# HOT MWIR detector with 5 μm pitch

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## ABSTRACT

Large format, high resolution, infrared Focal Plane Arrays (FPA) are enablers for several important Electro-optical (EO) defense and commercial imaging applications such as reconnaissance, persistent surveillance, and thermography, where a large number of pixels are required to image the field of view. The development of a small pixel enables the production of a relatively small FPA with high pixel count.

Over the last few years SCD has developed a new generation of Mid-Wave Infrared (MWIR) detector with 2560×2048 format and 5 μm pitch, which is based on the mature High Operating Temperature (HOT) MWIR XBn-InAsSb barrier detector technology. The combination of a small pixel and a high operating temperature of 150K results in a compact Integrated Dewar Cooler Assembly (IDCA) that operates with low power consumption and weighs only 360g. Several IDCA prototypes have already been integrated successfully into EO systems.

Achieving even smaller pixel size while maintaining the same electro-optical performance, namely high quantum efficiency, low dark current, low cross talk, high array uniformity, and high operability, is a serious technological challenge. In this work, we present how these challenges have been met in the new Crane FPA and IDCA.

## 1. INTRODUCTION

Applications such as reconnaissance, persistent surveillance, and thermography, require an image with a large Field of View (FOV). Imaging with a large number of pixels can be achieved by using several sensors or by using Step-and-Stare method. However, such solutions are expensive, complicated and large in Size, Weight and Power (SWaP), which is a real drawback especially for aerial applications where weight and mission duration are tied together. Alternatively, a Focal Plane Array (FPA) with very small pitch enables a preferable low SWaP solution for high resolution imaging.

The development of a FPA with very small pitch requires major changes in its architecture and manufacturing techniques. The infrared (IR) pixel and array should achieve high electro-optical performance, namely high Quantum Efficiency (QE), low dark current, low inter-pixel cross talk (XT), array uniformity and operability. The Read-Out Integrated Circuit (ROIC) should reach high functionality with sufficient pixel integration capacity, low readout noise, and high linearity. Finally, hybridization of the IR die to the CMOS ROIC is a technological challenge in large format, small pitch arrays.

Along with the development of small pixels and large arrays, there is a growing effort to increase the operating temperature of the FPA in order to reduce the cooling demands[1,2]. Higher FPA temperature has a major effect on the performance of the commonly used Stirling cycle cooler, affecting cooling rate, cooling power, and cooler lifetime. Low cooler power consumption is especially important for low SWaP applications, and also eases the problem of heat removal from the Integrated Detector Cooler Assembly (IDCA). Longer Mean Time to Failure (MTTF) is a crucial factor in 24/7 surveillance, terrain dominance, and homeland security systems.

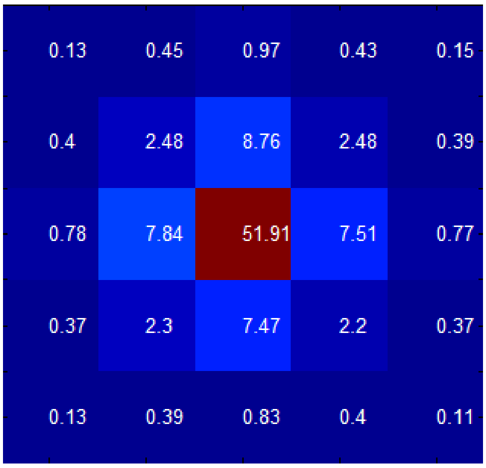
In the new 5 Mega-pixel (2560×2048 format) "Crane" detector[3] we combine a 5μm pixel array based on our mature High Operating Temperature (HOT) MWIR XBn-InAsSb technology with a new ROIC design utilizing advanced CMOS technology, which allows for dense layout of devices to maintain high level of functionality. These technologies enable outstanding FPA electro-optical performance at temperatures as high as 150K, and high readout speed of digital signal at reduced power consumption. The result is a compact IDCA of less than 360g weight, operating with relatively low power at a rate of 60Hz in full frame.

In this work we present measured performances of the new Crane detector.

