Integrating multispectral capability into III-V detectors

Mike Cooke reports on some recent developments in creating multi-band photodetection for more compact, lighter equipment.

Electromagnetic radiation is full of information, if only we can detect and analyze it. Apart from spatial information, humans and other animals have well-developed multi-spectral capabilities in the visible range that allow them to discriminate between objects such as ripe and unripe fruit. More recently, humans have discovered and exploited radiation with frequencies and wavelengths over some 20 orders of magnitude, while visible light covers a mere factor of two (about a third of an order of magnitude).

Multispectral detection has applications ranging from military and environmental sensing to failure analysis and medical imaging. Desirable characteristics for such equipment are small size, low weight, and simplicity. There is a number of ways to achieve such aims.

Much of the interest for applications centers on mid-wavelength (MWIR) and long-wavelength (LWIR) infrared in the range 3–15μm for which there is a number of atmospheric transmission windows. Also in this range, terrestrial objects (including human beings) emit radiation with distinct spectral signatures. These wavelengths allow chemical sensing, environmental monitoring and natural resources surveys to be carried out. In defense, one of many applications is the detection of heat sources such as rocket emissions from missiles.

Particularly attractive for semiconductor detection is hetero-structure integration using techniques similar to photovoltaic multi-junction solar cells where light is absorbed in bands given by the bandgaps of the various materials. In the upper layers of such devices, the high-frequency/energy radiation is absorbed/converted, while lower-frequency/energy photons are transmitted to be absorbed/converted in the layers beneath.

Using a similar principle for detection would eliminate the need for the bulky, heavy, and complex optical assemblies that are presently needed to observe in multiple bands, thereby enabling compact, lightweight imagers. Arranging such vertically, monolithically integrated sub-detectors in focal plane arrays (FPAs) with multicolor capability could reduce pixel size and thus increase image resolution.

Vertically integrated systems do exist in commercial form. Hamamatsu has a device that consists of a wafer-bonded indium gallium arsenide (InGaAs) p-i-n diode and silicon (Si) photodiode, giving two-color responses covering ultraviolet (UV > 0.32μm) to infrared (IR < 2.57μm) wavelengths. The company sees applications as being spectrophotometers, laser or flame monitors, and radiation thermometers.

Another company, Foveon, markets vertical multispectral detection that uses the different absorbance of red, green and blue light in silicon to create image sensors for multicolor visible light cameras.

There is a wide range of semiconductor materials that are popular in various frequency bands, such as mercury cadmium telluride alloys (HgCdTe, also known as MCT), but here we will focus on recent developments using III-V materials.

The direct bandgaps of most of these materials allow efficient detection of radiation, while the extensive research in light/laser emission and photovoltaic devices has created a large palette of energy gaps that can be exploited.

Visible / NIR combo

Ohio State University has been a keen developer of multispectral devices based on gallium arsenide (GaAs) substrates. In late 2011, researchers from Ohio described an optically aligned visible/near-infrared (NIR) photodetector based on indium gallium phosphide (InGaP) and InGaAs subdetectors [K. Swaminathan et al, J. Appl. Phys., vol110, p063109, 2011]. Funding for the work came from US Air Force Office of Scientific Research and US Army Research Office.

The researchers grew metamorphic materials (Figure 1) on n-type (100)-oriented GaAs substrates, intentionally off-cut 6° toward the nearest (111)A direction in a modified Varian GEN II solid-source MBE system with

