Mid-Wave and Long-Wave Infrared Dualband Megapixel QWIP Focal Plane Array


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ABSTRACT

Mid-wavelength infrared (MWIR) and long-wavelength infrared (LWIR) 1024x1024 pixel InGaAs/GaAs/AlGaAs based quantum well infrared photodetector (QWIP) focal planes and a 320x256 pixel dualband pixel co-registered simultaneous QWIP focal plane array have been demonstrated as pathfinders. In this paper, we discuss the development of 1024x1024 MWIR/LWIR dualband pixel co-registered simultaneous QWIP focal plane array.

Keywords: Infrared detectors, maga-pixel, QWIP, dualband, two-color, infrared imaging, focal plane arrays

1. 1024X1024 PIXEL MWIR QWIP FOCAL PLANE ARRAYS

A quantum well structure designed to detect infrared (IR) light is commonly referred to as a quantum well infrared photodetector (QWIP) [1-2]. The molecular beam epitaxy (MBE) grown mid-wavelength IR (MWIR) [3-10] 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%. A detail description on quantum efficiency measurements can be found elsewhere [1]. Due to the fact that the n-i-n QWIP device is a photoconductive device, the net (or external) quantum efficiency $\eta$ can be determined using $\eta = \eta_a g$, where $g$ is the photoconductive gain of the detector. The epitaxially grown material was processed into 200 µm diameter mesa test structures (area = $3.14 \times 10^{-4}$ cm$^2$) using wet chemical etching, and Au/Ge ohmic contacts were evaporated onto the top and bottom contact layers. The detectors were back illuminated through a 45° polished facet [1-2] and a responsivity spectrum is shown in Fig. 1. The responsivity of the detector peaks at 4.6 µm and the long wavelength cutoff is at 5.1 µm.
\[ g = \frac{i_n^2}{4eB} + 1/2N, \] where \( B \) is the measurement bandwidth, \( N \) is the number of quantum wells, and \( i_n \) is the current noise, which was measured using a spectrum analyzer. The photoconductive gain of the detector was 0.23 at \( V_B = -1 \) V. The peak net quantum efficiency was determined using \( \eta = \eta_a g \). Thus, the net peak quantum efficiency at bias \( V_B = -1 \) V is 4.6\%. The lower quantum efficiency is due to the lower photoconductive gain at lower operating bias. A lower operating bias is used to suppress the detector dark current. Due to a low readout multiplexer well depth (i.e., \( 8 \times 10^6 \) electrons) a lower dark current is mandatory to achieve a higher operating temperature and longer integration times. In background limited performance (BLIP) conditions the noise equivalent differential temperature (NE\( \Delta T \)) improves with increasing integration time. However, the absorption quantum efficiency can be increased further up to 60\% - 70\% with higher quantum well doping densities. As a result, the operating temperature of the devices will decrease [2]. The peak detectivity is defined as
\[ D_P^* = R_P \sqrt{AB} / i_n, \]
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 \( V_B = -1 \) V and temperature \( T = 90 \) K is \( 4 \times 10^{11} \text{ cm} \sqrt{\text{Hz}} / \text{W} \). These detectors show BLIP at a bias \( V_B = -1 \) V and temperature \( T = 90 \) K for 300 K background with f/2.5 optics.

After the two-dimensional grating array was defined by lithography and dry etching, the photoconductive QWIPs of the 1024x1024 FPAs were fabricated by dry chemical etching through the photosensitive GaAs/Al\(_x\)Ga\(_{1-x}\)As multi-quantum-well (MQW) layers into the 0.5 \( \mu \)m thick doped GaAs bottom contact layer. The pitch of the FPA is 19.5 \( \mu \)m and the actual pixel size is 17.5x17.5 \( \mu \)m. The two-dimensional gratings on top of the detectors were then covered with Au/Ge and Au for Ohmic contacts and high reflectivity. Indium bumps were then evaporated on top of the detectors for a silicon CMOS readout integrated circuit (ROIC) hybridization process. A few QWIP FPAs were chosen and hybridized (via an indium bump-bonding process) to a 1024x1024 silicon CMOS ROICs and biased at \( V_B = -1 \) V. This initial array gave excellent images with 99.95\% of the pixels working (number of dead pixels \( \approx 500 \)), demonstrating the high yield of GaAs technology. The operability was defined as the percentage of pixels having noise equivalent differential temperature less than 100 mK at 300 K background and in this case operability happens to be equal to the pixel yield.

