Demonstration of a 320×256 two-color focal plane array using InAs/InGaAs quantum dots in well detectors

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We report the demonstration of a two-color infrared focal plane array based on a voltage-tunable quantum dots-in-well (DWELL) design. The active region consists of multiple layers of InAs quantum dots in an In0.15Ga0.85As quantum well. Spectral response measurements yielded a peak at 5.5 μm for lower biases and at 8–10 μm for higher biases. Using calibrated blackbody measurements, the midwavelength and long wavelength specific detectivity \( D^* \) were estimated to be \( 7.1 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W} \) at 1.0 V and \( 2.6 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W} \) at 2.6 V at 78 K, respectively. This material was processed into a 320×256 array and integrated with an Indigo 9705 readout chip and thermal imaging was achieved at 80 K. © 2005 American Institute of Physics.

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For applications including night vision, missile tracking, and environmental monitoring, there is interest in developing midwavelength infrared (MWIR, 3–5 μm) and long-wavelength (LWIR, 8–12 μm) focal plane arrays (FPAs). Monolithic two-color detectors offer additional advantages over single-color detectors, in that it is possible to produce an absolute temperature map of a scene, even if emissivities are unknown, provided all the sensed radiation originates only from scene. Presently, many high performance MWIR and LWIR detectors are based on mercury cadmium telluride (MCT). Due to a dramatic change of the band gap as a function of material composition, it is very challenging to obtain large area homogeneous materials suitable for LWIR FPAs. In contrast, mature materials growth technologies for III–V semiconductors can provide very accurate control of compositions and homogeneity. There is therefore interest in developing IR photodetectors using III–V materials. One of the most successful III–V semiconductor LWIR detectors is the quantum well infrared photodetector (QWIP), which employs the intersub-band or the sub-band–to–continuum transitions in quantum wells. The major drawback of n-type QWIPs is that they cannot detect normally incident light due to the restriction of selection rules for the optical transition. (The requirement to incorporate a light coupling structure such as a grating or an optocoupler with the QWIP makes fabrication more complex, and hence more costly.) In contrast, the intersub-band optical transitions in quantum dots (QDs) do not have that restriction, due to the three-dimensional quantum confinement. Theoretically, quantum dot infrared photodetectors (QDIPs) and quantum dot-in-well (DWELL) detectors offer several advantages over QWIPs, including lower dark current (hence higher \( T \) operation), higher responsivity, normal incidence detection, and improved radiation hardness. Asymmetrically designed DWELL detectors have also been shown to have a bias-dependent spectral response that is suitable for hyperspectral imagery. However, while a number of QD-based devices have been demonstrated, their performance is usually inferior to that of QWIPs. One of the main reasons for this is that the growth of self-assembled QDs needs sufficient strain in order to be stable and, hence, higher performance. Nevertheless, more recently, QDIPs with dark current densities less than \( 10^{-5} \text{ A/cm}^2 \) and peak detectivities as high as \( 10^{11} \text{ cm Hz}^{1/2}/\text{W} \) at 100 K have been reported. Recently, a MWIR QDIP focal plane array (FPA) based on InGaAs/InGaP quantum dots has also been demonstrated.

In this article we report a two-color quantum dot FPA, based on a voltage-tunable InAs/InGaAs/GaAs DWELL structure. In the DWELL structure, InAs QDs are placed in the active region consisting of a 15-stack asymmetric quantum confined Stark effect (QCSE). The photocurrent spectra of the detectors reveal two peaks originating from the same active region. Using calibrated blackbody measurements on single pixels, specific detectivities \( D^* \) were estimated to be \( 7.1 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W} \) at 1.0 V and \( 2.6 \times 10^{10} \text{ cm Hz}^{1/2}/\text{W} \) at 2.6 V at 78 K for MWIR and LWIR band, respectively.

The detectors, grown by solid source molecular beam epitaxy (MBE), are similar to those previously reported. The detector structure consists of a 15-stack asymmetric

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whereas the LWIR peaks around 8–10 μm. Prior to fabrication of the FPAs, standard processing techniques were used to fabricate top-illuminated quantum dots (QDs) in an In_{0.15}Ga_{0.85}As well, itself placed in GaAs. The well widths below and above the dots are 50 and 60 Å, respectively. The well width asymmetry, combined with the inherent asymmetry associated with QD formation, leads to a voltage-tunable spectral response in the finished devices. Prior to fabrication of the FPAs, standard processing techniques were used to fabricate top-illuminated 400 μm × 400 μm test pixels, with aperture diameters ranging between 25 and 300 μm.