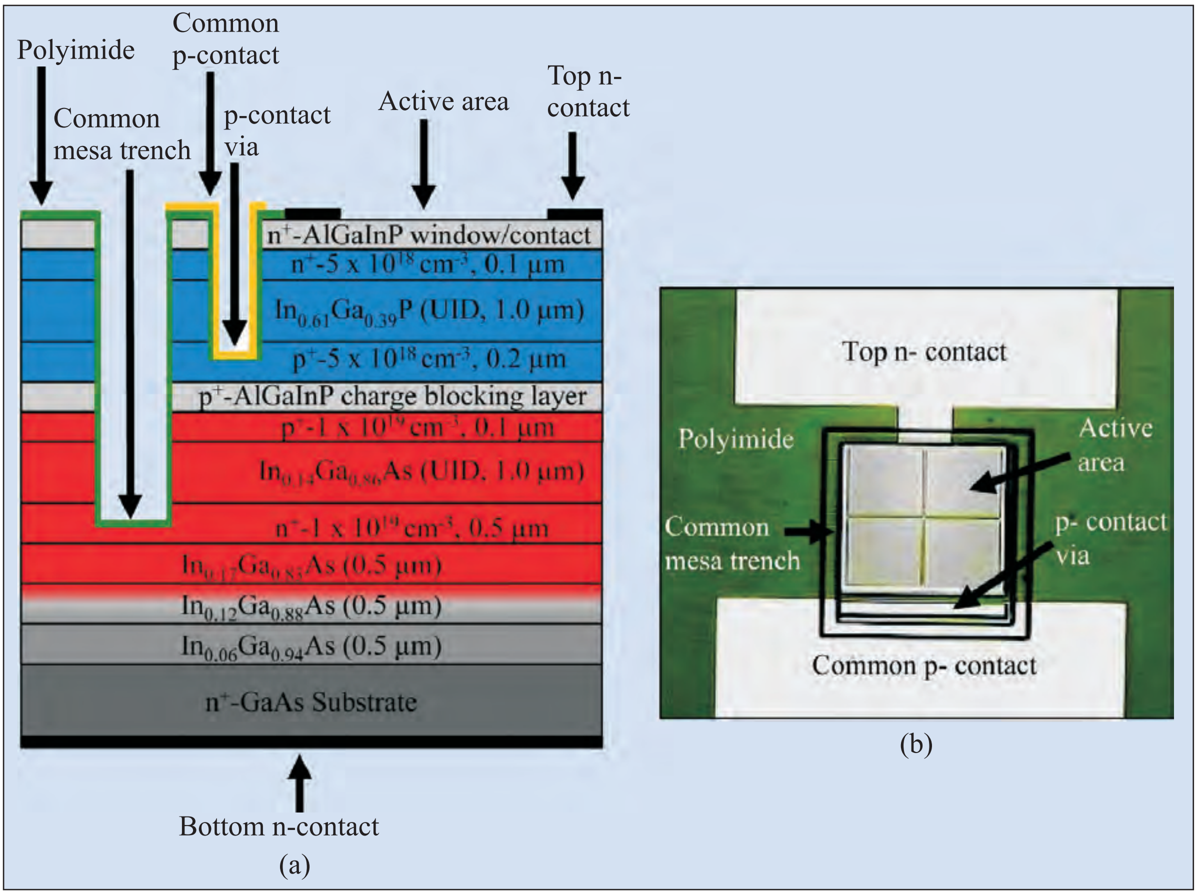

Figure 1. (a) Cross-sectional schematic of Ohio State University device (not to scale) of a fabricated n-i-p/p-i-n $In_{0.61}Ga_{0.39}P$/$In_{0.14}Ga_{0.86}As$ dual-photodetector with AlGaInP window and charge-blocking layers (0.1µm each). (b) Top-view photograph of a fully fabricated $In_{0.61}Ga_{0.39}P$/$In_{0.14}Ga_{0.86}As$ dual-photodetector.

valved P_2 and As_2 cracker sources. The back-to-back structures were doped to be p-type in the middle region and n-type at the top and bottom (n-i-p/p-i-n).

The three-step InGaAs buffer layers, with In-contents of 6%, 12% and 18%, were designed to bridge the ~1% lattice mismatch metamorphically between the GaAs substrate and the photodetector layers of $In_{0.14}Ga_{0.86}As$ and $In_{0.61}Ga_{0.39}P$.

The 6%-InGaAs buffer layer was grown at 550°C, while subsequent InGaAs layers were grown at 515°C. Phosphide layers were grown at 475°C.

Square photodetectors with active regions with 300µm sides were created using photolithography and plasma etching to create mesa and via trenches. The common p-type ohmic contact consisted of chromium/gold and the two n-type ohmic contacts were nickel/germanium/gold. A 4 minute 400°C treatment was used to anneal the n-type contact. No anti-reflective coating was used to improve performance.

The detector was designed so that both sub-detectors could be operated simultaneously and independently without the need for active bias control to select band sensitivity.

The dark currents at a reverse bias of –2V were 4x10^{-8}A/cm^2 for the InGaAs detector and 7x10^{-12}A/cm^2 for the InGaP detector. The InGaP detector was designed to absorb all photons above its bandgap, allowing lower-energy photons to be detected in the InGaAs region beneath.

The optical isolation was tested at –2V reverse bias, with the device showing overlap of detection in a relatively narrow wavelength range of 690–720nm (Figure 2). This cross-talk is attributed to near-bandgap photons that have a smaller InGaP absorption coefficient and thus leak through to the InGaAs device. This effect could be reduced by increasing the InGaP thickness.

