Spectrum tunable quantum dot-in-a-well infrared detector arrays for thermal imaging

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Abstract: The Center for High Technology Materials at the University of New Mexico has been investigating quantum dot and quantum well detectors for thermal infrared imaging applications. Recent advances in manufacturing have led to the development of a hybrid quantum dot-in-a-well configuration, allowing many of the benefits of each type of detector in addition to multiple transition energies. These transition energies (and thus wavelengths of detection) are also bias tunable providing the capability of spectrum tunability. These devices have been manufactured in 300 x 256 pixel arrays and can be adjusted to obtain a maximum responsivity to wavelengths ranging from 3 μm to nearly 30 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. This paper reports on the device specifications, spectral response measurements, noise characterization and reduction techniques, and discusses suitable applications in the field of thermal surveillance. It also reports on the most recent advances in manufacturing that have led to dramatic increases in quantum efficiency and joint work with other fabrication facilities that have led to the manufacture of mega-pixel (1200 x 1024) arrays.

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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 since 2002, 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.

1.0 Introduction

Due to convenient atmospheric transmission of infrared (IR) light, IR photodetectors are widely used in today's world for applications including motion detection, spectroscopy, thermal imaging, missile defense and satellite imaging. Additionally, IR photodetectors are also widely used for fiber optic systems. In the area of thermal IR imaging, much work has been invested in multi-spectral and hyper-spectral imaging systems[1-4]. Single pixel detectors originally existed with some spectral tunability. This technology progressed to focal plane arrays (FPAs) where multiple detectors were typically used in a multi-spectral system. Recent advances in semiconductor technologies have yielded FPAs that are spectrally tunable by an external bias voltage and contain novel combinations of quantum dot and quantum well structures[5]. These structures, called quantum dots-in-a-well, or DWELL, 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[5]. This structure offers broad spectral response due to the possibility of multiple absorption energies[6]. Photon absorption can take place via bound to bound transitions, bound to quasi-bound transitions and bound to continuum transitions[7], as shown in figure 1. This paper reports on the characterization of a DWELL FPA fabricated at the University of New Mexico Center for High Technology Materials, including spectral response and radiometry measurements in an attempt to develop a single detector multi-spectral imager with noise-reduced high precision radiometry.

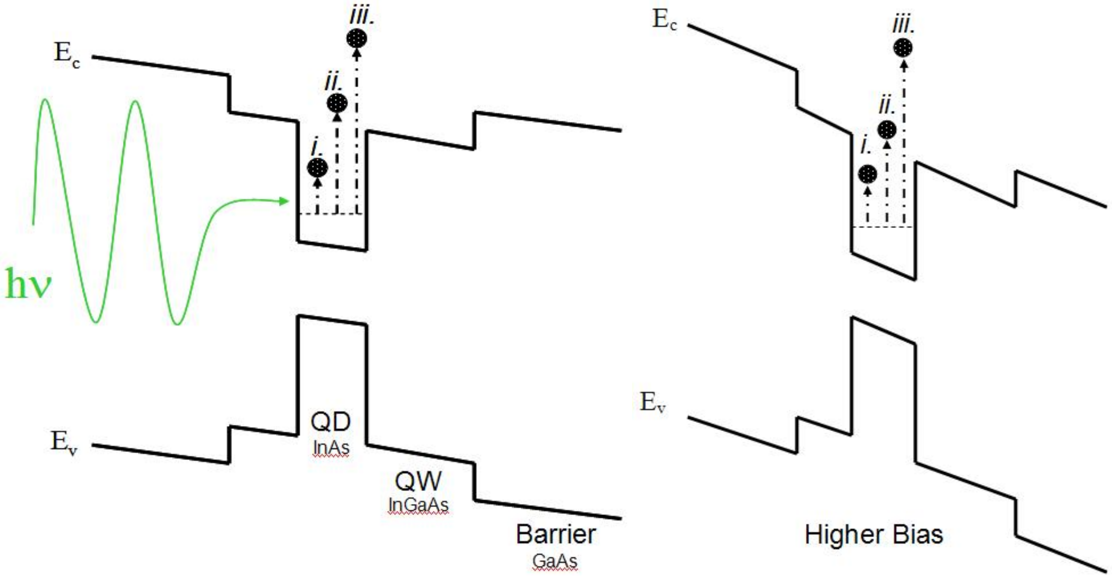

Figure 1. Multiple transitions allow for multiple photon responses. The three transitions are i) bound to bound, ii) bound to quasi-bound and iii) bound to continuum.

