The Future of Single- to Multi-band Detector Technologies: Review

M. Nurul Abedin[1], Ishwara Bhat[2], Sarath D. Gunapala[3], Sumith V. Bandara[3], Tamer F. Refaat[4], Stephen P. Sandford[1], and Upendra N. Singh[1]
[1]*NASA Langley Research Center, Hampton, VA 23681*
[2]*Rensselaer Polytechnic Institute, Troy, NY 12180*
[3]*Jet Propulsion Laboratory, Pasadena, CA 91109*
[4]*Old Dominion University, Norfolk, VA 23529*

Abstract

Using classical optical components such as filters, prisms and gratings to separate the desired wavelengths before they reach the detectors results in complex optical systems composed of heavy components. A simpler system will result by utilizing a single optical system and a detector that responds separately to each wavelength band. Therefore, a continuous endeavors to develop the capability to reliably fabricate detector arrays that respond to multiple wavelength regions. In this article, we will review the state-of-the-art single and multicolor detector technologies over a wide spectral-range, for use in space-based and airborne remote sensing applications. Discussions will be focused on current and the most recently developed focal plane arrays (FPA) in addition to emphasizing future development in UV-to-Far infrared multicolor FPA detectors for next generation space-based instruments to measure water vapor and greenhouse gases. This novel detector component will make instruments designed for these critical measurements more efficient while reducing complexity and associated electronics and weight. Finally, we will discuss the on-going multicolor detector technology efforts at NASA Langley Research Center, Jet Propulsion Laboratory, Rensselaer Polytechnic Institute, and others.

1. Introduction

Multi-band detector technology is progressing on a number of exciting applications, such as remote sensing and imaging, military, and medical imaging. Development of such technology in the uv- to far infrared region is critical and remains one of the important building blocks for the successful development of active and passive remote sensing capability in the ultra-violet to very long wave infrared region.

This multi-band detector consists of stacked arrangement of different materials in which the shorter wavelength detector is placed top of the longer wavelength detector. The top detector material absorbs only the shorter wavelength radiation and transmits the longer wavelength radiation to the bottom detector. To detect multi-wavelength simultaneously, optical components such as lenses, prisms and gratings can be used to separate the individual wavelength before it reaches the detectors. However, use of classical optical components is complicated, and use of photovoltaic detectors of stacked arrangement in the same image area is preferable.

HgCdTe and quantum well infrared photodetector (QWIP) technology is expanding in single-color to multicolor detectors and recently, QWIP have demonstrated multi-color detector arrays[1-3]. Development of multi-band array will continue[4-5] and two-band detectors were demonstrated based on HgCdTe FPAs[6-10]. A joint effort among NASA Langley, JPL, and RPI is developing a multicolor FPA with 3-dimensional structures to provide high-resolution spectroscopic for imaging Fourier-Transform interferometers. An increasing interest in multicolor imaging technology is materializing in the UV-to-Far infrared with the feasibility of focal planes founded on large and three-dimensional arrays.

At present, the availability of multicolor detectors is limited to the 3-15 microns spectral range and no multicolor detector technology has been reported spanning the spectral range of the UV-to-Far IR[11-12]. The advancement of the multicolor detector development has stimulated for detecting water vapor and greenhouse gases in the broad wavelength range. This technology development will be very valuable to the NASA Earth and Space Science Enterprises and Planetary Exploration Program, allowing critical measurements at improved accuracy with greatly reduced system complexity, weight, and cost. A simpler system would result by utilizing a single optical system and a detector that responds separately to each wavelength band as shown in Fig. 1 (Band1: detector#1, Band2: detector#2, Band3: detector#3, Band4: detector#4, and Band5: detector#5). The multicolor detector approach has the potential for application to several other terrestrial and planetary remote sensing applications.

To achieve the wavelengths either less than 1-micron or greater than 15-micron, one can extend the operating wavelengths by using Si-microbolometer and shorten the operating wavelengths by using phosphor coating on Si material[12]. In this study, there are significant problems in extending the wavelength of operation of detectors beyond 15 microns using Si-microbolometer due to hybridization and also in shortening the wavelength to ultraviolet range using Si by applying phosphor material on it to enhance the absorption at UV region. Quaternary layers of GaInAsSb with wavelength longer than 2.5-μm have been grown by metal organic chemical vapor deposition (MOCVD) with good optical and electrical properties. These layers are lattice-matched to GaSb or InAs substrates with cutoff wavelengths for absorption tailored from 1.7- to 3.5-μm. Epitaxial growth on a lattice-matched substrate is crucial in reducing unwanted defects that could lead to higher noise in the detector. There are at present few materials discussed above with varying band gaps that cover the ultraviolet to far IR wavelength band with lattice-matched conditions.