Fig. 2 shows the measured NE\( \Delta T \) of the imaging system at an operating temperature of \( T = 90 \) K, 60 msec integration time, bias \( V_B = -1 \) V for 300 K background with f/2.5 optics and the mean value is 23 mK. This agrees well with our estimated value of 15 mK based on test structure data. It is worth noting that the NE\( \Delta T \) of the detector array is reduced to 17 mK after removing the noise factors associate with ROIC, electronics, etc. The net peak quantum efficiency of the FPA was 3.8\% (lower focal plane array quantum efficiency is attributed to lower photoconductive gain at lower operating bias and lower well doping densities used in this device structure) and this corresponds to an average of three passes of infrared radiation (equivalent to a single 45° pass) through the photosensitive MQW region. It is worth noting that under BLIP conditions the performance of the detectors is independent of the photoconductive gain, and it depends only on the absorption quantum efficiency.

A 1024x1024 QWIP FPA hybrid was mounted onto a 5 W integral Sterling closed-cycle cooler assembly to demonstrate a portable MWIR camera. The digital acquisition resolution of the camera is 14-bits, which determines the instantaneous dynamic range of the camera (i.e., 16,384). However, the dynamic range of QWIP is 85 Decibels. The preliminary data taken from a test set up has shown mean system NE\( \Delta T \) of 22 mK (the higher NE\( \Delta T \) is due to the 65\% transmission through the lens assembly, and system noise of the measurement setup) at an operating temperature of \( T = 90 \) K and bias \( V_B = -1 \) V, for a 300 K background. A 1024x1024 QWIP FPA hybrid was mounted onto a 5 W integral Sterling closed-cycle cooler assembly to demonstrate a portable MWIR camera. Fig. 3 shows

![Fig 2. As shown in this figure, the measured NE\( \Delta T \) of the MWIR 1Kx1K QWIP camera is 23 mK.](image-url)
one frame of a video image taken with a 5.1 µm cutoff 1024x1024 pixel QWIP camera.

2. 1024X1024 PIXEL LWIR QWIP FOCAL PLANE ARRAYS

The MBE grown long-wave IR (LWIR) material was tested for absorption efficiency using a FTIR spectrometer. Test detectors with a 200 µm diameter were fabricated and back-illuminated through a 45° polished facet [1] for optical characterization and an experimentally measured responsivity spectrum is shown in Fig. 4. The responsivity of the detector peaks at 8.4 µm and the peak responsivity \( R_p \) of the detector is 130 mA/W at bias \( V_B = -1 \) V. The spectral width and the cutoff wavelength are \( \Delta \lambda / \lambda_c = 10\% \) and \( \lambda_c = 8.8 \) µm, respectively. The calculated peak detectivity at bias \( V_B = -1 \) V and temperature \( T = 70 \) K is \( 1 \times 10^{11} \) cm Hz /W. These detectors show BLIP at bias \( V_B = -1 \) V and temperature \( T = 72 \) K for a 300 K background with f/2.5 optics.

The pitch of the FPA is 19.5 µm and the actual pixel size is 17.5x17.5 µm². The two-dimensional gratings on top of the detectors were then covered with Au/Ge and Au for Ohmic contacts and high reflectivity. Nine 1024x1024 pixel QWIP FPAs were processed on a 4-inch GaAs wafer. Indium bumps were then evaporated on top of the detectors for hybridization with silicon CMOS ROICs. A single QWIP FPA was chosen and hybridized (via indium bump-bonding process) to a 1024x1024 CMOS multiplexer and biased at \( V_B = -1 \) V. At temperatures below 72 K, the signal-to-noise ratio of the system is limited by array nonuniformity, ROIC readout noise, and photocurrent (photon flux) noise. At temperatures above 72 K, the temporal noise due to the dark current becomes the limitation. Fig. 5 shows the measured NE\( \Delta T \) of the system at an operating temperature of \( T = 72 \) K, 29 msec integration time, bias \( V_B = -1 \) V for 300 K background with f/2.5 optics and the mean value is 16 mK. The noise of the camera system can be written as, \( N_{\text{SYS}}^2 = n_{\text{Detector}}^2 + n_{\text{ADC}}^2 + n_{\text{MUX}}^2 \), where \( n_{\text{Detector}} \) is the noise of the FPA, \( n_{\text{ADC}} \) is the noise of the analog-to-digital converter, and \( n_{\text{MUX}} \) is the noise of the silicon ROIC. The experimentally measured \( N_{\text{SYS}} \) is 2.4 units, and the \( n_{\text{ADC}} \) and \( n_{\text{MUX}} \) are 0.8 and 1 unit, respectively. This yields 2.0 noise units for \( n_{\text{Detector}} \). Thus, the NE\( \Delta T \) of the detector array is 13 mK at 300K