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^{TM} test platform. Figure 2 shows the device structure for each of the single pixels. Figure 3 shows the electron transitions and the corresponding wavelength of detection, namely mid-wave IR (MWIR), long-wave IR (LWIR) and very long-wave IR (VLWIR).

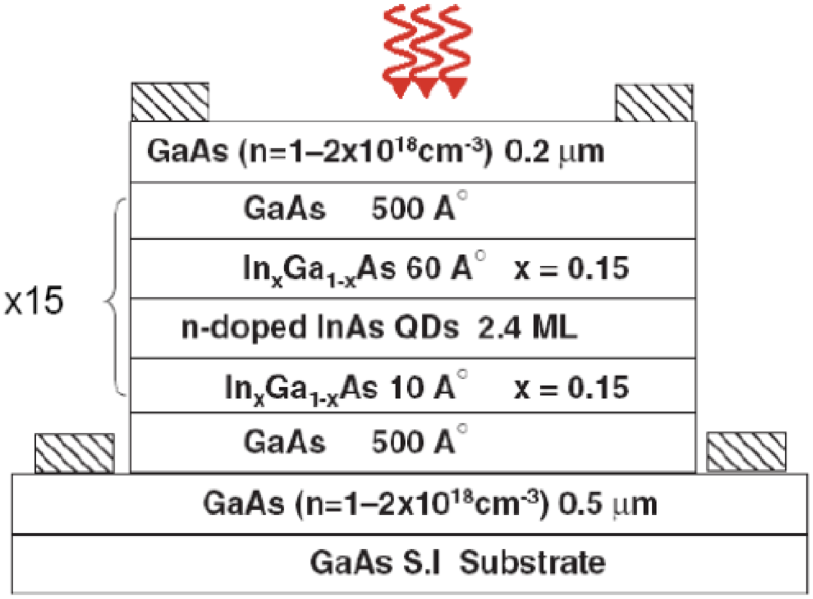

Figure 2. GaAs/InGaAs quantum dot in a well (DWELL) structure for bias tunable IR photodector.

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.

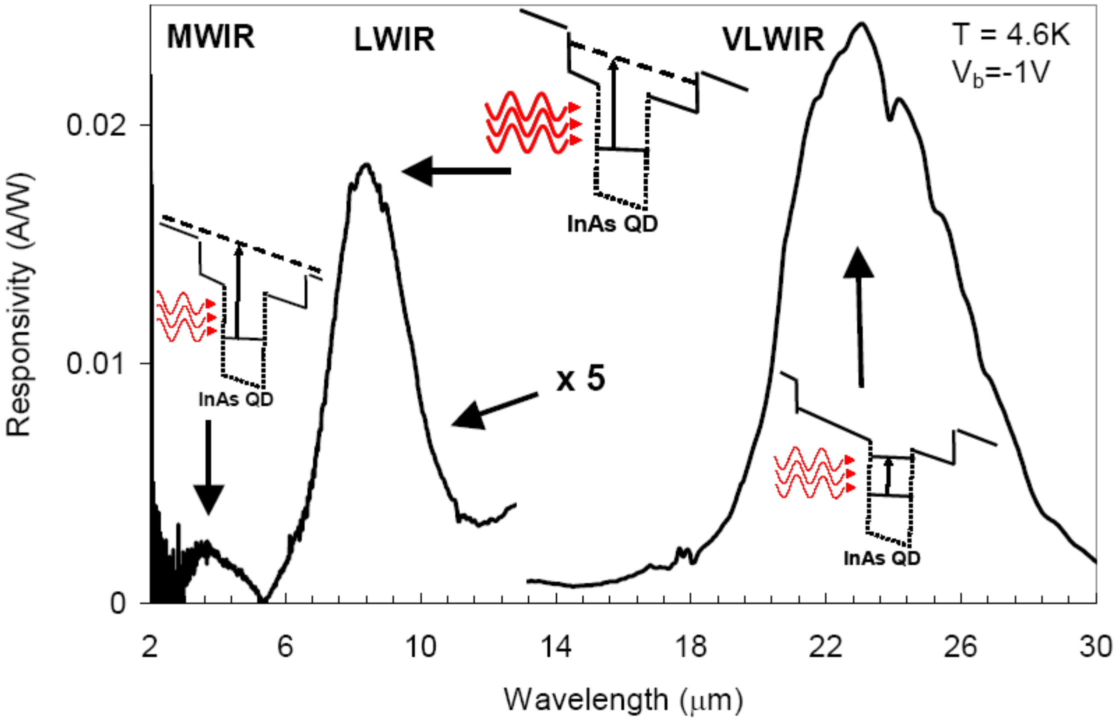

Figure 3. MWIR, LWIR and VLWIR response curves vs wavelength for bound to continuum, bound to quasi-bound and bound to bound transitions, respectively.

