Tunable wideband infrared detector array for global space awareness

Jonathan R. Andrews[1], Sergio R. Restaino[1], Scott W. Teare[2], Sanjay Krishna[3], Mike Lenz[3], J.S. Brown[3], S.J. Lee[3], Christopher C. Wilcox[1], Ty Martinez[1]
jonathan.andrews@kirtland.af.mil

Abstract: The Center for High Technology Materials at the University of New Mexico has been investigating tunable quantum well detectors for infrared detection. These devices have been manufactured in 320 x 256 pixel arrays and can be adjusted to obtain a maximum responsivity to wavelengths ranging from 1 μm to 10 μm by applying an external bias voltage. This detector has the capability of expanding the field of hyperspectral imaging by allowing real-time tunability over a very wide spectrum without switchable filters. Additionally, devices can be manufactured in a linear array and coupled with a grating to produce a spectrometer with a maximum sensitivity that is tunable over a wide range of frequencies. This paper reports on the device specifications, laboratory results, and discusses suitable applications in the field of space surveillance.

1 Naval Research Laboratory
Remote Sensing Division, Code 7216
3550 Aberdeen Ave SE
Kirtland AFB, NM 87117
Ph: 505-846-6037
Fx: 505-853-2498
jonathan.andrews@kirtland.af.mil
sergio.restaino@kirtland.af.mil
christopher.wilcox@kirtland.af.mil
ty.martinez@kirtland.af.mil

2 New Mexico Institute of Mining and Technology
Electrical Engineering Department
801 Leroy Place
Socorro, NM 87801
Ph: 505-835-5839
Fx: 505-835-5332
teare@ee.nmt.edu

3 University of New Mexico
Center for High Technology Materials
1313 Goddard SE
Albuquerque, NM 87106
Ph: 505-272-7892
Fx: 505-272-7801
skrishna@chtm.unm.edu

1.0 Introduction

Due to convenient atmospheric transmission of infrared (IR) light, infrared photodetectors are widely used in today's world for applications including motion detection, spectroscopy, thermal imaging, missile defense and satellite imaging. IR photodetectors are also widely used for fiber optic communications. Although many of these applications utilize different types of photodetectors, all operate on the principle that infrared photons incident on the detector cause a measurable physical change that is used as a signal of detection.

Typically, these detectors are single pixel detectors that only yield a single value for color information or irradiance. Multicolor information can be obtained by using a small array of single pixel devices with a fixed wavelength response for each. However, in order to measure wavefronts, capture images or create a spectrograph, focal plane arrays (FPA) are required. As the spectral response of most single pixel detectors is fixed, the spectral response of an array of these detectors are usually not sufficient for broad spectrum imaging. The sensors discussed in this paper have adjustable responsivities with applied bias voltage. As shown in figure 1, an external applied bias voltage bends the bands to change the distance an electron must move to the band edge, thereby changing the spectral response.

