3 Mega-pixel InSb Detector with 10 μm Pitch

G. Gershon, A. Albo, M. Eylon, O. Cohen, Z. Calahorra , M. Brumer, M. Nitzani, E. Avnon, Y. Aghion, I. Kogan, E. Ilan, and L. Shkedy

SemiConductor Devices (SCD), P.O. Box 2250, Haifa 31021, Israel

ABSTRACT

SCD has developed a new 1920x1536 / 10 μm digital Infrared detector for the MWIR window named Blackbird. The Blackbird detector features a Focal Plane Array (FPA) that incorporates two technological building blocks developed over the past few years. The first one is a 10 μm InSb pixel based on the matured planar technology. The second building block is an innovative 10 μm ReadOut Integrated Circuit (ROIC) pixel. The InSb and the ROIC arrays are connected using Flip-Chip technology by means of indium bumps. The digital ROIC consists a matrix of 1920x1536 pixels and has an analog to digital (A/D) converter per-channel (total of 1920x2 A/Ds). It allows for full frame readout at a high frame rate of up to 120 Hz. Such an on-chip A/D conversion eliminates the need for several A/D converters with fairly high power consumption at the system level. The ROIC power consumption at maximum bandwidth is less than 400 mW. It features a wide range of pixel-level functionality such as several conversion gain options and a 2x2 pixel binning. The ROIC design makes use of the advanced and matured CMOS technology, 0.18 μm, which allows for high functionality and relatively low power consumption. The FPA is mounted on a Cold-Finger by a specially designed ceramic substrate. The whole assembly is housed in a stiffened Dewar that withstands harsh environmental conditions while minimizing the environment heat load contribution to the heat load of the detector. The design enables a 3-megapixel detector with overall low size, weight, and power (SWaP) with respect to comparable large format detectors. In this work we present in detail the characteristic performance of the new Blackbird detector.

Keywords: Infrared Detector, InSb, Focal Plane Array, Large format FPA, 10 μm pixel.

1. INTRODUCTION

There is a growing demand over the last years for infrared detectors with large format in order to increase the system spatial resolution. This trend naturally yields a shift towards smaller pixel size, which allows higher resolution and wider field of view (FOV) in infrared imaging systems [1]. A smaller pixel size (pitch) thus enables the overall size of an FPA with a specific format to be reduced, or alternately, it allows a higher resolution for a given FPA dimension. SCD's roadmap of two dimensional (2D) InSb array detectors is aimed at answering these demands i.e. it reflects the continuing trend of pixel shrinkage and format growth in infrared 2D arrays. The roadmap started in 1997 with the introduction of 320×256 format, 30μm pitch detectors, and continued with the larger format of 640×512 elements and pixel sizes of 25, 20, and 15μm [2,3]. The shift to smaller pixel design required the migration from 0.5μm CMOS process to a more advanced, 0.18μm CMOS technology, to allow a higher value of capacitance per unit area, lower operating voltage which reduces power consumption, and a denser layout of devices to maintain a high level of functionality. The trend for larger format and smaller pitch continued with Hercules, an InSb detector with 1280×1024 pixels of 15μm pitch [4-5]. The new Blackbird detector is a natural step in this roadmap with 3 million pixels in the FPA and a pixel size of 10x10μm^2. The Blackbird design takes advantage of the knowledge and experience gained from its predecessors, to ensure maximum exploitation of the 0.18μm CMOS technology in terms of integration capacitance, power consumption, pixel readout rate, functionality, and readout noise. It features a self-controlled ROIC with several conversion gain options and an option for 2-by-2 pixel binning, both implemented at the pixel level. The ROIC with its 13 Bit sub-LVDS video output at a 120Hz frame rate combined with the newly designed 10μm pitch InSb diode array, makes Blackbird an attractive new Mid Wave Infra-Red (MWIR) detector for a wide range of applications. In this paper, the measured electro-optical performance of the new detector is presented. We describe the basic components and technologies which comprise the detector, as well as the detector's special features and performance.

