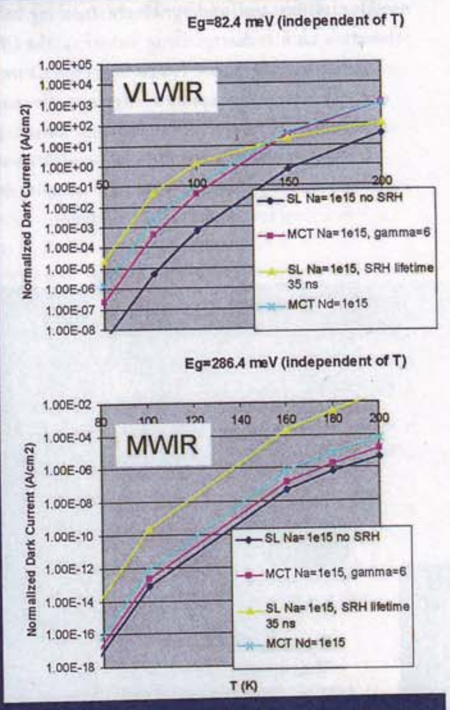
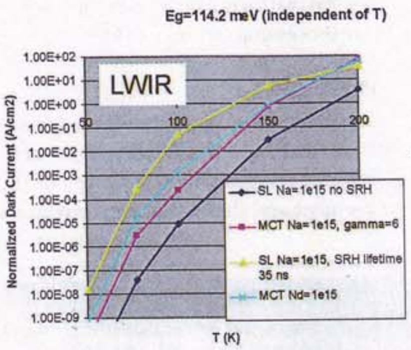
By Kristin Lewotsky

Imaging Advances Boost Defense

New materials and new detector architectures paved the way for lightweight, high-sensitivity IR imagers

Figure 1: Polymer photodiodes provide detectivities comparable or better than those of existing technologies. The data plot consists of measured data adjusted in absolute magnitude that point A (500 nm) and B (800 nm). (Image courtesy UCSB)





- DARPA
- Defense
- Optics
- Fabrication

On a battlefield, knowledge is power. Imaging systems monitor sites for weapons and personnel, or acquire targets for attack. Capturing clear, high-resolution images in the lab poses little challenge, but battlefield conditions are seldom so kind—dust, fog, camouflage, and cover of night act to obscure targets. The demands of stealth and portability mandate the lightest possible systems even as performance demands rise. Defense research labs are prepared to meet the challenge, however, with the development of novel detector architectures that promise to increase imaging capabilities across all wavelength bands.

CURVES AHEAD

A simple lens produces a curved focal surface while today's focal-plane arrays (FPAs) are flat. With enough lenses, nearly any image wavefront can be planarized, but at the cost of considerable size and weight, as anyone who has ever seen a semiconductor lithography objective knows. Developing high-resolution, wide field-of-view imagers that are compact and lightweight enough to be used by soldiers and in unmanned aerial vehicles presents an ever-increasing challenge. Often, the results are only well-corrected for a narrow field-of-view. The use of aspheric optics can mitigate those effects to some degree, but the trade-off is added cost.

Instead of designing a complex lens system to match the wavefront to the detector, scientists at the Defense Advanced Research Projects Agency (DARPA) have decided to go at the problem of another way by designing a detector to match the wavefront. The Hemispheric Array Detector for Imaging (HARDI) Program focuses on developing a curved FPA that will match the focal surface produced by a simple convex lens. Such a detector could enable low-aberration, wide field-of-view imagers for use in unmanned vehicle and perimeter defense applications.

The curved focal plane approach is nothing new. Previous groups have reported FPAs with radii of curvature as small as a few meters. The goal for the HARDI program is far more ambitious—to develop a FPA with radii of curvature on the order of 1 cm and an operating wavelength of 400 nm to 1.9 μm. The materials currently used over that wavelength range, including silicon and mercury cadmium telluride (MCT), involve brittle, planar substrates that are incompatible with such tight curvatures, meaning that engineers have in some ways replaced one challenge with another. "Although the program will leverage existing technologies for readout integrated chips (ROICs), a new approach is required for materials, focal plane array design, and fabrication," says HARDI program manager Devanand Shenoy.

