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Defense & Security

Type II superlattice enables high operating temperature

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A focal plane array based on a new material and detector architecture with improved electrical performance provides mid-wavelength-IR imaging of a human being at 170K.

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Infrared radiation is the portion of the electromagnetic spectrum that covers a range of wavelengths from 0.8 to 100 μm . Popularly known as 'heat radiation,' IR was first discovered using devices that resembled modern-day thermometers. Nowadays, IR detection has evolved from sensing a change in a material property such as expanding mercury (which is inherently slow) to direct collection of IR photons. Advances in fabrication also allow millions upon millions of detectors to be packed into portable devices much like an ordinary digital camera. These high-speed IR cameras could help reveal the thermal profiles of hidden targets or objects at night when no visible light source is available. In the efforts to combat terrorism and support national defense, IR cameras equip soldiers with new capabilities, such as night vision, target identification, and missile tracking. The devices also have applications in medicine. For example, they can be used to detect excessive heating and cooling in the body, which indicates an abnormality, such as inflammation, impeded blood flow, or cancerous tissue.

Depending on its use, IR radiation is divided into several wavelength regimes. Near-IR and short-IR ($\lambda < 2\mu\text{m}$) detection technologies are relatively mature and commercially available. However, this wavelength only facilitates active detection, which requires an 'illumination' source. Long and very long wavelength IR regimes ($\lambda > 8\mu\text{m}$) can be employed in passive detection mode without illumination for most terrestrial applications because near-room-temperature emits enough photons to be captured. IR photons have little energy, though. Consequently, detectors working in these regimes, especially in high-speed applications, often need to be cooled down to at least 77K to reduce electrical noise. Positioned between the two extremes, mid-IR (MWIR) detection ($\lambda = 3\text{--}5\mu\text{m}$) benefits from the capability of passive detection while working with photons whose energy is sufficient to enable higher operating temperatures. Suitable materials for this wavelength must offer the highest operating temperatures (without sacrificing performance) to reduce the burden of cryogenic cooling and, in turn, make detectors more compact, less expensive, and more portable.

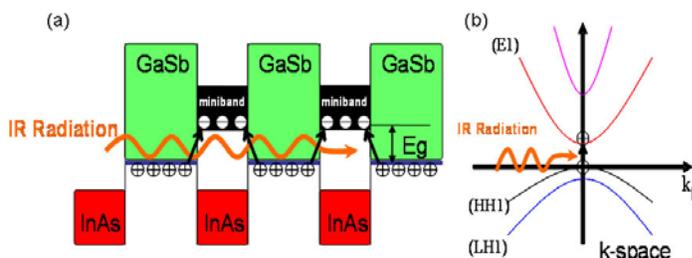


Figure 1. Energy bands of type II indium arsenide/gallium antimonide (InAs/GaSb) superlattices (T2SLs). (a) Spatial band alignment in T2SL (red regions represent InAs forbidden gap and green regions represent GaSb forbidden gap). (b) Band structure with direct band gap and absorption process in reciprocal space (k -space). E1: First conduction band level. HH1: First heavy hole (positive charge carrier) level. LH1: First light hole level. Eg: Energy gap.

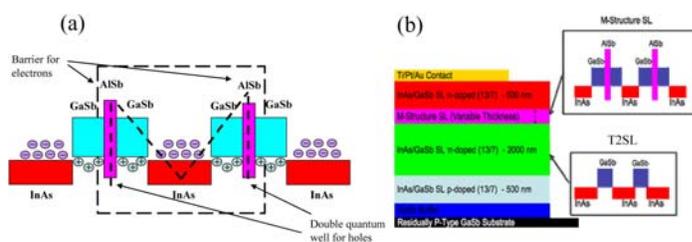


Figure 2. Schematic diagram of (a) M-structure superlattice's energy bands and (b) new device architecture incorporating M-structure as a potential barrier. AISb: Aluminum antimonide. Au: Gold. Pt: Platinum. Ti: Titanium. p, n, and nare all semiconductor types.

Currently, commercial technologies for MWIR detection and imaging are based on indium antimonide (InSb), mercury cadmium telluride (HgCdTe or MCT), or quantum-well IR photodetector systems. However, these materials are fundamentally limited by Auger recombination, which is a limiting factor for high-temperature operation. In the search for alternatives that are less susceptible to these restrictions, we have been developing a type II indium arsenide/gallium antimonide (InAs/GaSb) superlattice (T2SL).¹ This material system was first proposed by Nobel laureate Leo Esaki in the 1970s² and was predicted to spur innovation in the IR industry. T2SL is formed by multiple periods of alternating thin InAs and GaSb layers. This arrangement creates a 1D periodic structure like that of the atomic chain in naturally occurring crystals (see Figure 1). The type II 'broken gap' alignment leads to separation of electrons and holes (negative and positive charge carriers) in the InAs and GaSb layers, respectively.



Figure 3. Mid-wavelength IR images of a student captured with a T2SL focal plane array at a range of temperatures.

Band alignment of T2SL creates an effective energy gap that can be flexibly tuned across the entire IR regime through precise control of the interface composition and layer thicknesses, all without introducing large strain. Auger recombination can be suppressed by optimizing the electronic band structure of the superlattice.³ Moreover, being able to exploit the superlattice design to engineer the band structure opens a horizon for exploring novel device architectures that are unthinkable using simple binary or ternary compound semiconductors such as MCT.

We recently developed a novel variant of T2SL, the M-structure superlattice—see Figure 2(a)—with large effective mass and tunability of band-edge energies.⁴ This M-structure has been incorporated in a novel photodiode architecture—see Figure 2(b)—and results in more than one order of magnitude reduction in dark current.^{5–7} An MWIR detector with a 5 μ m cut-off wavelength shows a specific detectivity exceeding $1.9 \times 10^{14} \text{cm} \cdot \text{Hz}^{1/2} \text{W}$, and R_0A (differential resistance-area product at zero bias) exceeding $10^9 \Omega \cdot \text{cm}^2$ at 77K. It attains background-limited performance at 165K for a 300K background and 2n field of view.⁷ This simply means that a photosignal from a room temperature background is higher than the camera's noise when it operates at 165K and below.

In summary, using a new material with a novel device architecture, we fabricated an MWIR 320 \times 256 focal plane array (FPA).⁸ The dark current of the FPA was reduced sufficiently to prevent any increase in noise equivalent temperature difference ($\sim 11\text{mK}$) up to an operating temperature of 120K. Human bodies can be imaged with the camera at 170K. Figure 3 shows sample images at different temperatures. This achievement demonstrates the feasibility of a 'HOT' (high operating temperature) mode for T2SL FPAs that avoids liquid-nitrogen cooling in favor of other alternatives, such as thermoelectric coolers. Our next step will be to further raise the operating temperature while maintaining optimal material quality, and to develop in-house portable camera systems with low power consumption and liquid-nitrogen-free cooling.

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