Invited Presentation

Large Format Multicolor QWIP Focal Plane Arrays

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ABSTRACT

Mid-wave infrared (MWIR) and long-wave infrared (LWIR) multicolor focal plane array (FPA) cameras are essential for many DoD and NASA applications including Earth and planetary remote sensing. In this paper we summarize our recent development of large format multicolor QWIP FPA that cover MWIR and LWIR bands.

Keywords: infrared detectors, infrared imaging, quantum well devices.

INTRODUCTION

The quantum well infrared photodetectors (QWIPs) utilize the photoexcitation of electrons between the ground state and the first excited state in the conduction band quantum well (QW) (See references 1-3 for a detailed description on QWIPs). There has been much interest lately [1-6] in large format and multicolor QWIP focal plane arrays (FPAs). In this paper we discuss the design, fabrication, and test results of a 640x512 pixel multi-band focal plane array (FPAs), superpixel QWIP FPA for imaging multiple waveband temperature sensor and large format dual-band pixel collocated QWIP FPA.

640X512 PIXEL FOUR-BAND SPATIALLY SEPARATED FOCAL PLANE ARRAY

In this section, we discuss the demonstration of the first 640x512 pixel monolithic spatially separated four-band QWIP FPA. The unique feature of this spatially separated four-band FPA is that the four infrared bands are independently and simultaneously readable on a single imaging array. The multi-band FPAs based on narrow-band QWIP detector structures have the advantage over other broad-band detectors such as HgCdTe in that the spectral responses of QWIP are relatively narrow so that a detector designed for a specific spectral band only detects radiation in that band with little or no spectral crosstalk [5]. Thus, pixel co-located multi-band QWIP FPAs can operate in simultaneous read mode compared to the alternate frame read mode of multi-band FPAs based on other detector technologies [5]. These advantages lead to a reduction in instrument size, weight, mechanical complexity, optical complexity and power requirements since no moving parts are needed. Furthermore, a single optical train can be employed, and the whole focal plane can operate at a single temperature.

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The individual pixels of the four-color FPA were defined by photolithographic processing techniques (masking, dry etching, chemical etching, metal deposition, etc.). Four separate detector bands were defined by a deep trench etch process and the unwanted spectral bands were eliminated by a detector short-circuiting process. The unwanted top detectors were electrically shorted by gold-coated reflective two-dimensional etched gratings as shown in the Fig. 1. In addition to shorting, these gratings serve as light couplers for active QWIP stack in each detector pixel [6]. Design and optimization of these two-dimensional gratings to maximize QWIP light coupling are extensively discussed elsewhere [1]. The unwanted bottom QWIP stacks were electrically shorted at the end of each detector pixel row.

Typically, quarter-wavelength deep \( h = \frac{\lambda_p}{4n_{\text{GaAs}}} \) grating grooves are used for efficient light coupling in single-band QWIP FPAs. However, in this case, the height of the quarter-wavelength deep grating grooves is not deep enough to short circuit the top three MQW QWIP stacks (e.g.: three top QWIP stacks on 13-15 \( \mu m \) QWIP in Fig. 1). Thus, three-quarter-wavelength groove depth two-dimensional gratings \( h = \frac{3\lambda_p}{4n_{\text{GaAs}}} \) were used to short the top unwanted detectors over the 10-12 and 13-15 \( \mu m \) bands. This technique optimized the light coupling to each QWIP stack at corresponding bands while keeping the pixel (or mesa) height at the same level which is essential for the indium bump-bonding process used for detector array and readout multiplexer hybridization. Figure 2 shows the normalized spectral responsivities of all four spectral bands of this four-band FPA. Spectral band widths of the four detectors from shorter wavelength to longer wavelength in increasing order are \( \Delta\lambda/\lambda_p \sim 26\% \), 15\%, 17\%, and 11\%, respectively. Figure 3 shows the measured absolute responsivity at the peak wavelength for all four detectors. As expected, the narrower bandwidth and the flat responsivity near zero bias voltage indicate the bound-to-quasibound nature transition in the VLWIR detector [1]. Detectors in the 8.5-10 and 10-12 \( \mu m \) spectral-bands show a slightly broader spectral bandwidth, with increasing responsivity right at the beginning of the bias voltage, confirming the bound-to-continuum design [1]. The typical spectral width of a MWIR QWIP is about 0.5 \( \mu m \). The MWIR detector in this FPA is specifically designed to cover a 4-6 \( \mu m \) wavelength range with \( \Delta\lambda/\lambda_p \sim 26\% \) broader responsivity by utilizing three coupled QWs in each period of the MQW stack [7]. Also, the shorter wavelength response in this detector is achieved by using deeper In\(_{0.33}\)Ga\(_{0.67}\)As QWs with lattice mismatched Al\(_{0.3}\)Ga\(_{0.7}\)As barriers [7]. A high Al ratio is less desirable in these detectors because of the high defect density and the near crossing of the \( \Gamma \) and \( X \) valleys [1]. Also, the utilization of the coupled QWs within the MQW structure creates unbiased energy subbands where photexcited electrons can be easily relaxed before reaching the collector contact. These reasons could result in a very low optical responsivity in MWIR detector as seen in the Figure 3.

