Mid-infrared Quantum Dot Emitters utilizing Planar Photonic Crystal Technology

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Sandia National Laboratories

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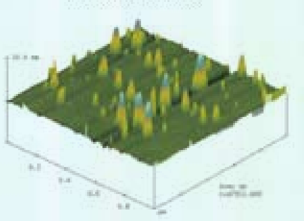
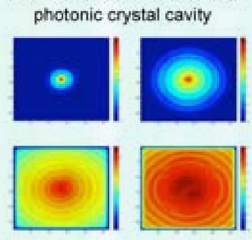
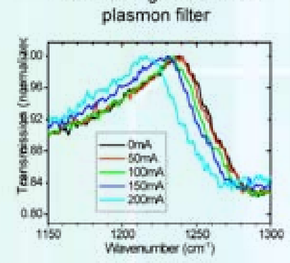
InAs dot on AlAs



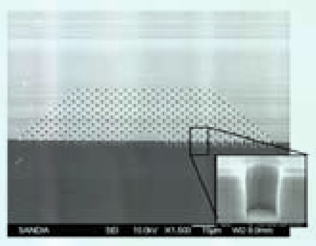
FDTD simulation of dots in a photonic crystal cavity



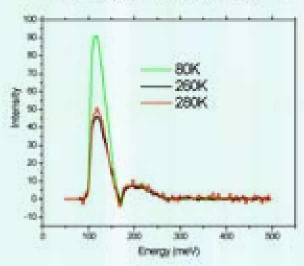
Active tuning of a surface plasmon filter



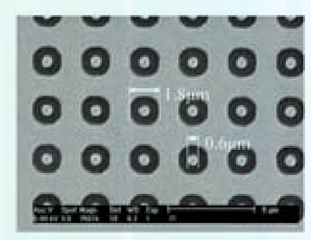
Photonic crystal fabrication



Electrically pumped, room temperature mid-IR quantum dot emission



Novel fabrication of surface plasmon devices (one step fab)



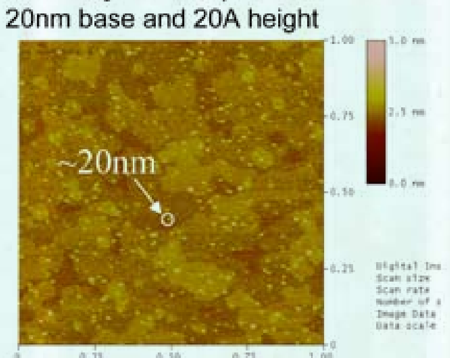
The Vision

- To create an all-electron cascadable InAs quantum dot medium for mid-IR photonics
  - In principle, may be more efficient than quantum well material utilized in more mature Quantum Cascade Lasers (QCLs)
  - Can naturally emit light normal to the growth direction, QCLs can not
- To integrate the material with photonic crystal cavities
  - Create a arrayable, wavelength tunable, surface emitting devices
- Use surface plasmon couplers to enhance pumping and photon extraction
  - Better understand the coupling of nanoparticles with macroscopic surface plasmon modes
  - Possible alternative route to arrayable, tunable emitters
  - Possible active detection platform

What are quantum dots?

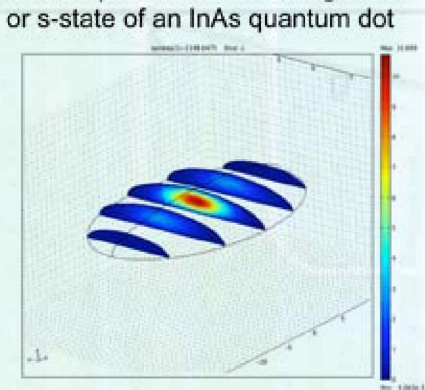
There are many forms of quantum dots these days. Essentially, these are man-made nanostructures small enough to exhibit characteristics of three-dimensional quantum confinement. Commonly discussed quantum dots can be individual particles grown in a chemical solution (CdSe for example), or, in our case, clusters of InAs that are 'self-assembled' in a GaAs or AlGaAs matrix during growth.

Self-assembled InAs dots are nominally lens shaped with a 20nm base and 20A height



AFM image of InAs dots on the surface of AlAs

Model representation of the ground or s-state of an InAs quantum dot

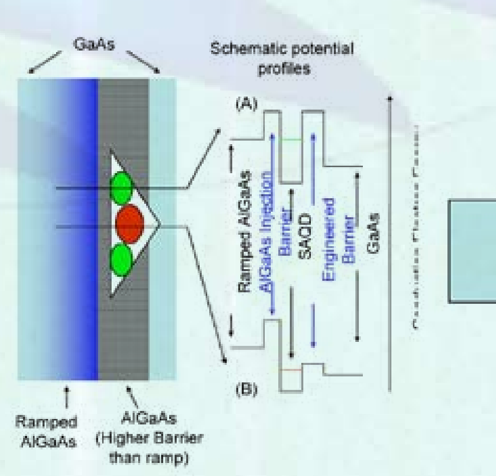


The problem with InAs dots:

The energy and momentum considerations involved in tunneling from quantum dots (zero-dimensional, 'artificial atoms') to quantum wells (two-dimensional) is different than what is normally considered for QCLs (quantum well to quantum well or 2D-2D).

Our initial approach:

Try to use the semiconductor matrix surrounding the InAs quantum dot to engineer tunneling rates through upper (p-states) and lower (s-states). We desired current injection into the upper p-state, followed by a mid-IR optical transition to the s-state.



The basic premise is to use the different wave-function distribution for the s (red) and p (green) states, combined with the surrounding material, to engineer tunneling rates so that a population inversion can be created.