Therefore, a multi-band detector array, sensitive in broadband range with different bands covering the 0.4-μm to far-IR wavelength range, was proposed[11,12]. To achieve this, it is anticipated that silicon (Si), gallium antimonite (GaSb), indium arsenide (InAs), III-V semiconductor ternary and quaternary alloy-based materials, vertically integrated, hetero-structure p-i-n diodes grown via metal-organic vapor phase epitaxy (MOVPE) and also wafer bonding techniques can be utilized. Adding up to four-to-five materials expands the flexibility of the semiconductor material system so that photo-excitation band gaps and lattice parameters can be adjusted independently, allowing us to find a lattice-matched substrate on which to grow these multicolor detector stacks monolithically, or lattice-mismatched detector stacks using wafer bonding technology.

2. Multicolor Single Element Detector Structures

The integration of silicon technology with antimonide based material system for the simultaneous detection of multi-wavelengths in the visible and the infrared (IR) is attempted. GaSb, AlSb and InAs are closely lattice-matched, but have widely different bandgaps. GaSb has a bandgap of 0.72 eV, AlSb has an indirect band gap of 1.63 eV and InAs has a bandgap of 0.356 eV. The lattice constants of these materials are 6.0959Å (GaSb), 6.136Å (AlSb), and 6.0583Å (InAs). The lattice constants of these materials are not perfectly matched, and hence we will still get high density of dislocations when one material is grown on the other. However, one can grow ternary and quaternary layers lattice-matched to one of the binaries, and the band gap of the quaternary layers can be tuned to any desired wavelength, still maintaining the lattice-matched condition. This allows great flexibility in device design, but the material growth will be more complicated. However, recent advances in MOVPE growth technique can allow reproducible growth of such quaternary layer possible. Growth of high quality quaternary layers was demonstrated very recently for use in thermophotovoltaic systems[13-14].

The multi-wavelength device structure in the uv-to-IR band is shown in Fig. 1. An n-type GaSb substrate is chosen on which a p-on-n InAs device structure is grown, followed by an n-on-p second IR detector in a quaternary layer of InGaAsSb. The band gap of the quaternary layer can be changed from 0.29 eV to 0.35 eV or from 0.7 eV to 0.5 eV (wavelength cut-off from 4.3- to 3.5-µm or from 1.7- to 2.5-µm), still maintaining the lattice matching with the substrate.

One important point to remember in the above structure is the band alignment. InAs-GaInAsSb has type-II band alignment. In the above configuration, i.e., n-p-P-N configuration, the minority carrier electrons in the P-GaInAsSb will not be collected by the lower band gap junction. However, the electrons from the lower band gap p-type layer can be collected by the common junction, and hence there will be a small amount of cross talk. The independent bias for the two junctions will alleviate this problem, and in addition, the p-type lower band gap material thickness should be kept to a minimum to reduce this cross talk further.

We propose to use wafer-bonding approach to overcome the lattice mismatch problem present in ternary layers. This allows us to optimize the detectors for each region of operation to achieve high quantum efficiency. The proposed multi-color detector is based on the integration of Si-microbolometer with the Si and the III-V compound-based IR detectors to obtain the wavelengths of interest. The IR detector structures used are grown on the GaSb substrate using MOVPE. The composite single detector layered structures are shown in Fig. 1a.

Fig. 1b shows the 3-D detector sketch with input radiation from the optical system impinging the detector stack. Light of the appropriate wavelengths of interest is absorbed in the first detector in this “sandwich”, while longer wavelengths are not absorbed. Longer wavelengths are passed into the second detector and this second set of wavelengths is absorbed in the second detector. The desired absorption wavelengths in each detector can be tailored for each atmospheric or geophysical sounding application, making for a very efficient instrument, as necessary spectral lines or spectral bands are processed.