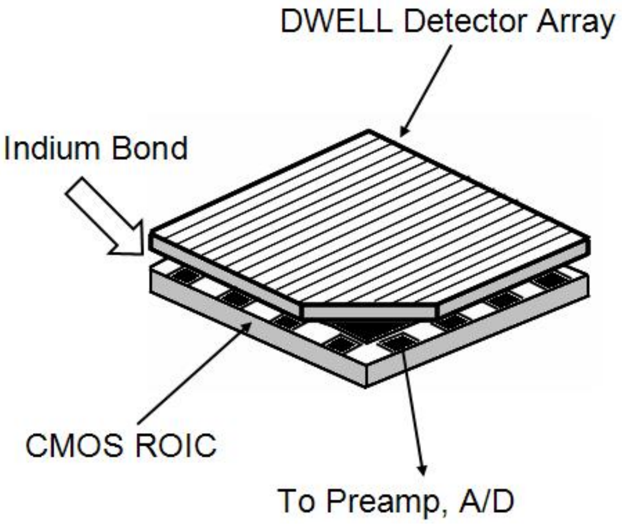

Figure 4. Readout Integrated Circuit for 320 x 256 focal plane array of DWELL structure.

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^{TM} is responsible for operating the ROIC and capturing the resulting data. A block diagram of this system is shown in figure 5.

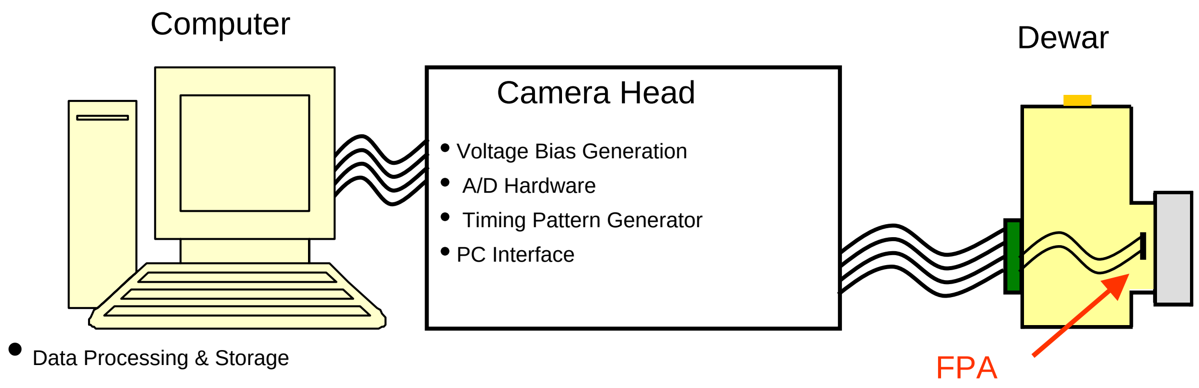

Figure 5. Block diagram of SE-IR CamIRa^{TM} hardware/computer software.

The combination of ROIC and CamIRa^{TM} 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 used in the DWELL FPA.

