

Multi-color QWIP FPAs for Hyperspectral Thermal Emission Instruments

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Abstract

Infrared focal plane arrays (FPAs) covering broad mid- and long-IR spectral ranges are the central parts of the spectroscopic and imaging instruments in several Earth and planetary science missions. To be implemented in the space instrument these FPAs need to be large-format, uniform, reproducible, low-cost, low 1/f noise, and radiation hard. Quantum Well Infrared Photodetectors (QWIPs), which possess all needed characteristics, have a great potential for implementation in the space instruments. However a standard QWIP has only a relatively narrow spectral coverage. A multi-color QWIP, which is comprised of two or more detector stacks, can be used to cover the broad spectral range of interest. We will discuss our recent work on development of multi-color QWIP for Hyperspectral Thermal Emission Spectrometer instruments. We developed QWIP comprising of two stacks centered at 9 and 10.5 μm , and featuring 9 grating regions optimized to maximize the responsivity in the individual subbands across the 7.5-12 μm spectral range. The demonstrated 1024x1024 QWIP FPA exhibited excellent performance with operability exceeding 99% and noise equivalent differential temperature of less than 15 mK across the entire 7.5-12 μm spectral range.

Keywords: infrared detectors, infrared FPA, Quantum Well Infrared Photodetectors (QWIPs)

1. INTRODUCTION

The air- and space- borne imaging spectrometers have numerous applications in remote sensing including studies of atmospheric and surface compositions of Earth and other Solar system bodies. Examples of these instruments include Airborne Visible InfraRed Imaging Spectrometer (AVIRIS)[1], which provided critically important data for better understanding of Earth global environment and climate change, and Moon Mineralogical Mapper [2] (M^3), which created the first mineralogical map of the lunar surface with high spatial and spectral resolution. The Decadal Survey sponsored by National Research Council recommended future mission named Hyperspectral Infrared Imager or HypsIRI[3] that will study the world's ecosystems and provide critical information on natural disasters such as volcanoes, wildfires and drought. One of the HypsIRI instruments will be multispectral imager measuring from 3 to 12 μm in the mid- and long - infrared. As part of technology demonstration for HypsIRI, JPL developed the Hyperspectral Thermal Emission Spectrometer (HyTES) that is compact 7.5-12 μm hyperspectral spectrometer utilizing novel multi-color Quantum Well Infrared Photodetector (QWIP).[4,5]

The GaAs/AlGaAs-based QWIP is an ideal candidate for the development of FPAs due to its inherent properties such as an ease of fabrication, ruggedness, pixel-to-pixel uniformity, high pixel operability and wavelength tailorability. [6,7,8] The megapixel size single-band[9] and dual band QWIP[10] focal plane arrays (FPAs) have been demonstrated. QWIP is based on a resonant absorption between ground state and a quasi-continuum state thus 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. The spectrometer requires infrared sensor with broad spectral coverage therefore multi-wavelength or broadband QWIP need to be used in this application. In these QWIPs multi-quantum well (MQW) stacks [11,12,13] are vertical integrated. Each MQW stack absorbs photons within the specified wavelength band allowing other photons to pass through. The wavelength of the peak response and cutoff can be continuously tailored by varying layer thickness (well width), barrier composition (barrier height), and carrier density (well doping density). The GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ material system allows the quantum well parameters to be varied over a range wide enough to enable light detection at

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any wavelength range between 6 and 20 μm [14,15]. The spectral bandwidth of these detectors can be tuned from narrow ($\Delta\lambda/\lambda \sim 10\%$) to wide ($\Delta\lambda/\lambda \sim 40\%$), according to application requirements [16].