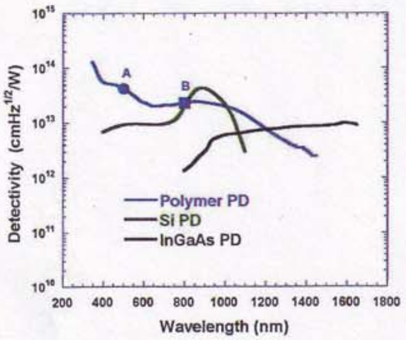


Figure 2: As data for MWIR/LWIR/VLWIR devices show, T2SL detectors (blue) feature predicted dark current levels much lower than that of MCT (magenta), allowing them to either operate at 20K higher temperature for a given noise level, or 10-fold less noise for a given temperature. (Courtesy C. Grein, 2008 US Workshop on the Physics and Chemistry of II-VI Materials)

It's a difficult challenge but nanotechnology comes to the rescue. In one project associated with the HARDI program, researchers from the University of California, Santa Barbara and collaborators have blended small-bandgap semiconductor polymers with fullerene derivatives to yield polymer photodetectors with spectral response over the wave band from 300 nm to 1,450 nm. The devices consist of a combination of the small-band-gap conjugated polymer, poly (5,7-bis (4-decanyl-2-thienyl)-thieno (3, 4-b) diathiazole-thiophene-2,5) (PDDTT), blended with the fullerene derivative, (6,6)-phenyl-C61-butyric acid methyl ester (PC60BM), and spin cast onto a substrate. "We literally mix the materials together in a common solvent and cast from solution," says UCSB physics professor Alan Heeger. "The phase-separated nanostructure forms spontaneously as the solvent evaporates."

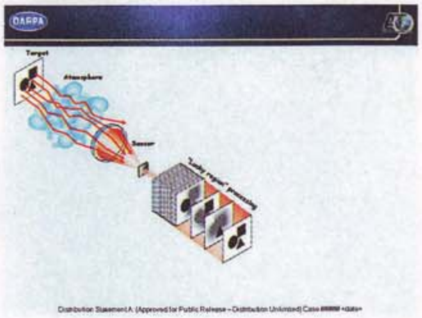


Figure 3: The graded band-gap photo-diode is tailored to suppress tunneling and recombination currents about the junction. By adjusting only layer thickness instead of alloy composition, T2LS designers can independently control characteristics such as band gap, conduction band, valence band, and lattice constant. (Courtesy E. H. Aifer et al., 2008 US Workshop on the Physics and Chemistry of II-VI Materials)

In tests, the room-temperature devices demonstrated detectivities of above 10^{13} cmHz$^{1/2}$/W over the waveband from 300 nm to 1150 nm, and greater than 10^{12}cmHz$^{1/2}$/W from 1150 nm to 1450 nm; for comparison, the detectivity of silicon photodetectors is ~4 x 10^{12} cmHz$^{1/2}$/W, and indium gallium arsenide (InGaAs) photodetectors exceed detectivities of greater than 10^{12} cmHz$^{1/2}$/W only when cooled to liquid nitrogen temperatures (see figure 1). The devices also achieved a photosensitive linearity of 100 dB, comparable to the 120 dB of silicon detectors and outperforming the 66 dB obtained from InGaAs. Most important, when fabricated on a plastic substrate, the photodetectors are deformable.

Materials are not enough, however. Current fabrication techniques for both active pixels and readout circuitry assume planar substrates. "The final program demonstration is a 1 MP FPA with 20-μm pixels," Shenoy says. "The FPA requires not only a grid of conductive contacts for each pixel, but also at least one transistor per pixel. These specifications mean that no previous fabrication techniques are adequate." At the University of Michigan (Ann Arbor, Mich.), researchers are exploring an imprint approach on deformable substrates. Meanwhile, Cbrite (Santa Barbara, Calif.) is directly patterning the functional materials onto a rigid curved surface.

At present, researchers affiliated with the program have demonstrated single pixels. The current program stage, phase II, calls for the demonstration of a 128 x 128 pixel FPA by summer 2010.

NO STRAIN, NO GAIN

For years, MCT has been the detector material of choice for the mid-wave infrared (MWIR, 3 to 5 μm) and long-wave IR (LWIR, 7 to 14 μm) spectral regions. Recent advances in III-V-based type-II superlattices (T2SLs) grown on gallium antimonide (GaSb) substrates promise to change all that. T2SLs generated intense interest during the mid-1990s for use in both IR lasers and detectors. High dark-current levels limited their efficacy as imaging detectors, though. Now that MCT faces limits of its own, renewed interest in T2SL-detectors has led to the development of novel detector architectures that hold a great deal of promise for future IR imaging applications.