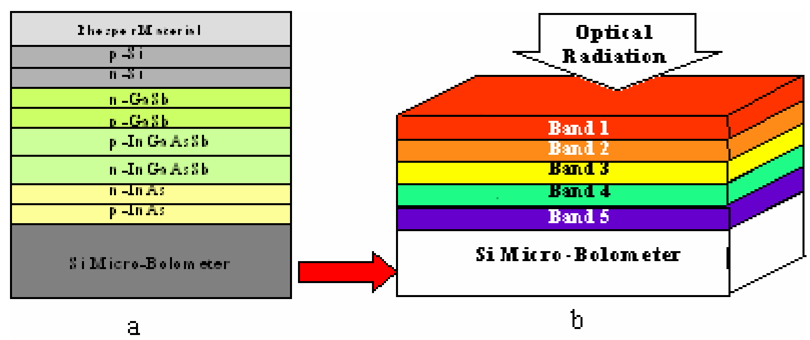

Figure 1. Schematic of multi-layer bias selectable multi-wavelength IR detector: (a) Single element layered structures and (b) 3-D Focal Plane Array Detector structures[12].

3. State-of-the-Art Multi-Color Focal Plane Array Detector Technologies

Many different device structures, such as HgCdTe, GaAs/AlGaAs quantum well photodetectors, strained layer InAs/GaInSb superlattices (SLS's), Schottky barrier on silicon, SiGe heterojunctions, pyroelectric detectors, silicon bolometers, and high temperature superconductors are used for the detection of UV-to-far infrared radiation. But the bulk single crystal semiconductor remains material of choice as efficient detector of electromagnetic radiation in the UV - long wavelength ranges[11].

At present, HgCdTe photodiodes and quantum well infrared photoconductors (QWIPs) present multicolor capability in the MWIR – LWIR wavelength range. HgCdTe is based on II-VI and QWIP is based on the well-developed III-V material systems, which have some advantages and disadvantages. HgCdTe FPAs have higher operating temperature, higher quantum efficiency, but lower yield and higher cost. On the other hand, QWIPs are easier to fabricate with high operability, good uniformity, high yield, and lower cost, but has lower quantum efficiency and lower operating temperature. In this section, we discuss the state-of-the-art multi-color detector based on II-VI (HgCdTe), III-V (quantum well) materials, and also future prediction on single crystal material systems[11].

II-VI (HgCdTe) Material Systems

There is a considerable attention in multispectral HgCdTe detectors employing liquid phase epitaxy (LPE), molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) for the growth of a variety of devices by research groups at BAE Systems, Hughes Research Laboratory, Rockwell Scientific Company, Leti LIR, SOFRADIR, Raytheon Vision Systems, and AIG AEG INFRAROT[15-26]. Devices for the sequential and simultaneous detection of two closely spaced sub-bands in the MWIR and LWIR radiation have been demonstrated.

An early example of two-color detector is the one described in references[20-21], where n-p-n three-layer structure in HgCdTe was epitaxially grown on CdTe substrates as shown in Fig. 2. Here, the lower case refers to lower band gap and upper case refers to higher band gap material. The detector array is illuminated from the backside through the substrate since CdTe has a bandgap much higher than the wavelengths of interest. The wavelength of interest can be selected by selecting the appropriate bias. This bias selectable two-color detector affords perfect spatial collocation of the two detectors, but it has inherent drawback of not allowing temporal simultaneity of detection. Either one or the other photodiode is functioning depending on the bias polarity applied across the back-to-back pair. Reine et al[15] demonstrated two-color detector, where a four-layer P-N-n-p structure was grown epitaxially on CdTe substrate. The first P-N junction was made of higher bandgap HgCdTe, where as the second p-n junction was made of lower bandgap HgCdTe. The signal enters through the substrate and the signal processing electronics is In-bonded to the top surface. This allows independent simultaneous detection of two colors. Two color detector in the 3-5 μm and 8-12 μm range was demonstrated. The layers were grown by metal organic vapor phase epitaxy. The cross section of the independently accessed back-to-back photodiode dual band detector is shown in Fig. 3. There are three ohmic contacts in this structure, one to the p-LW layer, one to the n-LW & N-MW layer and one to the P-MW layer (not shown). The common terminal is the contact to the n-LW and N-MW layer. The p-type region of all the MW photodiodes in the dual band array are electrically connected and are accessed at the edge of the array through a common array ground contact.