2. ROIC

Since 2002 SCD has been manufacturing ROICs with analog to digital (A/D) conversion at the focal plane [6-7]. The 1920x1536 matrix readout circuit for the 10x10 μm^2 P-on-N InSb photodiode array is designed to operate at around 77K, and is implemented in the advanced 0.18μm CMOS process. For imager applications the main drawback of an advanced process such as 0.18-μm is noise sources such as 1/f, Random Telegraph Signal (RTS), and various leakage mechanisms, which tend to increase at lower temperatures. Special attention was paid to overcome these noise sources in the design of the previous generation 15 μm pitch Hercules and PelicanD ROICs and this issue is addressed further in the Blackbird ROIC, as dictated by the pixel size reduction. The ROIC features several conversion gain options implemented at the pixel level. By enabling different conversion gains at the pixel level, charge capacity can be traded off with readout noise and adapted for different applications and scenarios. The main integration capacitor is 2.5 Me$^-$ for both integrate-then-read (ITR) and integrate-while-read (IWR) operation modes where the ITR mode has better noise performance. Other effective capacitors available are the 4.5 Me$^-$, 0.6 Me$^-$ (ITR only), and the High Gain 0.3Me$^-$. Figure 1(a) presents a measurement of the squared noise as a function of the signal in the InSb FPA, while the integration time is varied. The linear ratio between the squared noise and the signal indicates shot noise limited detector. These results represent a fine readout process from the ROIC pixel without the introduction of any additional noise components. Another key parameter of the ROIC is its linearity. A measurement of the Blackbird linearity is presented in Fig. 1(b). The deviation from linearity is less than 0.06% of the full dynamic range from 5% to 90% capacitor well-fill. This result demonstrates the excellent linearity exhibited by Blackbird over almost the full dynamic range.

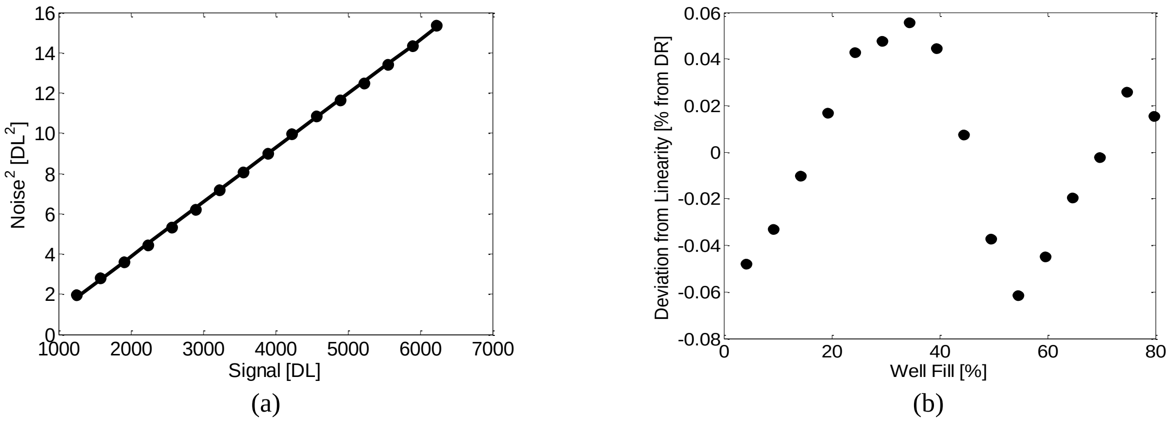
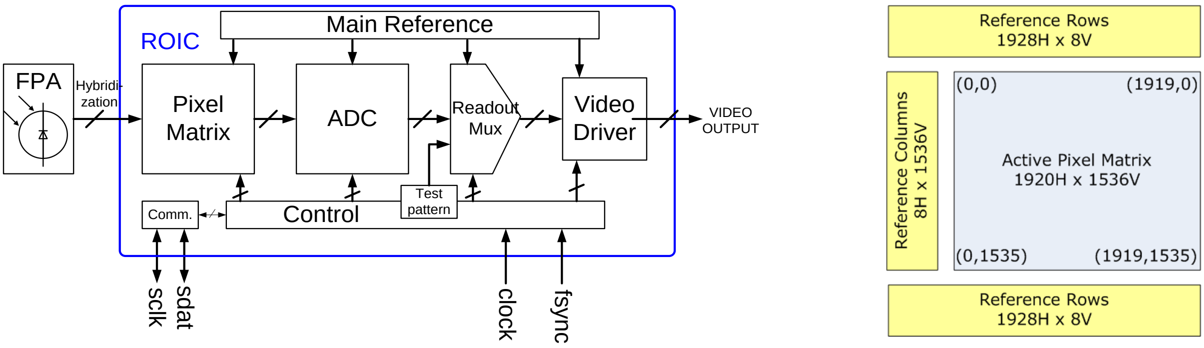