There was no detectable effect of photo-generated carriers recombining to produce new photons, which is an effect sometimes seen in high-quality multi-junction solar cells. The absence of this effect is attributed to the 0.2µm p$^+$-InGaP layer limiting the number of freely diffusing photo-generated carriers.

The responsivity and specific detectivity at –2V bias were, respectively, 0.30A/W and 2.0x10^{14}cmHz$^{1/2}$/W at 680nm, and 0.41A/W and 8.6x10^{11}cmHz$^{1/2}$/W at 980nm.

The researchers comment: “The use of properly designed $In_xGa_{1-x}As$ (and/or $In_zGa_{1-z}P$) graded buffers should enable the extension of the metamorphic detector platform across the entire lattice constant range between GaAs and InP, providing access to multi-band photodetectors with tunable bandgaps from 0.74eV to 1.9eV.”

Extension to even shorter wavelength could be achieved with Al-containing alloys. InAsP could be used for longer-wavelength detection. The researchers have also produced back-to-back diodes with opposite polarity (p-i-n/n-i-p) that were sensitive to wavelengths with cut-offs at 650nm and 870nm.

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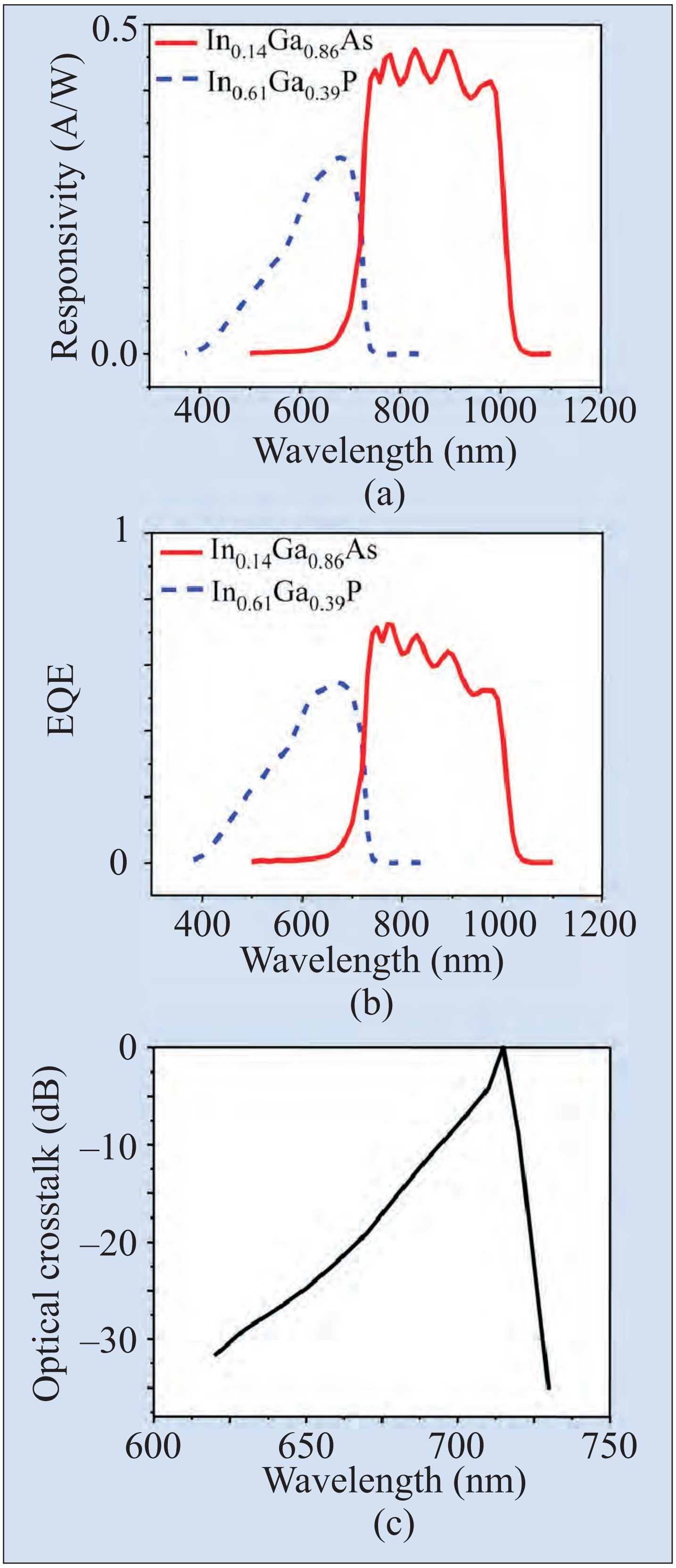

Figure 2. (a) Room-temperature spectral responsivity simultaneously measured by Ohio State University for both $In_{0.61}Ga_{0.39}P$ / $In_{0.14}Ga_{0.86}As$ sub-detectors at –2V bias, demonstrating high responsivities and very low optical cross-talk between sub-detectors. (b) EQE values for both subdetectors calculated from the corresponding responsivity values shown in (a). (c) Relative inter-detector optical cross-talk as a function of wavelength.