![Fig 3. One frame of video image taken with the 5.1 \( \mu \)m cutoff 1024x1024 pixel QWIP camera.](image)

![Fig 4. Responsivity spectrum of a bound-to-quasibound LWIR QWIP test structure at temperature \( T = 77 \) K.](image)

![Fig 5. NE\( \Delta T \) histogram of the 1,048,576 pixels of the 1024x1024 array showing a high uniformity of the FPA.](image)
background with f/2.5 optics and 29 msec integration time. This agrees reasonably well with our estimated value of 15 mK based on test detector data.

Video images were taken at a frame rate of 30 Hz at temperatures as high as $T = 72 \text{ K}$, using a ROIC capacitor having a charge capacity of $8 \times 10^6$ electrons. Fig. 6 shows one frame of a video image taken with a 9 µm cutoff 1024x1024 pixel QWIP camera. In addition, the minimum resolvable temperature difference was measured by a single observer using seven bar targets ranging in spatial frequency from 0.1 cycles/milli radian up to 1.33 cy/mr, which was the first target where no contrast could be measured (unclear). While the collection of the data does not adhere to the generally accepted requirements of having multiple observers, the data is consistent with the NEAT measurement and worth reporting. At the lowest spatial frequency, the minimum resolvable differential temperature (MRDT) was 16 mK.

3. DUALBAND FPA PATHFINDER

There are many applications that require MWIR and LWIR dualband FPAs. For example, a dualband FPA camera would provide the absolute temperature of a target with unknown emissivity, which is extremely important to the process of identifying a temperature difference between missile targets, warheads, and decoys. Dualband infrared FPAs can also play many important roles in Earth and planetary remote sensing, astronomy, etc. Furthermore, monolithically integrated pixel collocated simultaneously readable dualband FPAs eliminate the beam splitters, filters, moving filter wheels, and rigorous optical alignment requirements imposed on dualband systems based on two separate single-band FPAs or a broadband FPA system with filters. Dualband FPAs also reduce the mass, volume, and power requirements of dualband systems. Due to the inherent properties such as narrow-band response, wavelength tailorability, and stability (i.e., low 1/f noise) associated with GaAs based QWIPs [1-6], it is an ideal candidate for large format dualband infrared FPAs. In this section, we discuss the development of a 320x256 pixel MWIR and LWIR pixel collocated simultaneously readable dualband QWIP FPA.

As shown in Fig. 7, our dualband FPA is based on a 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 device structures of the MWIR and LWIR devices are very similar to the MWIR and LWIR devices described earlier in this paper. Both device structures and heavily doped contact layers were grown in-situ during a single growth run using molecular beam epitaxy. 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 QWIPs ideally suited for dualband FPAs with negligible spectral
cross-talk. As shown in Fig. 7, the carriers emitted from each MWQ region are collected separately using three contacts. The middle contact layer is used as the detector common. The electrical connections to the detector common, and the LWIR pixel connection, are brought to the top of each pixel using via connections.

Light coupling to a pixel collocated dualband QWIP device is a challenge since each device has only a single top surface area. We have developed two different optical coupling techniques. The first technique uses a dual period Lamar grating structure. The second technique uses the multiple diffraction orders. In this light coupling technique, we have used a 2-D grating with single pitch. The first diffraction orders (1,0), (0,1), (-1,0), and (0,-1) couple infrared radiation into LWIR pixels, and the second diffraction orders (1,1), (-1,1), (1,-1), and (-1,-1) couple infrared radiation into MWIR pixels. The spectral responsivity of dualband QWIP is shown in Fig. 8. 2-D periodic grating structures were designed to couple the 4-5 and 8-9 μm radiation into the detector pixels. The top 0.7 μm thick GaAs cap layer was used to fabricate the light coupling 2-D periodic grating. The 2-D grating reflectors on top of the detectors were then covered with Au/Ge and Au for Ohmic contact and reflection.

After the 2-D grating array was defined by photolithography and dry etching, the MWIR detector pixels of the 320x256 pixel FPAs, and the via hole to access the detector common, were fabricated by dry etching through the photosensitive GaAs/In$_{y}$Ga$_{1-y}$As/Al$_{x}$Ga$_{1-x}$As MQW layers into the 0.5 μm thick doped GaAs intermediate contact layer. Then LWIR pixels and via holes to access the LWIR pixels of FPAs 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 FPA is 40 μm and the actual MWIR and LWIR pixel sizes are 38x38 μm$^2$. Forty eight FPAs were processed on a four-inch GaAs wafer. Indium bumps were then evaporated on top of the detectors for silicon read out integrated circuit (ROIC) hybridization. Several dualband FPAs were chosen and hybridized (via an indium bump-bonding process) to a 320x256 pixel CMOS read out integrated circuit (ISC-0006).