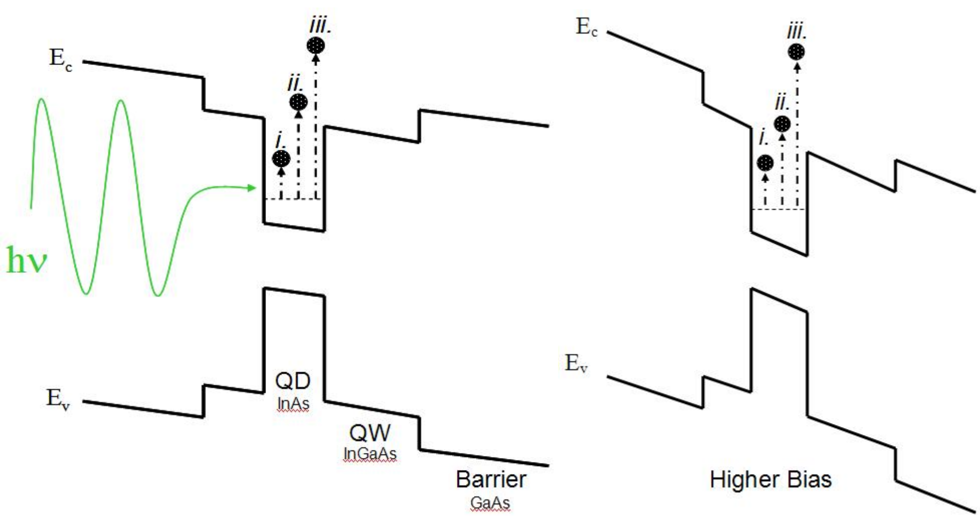

Figure 1. Multiple transitions allow for multiple photon responses. The three transitions are i) bound to bound, ii) bound to quasi-bound and iii) bound to continuum.

A typical quantum well infrared photodetector suitable for mid-wave infrared (MWIR) to long-wave infrared (LWIR) applications consists of a small bandgap material sandwiched between two larger bandgap materials. In this arrangement the small bandgap material absorbs the desired energy level (and thus wavelength) photons, while the surrounding layers act as a window layer with much larger bandgaps that cannot absorb lower energy photons. This configuration eliminates the typical problems with narrow bandgap materials, such as material strain limitations and difficulty of fabrication of large quantities of small bandgap material. Several layers of quantum wells are used to create the active region in the device.

Quantum dot structures are self-assembling three dimensionally bound structures whose size and density can be controlled to vary device characteristics. Unlike quantum wells which are only confined in one dimension, quantum dots are bound in three dimensions. This offers several advantages, such as sensitivity to normally incident light, broader spectral response and lower dark noise current. Similar to quantum well structures, several layers of embedded quantum dots in thin layers are constructed to create the active region.

This paper reports on the use of quantum dots in a well (DWELL) structures and their suitability for infrared imaging. The DWELL structure is a derived hybrid of the quantum dot photodetector that consists of an active region composed of InAs quantum dots embedded in InGaAs quantum wells. This structure offers broad spectral response due to the possibility of multiple absorption energies. Photon absorption can take place via bound to bound transitions, bound to quasi-bound transitions and bound to continuum transitions, as shown in figure 1.

2.0 Device Description

The DWELL samples were grown using molecular beam epitaxy and fabricated into 320 x 256 focal plane arrays with Indium bumps using standard lithography at the University of New Mexico. The samples were then hybridized to an Indigo Systems Corporation ISC9705 read out integrated circuit and evaluated with a SE-IR Corporation CamIRa™ test platform. Figure 2 shows the device structure for each of the single pixels.

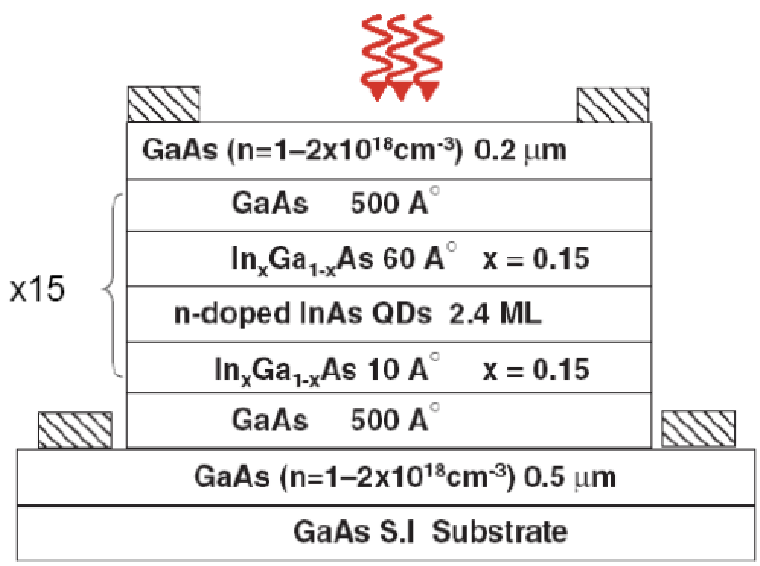

Figure 2. GaAs/InGaAs quantum dot in a well (DWELL) structure for bias tunable IR photodetector.