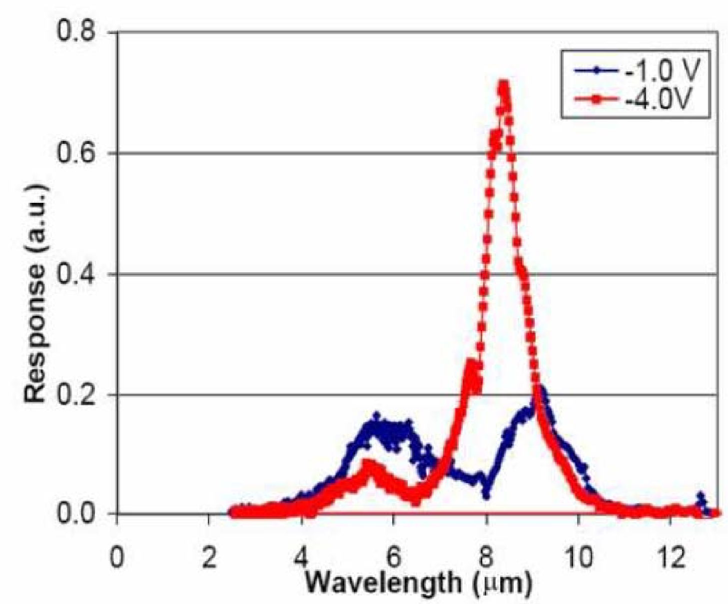

Figure 6. Response vs. wavelength for two externally applied bias voltages.

Shown in figure 7 is the measured device responsivity versus wavelength. All three curves were measured under a 1 Volt reverse bias across the device, and measurements were taken at 4.6, 10 and 15 degrees Kelvin. The 10 K figure was multiplied by a factor of 3 and the 15 K figure was multiplied by a factor of 5 for scaling in this figure. The three measured transitions are bound to bound shown as the VLWIR response centered at 24 µm, the bound to quasi-bound LWIR response centered at 8 µm, and the bound to continuum transition resulting in a MWIR response, centered at 5 µm.

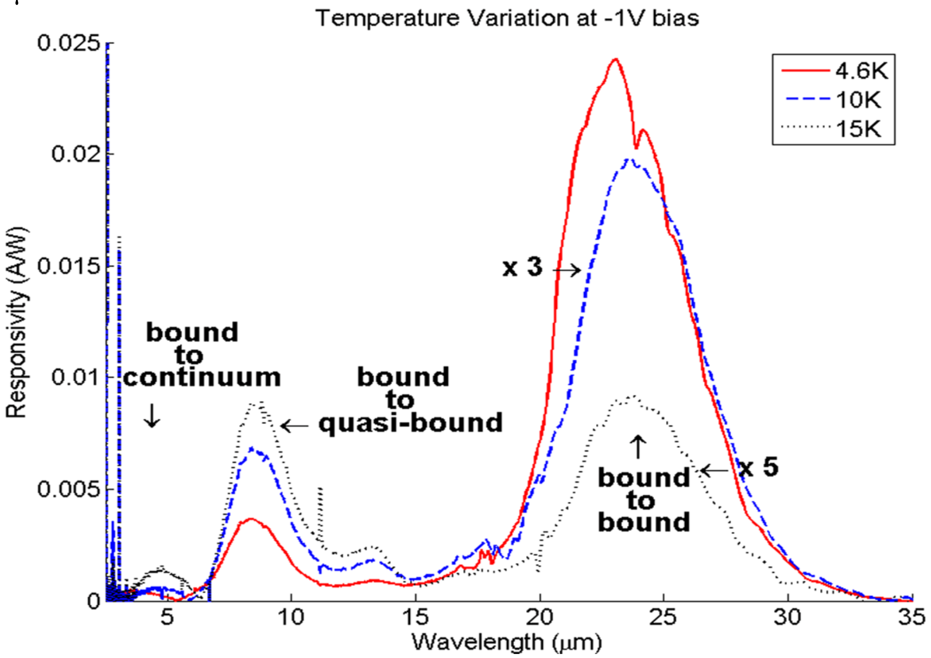

Figure 7. Responsivity versus wavelength for DWELL structure at -1V bias and three device temperatures.

4.0 Noise Measurements and Reduction

Characterization of the response of each pixel to incident photon flux is used to determine any nonlinearity in detector response. Due to imperfections in manufacture, each detector contains some pixels that are pegged high and some that are pegged low. Additionally, some pixels dramatically deviate from the average of the detector.

Only a careful measure of the response of each pixel to a range of illuminations will yield insight into this response. This information is then used to correct the device response to produce the highest precision images. Figure 8 displays the output analog to digital converter units averaged across the entire 320 x 256 pixel DWELL FPA. Also shown is the 1 σ standard deviation lines overlaid in red.

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 and 10 show the RMS noise for MWIR and LWIR device response, respectively.