## 2. XBn-InAsSb CRANE FPA

Moving to a smaller pitch array while maintaining standard pixel design leads to an unacceptable trade-off between the quantum efficiency and the inter-pixel cross-talk. A thinner active layer is needed in order to reduce electrical XT in a standard detector array. In this case, however, less radiation is absorbed and the QE is reduced[4]. For a small pitch array this architecture becomes irrelevant and a new pixel design must be introduced.

In Figure 1 we present the measured energy distribution over 5×5 pixels within the Crane FPA, around a central pixel which is uniformly illuminated over its entire area. More than 50% of the energy is collected by the central pixel, while ~8% is the XT to the nearest neighboring pixels and ~2.5% to the neighboring diagonal pixels.



|  |  |  |  |  |
|---|---|---|---|---|
| 0.13 | 0.45 | 0.97 | 0.43 | 0.15 |
| 0.4 | 2.48 | 8.76 | 2.48 | 0.39 |
| 0.78 | 7.84 | 51.91 | 7.51 | 0.77 |
| 0.37 | 2.3 | 7.47 | 2.2 | 0.37 |
| 0.13 | 0.39 | 0.83 | 0.4 | 0.11 |

Figure 1: Energy distribution over 5×5 pixels around a uniformly illuminated central pixel, measured in the 5M-pixel, 5µm Crane FPA

The Modulation Transfer Function (MTF) of the FPA, which is another representation of the XT phenomena, is plotted in Figure 2 for various XBn InAsSb FPA pixel sizes. The red curve shows the measured MTF of the 5µm pixel in Crane, while the black curve represents the calculated MTF of an ideal 5µm pixel without any XT. We find that although the actual 5µm pixel MTF is lower than the ideal one, it is still much higher relative to larger pixels in earlier generation MWIR detectors, and allows for a significantly higher spatial resolution imaging.

| Detector parameter | Value |
|---|---|
| Format / pitch | 2560 × 2048 / 5 µm |
| ROIC output | Digital |
| ROIC video interface | High Speed Serial video interface (JESD204B) |
| Data resolution | 12, 13 bit |
| Capacitors / Readout noise (at 12bit) | 0.25Me- / 90e- (ITR),<br>0.55Me- / 200e- (IWR),<br>0.6Me- / 160e- (ITR) |
| Maximum frame rate | 100Hz at 13 bit,<br>140Hz at 12 bit |
| Linearity | < 0.1% at 10 – 85% Well Fill |
| Modes of operation | Normal & 2×2 binning |
| Vertical windowing | 8 rows resolution |
| Maximum ROIC power consumption | 400mW |

Table 1. Typical ROIC performance

Figure 3 shows a map of the measured QE across the Crane FPA at 150K. The average QE over the 3.6 – 4µm spectral band is above 70%, similarly to FPAs with larger pixel size, and its uniformity is high. This figure demonstrates that the decent XT values mentioned above were obtained without compromising the QE.

SCD has been developing digital output ROICs since 2002[5]. The Crane ROIC of 2560×2048 pixel matrix was designed to support 5µm pitch p-on-n InSb photo-diode array as well as XBn-InAsSb barrier device array, operating at cryogenic temperatures from 77 to 150K.