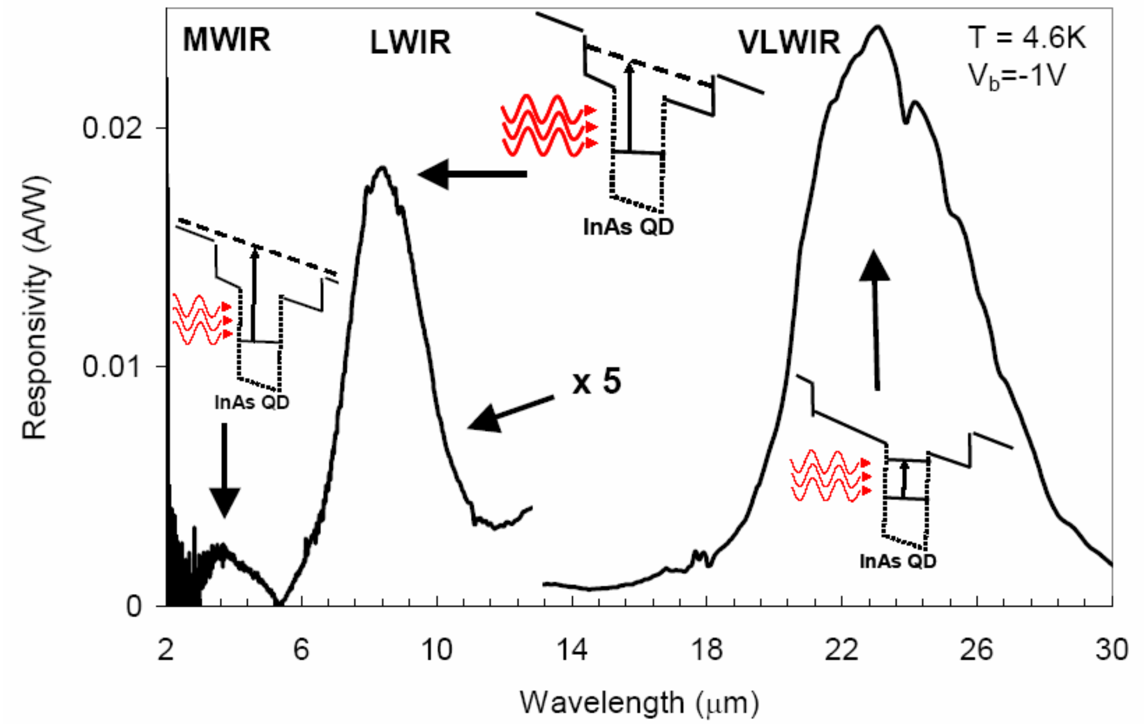

Figure 3. MWIR, LWIR and VLWIR response curves vs wavelength for bound to continuum, bound to quasi-bound and bound to bound transitions, respectively.

The readout integrated circuitry (ROIC) is manufactured by Indigo Systems Corporation, and is the ISC9705 model. This provides the complimentary metal-oxide semiconductor (CMOS) amplifiers for reading the current provided from electrons that were created through photon absorption. Figure 4 shows the ROIC structure attached underneath the DWELL structure with the Indium bump bonds.

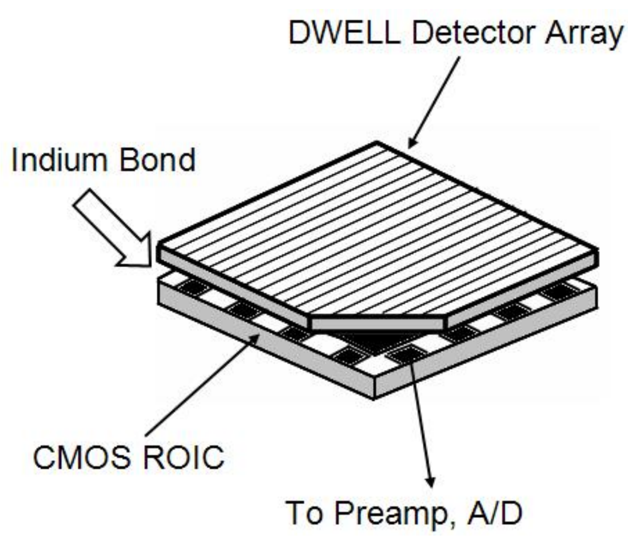

Figure 4. Readout Integrated Circuit for 320 x 256 focal plane array of DWELL structure.