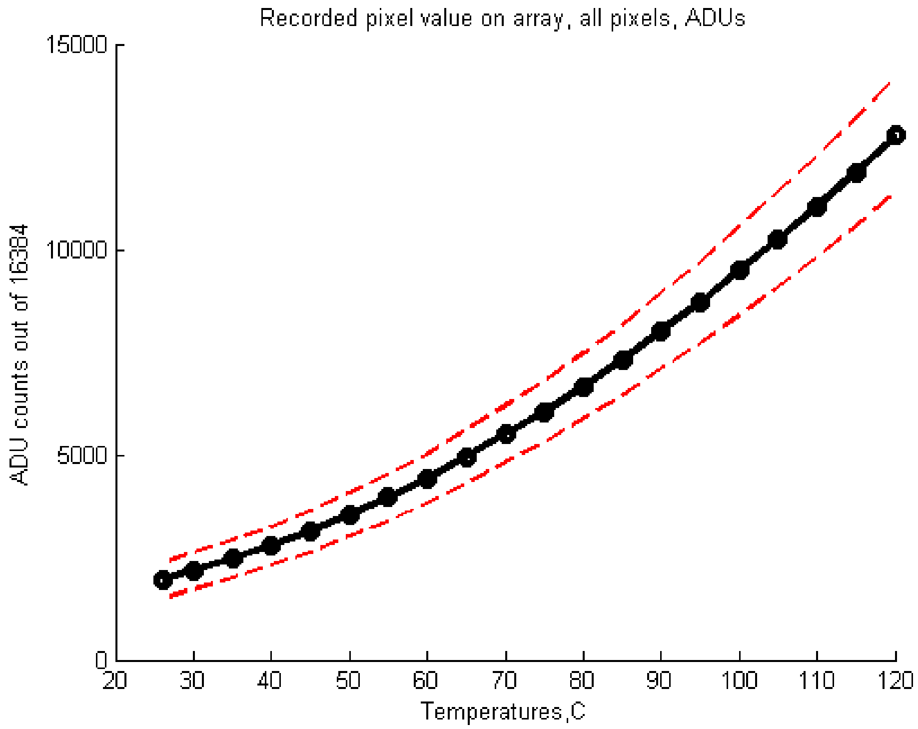

Figure 8. Analog to digital converter units output versus blackbody temperature, average of all pixels (black) and standard deviation (red).

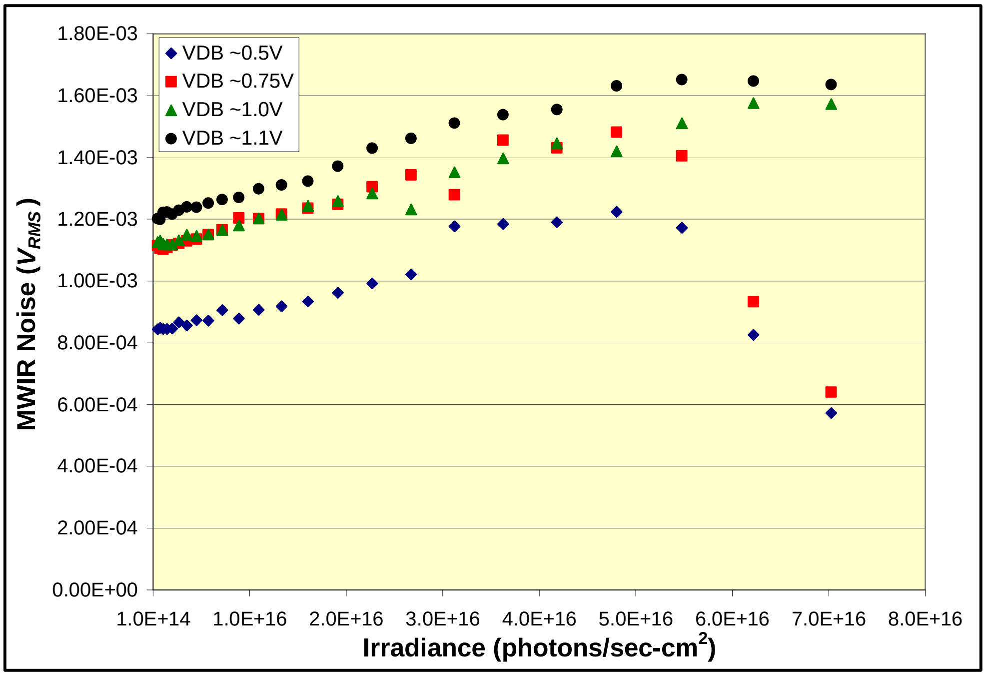

Figure 9. Mid-wave IR RMS noise vs. Irradiance for applied reverse bias voltages ranging from -0.5 to -1.1 Volts.

