Indium Arsenide Quantum Dot Lasers

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Introduction:

Electron leakage and heat generation due to the increasingly small scale and dense packing of device components are major limitations to further downscaling modern electronics. Optoelectronics, devices that utilize a combination of optical and electronic components, represent a potential solution to these problems by taking advantage of the fact that optical signals do not suffer from the issues of tunneling or Joule heating while also being more energy efficient and faster than electronic signals. In pursuit of these ideal characteristics, the goal of this project was to produce a suitable light source for optoelectronic applications.

Specifically, our goal was to produce a laser using indium arsenide (InAs) quantum dots (QDs) as the active region. InAs QDs are excellent candidates for data transfer applications due to their three-dimensional confinement, which leads to discrete energy levels dependent on the quantum dot size. This means not only that the emission wavelength of the laser can be tuned by changing the dot size, but also that the necessary threshold current densities are lower than those of quantum wells and bulk material because fewer carriers are needed for population inversion. Additionally, the large gap between energy levels gives quantum dot lasers (QDLs) essentially temperature invariant operation.

Material Design and Growth:

Molecular beam epitaxy (MBE) was used as the method of growing the laser materials. MBE is a technique that uses ultrahigh vacuum and careful control of material flux during deposition to ensure that materials form epitaxially on the surface. Due to the extreme vacuum, MBE is able to grow materials with remarkably low contamination levels. Meanwhile, the slow, epitaxial deposition means that the thickness of a deposited layer can be controlled with monolayer precision while—through controlling the flux of multiple materials at a time—the composition of a single layer can also be controlled with extreme precision.

The structure of our QDL is shown in Figure 1, while the band diagram for the material is shown in Figure 2. From the band structure, it can be seen that under an applied voltage conduction electrons will travel down the conduction band and be confined in the potential wells of the quantum dots, while holes will travel up the valence band and do the same. The result of this process was a large number of holes and electrons confined in the low bandgap region, where they could easily recombine producing photons, which in turn stimulate further radiative recombination.

Material Characterization:

Before actual laser devices were grown, the MBE growth conditions had to be calibrated. For this purpose, special calibration samples were grown that were similar to the actual laser structure, but with greatly thinned waveguiding

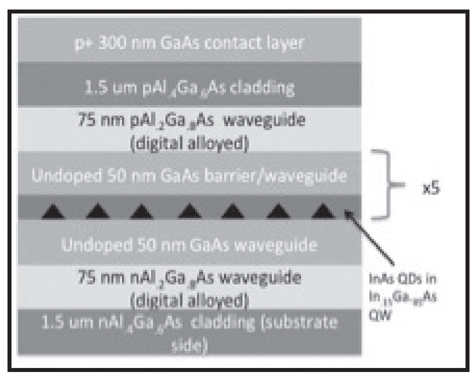

Figure 1: A schematic of the laser material.

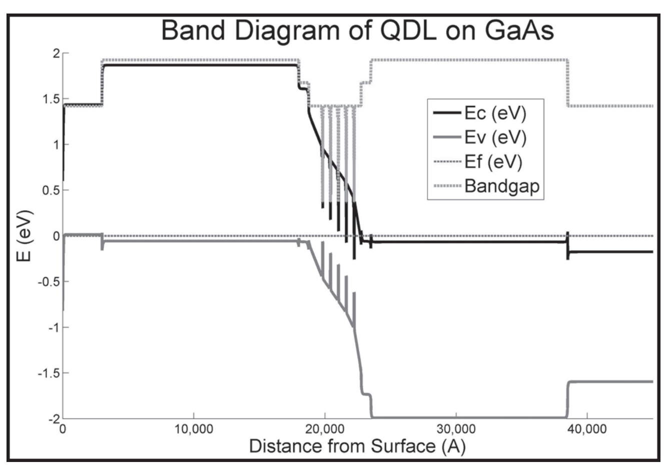

Figure 2: The band diagram of the laser material.

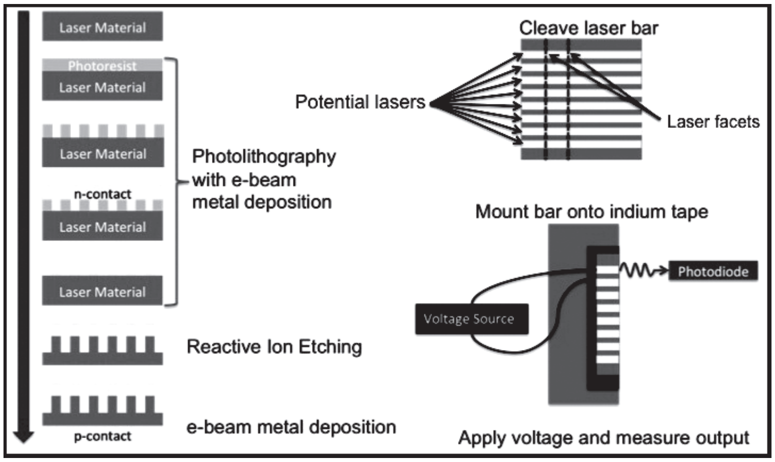

Figure 3: Laser processing procedure.

regions and an additional layer of QDs grown on the top surface at identical growth conditions to the centrally located QDs. These samples were characterized using atomic force microscopy (AFM) and photoluminescence (PL) to determine the morphological and optical properties of the quantum dots.

Atomic force microscopy was used to obtain an image of the quantum dots on the top surface of the material. These images were used to assess the uniformity and density of quantum dots on the surface, which were assumed to be similar to those that would be found in the identically grown active region. Calibration samples corresponding to the growth conditions of successful laser devices had estimated dot densities of $3.2*10^{10}$ cm^{-2}. Higher dot densities were considered better because it meant there were more recombination centers to generate photons.

Photoluminescence was used to characterize the optical properties of the calibration sample. This technique uses a laser to optically excite the quantum dots and then measures the light produced upon relaxation. PL measurements indicated that optical emissions occurred at a wavelength of 1220 nm in the central region of the sample, which corresponds to the region used in device production. The full width at half maximum was found to be very uniform across the sample surface with a value of 40 nm.

Device Processing:

Once the laser material was grown, a series of processing steps had to be performed to create a functioning laser. The process is summarized in Figure 3. A combination of photolithography and electron beam (e-beam) metal deposition was used to deposit the top electrode for the device in a series of bars. Reactive ion etching was then used to turn the bulk laser material into a series of laser bars by etching through the laser active region. Next, e-beam metal deposition was used to deposit the bottom electrode. To complete the process, a section of the sample was cleaved from the rest with the cleaved edges, becoming the laser facets.

Results:

InAs QDLs were successfully fabricated and found to lase at threshold current densities as low as 260 A/cm^2. The photoluminescence measurements suggest that this lasing occurs at a wavelength of 1220 nm, but the actual spectral profile of the light output has not yet been measured.

Future Work:

Future work is planned to refine the laser growth and processing procedures to achieve lower threshold currents. Once satisfactory devices are being produced, attempts will be made to grow the laser material on a silicon substrate—a necessary step to be able to integrate the lasers in current technology.

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