After the device was mated with the ROIC, an off-the-shelf data acquisition system was selected by SE-IR Corporation. The device, called the CamIRa™ is responsible for operating the ROIC and capturing the resulting data. A block diagram of this system is shown in figure 5.

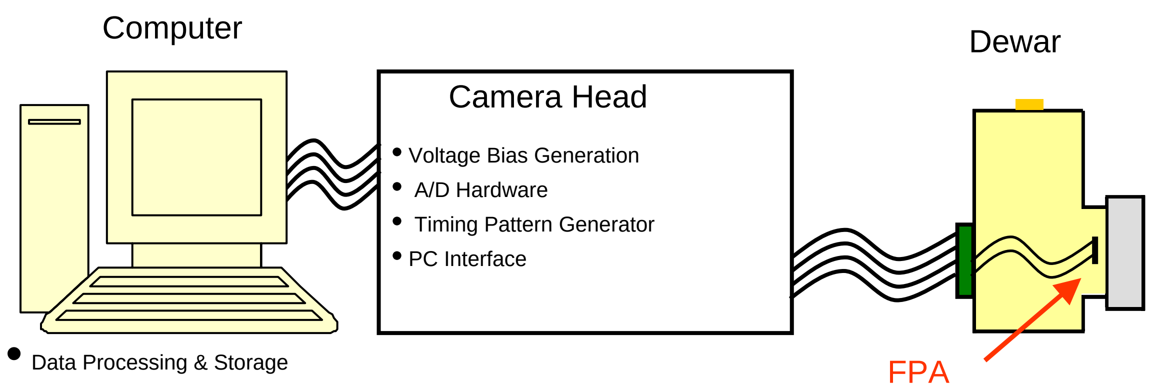

Figure 5. Block diagram of SE-IR CamIRa™ hardware/computer software.

The combination of ROIC and CamIRa™ data acquisition system does not allow for individual bias control for each pixel. A global bias can be applied across the entire device and updated at nearly 1kHz. However, an updated design will be required to allow individual pixels to be tuned to maximize spectral responsivity.

3.0 Spectral Measurements

Applying an external bias voltage allows the conduction and valence bands to bend sufficiently to change the absorption energy levels and change the device responsivity. Shown in figure 6 is the response vs. wavelength for a single pixel detector similar to that used in the DWELL FPA.

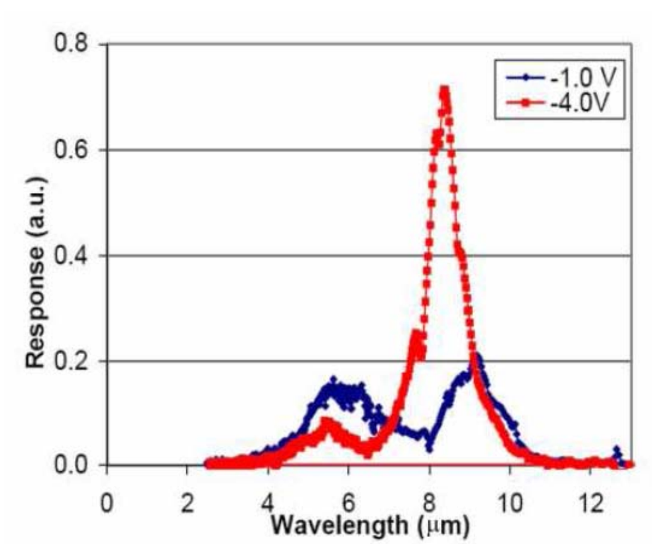

Figure 6. Response vs. wavelength for two externally applied bias voltages.