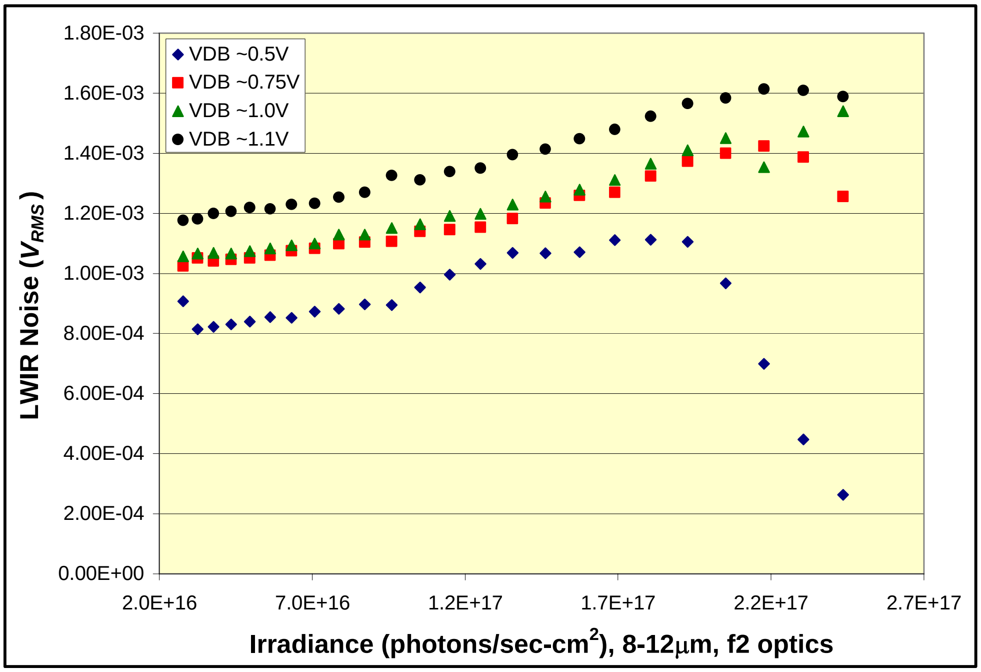

Figure 10. Long-wave IR RMS noise vs. Irradiance for applied reverse bias voltages ranging from -0.5 to -1.1 Volts.

The noise characteristics of the device along with the non-linear response of each pixel was used to generate corrected images. Figure 11 shows a partially noise-reduced corrected image from the DWELL FPA of a hand, a book, a cigarette lighter and a person (in the background).