Bias-dependent spectral response curves for a pixel with a 100 μm diameter aperture, measured using a Nicolet 870 Fourier-transform infrared spectrometer (FTIR), for detector bias voltages between −3 and +3 V at 50 K, are shown in Fig. 1. The spectra contain peaks centered in the MWIR and the LWIR regime, the relative magnitudes of these peaks clearly displaying bias dependency. The MWIR peak around 5 μm is dominant at smaller bias voltages (|V_b| < 2 V), whereas the LWIR peaks around 8–10 μm are dominant at higher biases (|V_b| > 2 V). We believe that the LWIR peaks arise from transitions from the ground state in the well to a lower lying state in the quantum well (QW), whereas the MWIR peak arises due to transitions from the ground state of the dot to a higher lying state in the well. This also explains the appearance of the LWIR peak at increased bias since the carriers in the lower lying state are extracted by field assisted tunneling, a process that dominates at higher biases. The peak positions are independent of temperature, although the ratio of the peak heights varies as a function of temperature. The dark current density characteristics for the device, in the temperature range 30–100 K, were measured. The 300 K dark current density characteristics for the device, in the temperature range 30–100 K, were measured. The 300 K current amplifier and then displayed by a SRS 760 fast Fourier transform (FFT) spectrum analyzer. The responsivity and detectivity obtained from the test devices at 78 K are shown in Fig. 2. Using bandpass filters to limit the incident radia-

FIG. 1. Bias-dependent spectral responses at 50 K for a single-pixel (100 μm) DWELL detector. Note that the MWIR peak dominates at lower biases whereas the LWIR peaks dominate at higher biases.

FIG. 2. Peak responsivity and detectivity for a 15 stack DWELL detector at 78 K obtained using a calibrated blackbody source. Solid squares: MWIR responsivity; solid triangles: LWIR responsivity; open squares: MWIR detectivity; open triangles: LWIR detectivity.

FIG. 3. (a) MWIR and (b) LWIR images of a soldering iron obtained from the 320 × 256 DWELL focal plane array at 80 K.
Due to the thin epitaxial layer, the cavity resonance cutoff was estimated to be 6 μm, which lead to a reduced response in the LWIR regime.

Thermal imaging was undertaken at an estimated FPA temperature of 80 K, using different optical filters between 3–5 and 8–12 μm, so as to demonstrate two-color operation. Figure 3 shows an image of a soldering iron obtained using the QDIP FPA using a MWIR and LWIR filter. The two-color response originating from the same active region makes this technology promising for applications in which low registration errors are important. Figure 4 shows an image of the scientific personnel involved with testing of the FPA that was fabricated from a different QDIP wafer with a similar design. There are two rows of nonoperating pixels in the center of the FPA arising due to a problem with the ROIC. The operability of the FPA was greater than 99%. The noise-equivalent temperature difference was estimated to be less than 100 mK for f#1(3–5 μm) and f#2(5–9 μm) optics.

It should be noted that the present FPA has not been optimized. Mechanical thinning, coupled with no antireflection coating cause optical losses such as scattering and reflection. Moreover, the thin cavity resulted in reduced performance in the LWIR regime. Furthermore, the ROIC was not optimized for the given QDIP device. Nevertheless, the excellent imagery obtained from these devices is a promising beginning for the development of QD FPAs.

In conclusion a two-color 320×256 InAs/InGaAs/GaAs DWELL-based FPA has been demonstrated. Using calibrated blackbody measurements on single pixel devices, specific detectivities of $2.6 \times 10^{10}$ cm Hz$^{1/2}$/W($V_b=2.6$ V) and $7.1 \times 10^{10}$ cm Hz$^{1/2}$/W($V_b=1$ V) were obtained for the LWIR and MWIR bands, respectively. Thermal imaging at 80 K has been demonstrated in the wavelength bands 3–5 and 8–12 μm using a 320×256 FPA. Strain-compensated designs, allowing for more QD absorbing layers, together with process and integration optimization can be expected to lead to improved performance of the QDIP FPAs.

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