In its simplest form, a T2SL consists of alternating layers of indium arsenide (InAs) and GaSb. The band-gap alignment of these materials is such that the conduction band minimum of InAs actually lies lower in energy than the valence band maximum of GaSb, forming a "broken-gap" or type-II, interface. The lattice constant of InAs is 0.6 percent shorter than that of GaSb, which introduces significant strain between the layers; hence, the name.

Although T2SL detectors operate over the same range as MCT (3 μm to 30 μm), the material system offers significant advantages over the incumbent technology. Tunneling, which contributes to performance-degrading dark current, grows exponentially with decreasing mass and bandgap. T2SLs exhibit an in-plane electron effective mass of more than three times that of MCT, while the mass along the field direction of the junction may be independently increased by more than a factor of three. This dramatically reduces tunneling current—and hence, dark current—especially in longer wavelength devices.

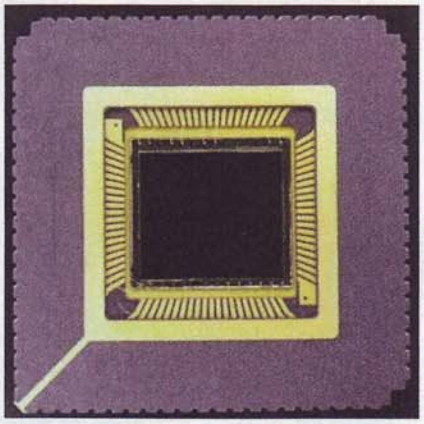


Figure 4: Type-II superlattice detectors like this 320-x-256-pixel indium arsenide/gallium antimony focal-plane array provide low-noise imaging across the midwave and longwave IR spectral regions. (Courtesy Northwestern University)

T2SLs also strongly suppress Auger recombination, a fundamental process that sets an upper limit on the operating temperature of a photodiode. This constitutes a critical advantage over MCT. "In type II superlattices, the Auger-limited dark current can be a factor of 10 or more lower in the very long wavelength range and a factor of five lower in the mid-wave," says Edward Aifer, engineer at the Naval Research Laboratory (NRL; Washington, D.C.). "In terms of temperature, it means that in the very long wave you're talking 20K higher operation, or about 10K higher in the mid-wave (see figure 2)."

The T2SL material system also offers more degrees of design freedom than MCT, he notes. "While you can vary the band-gap in an MCT photodiode to shift the cut-off wavelength, you can't, as in T2SLs, independently change the conduction band and valence band alignments. [T2SL flexibility] has enabled us to implement graded band-gap photodiodes tailored to suppress specific dark-current mechanisms (see figure 3). The result is that starting from over a factor of 100 higher dark current than Auger-limited MCT in discrete devices, we now come within about a factor of five matching the MCT dark-current performance."

That is not to say that the new approach is perfect. At present, it exhibits minority carrier lifetimes of tens of nanoseconds versus the microseconds of MCT. Since lifetime has an inverse relationship to dark current, it is an essential problem to solve.

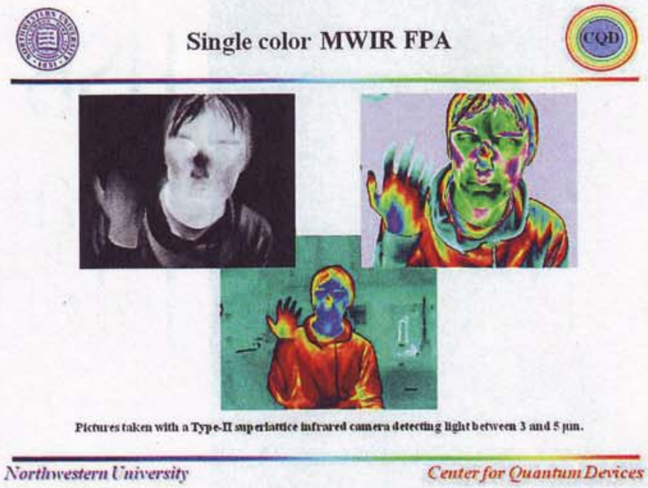
PRACTICAL MATTERS

Part of the appeal of T2SLs lies in more practical considerations, says Aifer, whose group at NRL is presently working on T2SL development and tech transfer as part of the U.S. Missile Defense Agency's Fast FPA program.[1] The cadmium zinc telluride (CdZnTe) substrates used for MCT detectors are expensive to produce. They are also difficult to grow in diameters that lend themselves to the production of large-area devices or allow device manufacturers to leverage batch processing, with its economies of scale. The fact that the consumer market is limited largely to the government has not helped spur development.

