

# A large-scale quantum dot IR focal plane array

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*The artificial atomlike properties of self-assembling quantum dots enable high-operating-temperature long-wavelength IR focal plane arrays.*

Potential uses for light detectors operating in the 8–15 $\mu\text{m}$  wavelength range include ground- and space-based applications such as night vision, temperature detection, early warning systems, navigation, flight control systems, weather monitoring, as well as security and surveillance. In addition, they can be used to monitor and measure pollution, relative humidity profiles, and the distribution of different gases (such as ozone, carbon monoxide, and nitrous oxide) in the atmosphere. This is due to the fact that most of the absorption lines of gas molecules lie in this IR spectral region. The earth's atmosphere is opaque to most of the IR. Of its few transparent windows, the 8–12 $\mu\text{m}$  is one of the clearest. Cameras operating in this wavelength range and used in ground-based telescopes will be able to see through the earth's atmosphere, image distant stars and galaxies, and help in the search for cold objects such as planets orbiting nearby stars.

Traditional quantum well IR photodetectors are made from a combination of group III and group V elements and already offer extremely high operability, mature fabrication technology, very large formats, and material production that is increasingly high volume and low cost. However, operating temperatures are moderate (40–80K), and efficiency is limited. Past attempts at solving these issues focused on improving materials quality and designing new devices. In this work we exploited the artificial atomlike properties of self-assembling quantum dots (QDs) to develop more efficient large-scale (640 $\times$ 512 pixel) high-operating-temperature long-wavelength infrared (LWIR) focal plane arrays (FPAs) without sacrificing the economic advantages of the mature III-V IR imaging system pipeline.

QDs are nanometer-scale islands that form spontaneously on a semiconductor substrate due to lattice mismatch. QDs can confine the carriers (i.e., electrons or holes) in 3D, modifying the optical transition selection rule that forbids a quantum well from absorbing normal incident radiation and enhancing quantum efficiency. The 3D confinement of the photoexcited carrier by a quantum dot IR photodetector (QDIP) also increases its lifetime



**Figure 1.** An image taken with the first 640 $\times$ 512 pixel QDIP LWIR FPA operating at 60K.

via the 'phonon bottleneck' mechanism.<sup>1</sup> In a traditional quantum well IR photodetector, carriers can relax by emitting (or be excited by absorbing) phonons (i.e., lattice vibrations). But confinement of the carriers in a QD results in discrete (quantized) energy levels that prevent relaxation and permit a higher operating temperature. While individual QDs are good absorbers, typical QD densities are too low to achieve high quantum efficiency. Improving it is key to achieving a competitive QD-based FPA technology. This can be accomplished by increasing the QD density or by enhancing the IR absorption in the QD-containing material.

Our specific implementation used indium arsenide (InAs) and indium gallium arsenide (InGaAs) QDs embedded in gallium arsenide/aluminum gallium arsenide (GaAs/AlGaAs) multi-quantum well structures.<sup>2</sup> This material system can sustain a large number of QD layers grown on top of each other without suffering material degradation, thereby allowing high dot density. These dot-in-a-well (DWELL) materials operate by the photoexcitation of electrons between energy levels in the potential well created by the nanoscale QD in a well structure. Under

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an applied bias voltage, these photoexcited carriers can escape from the potential wells and be collected as photocurrent. The wavelengths of the spectral peaks ( $\lambda_p$ ) are determined by the energy difference between quantized states in the DWELL. The hybrid quantum dot/quantum well device offers two advantages: challenges in wavelength tuning through dot-size control can be compensated in part by engineering the quantum well sizes, which can be controlled precisely; and quantum wells can trap electrons and aid in carrier capture by QDs, thereby facilitating ground state refilling.

All DWELL wafers were grown on semi-insulating 4in GaAs substrates using molecular beam epitaxy.  $640 \times 512$  pixel QDIP arrays were fabricated using standard lithographic techniques and hybridized with  $640 \times 512$  pixel silicon readout integrated circuits via an indium bump-bonding process. The FPAs were characterized for quantum efficiency, noise, detectivity (the signal-to-noise ratio normalized to unit area and bandwidth), noise equivalent temperature difference (NE $\Delta$ T), uniformity, and pixel operability. The peak spectral responsivity of the FPA was at  $8.6 \mu\text{m}$  with full-width at half maximum of 18.7%.

The experimentally measured peak quantum efficiency and NE $\Delta$ T of an FPA were 5.0% (up from 0.1%) and 40mK (at 300K background with f/2 optics), respectively. The corrected NE $\Delta$ T nonuniformity of the  $640 \times 512$  pixel FPA is about 0.2%. Video images were taken at a frame rate of 60Hz. Figure 1 shows an image taken with this LWIR QDIP FPA. However, the new QDIP devices have shown improved quantum efficiency up to 20%. Mid-IR wavelength imagery of 300K scenery based on QD arrays up to 130K are known.<sup>3</sup> Although this is for mid-IR rather than long-IR wavelengths, it demonstrates the potential of the QDIP technology to operate at higher operating temperatures with high quantum efficiency.

Of particular interest is the role that other FPA parameters such as operability and uniformity play in the quality of an image from an FPA. A more detailed discussion on this subject can be found elsewhere.<sup>2,4</sup> This treatment makes the significant point that when detectivity is greater than  $10^{10} \text{cmHz}^{1/2} \text{W}^{-1}$ , the FPA performance is limited by array uniformity and thus essentially independent of the detectivity.

In summary, we have succeeded in increasing the detectivity of the QDIP by raising quantum efficiency from 0.1 to 5.0% for a large ( $640 \times 512$  pixel) FPA. Our next goal is to develop a megapixel FPA with 20% quantum efficiency.

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