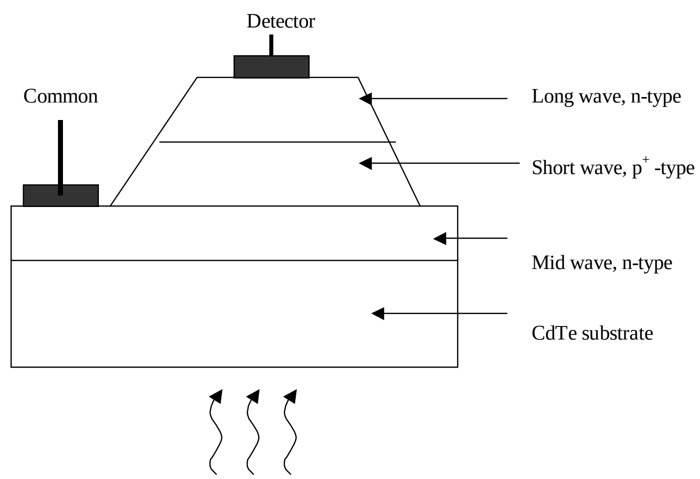

Figure 2. Schematic cross section of triple layer bias selectable dual wavelength IR detector in HgCdTe [20].

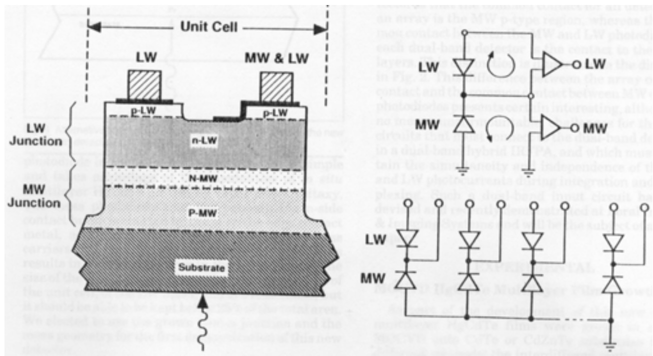

Figure 3. Schematic diagram of dual band detectors in HgCdTe (M.B.Reine et al[6]).

The above two color detectors are possible in HgCdTe since the bandgap of HgCdTe can be continuously varied from 0 to 1.4 eV without any changes in the lattice constant. Hence, it is possible to grow high quality materials with minimum defects on CdTe substrates. Since CdTe has higher bandgap, backside illumination is possible without extra processing steps.

64x64 MW/LW dual-band MOCVD HgCdTe array has been demonstrated in ref. 6 and also discussed in ref. 22. A unit cell size of 75x75 μm^2 of these arrays was hybridized to a dual-band silicon multiplexer readout chip. This allowed the MW and LW photocurrents to be integrated simultaneously and independently. The average cut-off wavelengths of the MW and LW are in the 4.27-4.35-μm and 10.1-10.5 μm ranges at 77K, respectively. High average quantum efficiencies of 79% and 67%, high median detectivities of $4.8x10^{11}$ cm.√Hz/W and $7.1x10^{10}$ cm.√Hz/W, and low median noise equivalent differential temperatures (NEDTs) of 20 mK and 7.5 mK were demonstrated for MW and LW infrared dual-band detector at T_{scene} = 295 K and f/2.9. Tissot at CEA/LETI[27] demonstrated a high performance MWIR two-color detector by superposition of HgCdTe layers with different composition. This two-color detector structure allows simultaneous detection of 3-μm cutoff wavelength for Band 1 and 5-μm cutoff wavelength for Band 2 radiation in the same pixel. He has demonstrated the average R_oA value of 10^7 Ω-cm^2 for the Band 1 and R_oA value of $4x10^5$ Ω-cm^2 for the Band 2 diodes at 77 K. Quantum efficiencies of 75% for Band 2 and 50% for Band 1 are determined without AR coating and also a value of 2% for Band 1 to Band 2 crosstalk is observed. Tennant et al[19] obtained two-color FPAs with background limited detectivity performance for Band 1 (MWIR: 3-5-μm) devices at T > 130 K and Band 2 (LWIR: 8-10-μm) devices at T~80K. 128x128 pixels of these FPAs were based on these devices with 40-μm pixel pitch and this FPA also shows low NEDT values of 9.3 mK for Band 1 and 13.3 mK for Band 2, and these values are similar to good quality single color FPAs. Finally, this group demonstrated 79% of broadband quantum efficiency for Band 1 with only a 4% variation over the pixels and 75% for Band 2 with a 2% variation over the pixels without AR coating. They also predicted that the larger variation in Band 1 is due to the effect of crosstalk on pixels adjacent to a defective pixel.

