Abstract—Quantum well infrared photodetectors (QWIPs) are well known for their stability, high pixel-pixel uniformity and high pixel operability which are quintessential parameters for large area imaging arrays. In this paper we report the first demonstration of the megapixel-simultaneously-readable and pixel-co-registered dual-band QWIP focal plane array (FPA). The dual-band QWIP device was developed by stacking two multi-quantum-well stacks tuned to absorb two different infrared wavelengths. The full width at half maximum (FWHM) of the mid-wave infrared (MWIR) band extends from 4.4 – 5.1 μm and FWHM of the long-wave infrared (LWIR) band extends from 7.8 – 8.8 μm. Dual-band QWIP detector arrays were hybridized with direct injection 30 μm pixel pitch megapixel dual-band simultaneously readable CMOS read out integrated circuits using the indium bump hybridization technique. The initial dual-band megapixel QWIP FPAs were cooled to 68K operating temperature. The preliminary data taken from the first megapixel QWIP FPA has shown system NEΔT of 27 and 40 mK for MWIR and LWIR bands respectively.

I. INTRODUCTION

Single-band Quantum well infrared photodetectors (QWIPs) are well known for their ease of fabrication, ruggedness, pixel-to-pixel uniformity and high pixel operability [1]. QWIP is based on a resonant absorption between ground state and a quasi-continuum state. The spectral response of QWIPs are inherently narrow-band and the typical full-width at half-maximum (FWHM) is about 10% of the peak wavelength. This makes it suitable for fabrication of negligible optical cross-talk dual-band detector arrays.

There are many applications that require mid-wavelength infrared (MWIR) and long-wavelength infrared (LWIR) dual-band focal plane arrays (FPAs). For example, a dual-band FPA camera would provide the accurate temperature [2] of a target with unknown emissivity which is extremely important to the process of identifying objects based on their surface temperature. Dual-band infrared FPAs can also play many important roles in Earth and planetary remote sensing, astronomy, etc. Furthermore, monolithically integrated pixel co-located simultaneously readable dual-band FPAs eliminate the beam splitters, filters, moving filter wheels, and rigorous optical alignment requirements imposed on dual-band systems based on two separate single-band FPAs or a broad-band FPA system with filters. Dual-band FPAs also reduce the mass, volume, and power requirements of dual-band 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], it is an appropriate detector choice for large format dual-band infrared FPAs.

II. DUAL-BAND QWIP DEVICE

As shown in Fig. 1, our dual-band FPA is based on two different types of (i.e., MWIR and LWIR) QWIP devices separated by a 0.5 μm thick, heavily doped, n-type GaAs layer. One can stack the MWIR and LWIR multi-quantum-well (MQW) structures in different ways. The device structure shown in Fig. 1(a) is commonly used and described in reference [3]. Fig. 1 (b) –(c) are novel and these structures have two heavily doped GaAs contact layers between MWIR and LWIR MQW regions and an undoped AlGaAs layer embedded between these two GaAs contact layers. Device structure in Fig. 1 (b) uses two separate detector-common (or ground) contacts, which are connected via the read out integrated circuit (ROIC). Also, it is worth noting in this structure that MWIR and LWIR detectors operate with opposite polarities. Fig. 1 (c) shows a similar device structure to Fig. 1 (b), the only difference is both the MWIR and LWIR device will operate on the same polarity.

Fig 1. 3-D view of four possible dual-band QWIP device structure showing via connects for independent access of MWIR and LWIR devices. The color code is as follows, orange - isolation layer; green - LWIR QWIP; light blue - MWIR QWIP; grey - contact layer; dark blue - metal bridges between MQW regions; yellow - indium bumps
Fig. 1 (d) shows an interesting dual-band device structure that uses only two indium bumps per pixel compared to three indium bumps per pixel with all pixel co-located dual-band devices [3]. In this device structure the detector-common 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 was used in this device to broaden the responsivity spectrum. In the MWIR device, each period of the MQW structure contains a 300 Å thick un-doped barrier of Al$_{0.25}$Ga$_{0.75}$As, and a double quantum well region. The double QW region contains two identical quantum wells separated by a 45 Å of Al$_{0.25}$Ga$_{0.75}$As un-doped barrier. Each of the two quantum wells consists of 3 Å AlAs, 5 Å GaAs, 32 Å In$_{0.2}$Ga$_{0.8}$As, 5 Å GaAs, and 3 Å AlAs; the quantum well is doped $n = 4 \times 10^{18}$ cm$^{-3}$. This period was repeated 13 times. In the LWIR device, each period of the MQW structure contains a 580 Å thick un-doped of Al$_{0.25}$Ga$_{0.75}$As barrier, and a triple quantum well region. The triple QW region contains three identical 50 Å GaAs quantum wells (doped to $n = 5 \times 10^{17}$ cm$^{-3}$) separated by 50 Å of Al$_{0.25}$Ga$_{0.75}$As un-doped barriers. This period was repeated 16 times. These two photosensitive MQW structures are sandwiched between GaAs top and bottom contact layers doped $n = 1 \times 10^{18}$ cm$^{-3}$, grown on a semi-insulating GaAs substrate by molecular beam epitaxy (MBE). Top contact was a 0.7 µm thick GaAs cap layer on top of a 350 Å Al$_{0.25}$Ga$_{0.75}$As stop-etch layer grown in situ on top of the dual-band device structure to fabricate the light coupling optical cavity. The bottom contact layer was a 2 µm thick GaAs layer. A 0.4 µm thick un-doped AlGaAs layer was embedded between the top contact of the LWIR and bottom contact of the MWIR MQW regions. As shown in Fig. 2, the MWIR device uses a bound-to-continuum design to help further.