A blackbody radiator is used as a source with various camera lenses to demonstrate the spectral response of the detector. Shown in figure 7 are images taken using a MWIR infrared (3-5 um) lens of a blackbody source. In front of the blackbody radiator are two bandpass filters of 3.5 um and 4.5 um with a width of 1 um. Although the camera lens will allow transmission from 3 to 5 um, there is almost no transmission at 3.5 um due to the applied bias on the device and lower inherent responsivity at that wavelength. As shown in figure 6, the responsivity is low at 3.5 um regardless of bias. Figure 8 shows similar results with a LWIR lens and filters at 8.5 um and 9.5 um.

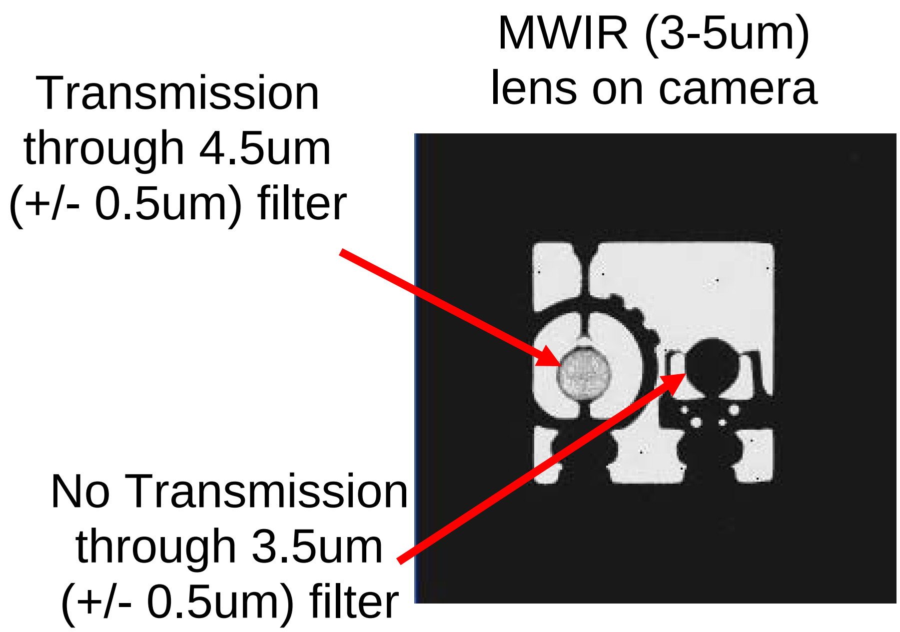

Figure 7. Images of mid-wave infrared (3-5 um) lens of blackbody source. Note transmission through 4.5 um filter and no transmission through 3.5 um filter.

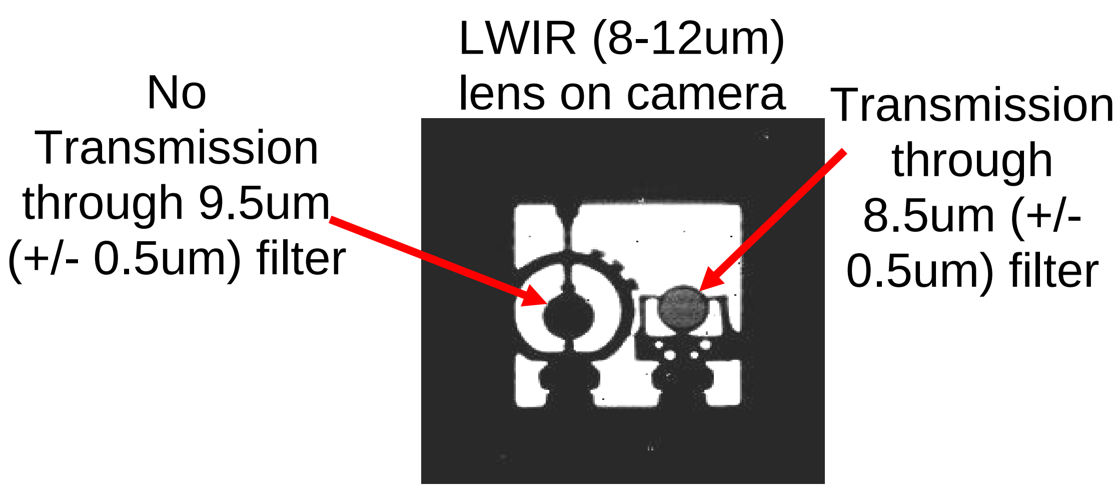

Figure 8. Images of long-wave infrared (8-12 um lens) of blackbody source. Note transmission through 8.5 um filter and no transmission through 9.5 um filter.