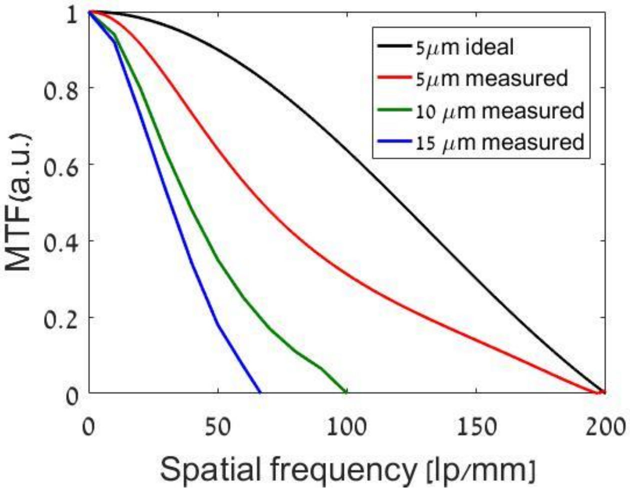


Figure 2: MTF of XBn-InAsSb FPAs of different pitch

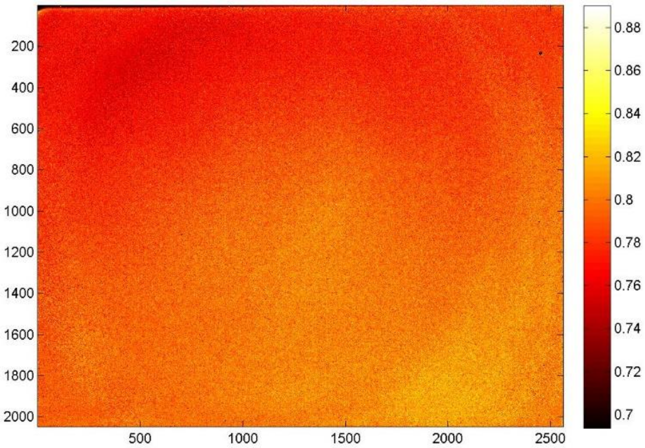


Figure 3: Measured quantum efficiency map of the Crane FPA

The ROIC uses advanced CMOS technology that support the implementation of improved Analog to Digital Converter (ADC) and high-speed JESD240B serial interface, which enables very high throughput of more than 15Gbps, resulting in Frame Rates (FR) of up to 140Hz at full format. The Crane ROIC supports several operation modes: Integrate While Read / Integrate Then Read (IWR / ITR), low gain with a capacitor of 0.6Me- and high gain with a capacitor of 0.25Me-. The 2×2 pixel Binning mode allows for 1280×1024/10µm format, which is useful when a higher signal-to-noise (SNR) ratio and / or higher frame rate are needed. A full summary of the electro-optical characteristics for the different operating modes of the Crane ROIC is presented in Table 1.

Hybridization is one of the main challenges in realizing a large format, small pixel array. In Figure 4 we present a non-operable pixel map of shorted (top) and disconnected (bottom) pixels in a Crane FPA. The low count of such defective pixels (6 shorted, 141 disconnected) is indicative to the quality of the FPA hybridization process. In Figure 5 we show the map of all defective pixels in the FPA, which includes NETD defects, RNU defects, and other imperfect pixels. In this case there are 4407 defective pixel which is less than 0.1% of the total pixel count.

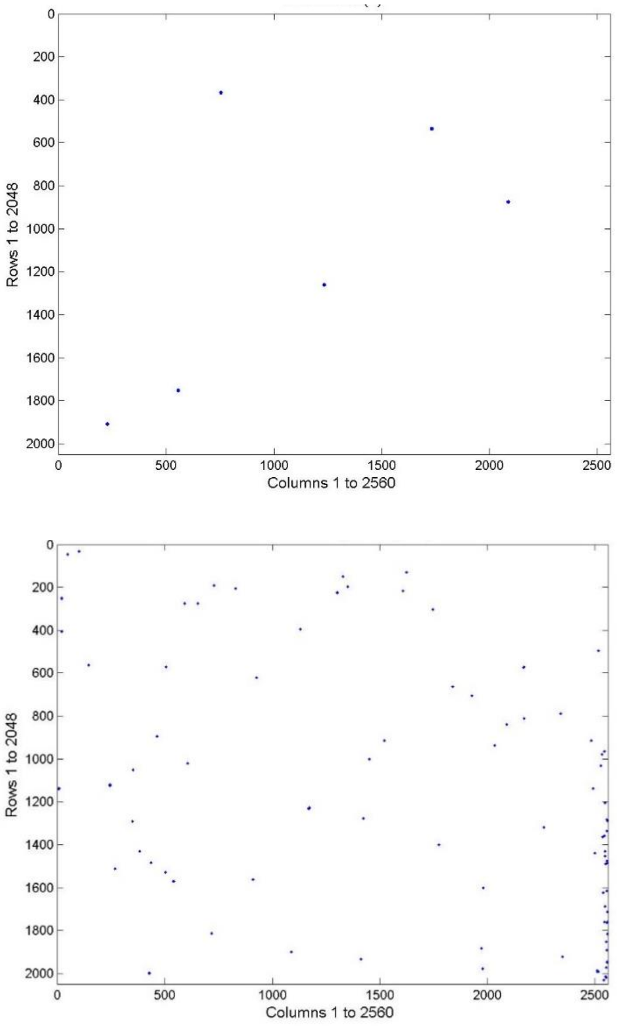


Figure 4: Defective pixels map of shorted (top) and disconnected (bottom) pixels in a Crane FPA