A selected MWIR:LWIR pixel co-registered simultaneously readable dualband QWIP FPA has been mounted on to the cold finger of a reusable dewar, cooled by a Stirlin cycle cooler and the two bands (i.e., MWIR and LWIR) were independently biased. At temperatures below 68 K, the signal to noise ratio of the system is limited by array non-uniformity, ROIC readout noise, and photo current (photon flux) noise. At temperatures above 72 K, temporal noise due to the LWIR QWIP’s higher dark current becomes the limitation. Since the QWIP is a high impedance device, it should yield a very high charge injection coupling efficiency into the integration capacitor of the multiplexer. The FPA was back-illuminated through the flat thinned substrate membrane (thickness ≈ 500 Å). This initial array gave good images with 95% of the pixels working, which is excellent compared to the difficulty in the fabrication process of this pixel co-registered simultaneously readable dualband QWIP FPA. The operability was defined as the percentage of pixels having NE$\Delta T$ within 3σ of the NE$\Delta T$ histograms taken at 300 K background with f/2 cold shield.

A 320x256 pixel co-registered simultaneously readable dualband QWIP FPA hybrid was mounted onto a 5 W integral Sterling closed-cycle cooler assembly to demonstrate a portable MWIR:LWIR dualband QWIP camera. The digital acquisition resolution of the camera is 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 = 68 K, using two ROIC capacitors having a charge capacities of 21x10E6 and 87x10E6 electrons for the MWIR and LWIR bands respectively. Fig. 9 shows an image taken with the 320x256 pixel co-registered simultaneously readable MWIR:LWIR dualband QWIP camera.
As expected (due to BLIP), the estimated and experimentally obtained NEΔT values of the LWIR detectors do not change significantly at temperatures below 65 K. The estimated NEΔT of MWIR and LWIR detectors at 65 K are 22 and 24 mK, respectively. These estimated NEΔT values based on the test detector data agree reasonably well with the experimentally obtained values. The experimentally measured NEΔT values are shown in the Fig. 10 (a) and (b). The experimentally measured NEΔT values are slightly higher than the estimated NEΔT value based on the results of single element test detector data. This degradation in signal-to-noise ratio is attributed to the inefficient light coupling of the dual feature lamellar grating coupler, unoptimized ROIC, and the significant amount of 1/f noise in the FPA characterization equipment.

As we have mentioned earlier, QWIP is an ideal detector for the fabrication of pixel co-registered simultaneously readable dualband infrared focal plane arrays, because, QWIP absorbs infrared radiation only in a narrow spectral band which is designed to do so, and transparent outside of that absorption (i.e., detection) band. Thus it provides zero spectral cross-talk when two spectral bands are a few microns apart. The initial GaAs substrate of these dualband FPAs are completely removed leaving only a 50 nm thick GaAs membrane. Thus, these dualband QWIP FPAs are not vulnerable to FPA delamination and indium bump breakage during thermal recycling process, and has zero pixel-to-pixel optical cross-talk. Inspired from this success, now we are developing a megapixel (1024x1024 pixel) dualband QWIP FPA sensitive in MWIR and LWIR spectral bands.
4. DEVELOPMENT OF 1024X1024 PIXEL MWIR AND LWIR DUALBAND QWIP FPA

Most infrared FPAs consist of non-silicon detector arrays and silicon ROICs. Silicon ROICs are usually fabricated on large area (i.e., 8 – 12-inch dia.) wafers. In the process of large format IR FPA development, it is necessary to select an IR detector technology based on large area wafers. QWIP FPA technology is entirely based on the highly stable III-V material system that can be easily processed with the more mature fabrication technologies.