Optical switching

Arizona State University and Sandia National Laboratories have developed two-terminal devices capable of detecting NIR and LWIR [O. O. Cellek et al, Appl. Phys. Lett., vol100, p241103, 2012]. This is achieved by optical switching between the two IR bands. The need for only two terminals allows denser packing of detectors in FPAs and the use of simpler read-out ICs. “These devices enable the use of only a single indium-bump per pixel for multi-band image sensor arrays to have maximum fill factor,” the team writes.

A previous proof-of-concept consisted of a triple-junction device with visible, NIR and SWIR bands. The detection band was selected by illuminating the device with wavelengths for the non-selected bands. The new device (Figure 3) extends the idea to

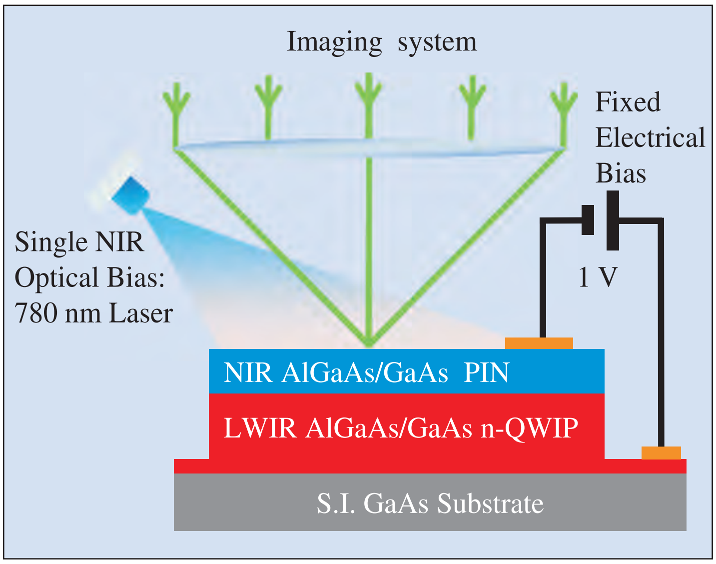

Figure 3. Schematic of Arizona State University / Sandia NIR / LWIR optically addressed photodetector using single optical bias source.

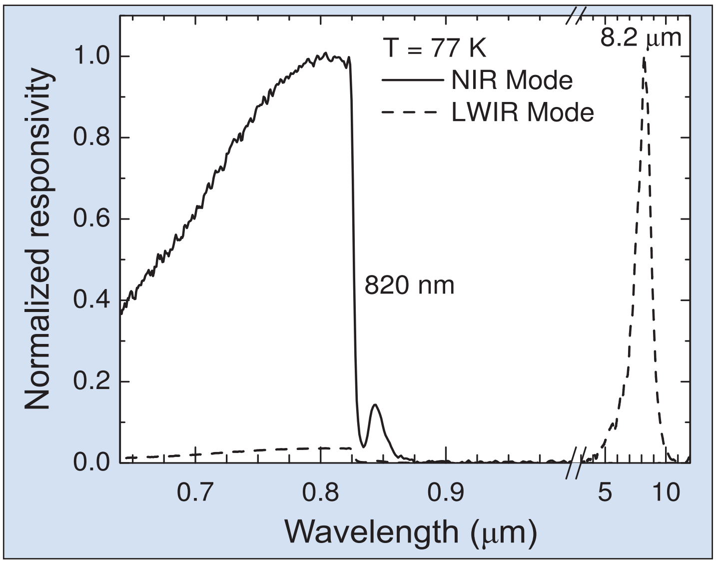

Figure 4. Spectral response in NIR and LWIR modes of operation at 77K measured by Arizona State University / Sandia with different beam splitters in an FTIR system.

NIR/LWIR dual-band detection. To avoid the use of tunnel junctions as used in the original concept, the new design couples a unipolar quantum well infrared photodetector (QWIP) with a p-i-n bipolar detector. In operation, the p-i-n NIR detector is reverse biased.

The epitaxial layers are produced using molecular beam epitaxy (MBE). Mesa isolation (150µm x 150µm) was achieved through etching. Conventional ohmic contacts were used. The optical bias was supplied by a 780nm laser diode.