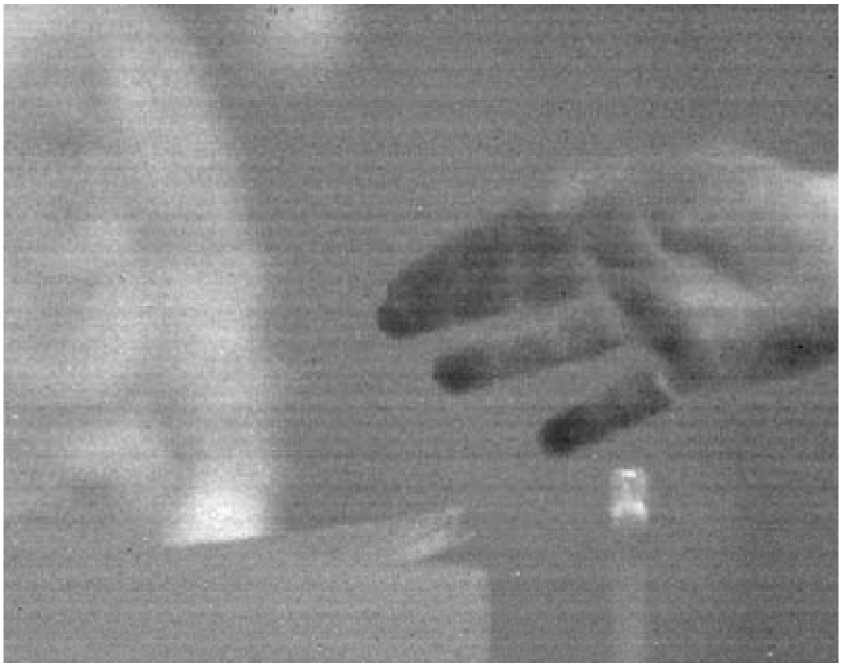

Figure 11. Corrected image from 320 x 256 pixel DWELL FPA

5.0 Thermal Imaging and Future Work

These DWELL detectors operate within the thermal regions of the infrared spectrum and can be used for such an application. There are several sensors on the market that offer similar or better performance in thermal imaging. However, this sensor has the capability of switching wavelengths to provide a multi-spectral or hyper-spectral imaging system on one focal plane array. One of the more interesting applications is the development of an infrared retina. Similar to the human eye, different pixels are programmed to accept different wavelength ranges and in effect a true “color” image within the thermal infrared spectrum can be realized. This is demonstrated in Figure 12.

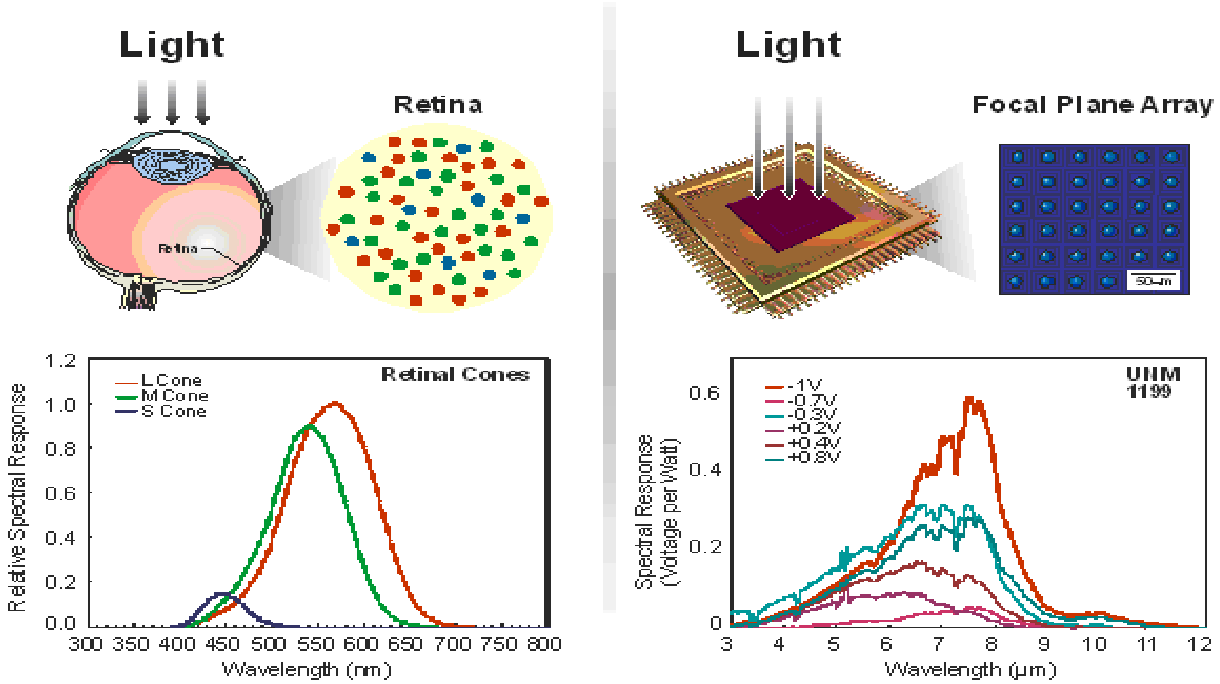

Figure 12. Human eye retina and thermal infrared retina using this technology

Recent work by colleagues at the Jet Propulsion Laboratory has yielded further advancements in this technology. JPL has been using more advanced facilities and manufacture techniques to push the size of the FPA up to 640 x 512 pixels (as shown in images in Figure 13). They have also started development of a mega-pixel (1280 x 1024 pixel) FPA based on the DWELL structure. These advancements are helping to push this technology forward and are also increasing device responsivity with every generation.

Figure 13. Images taken from the 640 x 512 DWELL FPA developed by JPL

6.0 Summary

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 noise processes and optimizing the radiometry of this device.

References

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