The state-of-the-art array fabrication processes are based on either mask aligners or reticle-based steppers. A typical reticle field is 22x22 mm². The pixel pitch of the largest 1Kx1K array fits in to a reticle field that is 18 µm. The pixel pitch of the 1Kx1K pixel dualband QWIP FPA is 30 µm. Thus, a 30 µm pixel pitch 1Kx1K array cannot be fabricated using conventional reticle stepping or mask aligning methods. As shown in Fig. 11, a large detector array can be fabricated using “Stitching”. Stitching is a new photolithographic technique that can be used to fabricate detector arrays larger than the reticle field of photolithographic steppers. We have used stitching technique to fabricate 1Kx1K arrays that can be easily extended into the fabrication of 2Kx2K and 4Kx4K detector arrays. In this case, the detector array layout is divided into smaller portion “tiles”, which together fit in the reticle field. Array characteristics or repeated sections of the detector array are exploited to minimize the required reticle area by using multiple exposures of smaller blocks to create a large array. Each detector array is then photocomposed on the wafer by multiple exposures of detector array sections at appropriate locations on the wafer. Single sections of the detector array are exposed at one time, as the optical system allows shuttering, or selectively exposing only a desired section of the reticle. Fig. 11 depicts photocomposition of detector array on a wafer by stitching. It should be noted that stitching creates a truly seamless detector array, as opposed to an assembly of closely butted pieces.

After the 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/In₀.₅Ga₀.₅As/Al₀.₃Ga₀.₇As MQW layers into the 0.5 µm thick doped GaAs intermediate contact layer. Then LWIR pixels and via holes to access the LWIR pixels of FPAs 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 FPA is 40 µm and the actual MWIR and LWIR pixel sizes are 28x28 µm². Five detector arrays were processed on a four-inch GaAs wafer. Indium bumps were then evaporated on top of the detectors for hybridization with ROICs. Several dualband detector arrays were chosen and hybridized (via an indium bump-bonding process) to grade B (i.e., some dead columns) 1024x1024 pixel silicon ROICs.

Array thinning or the substrate removal process is critical to the success and durability of large format cryogenic FPAs. Thus, after the detector array and ROIC hybridization process via indium bumps, the gaps between FPA detectors and the ROIC are backfilled with epoxy. This epoxy backfilling provides the necessary mechanical strength to the detector array and ROIC hybrid prior to the thinning process. During the first step of the thinning
process, an approximately 630 µm thick GaAs layer was removed using diamond point turning. Then Bromine-Methanol chemical polishing was used to remove another approximately 100 µm thick GaAs layer. This step is very important because it removes all scratch marks left on the substrate due to abrasive polishing. Otherwise these scratch marks will be enhanced and propagated in to the final step via preferential etching. Then, wet chemical etchant was used to reduce the substrate thickness to several microns and then SF$_6$:BCl$_3$ selective dry etchant was used as the final etch. This final etching completely removed the remaining GaAs substrate. At this point the remaining GaAs/AlGaAs material contains only the QWIP pixels and a very thin membrane (~500Å). The thermal mass of this membrane is insignificant compared to the rest of the hybrid. This allows it to adapt to the thermal expansion and contraction coefficients of the silicon ROIC and completely eliminates the thermal mismatch problem between the silicon based readout and the GaAs based detector array. This basically allows QWIP FPAs to go through an unlimited number of temperature recycles without any indium bump breakage and array delamination. Furthermore, this substrate removal process provides two additional advantages for QWIP FPAs: those are the complete elimination of pixel-to-pixel optical cross-talk and a significant (a factor of two with 2-D periodic gratings) enhancement in optical coupling of infrared radiation into QWIP pixels. Figure 12 shows a megapixel dualband QWIP FPA mounted on a 124 pin LCC.

Primary goal of these test hybrids were to test their mechanical stability, substrate removal, and pixel connectivity. A test (i.e., used grade B RIC) MWIR:LWIR pixel co-registered simultaneously readable dualband 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 temperature 68 K. An image is shown in Fig. 13. Left panel shows MWIR image and right panel shows LWIR image of a person holding a hair dryer. Poor image quality of MWIR image is due to poor pixel connectivity (~ 60%), which attributes to the breakage of metal connectors in via holes. Figure 14 shows some SEM pictures of the via connects, which connects the bottom of MWIR pixels to the bottom detector common under the LWIR pixels. Left panel shows the connectivity of this via metal connectors, which attributes to the breakage of metal connectors in via holes.
however, right panel shows some broken metal connectors. This confirms the poor pixel operability of MWIR is due to via metal breakage. These metal layers were deposited via e-beam metal evaporation. We think this metal breakage issue can be solved with sputtering based metal deposition due to its conformal coverage. During next wafer run we should be able to improve the pixel operability and performance by using sputter deposition of via connect metal and grade A ROICs.

Fig. 14. Scanning electron micrographs (SEMs) of via holes and metal bridges which connect the MWIR detector commons and LWIR detector common at the bottom of both pixels. The left panel shows good connectivity, whereas right panel shows disconnected metal bridges.

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6. REFERENCES