The device has a 0.82µm cut-off for NIR and a 8.2µm peak for LWIR response (Figure 4). The quantum efficiency for NIR radiation is 65% and the specific detectivity is 2×10^9cmHz$^{1/2}$/W in the LWIR band at 68K. The cross-talk is better than 25dB.

The researchers comment: "Further addition of more detection bands is possible by using different active layers grown on the same substrate and by adding more corresponding optical bias sources."

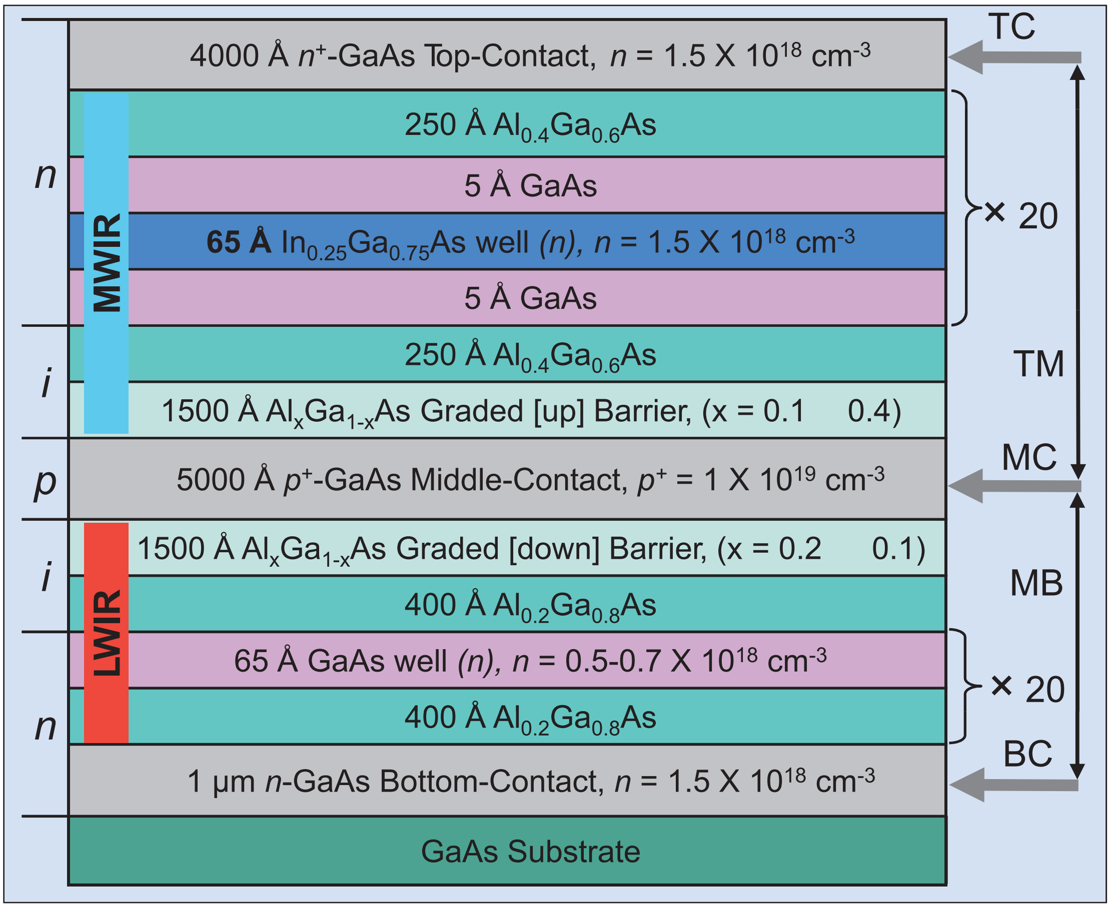

Figure 5. Schematic diagram of Georgia State University n-p-n-QWIP, as-grown. Three doped layers (TC, MC, and BC) separate two major active regions; one containing InGaAs MWIR quantum wells and the other containing GaAs LWIR quantum wells. Three different measurement configurations (TM, MB, and TB) are also indicated.

Five-band detection

Multispectral infrared and ultraviolet detectors are also being developed at Georgia State University. In 2010 [G. Ariyawansa et al, Appl. Phys. Lett., vol97, p231102, 2010]. Georgia State University reported a five-band device that consisted of two back-to-back p-i-n diodes with InGaAs/GaAs and GaAs/AlGaAs-based quantum wells integrated within the n-regions (Figure 5). The bias polarity was used to select responses at 80K from two groups of three bands: 0.6–0.8µm, 3–4µm, and 4–8µm ranges in one group and 0.8–0.9µm, 0.9–1.0µm, and 9–13µm ranges in the other. The polarity puts one of the diodes into reverse bias. Illumination creates carriers in the reverse biased device, giving a photo-current (Figure 6).