A few QWIP FPAs were chosen and hybridized to a 640x512 pixel silicon CMOS ROIC and biased at \( V_B = -1.5 \) V. At temperatures below 83 K, the signal to noise ratio of the 4-6 \( \mu m \) spectral band is limited by array nonuniformity, multiplexer readout noise, and photon current (photon flux) noise. At temperatures above 45 K, temporal noise due to the 13-15 \( \mu m \) QWIP’s higher dark current becomes the limitation. The 8.5-10 and 10-12 \( \mu m \) spectral bands have shown BLIP performance at temperatures between 45 and 83 K. This initial array gave excellent images with 99.9\% operability (number of dead pixels \( \approx 250 \)).

A 640x512 pixel four-band QWIP FPA hybrid was mounted onto a 84-pin lead-less chip carrier and installed into a laboratory dewar which is cooled by liquid helium to demonstrate a 4-band simultaneous imaging camera. The FPA was cooled to 45 K and the temperature was stabilized by a temperature controller and regulating the pressure of gaseous helium. The optical assembly of the FPA test setup consists a 100 mm focal length anti-reflection coated germanium lens, which gives a 9.2° field-of-view. A SEIR™ image processing station was used to obtain clock signals for the readout multiplexer and to perform digital data acquisition and nonuniformity corrections. The digital data acquisition
resolution of the camera is 14-bits, which determines the instantaneous dynamic range of the camera (i.e., 16,384). Video images were taken at a frame rate of 30 Hz at temperatures as high as T = 45 K, using a ROIC capacitor having a charge capacity of 11x10^6 electrons. Figure 4 shows one frame of a video image taken with the four-band 640x512 pixel QWIP FPA. It is noticeable that the object in the 13-15 μm band is not very clear due to the reduced optical transmission of the germanium lens beyond 14 μm.

Figure 5 shows the peak detectivities of all four spectral-bands as a function of operating temperature. Based on single element test detector data, the 4-6, 8.5-10, 10-12, and 13-15 μm spectral bands show BLIP at temperatures 40, 50, 60 and 120 K, respectively, for a 300 K background with a f/5 cold stop. As expected (due to BLIP), the estimated and experimentally obtained NEDT values of all spectral-bands do not change significantly below their BLIP temperatures. The experimentally measured NEDT of 4-6, 8.5-10, 10-12, and 13-15 μm detectors at 40 K are 21, 45, 14, and 44 mK, respectively. The experimentally observed NEDT values of 4-6 and 10-12 μm spectral bands agree reasonably well with the estimated NEDT values based on the single element test detector data. On the other hand, the NEDT values obtained for 8.5-10 and 13-15 μm spectral bands are almost a factor of two higher than the estimates based on single element test detector data. This decrease in performance attribute to the processing related nonuniformity.

![Figure 3](image3.png) Fig. 3 Bias dependent peak responsivities of the detectors in four-band QWIP FPA. The peak response wavelength for detectors D1, D2, D3, and D4 are λ_p = 5 μm, λ_p = 9.1 μm, λ_p = 11 μm, and λ_p = 14.2 μm, respectively. The responsivity curve for detector D1 is multiplied by a factor of 5 to fit to the scale.

![Figure 4](image4.png) Fig. 4 One frame of video image taken with the 4-15 μm cutoff four-band 640x512 pixel QWIP camera. The image is barely visible in the 13-15 μm spectral band due to the poor optical transmission of the anti-reflection layer coated germanium lens.