2. QWIP FPA DESIGN

A typical QWIP consists of a 50-period MQW structure of GaAs quantum wells, separated by $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barriers, sandwiched between two GaAs contact layers [3–5]. Both GaAs contact layers and GaAs quantum well layers are doped with Si (n-type) in order to provide carriers for photoexcitation. The present structure has two QWIP stacks separated by intra-stack contact layer. The top stack is designed to cover 7.5-10 μm spectral band and bottom stack covers 10-12 μm spectral band (Figure 1). We used the coupled-quantum well structure in this device to broaden the responsivity spectrum. Both regions use 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. In the top stack device, each period of the MQW structure contains a 500 Å thick un-doped barrier of $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$, and a double quantum well region. The double QW region contains two 50 Å identical quantum wells (doped $n = 1 \times 10^{18} \text{ cm}^{-3}$) separated by 80 Å of $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$ un-doped barrier. This period was repeated 20 times. In the bottom stack, each period of the MQW structure contains a 735 Å thick un-doped of $\text{Al}_{0.22}\text{Ga}_{0.78}\text{As}$ barrier, and double quantum well region. The double QW region contains two identical 56 Å GaAs quantum wells (doped to $n = 5 \times 10^{18} \text{ cm}^{-3}$) separated by 79 Å of $\text{Al}_{0.18}\text{Ga}_{0.82}\text{As}$ un-doped barriers. This period was repeated 20 times too. These two photosensitive MQW structures are sandwiched between GaAs top and bottom contact layers doped $n = 2.5 \times 10^{17} \text{ cm}^{-3}$. Top contact was a 0.75 μm thick GaAs cap layer and the bottom contact layer was a 1 μm thick GaAs layer. The thickness of each QWIP stack is determined by the width of the quantum well, width of the barrier, number of periods in the MQW and the contact layer thickness. Usually, these thicknesses, together with well doping densities, are determined to optimize device performances without any external constraints. However, in the present structure, the stack thicknesses are limited by the groove depths of the light coupling gratings, by the requirements to have a small variations of spectral response across the whole 7.5-12 μm spectral band and by the constraint of obtaining a nearly flat top surface (<1 μm variation) across the detector array (Fig. 2). The flat top surface is required to ensuring successful hybridization with the readout multiplexer via indium bump-bonding.

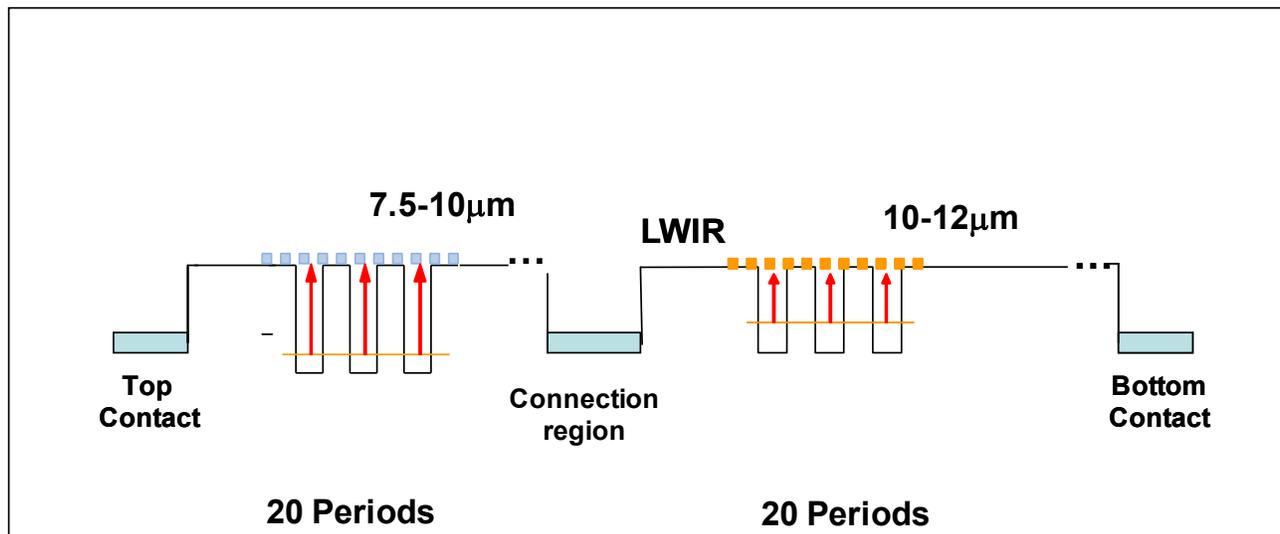


Figure 1. Energy band diagram of the QWIP structure.