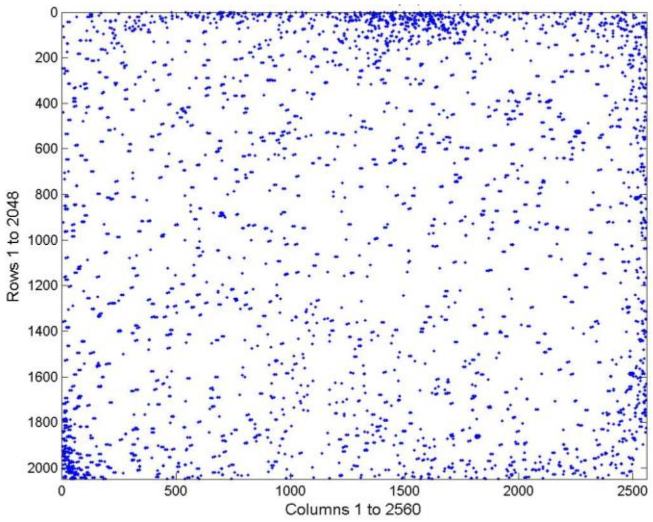


Figure 5: Total defective pixels map in a Crane FPA

The Noise Equivalent Temperature Deference (NETD) is an important figure of merit for IR detector performance evaluation. It is defined as the minimum temperature change in the object under observation that the detector is able to detect. Low intrinsic noise and high response leads to low NETD that represents high level of performance. Due to the low readout noise in the Crane ROIC, the NETD is radiation background limited (BLIP) even at low signal (low well-fill). At very low signal level the NETD is dominated by the ROIC readout noise, which is defined as the temporal noise of the signal recorded at zero integration time. In Figure 6 (top) the measured squared temporal noise averaged over all pixels is plotted as a function of the average signal. The linear dependence indicates that the dominant noise mechanism is photon shot-noise. The map on Figure 6 (bottom) shows an NETD of 45mK at approximately 70% well-fill. The NETD noise is random and without any spatial patterns.

Due to minor variations between the response and the dark current of any two pixels, including contributions from both the IR sensor and the silicon ROIC, the raw image of the detector is never perfectly smooth and Non-Uniformity Correction (NUC) algorithm must be employed in order to optimize the image. Assuming the response of a pixel is linear it is possible to expose the detector to two different flux levels and use a linear transformation to correct each pixel to the average response of all pixels (2-point NUC). As can be seen in Figure 7 the non-linearity of the detector between 5% and 85% well-fill is below 0.1% of the Dynamic Range (DR). The Residual Non Uniformity (RNU) of the image after the 2-point NUC represents spatial noise that can limit the detector performance, and thus is also an important figure of merit. In Figure 8 we present an image from the detector in front of a uniform blackbody target after 2-point NUC, where the RNU is smaller than 0.06% of the detector DR.