Although the device incorporated a middle contact for testing purposes, the aim of the work was to have wavelength selection from biasing only the top and bottom contacts.

Nitride quantum cascade detector (QCD)

Quantum cascade (QC) structures consisting of large numbers of steps through which electrons flow have been widely studied for laser emission and photodetection in the far- and mid-infrared spectral regions, using arsenide- and phosphide-based semiconductors.

Researchers in France and Switzerland have recently used nitride semiconductor QC structures to detect two-color short-wavelength infrared light [S. Sakr et al, Appl. Phys. Lett., vol100, p181103, 2012]. The team was based variously at University of Paris-Sud (UPS) and Ecole Polytechnique Fédérale de Lausanne (EPFL).

The nitride semiconductor structure enabled detection of the shortest wavelength so far of 1µm for QC detectors. This raises the possibility of use with infrared fiber-optic communication systems.

QC detectors (QCDs) have advantages over other techniques such as low noise at zero bias due to the absence of dark current. Further attractions include high-frequency operation due to short electron transit times and easy tuning of detected wavelengths with quantum well thickness.

The UPS/EPFL device contained active quantum well (QW) regions consisting of seven monolayers (1ML =

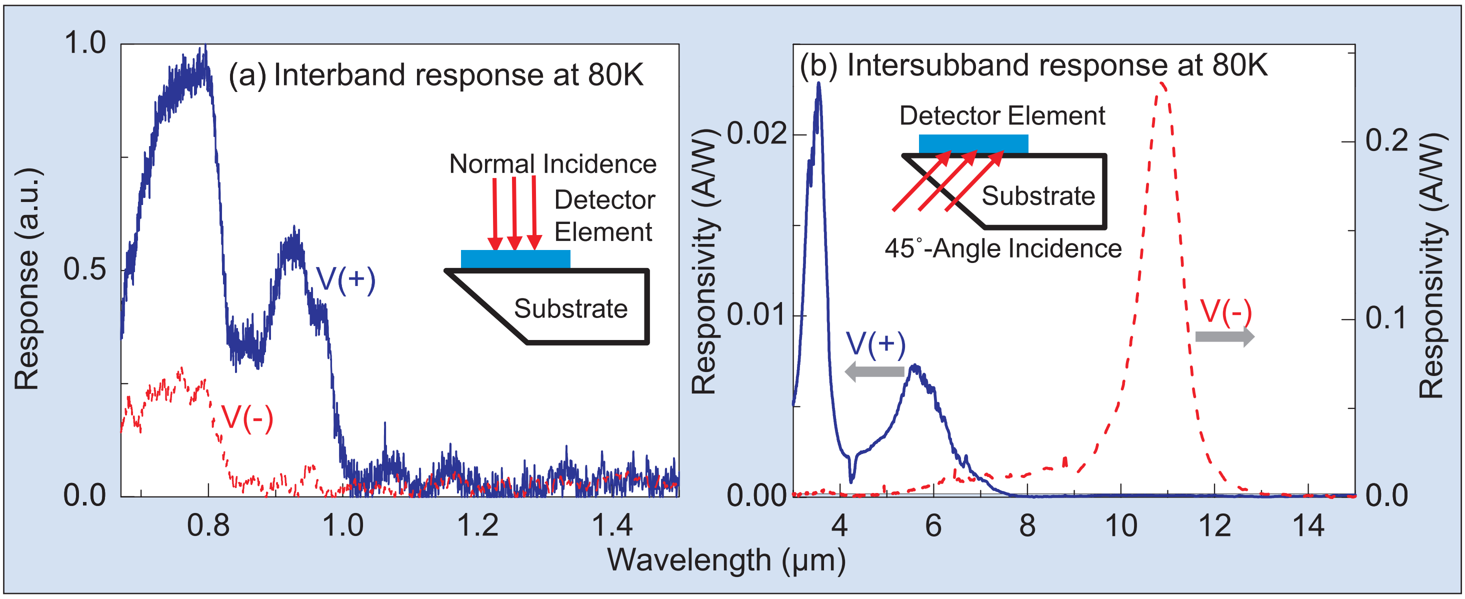

Figure 6. (a) Interband response of Georgia State University n-p-n-QWIP measured with front-side illumination. (b) Intersubband spectral response measured with 45° back-side illumination at 80K for positive (left scale) and negative (right scale) bias voltages indicated by V(+) and V(-). When the detector is coupled with a grating, both interband and intersubband responses can be measured with normal incidence light.