Recently, Raytheon Vision Systems (RVS) developed two-color detectors with MWIR and LWIR cut-off wavelengths of 5.5-μm and 10.5-μm with quantum efficiency >70% for both MW and LW performance at 78 K[9-10]. 1280x720 MWIR/LWIR FPAs with 20 μm unit-cell and pixel operability 99% have been demonstrated and high quality simultaneous imaging of the spectral bands has been achieved by mating the FPA to a readout integrated circuit (ROIC). Smith et al9-10 have demonstrated large format mega pixel 2048x2948 FPA with 20-μm unit-cell and 2560x512 FPA with 25-μm unit-cell using double layer heterojunction HgCdTe growth on Si substrates in the short wavelength infrared (SWIR) and MWIR spectral range.

III-V Compound Material Systems

QWIP based on III-V compound materials have been extensively investigated for high background using large area highly uniform focal plane arrays (FPAs) and this technology demonstrates considerable development in the fabrication of multicolor FPAs[28-33]. Among the different types of QWIPs, GaAs/AlGaAs multiple quantum well detectors are the most mature[34-36]. Sundaram and co-workers at BAE Systems demonstrated three separate two-color FPAs with MW/MW (4.0-μm/4.7-μm), MW/LW (5.1-μm/8.5-μm), and LW/LW (8.3-μm/11.2-μm) for simultaneous detection[30,37]. Typical operating temperature for these QWIP detectors is in the region of 40-100 K. Peak responsivities of both blue and red QWIPs (LW/LW) are around 320 and 480 mA/W at a temperature of 40 K and at an operating bias of -2.0 V, 35 and ~95 mA/W for the blue and red QWIPS (LW/MW) at an operating bias -2.0 V, and ~12 and ~27 mA/W for the blue and red QWIPs (MW/MW) at an operating bias -2.0 V. This group has demonstrated high operability (>99%) and reasonably high peak responsivity in both colors in several different color combinations (MW/MW, MW/LW, LW/LW FPAs). Large format single color 640x480 pixels with 22-μm squares on 24-μm centers giving a fill factor of 84% and this LWIR QWIP FPA was fabricated by BAE Systems for US Army Research Laboratory (ARL). Goldberg et al[38-39] at ARL also demonstrated the potential of dual-band (MWIR/LWIR) (developed by BAE Systems) imaging for tactical environments by the application of a color image fusion technique. Recently, Goldberg et al[31] presented results of a large format mega pixel 1024x1024 QWIP FPA, which was produced by QWIP Technologies, Inc. This device was tested at the ARL and results obtained including conversion efficiency close to 10%, the spectral response peak at 8.55 μm, and the level of dark current low enough to allow background limited infrared performance (BLIP) at 76 K.

Gunapala et al[28] have demonstrated LWIR and very LWIR (8-9 and 14-15-μm) two-color imaging camera based on a 640x486 dual-band QWIP FPA. This dual-band QWIP device can be processed into simultaneously readable dual-band FPA with triple contacts to access the CMOS readout multiplexer[40] or interlace readable dual-band FPA (i.e., odd rows for one color and the even rows for the other color).

The first approach requires a special dual-band readout multiplexer that contains two readout cells per detector unit cell, whereas the second approach needs only existing single-color CMOS readout multiplexer. The advantages of this scheme are that it provides simultaneous data readout and allows the use of currently available single-color CMOS readout multiplexers. However, the disadvantage is that it does not provide a full fill factor for both wavelength bands. The device structure, shown in Fig. 4[22,28], consists of a 30 period stack (500 Å AlGaAs barrier and a 60 Å GaAs well) of VLWIR structure and a second 18 period stack (500 Å AlGaAs barrier and a 40 Å GaAs well) of LWIR structure separated by a heavily doped 0.5-μm thick intermediate GaAs contact layer. The VLWIR QWIP structure has been designed to have a bound-to-quasibound intersubband absorption peak at 14.5-μm, whereas the LWIR QWIP structure has been designed to have a bound-to-continuum intersubband absorption peak at 8.5-μm, since photocurrent and dark current of the LWIR device structure is relatively small compared to the VLWIR portion of the device structure. The performance of dual-band FPAs has been tested at a background temperature of 300 K, with f/2 cold stop, and at 30 Hz frame rate and are discussed in ref. 30. The mean values of quantum efficiency at operating temperature T = 40 K and bias V_B = -2V are 12.9% and 8.9% in LW and VLW spectral range, respectively. The estimated NEDTs of LWIR and VLWIR detectors at 40 K are 36 and 44 mK, respectively. Recently, Gunapala et al[32-33] demonstrated MWIR and LWIR 1024x1024 pixel QWIP FPAs with excellent imaging performance. The MWIR and LWIR prototype cameras with similar optics have shown BLIP performance at at 90 K and 70 K operating temperatures respectively, at 300 K background.