Measurements were performed with various applied reverse bias voltages of the output voltage of the ROIC with irradiance calculated from the blackbody radiator. Figure 9 shows the output voltage vs. irradiance, while figure 10 and 11 show the RMS noise for MWIR and LWIR, respectively.

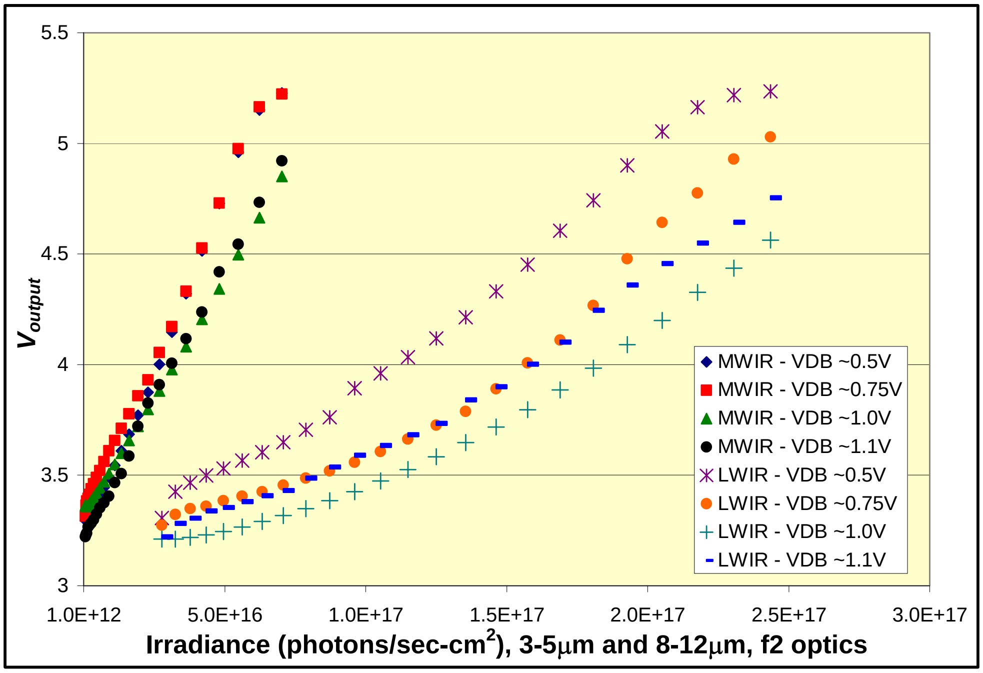

Figure 9. Output voltage vs. Irradiance for several wavelengths and applied reverse (negative) bias voltages.

