The Brighter Side of Semiconductors

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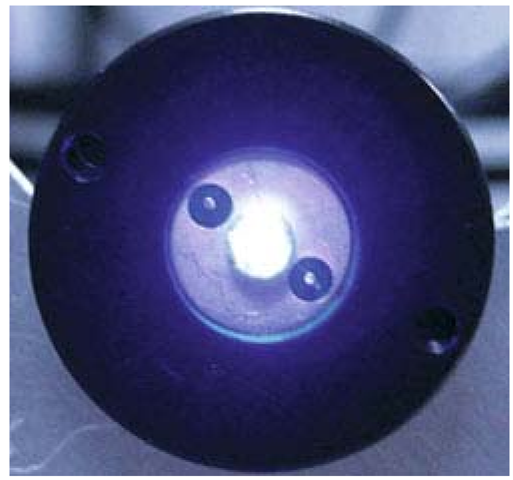
The vast majority of activity in the semiconductor industry revolves around silicon. However, the other semiconductors are not to be overlooked. “Compound semiconductors are like salt is to food,” said Professor Manijeh Razeghi, director of the Center for Quantum Devices at Northwestern University (Evanston, Ill.). Each play an important role, contributing something the other cannot.

Since its opening in 1992, the Center for Quantum Devices (CQD) has been amassing a list of “firsts” and breaking records in the area of lasers diodes, photodetectors and focal plane arrays (FPA), covering a wide slice of the optical spectrum. A pioneer in the area of III-V compound semiconductors and optoelectronic devices, Razeghi started with 8000 ft² of empty space and a vision. Today, the CQD's laboratory space includes 3000 ft² of cleanroom space — nearly 40% of the lab — with state-of-the-art equipment to enable the full range of quantum device development, from device modeling to crystal growth (MBE and MOCVD), material characterization, device fabrication, testing and packaging.

Wavelength control is fundamental to optoelectronic devices. Control is typically achieved through atomic engineering by manipulating the thickness and composition of the quantum wells that make up the active layers, some of which can be made up of thousands of atomically thin layers. The CQD moves beyond that by studying different material systems (Fig. 1) and investigating novel structures that, for example, confine the charge carriers in quantum dots, and applying these methods to a variety of optoelectronic devices, including quantum cascade lasers, type-II superlattice photodiodes, and quantum dot infrared photodetectors.



1. Wider bandgap III-V nitrides operating in the visible to deep ultraviolet (DUV) were used to process a range of blue and UV light-emitting diodes and, recently, avalanche photodiodes that may one day offer a more robust alternative to the current photomultiplier (vacuum) tube technology.

Quantum cascade lasers

One of CQD's early achievements established them as the leader in high-power quantum cascade laser diodes — lasers operating in the mid- and far-infrared (3-16 µm) spectral region. At that time, the only such laser technologies available were based on bulky gas or solid-state lasers, as well as cryogenically cooled semiconductor lasers. In 1997, CQD developed a room-temperature infrared quantum cascade laser (QCL) based on GaInAs/AlInAs/InP materials system, and has led the R&D work in this area since then. The inherently compact, longer-lifetime QCL eliminated the need for bulky, unreliable cryogenic cooling systems.

A QCL has an extremely complex structure, typically consisting of over 1000 nm-scale layers. Light is emitted by intersubband transitions made inside quantum wells. This unique structure does not rely on the material's inherent bandgap to determine wavelength. Instead, within a single material system, wavelengths can be changed by simply altering the thickness of the constituent layers.