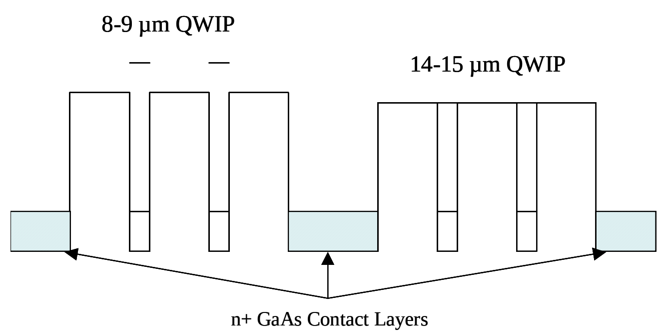

Figure 4. Conduction band energy diagram of the long-wavelength two-color infrared detector. The long-wavelength (8 - 9 μm) sensitive MQW stack utilizes the bound-to-continuum intersub-band absorption. The very long-wavelength (14 - 15 μm) sensitive MQW stack utilizes the bound-to-quasibound intersub-band absorption[28].

A joint effort among Goddard Space Flight Center, Jet Propulsion Laboratory, and ARL demonstrated a four-band, hyperspectral, and 640x512 QWIP array for NASA Earth Science mission[1,41]. Currently, Bandara et al[2-3] have shown remarkable success by realizing large format FPAs in both multi-bands and broadbands. This QWIP FPA has been developed for an imaging interferometer based on InGaAs/GaAs/AlGaAs material system. This produces the spectral range from 3 to

15.4-µm. This FPA consists of four independently readable IR bands and these are (1) 3 - 5-µm, (2) 8.5 -10-µm, (3) 10 - 12-µm, and (4) 14 - 15.4-µm. Each band occupies 640x128 pixel area within the single imaging array. A conceptual design of the multiple quantum well four bands QWIP and spectral response are shown in Fig. 5[1].

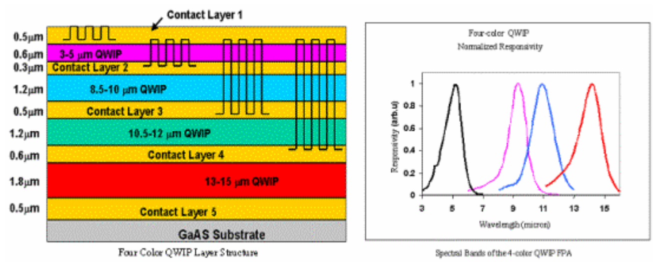

Figure 5. JPL Completed a Four-Color 640x512 imaging focal plane array (3 to 15 micron) for the Hyperspectral QWIP Imaging System [1].

Most recently, NASA Langley Research Center with partnerships at RPI and JPL proposed to develop the technical capability to reliably fabricate detector arrays that respond to multiple wavelength regions[11,12]. We plan to use wafer epitaxial growth followed by wafer bonding approach to overcome the lattice mismatch problem. This will allow us to optimize the detectors for each region of operation to achieve high quantum efficiency. The proposed multicolor detector will be based on the integration of silicon detectors with the antimonide-based IR detectors to obtain the wavelengths of interest. The IR detector structures will be grown on the GaSb or InAs substrates using metal organic vapor phase epitaxy (MOVPE) and these detector structures will be transferred to the silicon substrates using wafer bonding technology. The composite single element detector structure is shown in Fig. 1.

4. Conclusion

Multi-color detector technology is rapidly advancing on a number of exciting applications, such as remote sensing and imaging, military, and medical imaging. HgCdTe and QWIP technology is expanding in single-band to multi-band detectors and recently, QWIP have demonstrated multi-band detector arrays. Development of multi-band array will continue and three-band detectors will be soon demonstrated based on HgCdTe FPAs. A joint effort among NASA Langley, RPI, and JPL was proposed to develop a multi-band FPA with 3-Dimensional structures to provide high resolution spectroscopic imaging for military, medical, hyperspectral and Fourier-Transform interferometers. An increasing interest in multi-band imaging technology is materializing in the UV-to-Far infrared with the feasibility of focal planes founded on large and three-dimensional arrays.

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