![Figure 5](image5.png) Fig. 5. Detectivities of each spectral-band of the four-band QWIP FPA as a function of temperature. Detectivities were estimated using the single pixel test detector data taken at V_B = –1.5 V and 300 K background with f/5 optics.
SUPERPIXEL QWIP FOCAL PLANE ARRAY FOR IMAGING MULTIPLE WAVEBAND TEMPERATURE SENSOR

There are two methods for the remote sensing of temperature: the imaging radiometers based on single thermal IR band and the imaging radiometers based on multiple thermal IR bands. Traditional radiometric techniques using monochromatic sensors must have prior knowledge of the emissivity of the target to measure the temperature accurately. However, this is not always practical as the emissivity may change or be unknown. This is a major shortfall for monochromatic sensors.

This critical deficiency of single band detector measurement can be overcome by taking the signals measured at different wavelengths using a multi-band detector. Figure 6 illustrated a four-band detector measurement. Assuming simple analytical forms for spectral emissivity, such as quadratic polynomial, the true temperature and emissivity of the surface can be calculated from the measured signals. In this manner, more precise determination of temperature can be made by reducing the uncertainties due to unknown emissivity of the object. Numerical simulations have shown that this technique works well as long as the shape of the object's spectral emissivity can be well represented by a \((N-1)\) parameter function, where \(N\) is the number of spectral bands.

Multi-band IR temperature determination is far more accurate than its single band counterpart. However, from a practical perspective, achieving such precision alignment for two or more independent thermal IR radiometer cameras is extremely difficult, expensive, and impractical for the field environment due to alignment difficulties, limited space on tracking instrumentation, and the mobile nature of the systems. Furthermore, such hybrid systems are bulky and have complicated optical trains, which are susceptible to post-fabrication miss-alignments during operation or transport. In the work described in this section, we address this problem and report results of initial research and development on a novel four-band IR imaging system with simultaneously readable collocated pixels. This system can be used for measuring temperature on surfaces of unknown emissivity.

We have developed a novel approach for realization of four band infrared imaging FPA with collocated pixels. In this FPA the area array is divided into 2x2 sub-pixel areas that function as superpixels for temperature measurement (Fig. 7). Each QWIP sub-pixel, marked as Q1, Q2, Q3 and Q4 in Fig. 8, is sensitive to one of four specific wavelength bands. The apparent black-body temperature of the object in each spectral band can be found using multi-point calibration curve from the signal measured by each subpixel. Next, the actual surface temperature can be calculated from these four apparent temperatures and guess of the functional form of the spectral emissivity curve.

The actual device structure consists of a 0.3 \(\mu m\) thick stack of 8 period MQW structure (Q1), a 0.4 \(\mu m\) thick stack of 8 period MQW structure (Q2), a 1.1 \(\mu m\) thick stack of 20 period MQW structure (Q3), and a 1.2 \(\mu m\) thick stack of 20 period MQW structure (Q4) (Fig. 8). The quantum well parameters of Q1, Q2, Q3, and Q4 were designed to respond at...
3.5-4.5, 4.5-5.5, 7.5–8.5, and 9–10 µm wavelength range respectively. Each photosensitive MQW stack was separated by a heavily doped intermediate GaAs contact layer, with a thickness ranging from 0.4 to 0.8 µm (see Fig. 8). The quantum wells in the Q1, Q2, Q3 and Q4 structures are doped with Si up to a carrier density of $n = 3 \times 10^{18}$ cm$^3$, $n = 2 \times 10^{18}$ cm$^3$, $n = 5 \times 10^{17}$ cm$^3$, and $n = 5 \times 10^{17}$ cm$^3$ respectively. This whole four-band QWIP device structure is then sandwiched between 0.4 and 1 µm GaAs top and bottom contact layers doped with $n = 1 \times 10^{18}$ cm$^3$ and $n = 5 \times 10^{17}$ cm$^3$.

The sample was grown by molecular beam epitaxy on a 4-inch semi-insulating GaAs substrate wafer. In order to characterize the device, large test mesas, 200–400 µm in diameter, were fabricated using wet chemical etching and evaporation of Au/Ge ohmic contacts on the top and bottom contact layers. The responsivity spectra of these detectors were measured using a 1000 K blackbody source and a grating monochromator. The detectors were back illuminated through a 45° polished facet to obtain normalized responsivity spectra at different bias voltages. Then the absolute spectral responsivities were obtained by measuring the total photocurrent due to a calibrated blackbody source.