Superlattices

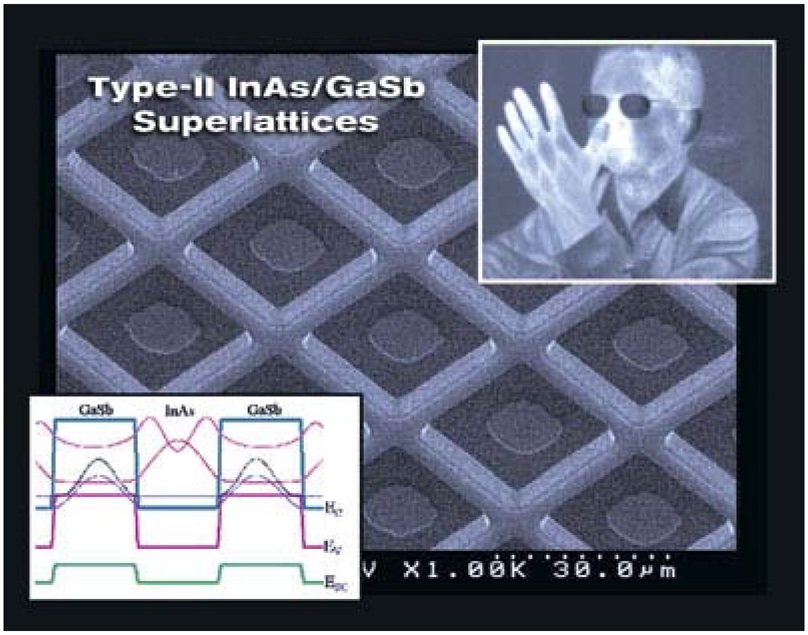
The unique band alignments and physical properties of superlattices may lead to new levels of performance, such as 100 GHz logic circuits and terahertz transistors. A superlattice is an artificial crystal lattice in which the effective bandgap can be engineered, making use of the internal strain effects. Unlike naturally existing crystals, such as NaCl, which has a periodic arrangement of atoms, a superlattice such as InAs/GaSb consists of periodic alternating layers of InAs and GaSb, as thin as a few atomic layers.

InAs and GaSb are unique in that the bottom of the InAs conduction band lies below the top of the GaSb valence band, resulting in a spatial separation of electrons and holes. The interaction of electrons and holes with neighboring wells gives rise to an artificial band structure that can be tuned, like the QCL, by changing the thickness of the constituent layers. This sort of band alignment is referred to as type-II misalignment, giving these superlattices the name type-II superlattice or strained-layer superlattice (SLS).

As a lower cost, longer-life alternative to mercury cadmium telluride (HgCdTe, MCT) detectors, the CQD investigated InAs/GaSb type-II SLS for infrared detector applications. MCT is currently the material of choice for highly demanding strategic and tactical sensor systems in use by the military. However, the type-II material system can provide a strong broadband absorption and cut-off wavelengths comparable to MCT with significantly reduced tunneling and Auger recombination rates, allowing for higher-temperature operation and better sensitivity.

The device structure is typically grown using MBE, consists of 1000-2000 layers — each ~2-3 nm thick — and takes 8-12 hr. Therefore, prior to crystal growth, an intense modeling scheme requiring a large dose of quantum mechanics and atomic engineering is needed to blueprint the complex recipe.

Among the CQD's achievements in this material system was the first demonstration of type-II detectors with a 32 µm cut-off wavelength; more recently, the world's first FPA in this material system was demonstrated at 8 µm and again at 12 µm (Fig. 2).



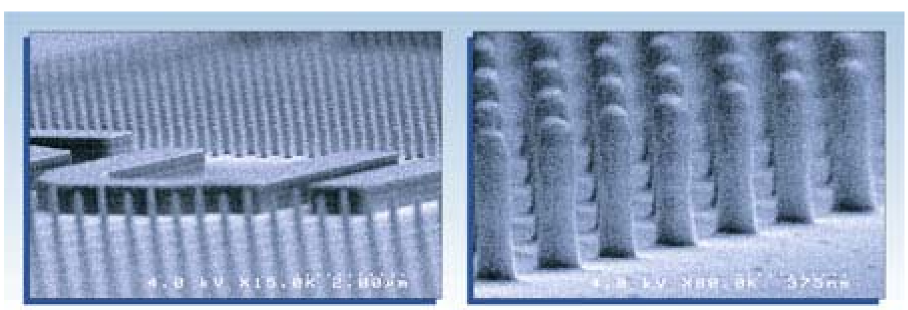
2. A SEM of a type-II focal plane array (FPA) with the band alignment and wave functions arising from the superlattice illustrated (lower left inset) and a still frame from the 256 × 256 array (upper right inset).

The success of these devices encouraged the researchers to attempt fabrication of nanopillars in these materials. Interestingly, the characteristics of silicon nanopillars and their light-emitting properties were demonstrated well before III-V and type-II InAs/GaSb pillars.

Nanopillars

Theoretically, as the superlattice period and pillar diameter approach the nanometer scale, the structure begins to act like a collection of stacked quantum dots. According to the researchers, ideal quantum dots are 0-D structures, wherein the momentum of electrons is quantized in all directions. Consequently, the energy levels are discrete, much like an artificial atom. By controlling the dot dimension, direct engineering of energy levels within the crystal should be achievable. With further analysis, a decision was made to fabricate nanostructures in superlattice materials, which would increase carrier lifetimes at high temperatures and also open the door to tuning and multicolor sensing applications.

