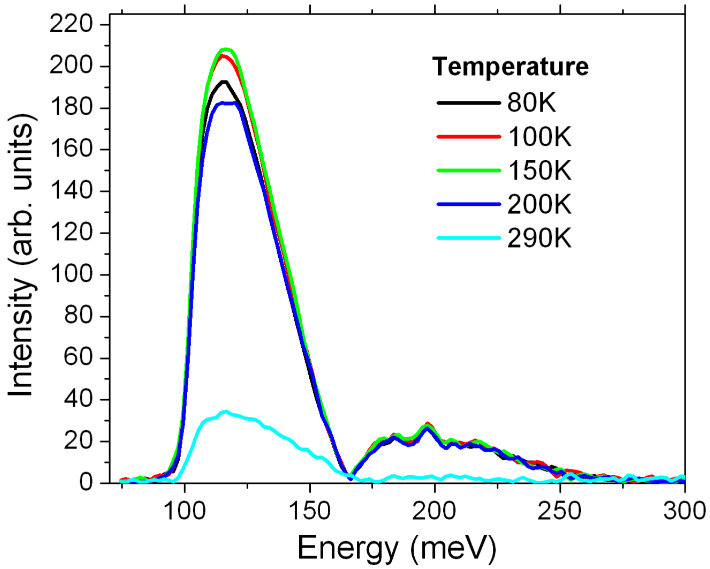

Figure 3: Emission spectra of electrically pumped quantum dot material. Up to 200K in temperature, the emission is relatively unchanged. At room temperature, the peak intensity at 120 meV is down to approximately 15% of its low temperature value, but emission is still observed.

In QCLs, it is common to design structures where active region energy states are aligned to filter states in order to control photon emission and electron extraction from the active region. Until recently, an appropriate design rule to guide filter design did not exist for quantum dots. While it might seem like a similar problem to align energy states between the dot and filter stage, it turns out this is not the ideal condition. Instead, the ground state and excited state of the dot need to be intentionally mis-aligned (figure 2), such that the ground state lies slightly above the filter extraction state, and the excited p-state lies just below the next available tunneling state. This divergence from QCL architecture arises from differences in dot-to-well electron tunneling compared to QCL well-to-well transitions.

The end result of this new design is electrically pumped quantum dot material that emits up to room temperature (figure 3). Previous iterations of this material design, with a non-optimized quantum well filter, exhibited reduced performance and only worked at cryogenic temperatures. While research still needs to be done in order to obtain gain/lasing action in this material, this result is intriguing as it demonstrates that engineering the layers around the quantum dots can greatly impact performance. Unlike well-based QCLs, mid-IR quantum dots can naturally emit light normal to the surface. This makes them ideal candidates for surface emitting sources as well as enabling their integration into high-Q photonic cavities to enhance output and tune emission wavelength. This advantage also opens up the possibility for quantum dots as mid-IR single photon sources for quantum communications.

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