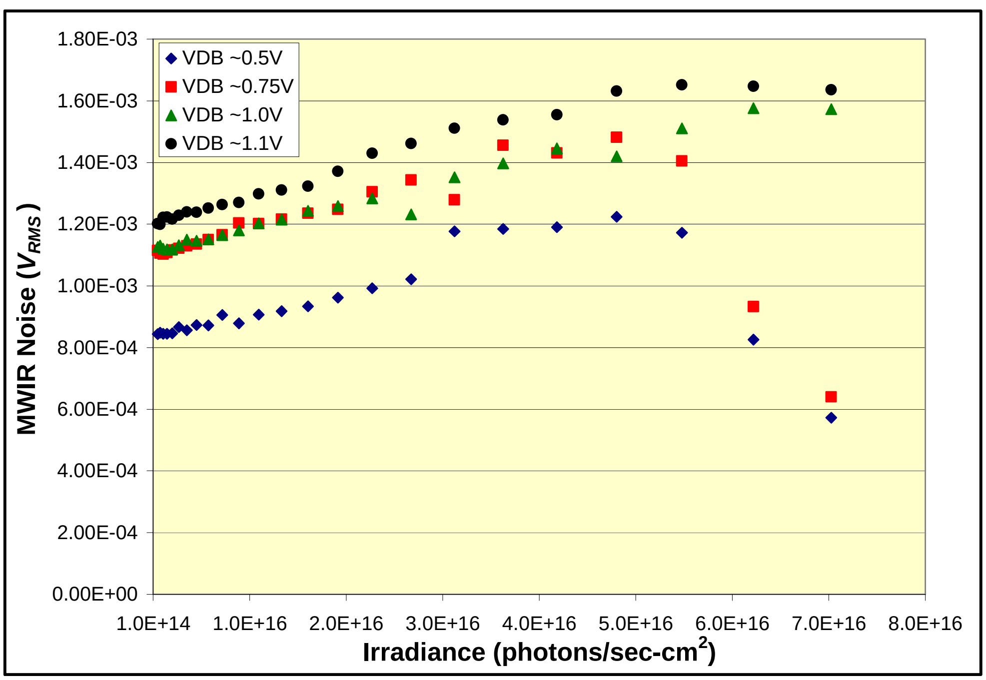

Figure 10. Mid-wave IR RMS noise vs. Irradiance for applied reverse bias voltages ranging from -0.5 to -1.1 Volts.

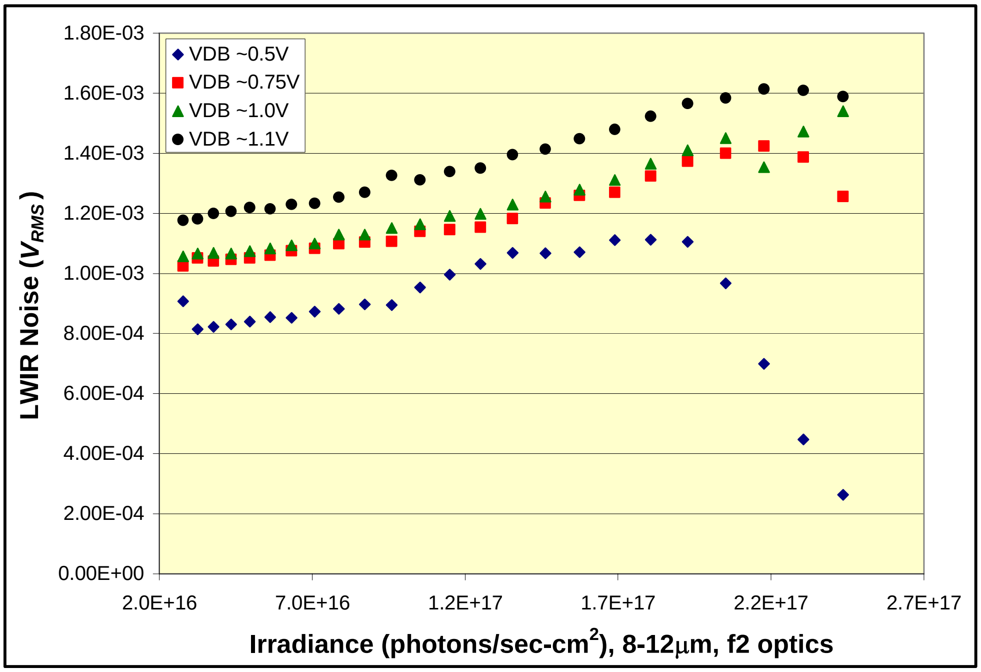

Figure 11. Long-wave IR RMS noise vs. Irradiance for applied reverse bias voltages ranging from -0.5 to -1.1 Volts.

4.0 Applications of DWELL FPA

The DWELL structure can be used as a tunable infrared detector for space situational awareness and imaging through barriers applications. This detector has the capability of expanding the field of hyperspectral imaging by allowing real-time tunability over a very wide spectrum without switchable filters. A filter setup, similar to the Bayer color scheme implemented with CCD and CMOS visible camera systems could also be implemented to provide a 'color' infrared imaging system. Any of these systems would require a custom ROIC and data acquisition system for this device so that the responsivity of individual pixels can be tuned.