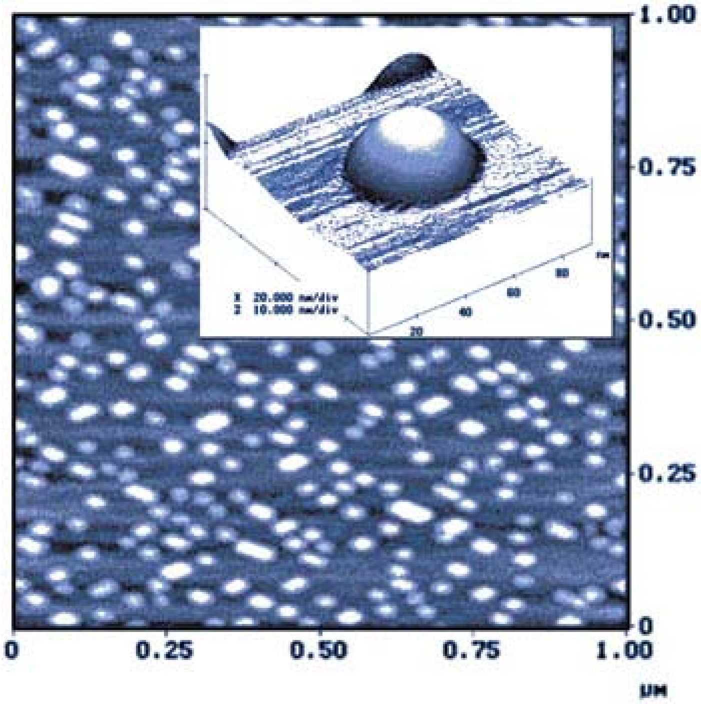
To make these high-resolution nanostructures, electron beam lithography was used, which allows the operator to precisely delineate the placement and dimensions of nanoscale features in a variety of materials. The pattern is defined in photoresist and transferred using additive methods, such as metal deposition and lift-off, or subtractive methods, such as dry or wet etching. The aspect ratio for the nanopillars was 10:1, with diameters <20 nm (Fig. 3).



3. Electron-beam lithography is used for its accuracy, size control and placement after pattern transfer into type-II InAs/GaSb superlattices to produce nanopillars with aspect ratios of 10:1.

Quantum dot devices

Quantum dots have unique electronic properties, which can significantly improve the performance of high-speed electronic and photonic devices. Also known as artificial atoms, quantum dots are nanometer-scale islands in which electrons and holes are confined in a 3-D potential. The strong confinement imposed on all three dimensions can produce extremely sharp and discrete density of states, which are very similar to those in atoms (Fig. 4).



4. Atomic force microscopy of a single InAs quantum dot (inset) and a 1 × 1 μm surface image of InAs dots on GaAs/InP.

Among the devices fabricated at the CQD, which are based on quantum dots, are laser diodes and infrared photodetectors. The unique properties of quantum dots in laser diodes enable low-threshold currents, higher-modulation bandwidths, narrower spectral linewidths, and reduced-temperature sensitivity, compared with their quantum well laser structure counterparts. Similarly, the quantum dot infrared photodetector, higher sensitivity and higher-temperature operation have been achieved relative to quantum well infrared photodetectors.

Multidimensional quantum confinement resulted in stimulated emission observed at 995 nm with an injection current of 400 mA. Infrared FPAs consisting of 256 × 256 quantum dots were considered a world's first based on InGaAs/InGaP/GaAs. More recently, a 320 × 256 FPA with the highest operating temperature (200 K) was demonstrated in InAs/InGaAs/InAlAs/InP. Such contributions from this relatively small lab, ~15 students at any point in time, will continue as long as there is a need for “artificial eyes” to provide vision after dark in cold and hot environments and into space.

Center for Quantum Devices

Northwestern established a distinct degree program in engineering in 1873, 21 years after the initial founding of the University. But it was not until the mid-1920s that the College of Engineering became the School of Engineering, with faculty members devoted exclusively to engineering. Today, the Robert R. McCormick School of Engineering and Applied Science is home to the Center for Quantum Devices, distinguished for having over 364 published technical papers, 500 invited and plenary talks, and 56 patents issued since its inception.

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