During the fabrication of detector arrays, first, the groves of two dimensional gratings on top of the pixels (Fig. 9) were defined by optical photolithography and dry etching for each infrared band. Next, the individual pixels were fabricated by photolithographic processing techniques. Four separate detector bands were defined by a deep trench etch process, and a detector short-circuiting process eliminated the unwanted spectral bands. As shown in the Fig. 8, the unwanted top detectors were electrically shorted by a gold coated reflective 2-D etch gratings. The unwanted Q2 detector underneath the Q1 was shorted by etching a step-like via hole and then putting a metal strip. All the other bottom detectors were electrically shorted through the column or rows from the outside of the array. The fabricated detector arrays are being hybridized to CMOS multiplexers. After that they will be mounted into 84-pin lead-less chip carrier and will be installed into a laboratory dewar for characterization.
**DUAL-BAND FOCAL PLANE ARRAY**

Researchers have already demonstrated megapixel size single-band QWIP focal plane arrays (FPAs) [8]. There are many applications that require mid-wavelength infrared (MWIR) and long-wavelength infrared (LWIR) dual-band FPAs. In this paper we summarize the development of large format dual-band pixel collocated QWIP focal plane array (FPA) and the details of this work will be available elsewhere [10]. As shown in Fig. 10, our dual-band FPA is based on two different types of (i.e., MWIR and LWIR) QWIP devices separated by a 0.5 micron thick, heavily doped, n-type GaAs layer. The MWIR multi-quantum-well (MQW) structure are placed on top of the LWIR MQW structure because the MWIR MQW region consists of lattice miss-match InGaAs layers. This has an advantage from the epitaxial materials growth perspective. However, this is a disadvantage from the material processing standpoint since it is hard to etch InGaAs material compared to other III-V materials such as GaAs and AlGaAs. In this work we implement a dual-band device structure that uses only two indium bumps per pixel (Fig. 10) compared to three indium bumps per pixel with pixel co-located dual-band devices [9-11]. In this device structure the detector common (or ground) is shorted to the bottom detector common plane via a metal bridge. Thus, this device structure reduces the number of indium bumps by 30% and has a unique advantage in large format FPAs, since more indium bumps require additional force during the FPA hybridization process.

A coupled-quantum well structure are used in this device to broaden the MWIR responsivity spectrum and the LWIR device uses a standard bound-to-quasibound design, where the upper levels involved in the infrared optical transition is in approximate resonance with the conduction band edge of the barrier. These two photosensitive MQW structures are sandwiched between GaAs top and bottom contact layers doped n = 1x10^18 cm^-3, grown on a semi-insulating GaAs substrate by molecular beam epitaxy (MBE). The top contact was a 0.7 µm thick GaAs cap layer on top of a 300 Å Al_{0.27}Ga_{0.73}As stop-etch layer which was grown in situ on top of the dual-band device structure to fabricate the light coupling optical cavity [9-13]. The bottom contact layer was a 1.2 µm thick GaAs layer. A 0.4 µm thick undoped AlGaAs layer is embedded between the top contact of the LWIR and bottom contact of the MWIR MQW regions. It is worth noting that the photosensitive MQW region of each QWIP device is transparent at other wavelengths, which is an important advantage over conventional interband detectors. This spectral transparency makes QWIP suitable detector material for pixel co-located dual-band FPAs with minimal spectral cross-talk. As shown in Fig. 10, the carriers emitted from each MWQ region are collected separately using two indium bumps. The bottom of the MWIR device is shorted to the detector common (i.e., LWIR bottom contact) layer by a metal bridge fabricated through a via-hole. Top contact of the LWIR detector is accessed by another metal bridge fabricated through a via-hole.

The MBE grown material was tested for absorption efficiency using a Fourier Transform Infrared (FTIR) spectrometer. The experimentally measured peak absorption (or internal) quantum efficiency (\(\eta_a\)) of this material at room temperature was 19% and the spectral width and the cutoff wavelength were \(\Delta \lambda / \lambda = 15\%\) and \(\lambda_c = 5.1\ \mu m\) respectively. The peak detectivity is defined as 

\[
D^* = R_P \sqrt{AB / i_n},
\]

where \(R_P\) is the peak responsivity, \(A\) is the area of the detector and \(A = 3.14 \times 10^{-4}\ \text{cm}^2\). The measured peak detectivity at bias \(V_B = -1\ \text{V}\) and temperature \(T = 90\ \text{K}\) is \(4 \times 10^{11}\ \text{cm Hz}^{-1/2}\ \text{W}\). The LWIR detectors have spectral width and the cutoff wavelength of \(\Delta \lambda / \lambda = 10\%\) and \(\lambda_c = 8.8\ \mu m\), respectively. The peak detectivity of the LWIR detector was calculated using experimentally measured noise current \(i_n\). The calculated peak detectivity at bias \(V_B = -1\ \text{V}\) and temperature \(T = 70\ \text{K}\) was \(1 \times 10^{11}\ \text{cm Hz}^{-1/2}/\text{W}\).