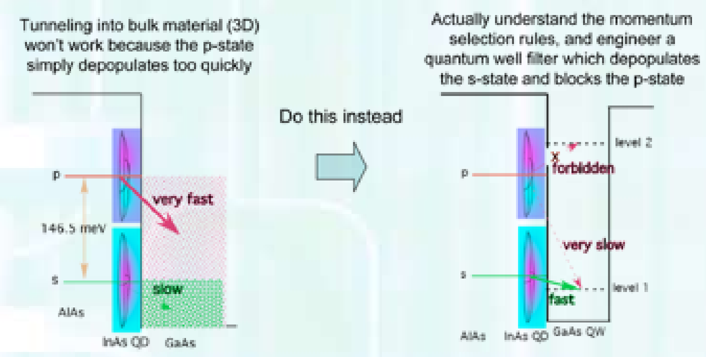
This would have been nice because it can be thought of as tunneling from 0D to 3D, or bulk, states. It turns out, this approach is theoretically untenable using any reasonable combination of materials.

Our second approach:

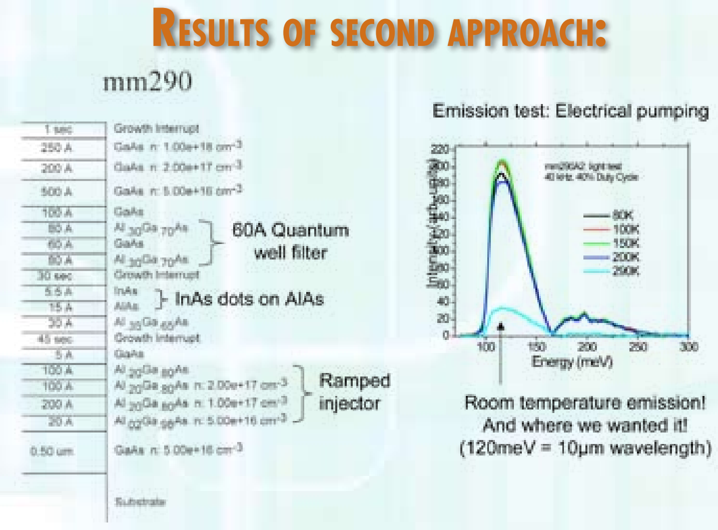
(turns out to be similar to a guess we made several years ago, but now has some better understanding behind it)

Go ahead and tackle the 0D to 2D tunneling problem → Get a good physicist, Ken Lyo, and let him figure it out

Ken's Answers (significantly simplified)

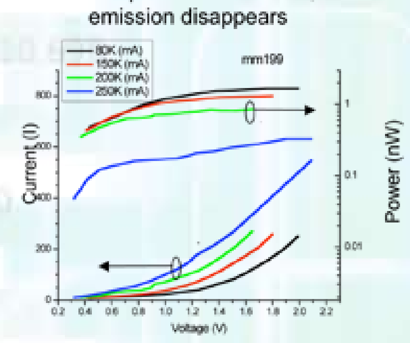


Results of second approach:

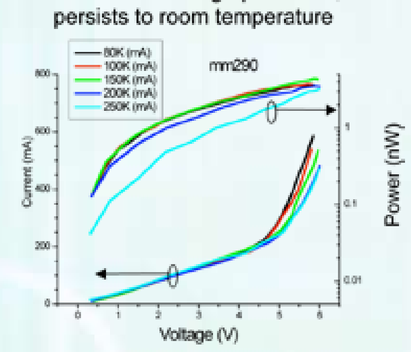


Comparison to a previous attempt with a quantum well filter

51A QW filter: As temperature increases, emission disappears



60A QW filter (the new design): Emission is strong up to 200K, persists to room temperature



Why this is important:

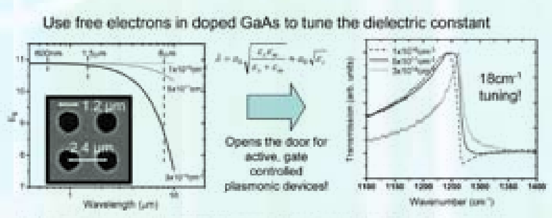
- We can get room temperature emission
- The injector and filter structure you place around the dots significantly impacts characteristics (I-V, emission saturation) and performance
- The theoretical understanding of how this works has been developed giving us a path forward to further development

Surface plasmons

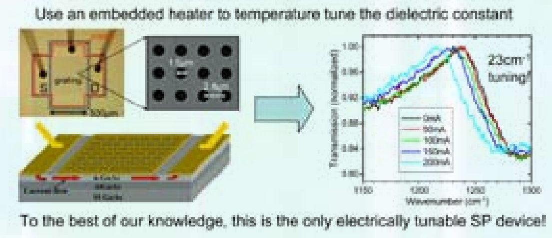
- What are they?
  - Charge oscillations on a metal surface
  - Coupling to light can be facilitated by fabricating a lattice of holes in metal films
- Why do we care?
  - Properly designed metal meshes lead to 'extraordinary transmission'. Essentially an optical bandpass filter which can coherently transmit over 90% on resonance. Good for output coupling and wavelength tuning.
  - If they can be made 'tunable' either by an electrical current or gate bias, plasmonic devices can be used for active filters, modulators, and beam steerers

Tunable mid-IR surface plasmon devices

Use free electrons in doped GaAs to tune the dielectric constant



Use an embedded heater to temperature tune the dielectric constant



To the best of our knowledge, this is the only electrically tunable SP device!

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