As a III-V materials system, T2SLs can leverage a broad, already-existing commercial infrastructure. Just a few years ago, the GaSb substrates were widely available only in 2-inch diameter. Today, without major retooling, multiple manufacturers supply high quality 3-inch substrates in bulk, and are now beginning to offer 4-inch substrates. "Going to 6-inch diameter GaSb substrates appears to be mainly a function of demand since there do not appear to be any major issues in scaling to larger substrates," Aifer says. "The MCT industry on the other hand, has been pulling out all stops for a long time to obtain the largest substrates they can, and they're only up to about up to about 3-in. diameters in very limited quantities. I believe that further size scaling will be much more manageable using GaSb."

Today, type II superlattice development has moved beyond discrete devices to the production of MWIR and LWIR focal plane arrays, due in part to technology transferred over via the Fast FPA program (see figure 4). A team at Northwestern University, led by seminal T2SL researcher Manijeh Razeghi, has fabricated a 256-x-320-pixel InAs/gallium antimony FPA that has achieved a noise-equivalent temperature difference (NETD) of 10 mK over the 3 to 5 μm wave band, for example (see figure 5). A 256-x-320-pixel superlattice device operating over 8 to 11 μm exhibited an NETD of 20 mK and a quantum efficiency of 75 percent, which rose to 90 percent with the addition of an antireflection coating (see figure 6). In the VLWIR spectral region, they have demonstrated single photodiodes operating at wavelengths of up to 20 μm and are currently working on a 500-x-500-pixel, two-wavelength FPA and a 1000-x-1000-pixel single-wavelength FPA.[2]

Although there has been concern in some quarters that shifting to FPA development before the discrete photodiodes are fully optimized is premature, Aifer contends that it allows scientists and engineers to get a jump on the problems inherent in bringing a laboratory technology to the real world. "This is the way you really understand what the nature of problem is," he says. "When you make a photodiode in the laboratory you ask, 'How high is the QE, and how large is the dark current?' But when you make a focal plane array from that material, a bunch of more subtle issues arise."



Single color MWIR FPA

Pictures taken with a Type-II superlattice infrared camera detecting light between 3 and 5 μm.

Northwestern University

Center for Quantum Devices

Figure 5: The 320-×-256-pixel indium arsenide/gallium antimony focal-plane array that captured this MWIR image (3 to 5 μm) operates with a noise equivalent temperature difference of 10 mK and a quantum efficiency of 40 to 50 percent. (Courtesy Northwestern University)

Indeed, fabricating T2SL FPAs introduces a whole new set of problems to overcome, such as bias dependence, 1/f noise, cross talk, and more. Beyond device-level performance, fabrication itself poses a challenge. "You need to know how to etch this material, you have to know how to passivate it in order to eliminate surface defects," Razeghi says by way of example. Indeed, in terms of pushing T2SL detectors forward, the primary limiting factors appear to have little to do with the active layers. "For the very long wavelength, more than 14 μm, we have optimized the material," she says. "The problem is the read out integrated circuits (ROICs). For VLWIR, a new ROIC has to be designed to accommodate the low resistance of the detectors."

Development of a fabrication infrastructure well-suited for T2SL is another challenge. Achieving high quantum efficiencies in T2SL FPAs requires thick layers. Predictable performance can only come with precision fabrication—a few angstrom error in layer thickness can change operating wavelength by microns. Today's molecular-beam epitaxy systems are designed for more forgiving material systems and applications. For T2SL FPAs to realize their potential, the industry needs to develop the proper tools to easily and consistently produce quality product.

These projects represent only a sample of the many defense imaging technologies in development. Even decades after the introduction of the CCD, electronic imaging holds the potential for dramatic performance improvements at all wavelengths. With the aid of researchers around the world, tomorrow's military will find itself better equipped than ever. ***AI***

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[1] *Recent developments in type-II superlattice-based infrared detectors, Edward Aifer, et al., paper 7660-54, SPIE's Defense & Security Symposium, 2010.*

[2] *Type-II antimonide-based superlattices for the third-generation infrared focal plane arrays, Manijeh Razeghi, Paper 7660-43, , SPIE's Defense & Security Symposium, 2010.*