In order to be absorbed by the confined carriers in the quantum wells, the light polarization must have an electric field component normal to the layers of quantum wells (i.e., along the growth direction). Thus, for imaging, it is necessary to fabricate a light-coupling grating on top of the detector pixel, which reflects light along the layer plane, enabling absorption. For efficient coupling to the absorbing QW layer, the grating should perform two important functions: (1) diffract efficiently into high angles and (2) have a near-zero diffraction efficiency at low angles. Condition 1 can be produced by a grating that has significant depth variation on the scale of one wavelength. Condition 2 can be

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produced by a grating that produces destructive interference of all reflected waves in the direction normal to the surface. This can be expressed as

$$h = m \frac{\lambda_p}{4n_{\text{GaAs}}}, \quad m: 1, 3, 5, \dots,$$

where h is the grating groove depth, λ_p is the peak response wavelength of QWIP stack, and n_{GaAs} is the refractive index of GaAs [17].

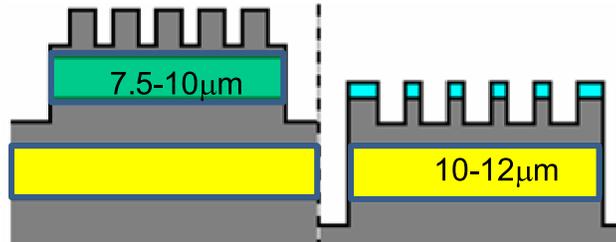


Figure 2. HyTES pixel design – cross-sectional zoom at the transition point, showing two bands with $\frac{1}{4}$ lambda gratings on each

Typically in single color QWIP FPA, quarter wavelength deep ($h = \lambda_p/4n_{\text{GaAs}}$) grating grooves are used to fulfill the above equation. However, this FPA is designed for use in imaging spectrometer. In the spectrometer, the image spatial information is projected along 1024 pixel (Fig. 3, horizontal direction), and the spectroscopic information is recorded in perpendicular direction by 512 pixels. The wavelength of the light incident on FPA increases in the vertical direction therefore the peak spectral responsivity of each row should be adjusted to match it. To achieve that, the FPA is designed to have a roughly half of the illuminated area to respond in the 7.5-10 μm range (QWIP 1 area), and the other half to cover the 10-12 μm range (QWIP 2 area). In addition, grating groove parameters are modified across the FPA. As shown in Figure 4, the FPA is divided into nine regions. Each region has the grating groove parameters that were designed to maximize the light coupling in the specific spectral band indicated in Figure 4.

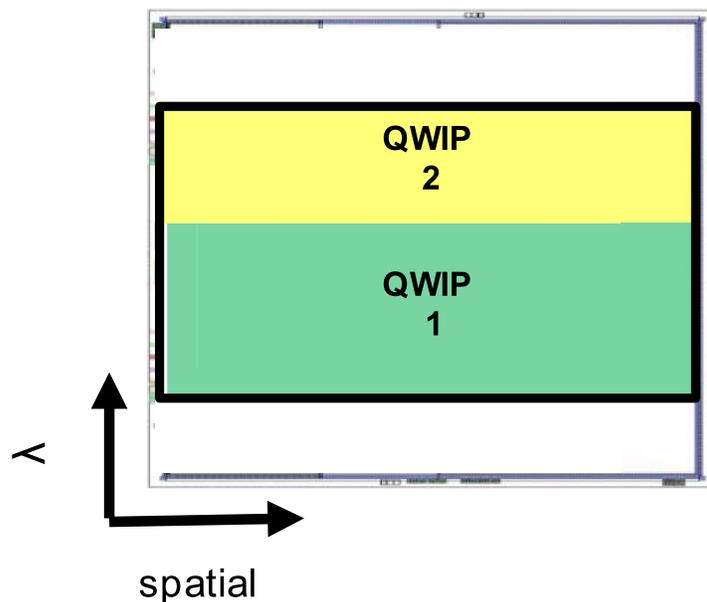


Figure 3. Top-down view of FPA Illuminated area shown in green and yellow

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Figure 4. Map of FPA grating regions. The target spectral band of each grating region is indicated in the map.