Additionally, devices can be manufactured in a linear array and coupled with a grating to produce a spectrometer with a maximum sensitivity that is tunable over a wide range of frequencies.

Recent work by our group has aimed at implemented an infrared version of the human retina. As shown in figure 12, the human eye has different retinal cones with overlaps between the red, green and blue colors. Using various bias values, we have obtained a similar spectral response with the DWELL FPA device. The human eye has these various colored cones disturbed throughout the retina. As such, a similar construction of variously tuned pixels in the FPA will have to be implemented to provide an infrared retina. This again will require a new ROIC and data acquisition system to allow tenability at the pixel level.

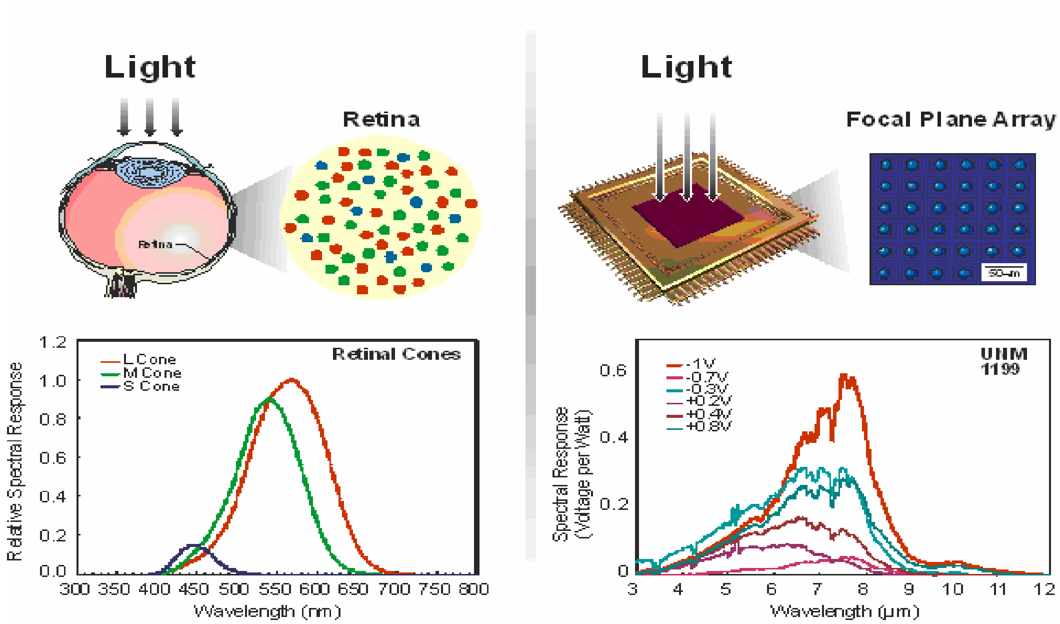

Figure 12. Comparison of infrared FPA and the human eye. Tunable spectral response can yield an infrared retina.

5.0 Summary and Future Work

This paper has reported the current work on the quantum dot in a well infrared focal plane array developed by the University of New Mexico's Center for High Technology Materials. Application of a bias voltage on the device leads to a variation of responsivity vs. wavelength that would be beneficial for hyperspectral imaging, space situational awareness and imaging-through-barriers applications. The spectral response of this device is still being characterized and should continue with the acquisition of new ROIC and data acquisition hardware capable of applying larger forward and reverse bias voltages. Work will also continue with measuring the precision radiometry capable with this device.

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BIOGRAPHY

Jonathan Andrews is a PhD candidate in Electrical Engineering at the University of New Mexico. He has been working with the Remote Sensing division of the Naval Research Laboratory for 5 years, and recently transferred to the newly formed Adaptive Optics and Wavefront Sensing & Control section. His research areas include novel electro-optical configurations, adaptive optics, and remote sensing instrumentation. He earned his B.S. and M.S. in Electrical Engineering at the New Mexico Institute of Mining and Technology in 2003 and 2005, respectively.