0.26nm) of n-type gallium nitride (n-GaN). These QWs were separated by extractor regions (Figure 7) composed of four repetitions of undoped AlN/$Al_{0.3}Ga_{0.7}N$ (4ML/6ML). These structures were grown as a 50-period cascade.

The QC arrangement was simulated to have three bound states (e_1, e_2, e_3) between which transitions could be excited by infrared illumination. The energies for intersubband (ISB) transitions from the ground state (e_1) were 0.7eV (e_2) and 1.3eV (e_3). The extractor structures were tuned to encourage transfer to the next period via scattering with the GaN longitudinal optical phonon of energy 92meV.

The QC structure was sandwiched between n-$Al_{0.3}Ga_{0.7}N$ cladding layers. The material was grown on AlN on c-sapphire templates using ammonia-source molecular beam epitaxy. The active-region growth temperature was 800ºC.

For electro-optic measurements, the material was formed into 700μm x 700μm mesas by etching; then titanium/aluminium/titanium/ gold top and bottom contacts were applied. The center of the top layer was unmetallized to allow illumination into the device.

The current–voltage curves of the devices were more symmetric than expected, given the polarization electric field in the structure (giving the triangular wells/barriers in Figure 7 simulation), suggesting that perhaps dislocations were creating parasitic conduction channels. The polarization electric field was part of the design of the device, allowing transitions to the second excited state (e_3) through symmetry breaking.

The photovoltage and absorption spectra were measured in a Fourier transform infrared (FTIR) spectrometer (Figure 8). The absorption of the active region was measured in

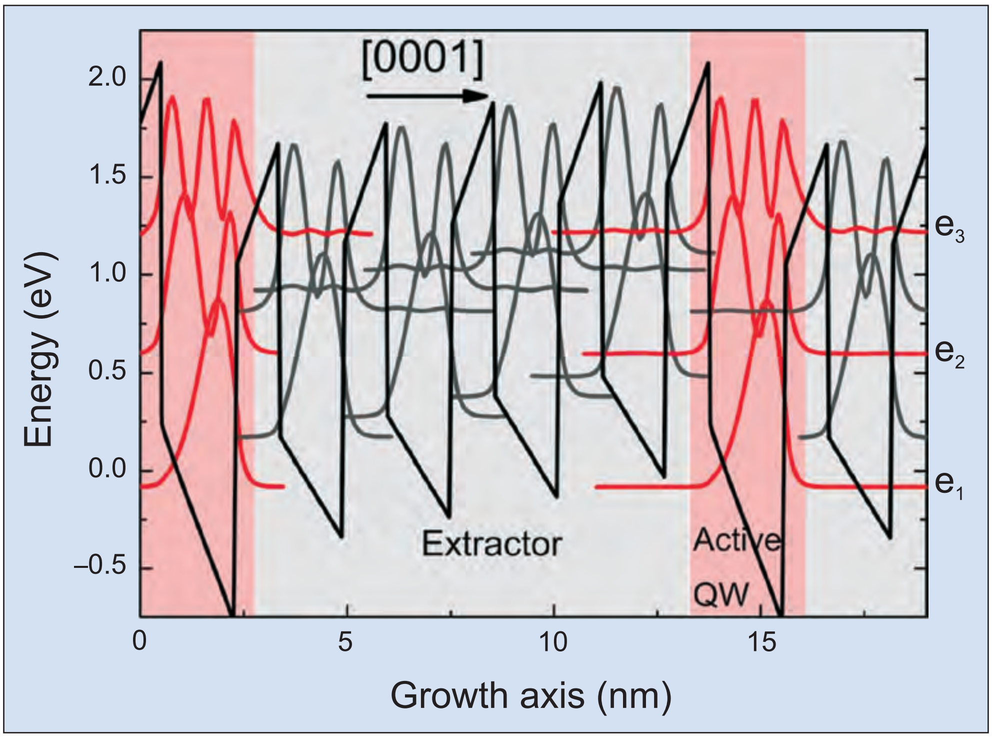

Figure 7. Conduction-band diagram of one period of UPS/EPFL QCD with adjacent active QW. The red and grey regions correspond to active QW and extractor stages, respectively.

scans across facets at 45° to the substrate. Both photovoltage and absorption spectra showed peaks at 1.7µm (0.71eV). The 1µm (1.25eV) peak was only seen in the photovoltage measurement.