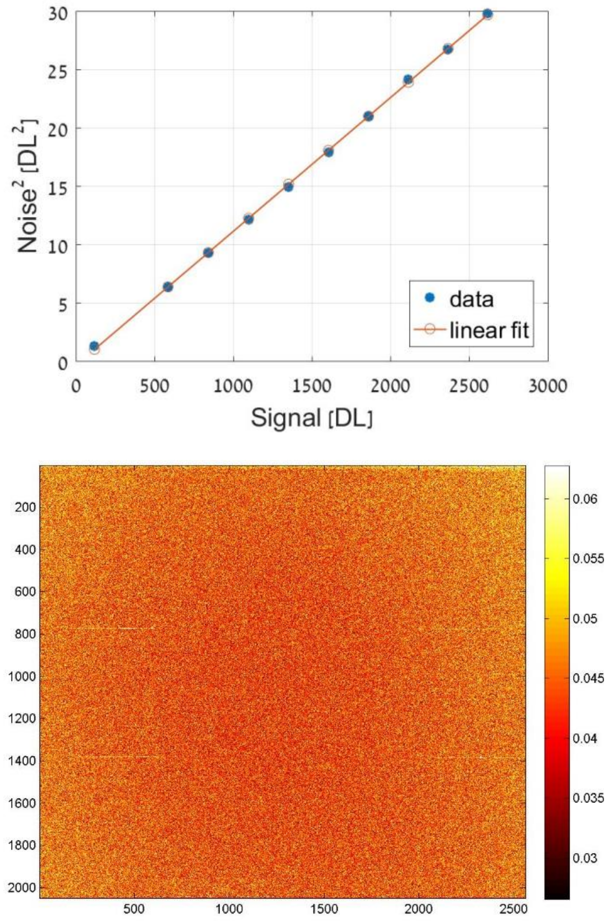
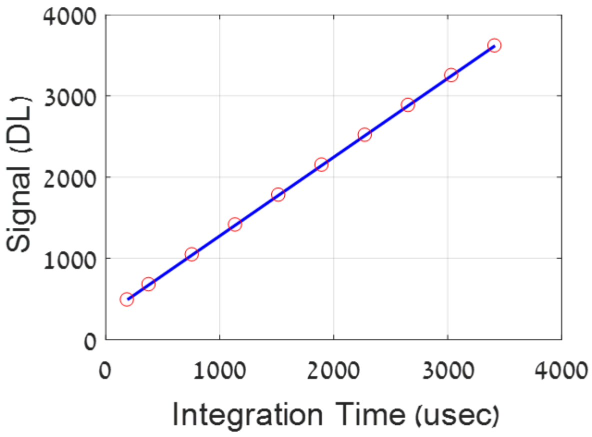


Figure 6: top: Squared temporal noise averaged over all pixels of the FPA versus the average signal; bottom: NETD image at 70% well fill (scale in K)



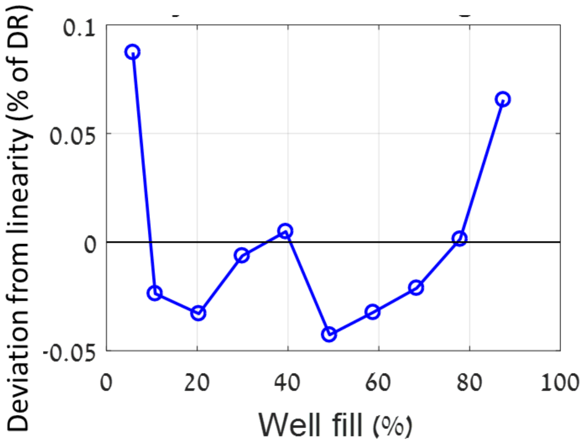


Figure 7: Top: Signal linearity. Bottom: Deviation from linearity between 5% and 85% well-fill