After the light coupling 2-D grating array was defined by stepper based photolithography and dry etching, the MWIR detector pixels of the 1024x1024 pixel detector arrays, and the via-hole to access the detector common, were fabricated by dry etching through the photosensitive GaAs/In_{0.3}Ga_{0.7}As/Al_{0.27}Ga_{0.73}As MQW layers into the 0.5 µm thick doped GaAs intermediate contact layer. Then LWIR pixels and via-holes for MWIR pixels to access the array detector common were fabricated. A thick insulation layer was deposited and contact windows were opened at the bottom of each via-hole and...
on top surface. Ohmic contact metal was evaporated and unwanted metal was removed using a metal lift-off process. The pitch of the detector array is 30 µm and the actual MWIR and LWIR pixel sizes are 28x28 µm². Five detector arrays were processed on a four-inch diameter GaAs wafer. Indium bumps were then evaporated on top of the detectors for hybridization with ROICs. Several dual-band detector arrays were chosen and hybridized (via an indium bump-bonding process) to grade A 1024x1024 pixel silicon CMOS ROICs. Arrays were back filled with epoxy and the initial GaAs substrate was removed by lapping and dry-etching process.

Fig. 11  An image taken with the first megapixel simultaneous pixel co-registered MWIR:LWIR dual-band QWIP camera. The flame in the MWIR image (left) looks broader due to the detection of heated CO₂ (from cigarette lighter) re-emission in 4.1–4.3-micron band, whereas the heated CO₂ gas does not have any emission line in the LWIR (8–9 microns) band. Thus, the LWIR image shows only thermal signatures of the flame. However, the silicon wafer blocked most of the LWIR signal.

A MWIR:LWIR pixel co-registered simultaneously readable dual-band QWIP FPA has been mounted on to the cold finger of a pour fill dewar cooled by liquid nitrogen and the two bands (i.e., MWIR and LWIR) were independently biased. Some imagery was performed at 70 K. An image taken with the first megapixel simultaneous pixel co-registered MWIR:LWIR dual-band QWIP camera is shown in Fig. 11. The flame in the MWIR image (left) looks broader due to the detection of heated CO₂ (from a cigarette lighter) re-emission in a 4.1–4.3-micron band, whereas the heated CO₂ gas does not have any emission line in the LWIR band. Thus, the LWIR image shows only thermal signatures of the flame. However, the silicon wafer blocked most of the LWIR signal. This initial array gave good images with 99% of the MWIR and 97.5% of the LWIR pixels working in the center 512x512 pixels region, which is excellent compared to the difficulty in the fabrication process of this pixel co-registered simultaneously readable dual-band QWIP FPA. The digital acquisition resolution of the imaging system was 14-bits, which determines the instantaneous dynamic range of the camera (i.e., 16,384). However, the dynamic range of QWIP is 85 Decibels. Video images were taken at a frame rate of 30 Hz at temperatures as high as T = 70 K. The total ROIC well depth is 17x10⁶ electrons with a LWIR to MWIR well depth ratio of 4:1. The estimated NEAT based on single pixel data of MWIR and LWIR detectors at 70 K are 22 and 40 mK, respectively. The experimentally measured NEAT values 27 and 40 mK for MWIR and LWIR respectively. The measured MWIR value closely agrees with estimated number.

As we have mentioned earlier, QWIP is an excellent detector choice for the fabrication of pixel co-registered simultaneously readable dual-band infrared focal plane arrays, due to its narrow band spectral response. Thus, it provides negligible spectral cross-talk when two spectral bands are a few microns apart. The initial GaAs substrate of these dual-band FPAs are completely removed leaving only a 50 nm thick GaAs membrane. Thus, these dual-band QWIP FPAs are not vulnerable to FPA de-lamination and indium bump breakage during thermal recycling process, and have negligible pixel-to-pixel optical cross-talk. We feel that FPA non-uniformity and associated spatial noise could be significantly reduced by improving the detector array processing and optimizing

ACKNOWLEDGEMENTS

Authors are grateful to P. Dimotakis, T. Cwik, M. Herman, E. Kolawa, A. Larson, R. Liang, T. Luchik, and R. Stirbl for encouragement and support during the development and optimization of QWIP FPAs at the Jet Propulsion Laboratory for various applications. The research described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the Missile Defense Agency and the Air Force Research Laboratory.
REFERENCES