The peaks were only seen with p-polarized light (i.e. with the field direction parallel to plane of incidence) and not with s-polarized (perpendicular) light. This is taken as a "clear indication that they originate from ISB transitions".

The researchers comment: "It should be noted that the 1µm peak detection wavelength is the shortest value ever reported for an ISB detector."

The response at 77K was 1.6x that at room temperature. The 1.7µm peak had a response of 0.1mA/W at 77K; the value for the 1µm peak was 0.008mA/W.

The researchers believe that the response could be improved by reducing the material defects in the active region. Longer-wavelength devices could be produced with lower-Al-content alloys.

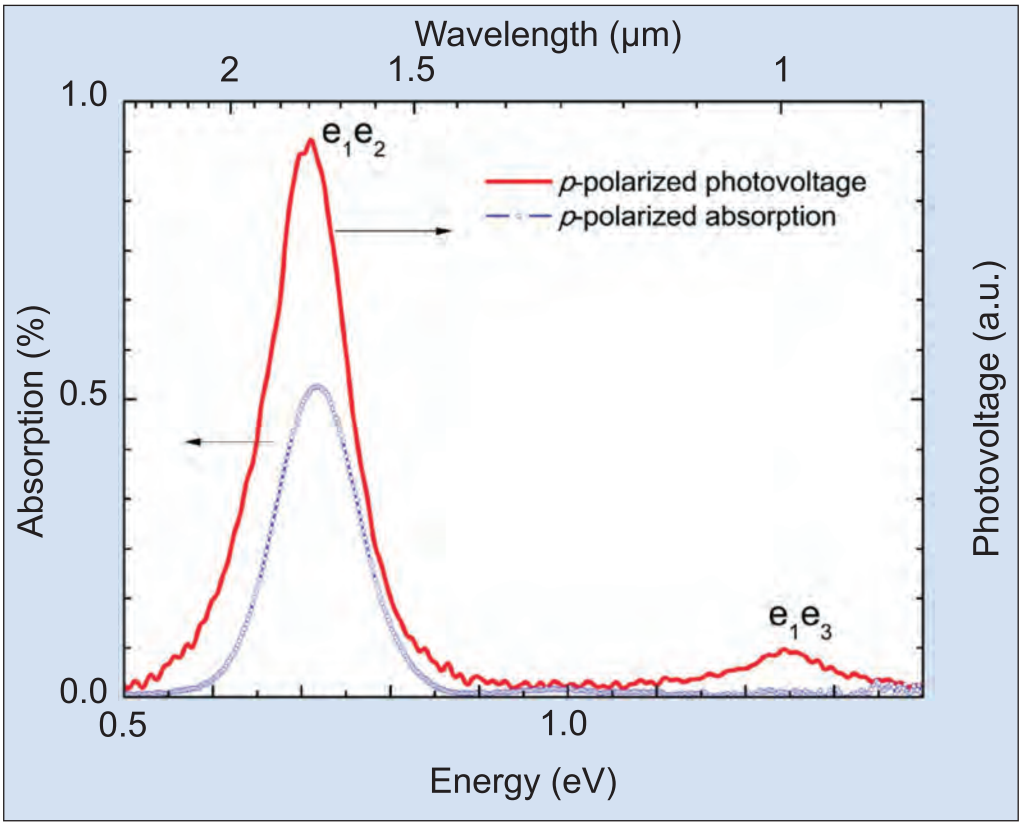

Figure 8. Absorption (solid lines with a square) and photovoltage spectra of UPS / EPFL QCD under p-polarization.

Although only detecting a single band, a recent report from Boston University [Faisal F. Sudradjat et al, Appl. Phys. Lett., vol100, p241113, 2012] is of far-infrared (FIR) intersubband photodetectors based on double-step nitride semiconductor quantum wells. The detected FIR at 20K was centered around 54meV photon energy (23µm, 13THz). The responsivity of the device was estimated to be 7mA/W at the same temperature.

The Boston device was designed to virtually eliminate the internal electric fields that are common in nitride semiconductor material structures. The double-step well was repeated 20 times. The structure was grown on free-standing GaN using rf-plasma-assisted molecular beam epitaxy.

The researchers see potential applications in biomedical sensing, explosive and drug detection, security screening, industrial process control, and spectroscopic imaging for astronomy and space physics. The large longitudinal optical phonon frequency (22THz in GaN versus 9THz in GaAs) suggests that such devices could eventually be operated at room temperature. ■

The author Mike Cooke is a freelance technology journalist who has worked in the semiconductor and advanced technology sectors since 1997.