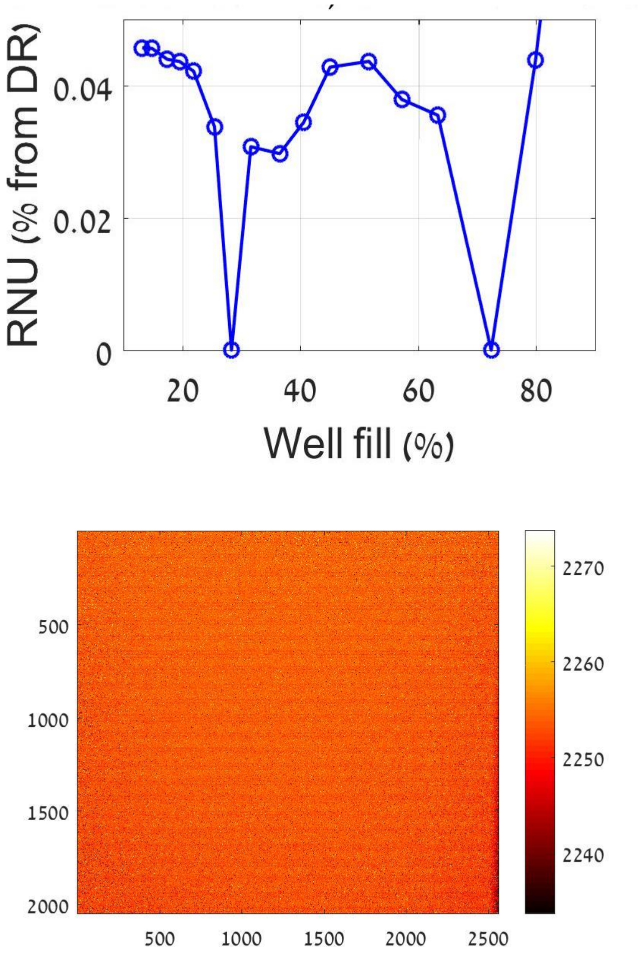


Figure 8: Top: Image from the FPA in front of a uniform target (in digital levels) after applying a 2-point NUC. Bottom: Residual Non Uniformity between 2% and 80% well-fill as a percentage of the Dynamic Range.

## 3. LOW SWAP CRANE IDCA

When integrated into a Dewar with a cryo-cooler and connected to an Electronic Proximity (Proxy) board the FPA is ready to operate. The Integrated Detector Cooler

Assembly (IDCA) makes a compact MWIR detector that generates a 12 Bit image from 5 million pixels and operates at a frame rate of 60Hz with a total power consumption of less than 10Watt. Despite the large format of the FPA, due to the very small pixel size, the high operating temperature and the relatively low power consumption of the ROIC, the Crane IDCA is integrated into a compact package of less than 360g weight.

The Dewar is based on a rugged envelope with low thermal conductivity and stiff cold finger. The structure and the geometry were optimized to achieve sub-pixel lateral movement of the FPA when subject to realistic external vibrations. The Electronic Proximity board was designed to support the very high data rates from the ROIC. It consists of an FPGA that samples the digital data coming out from the ROIC at JESD204B format and converts the data to standard 4 channel CoaXPress video format, supporting a video data rate of up to 4×5Gbps . The power supply and the synchronization signals are delivered to the Proximity Electronics through the same interface (power over CoaXPress). The system controls the detector through standard GeniCam protocol.

| Detector parameter | Value |
|---|---|
| Format / pitch | 2560 × 2048 / 5µm |
| FPA spectral band | 1.7 – 4.2 µm |
| Quantum Efficiency | > 70% |
| Dark current | 200fA at 150K |
| IDCA spectral band | 3.6 – 4.2 µm |
| F# | 1.6 |
| NETD | 47mK at 70% WF |
| Global RNU | 0.25Me- / 0.06% of DR<br>0.6 Me- / 0.06% of DR |
| Local RNU | 0.25Me- / 0.04% of DR<br>0.6 Me- / 0.04% of DR |
| Operability | > 99.5% |
| IDCA maximal frame rate | 60Hz (12 bit) |
| Cooler | Stirling rotary cooler optimized to 150K |
| Cooler power consumption | 4 W at 23°C |
| Proxy power consumption | 5 W at 23°C |
| Video output | 4 channel - CoaXPress |
| Size | 88 × 71 × 68 mm3 |
| Weight | 360g |

Table 2: Main performance parameters of the Crane IDCA

## 4. SUMMARY

In Figure 9 we present an image from the Crane IDCA with 75 mm optics. The new detector is a compact, large format, small pitch MWIR sensor designed for high resolution, large FOV, and low SWaP electro-optical systems. The Crane IDCA combines 5µm pitch XBn array that operates at 150K, advanced ROIC for low power consumption, compact Dewar and low SWaP cryo-cooler, and customized Proximity electronics. The excellent electro-optical characteristics of the Crane detector enable a high-end solution for a variety of defense and commercial applications.

Figure 9: Image from the Crane detector. The mountains at the top are about 40km from the camera

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