3. QWIP FPA FABRICATION

During the fabrication of detector arrays, first, the groves of two dimensional gratings were defined by optical photolithography and dry etching on top of the pixels in the half of the FPA covering 7.5-10 μm band. Next, QWIP 2 area was thinned by dry etching to achieve thickness optimal for the fabrication of grating groves on the top of 10-12 μm QWIP stack (Figure 2). Next, groves were defined in QWIP 2 part of the FPA. After that, the individual pixels were fabricated in the QWIP 1 area first and then in the QWIP 2 area. Next, contact metal was evaporated and unwanted metal was removed using a metal lift-off process. Finally, indium bumps were evaporated on top of the detectors for hybridization with ROICs. Figure 5 shows SEM image of the individual pixels with indium bumps evaporated on the top of the pixel. Figure 6 shows 3-demsional profile of the fabricated groves array that was measured near the border between QWIP 1 and 2 areas. The etching depth and pixel height differences between these areas are clearly visible.

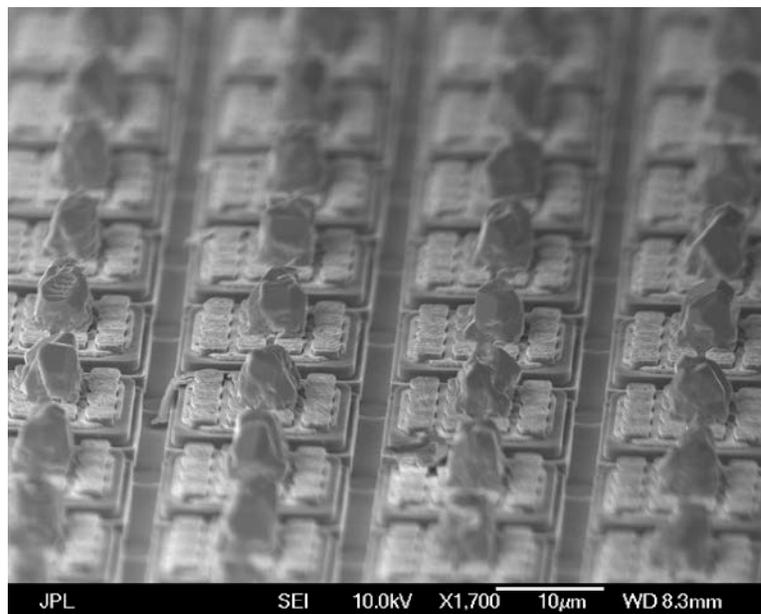


Figure 5. SEM image of the individual pixels with indium bumps evaporated on the top of the pixel.

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Several dual-band detector arrays were chosen and hybridized (via an indium bump-bonding process) to grade A 1024x1024 pixel silicon ROICs. After hybridization, the gaps between FPA detectors and the ROIC were 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 thinning process, the GaAs substrate was completely removed. 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 mis-match 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 cycles without any indium bump breakage and array de-lamination. 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.