The experimentally measured LWIR 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 $\Delta\lambda/\lambda = 10\%$ and $\lambda_c = 8.8$ µm, respectively.

Fig. 3. Responsivity spectrum of a bound-to-quasi-bound MWIR QWIP test structure at temperature $T = 77$ K. The spectral response peak is at 4.6 µm and the long wavelength cutoff is at 5.1 µm.

The experimentally measured LWIR 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 $\Delta\lambda/\lambda = 10\%$ and $\lambda_c = 8.8$ µm, respectively.
Fig. 4. Responsivity spectrum of a bound-to-quasibound LWIR QWIP test structure at temperature $T = 77$ K. The spectral response peak is at 8.4 µm and the long wavelength cutoff is at 8.8 µm.

III. 1024x1024 PIXEL DUAL-BAND QWIP FOCAL PLANE ARRAY

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-holes to access the detector-common, were fabricated by dry etching through the photosensitive GaAs/In$_x$Ga$_{1-x}$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 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 the 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 µm$^2$. 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 dual-band detector arrays were chosen and hybridized (via an indium bump-bonding process) to grade A 1024x1024 pixel dual-band silicon ROICs.

Fig. 5 shows a megapixel dual-band QWIP FPA mounted on a 124-pin lead less chip carrier.

A MWIR:LWIR pixel co-registered simultaneously readable dual-band QWIP FPA has been mounted onto 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 a temperature of 68 K. An image taken with the first megapixel simultaneous pixel co-registered MWIR:LWIR dual-band QWIP camera is shown in Fig. 6.

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 $T = 68$ K. The total

Fig. 5. Picture a 1024x1024 pixel dual-band QWIP FPA mounted on a 124-pin lead less chip carrier.

Fig. 6. 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 CO$_2$ (from cigarette lighter) re-emission in 4.1–4.3-micron band, whereas the heated CO$_2$ 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.
ROIC well depth is $17 \times 10^6$ electrons with LWIR to MWIR well depth ratio of 4:1. The estimated NE$\Delta$T based on single pixel data of MWIR and LWIR detectors at 68 K are 22 and 24 mK, respectively. The measured mean NE$\Delta$T was estimated at 27 and 40 mK for MWIR and LWIR bands respectively at a flat plate blackbody temperature of 300 K with f/2 cold stop.

The experimentally measured NE$\Delta$T histograms distributions at blackbody temperature of 300 K with f/2 cold stop are shown in the Fig. 7 (a) and (b). The experimentally measured MWIR NE$\Delta$T value closely agrees with the estimated NE$\Delta$T value based on the results of a single element test detector data. However, the measured LWIR NE$\Delta$T value is higher than the estimated NE$\Delta$T value based on the single pixel data. This is due to the fact that we could not completely independently optimize the operating bias of LWIR band due to a ROIC pixel short circuit occurred at the MWIR band.

The operability was defined as the percentage of pixels having NE$\Delta$T within 3$\sigma$ of the NE$\Delta$T histograms taken at 300 K background with f/2 cold shield. However, the pixel operability dropped to approximately 90% for both bands with full frame. The poor pixel operabilities of both bands are due to via-metal bridge 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. Array non-uniformities before correction were 22% and 20% for MWIR and LWIR bands respectively. After two-point corrections non-uniformities were reduced to about 1%. The dual-band image shown in Fig. 6 was taken with full frame after two-point correction. High array non-uniformity and low pixel operability are directly related to the metal connections fabricated through via-holes. Pixel co-located dual-band array process (thirteen layer photolithography) is much more complicated compared to the single-band QWIP detector array process (three layer photolithography).

As we have mentioned earlier, QWIP is a good detector choice for the fabrication of pixel co-registered simultaneously readable dual-band infrared focal plane arrays due to its narrow spectral 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 the ROIC.

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