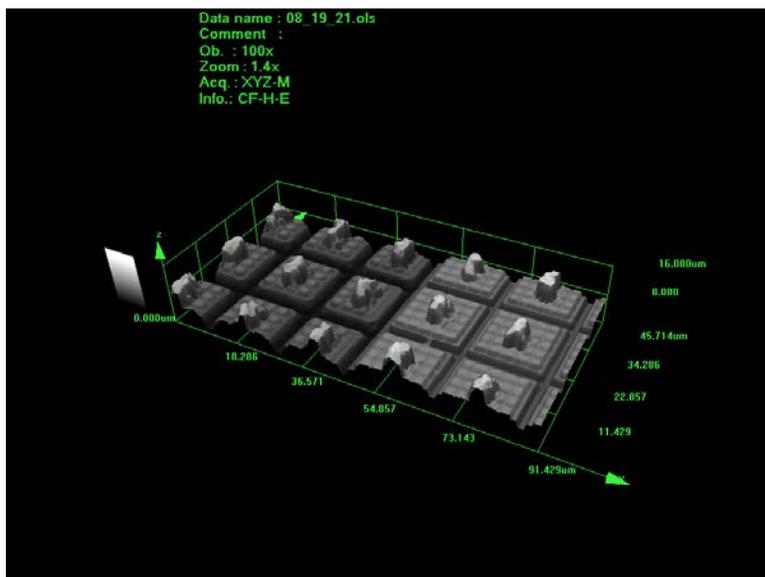


Figure 6. Three-dimensional profile of the pixels in fabricated array that was measured near the border between QWIP 1 and 2 areas

4. QWIP FPA PERFORMANCE

The LCC-mounted FPA was loaded into a SEIR liquid helium pour-fill dewar with an f/2 cold-stop for testing and characterization. A general purpose SEIR test system was used to conduct data acquisition and ROIC command interfacing. The FPA was cooled down to $T = 40\text{K}$ during the testing and all measurements were performed directly on the FPA. Figure 7 shows image acquired with developed 1024x1024 QWIP FPA operating at $T = 40\text{K}$ with a frame rate of 15 Hz, integration time of 9 msec, and f/2 cold stop. The image quality is very good with more than 99% of the pixels operable. Measurements of spectral response of each FPA region showed that wavelength of peak responsively changed across the FPA in good agreement with the grating design.

NEDT provides the thermal sensitivity of an infrared imaging system and it is a very useful diagnostic tool to evaluate the full operational performance available. It is defined as the minimum temperature difference required at the target to produce signal-to-noise-ratio of one. We have used the following equation to calculate the noise equivalent

temperature difference NE ΔT of the FPA, $NE\Delta T = \frac{\sigma_{total}(25^{\circ}C)}{Mean(30^{\circ}C) - Mean(20^{\circ}C)} [30^{\circ}C - 20^{\circ}C] [K]$. The σ_{total} is

measured standard deviation count matrix at 25°C the blackbody temperature, $Mean(30^{\circ}C)$ and $Mean(20^{\circ}C)$ are the mean FPA count matrices measured at 30°C and 20°C blackbody temperatures so $Mean(30^{\circ}C) - Mean(20^{\circ}C)$ is the FPA thermal response in count. NE ΔT was evaluated for each spectral region of developed FPA. The experimentally

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measured NEAT was very low, less than 14mK for all regions and histograms distributions were very tight (Fig. 8). These results demonstrate good noise properties of the demonstrated FPA.



Figure 7. Images taken with a 1024×1024 QWIP focal plane array at an operating temperature of 40K.

5. ACKNOWLEDGEMENTS

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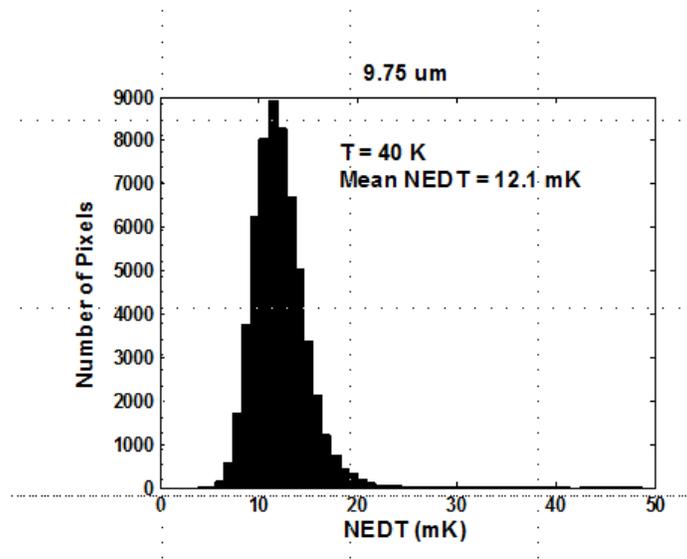


Figure 8. Measured NEAT histogram of QWIP FPA region covering 9.5-10µm spectral band. The mean NEAT is 12.1 mK.

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