Fig. 1 (a) Squared noise as a function of signal in digital level measured for the Blackbird InSb FPA, where the integration time is varied **(b)** Deviation from linearity. The well-fill is varied using the integration time.

A 2-by-2 pixel binning feature is implemented at the ROIC level as well, improving Signal to Noise Ratio (SNR) and enabling higher frame rate by a factor of four for an effective 20μm pixel. The ROIC achieves a 120 Hz frame rate at the full format, with a power consumption of less than 400mW. A high speed digital video interface is developed to output the required data bandwidth at a reasonable pin count. The ROIC main features are:

- 3Mpxl, 10μm pitch,
- Multiple in-pixel gain modes,
- Simple interface and operation,
- Self-initialization from external E^2PROM,
- Internal frame sequence,
- Glue-less video output,
- Standard serial interface (E^2PROM compatible),
- 120 Hz maximum frame rate,
- Reduced bandwidth & power consumption modes,
- Reset options: software command reset, Hard reset,
- Temperature reading by video output,
- Direct-access temperature diode, available also when chip is off,

The dedicated column ADC is a Dual Ramp convertor. It is designed for low noise and low power consumption reaching less than 160 μV Input-Referred Noise and less than 35 μW power consumption per each column ADC, while reaching a 95 kHz sampling rate. The ROIC consists of two rows of 1920 column ADCs integrated on chip at opposites edges of the matrix including an output MUX (which multiplexes 1920x2 ADCs to the chip output). This MUX is compact enough not to increase the die size significantly, despite the 10 μm column pitch. Reading the pixel signals simultaneously with the 3840 column ADCs yields a total conversion rate of over 360 Mpxl/sec which enables full frame readout at 120 Hz. To output 1920 x 1536 pixels of 13 bits each, at a frame rate of 120 Hz, a data bandwidth greater than 4.6 Gbps (without taking into account headers and status bits) is required. A sub-LVDS based video output was developed where each sub-LVDS pair will output 560 Mbps by utilizing a low-jitter-low-power Phase Locked Loop (PLL) to multiply the input clock frequency, and a serializer to send the parallel pixel data over the serial link. The video outputs are arranged in a channel-link manner, each group including four lanes of data and one lane of sampling clock for receiver synchronization.



(a) (b)

Fig. 2 (a) ROIC functional block diagram. (b) A scheme of the pixel matrix structure

The ROIC is controlled through a standard serial communication protocol, as well as frame-sync. It enables 3 basic modes of frame readout rate which are termed Full-Rate, Half-Rate and Quarter-Rate. These modes enable lower power consumption at lower frame rates, as well as a reduced pixel rate at the video output. The reduction of pixel rate is achieved by operating only part of the video channels, which means a reduced pin count at the Dewar interface. This allows for system optimization by reducing the size, power and cost of the external electronics required to handle the data bandwidth. Additional functionality in the ROIC includes self-initialization from an external E^2PROM device. The same ROIC I/O pins serve also as an E^2PROM compatible communication port for system control. The ROIC enables windowing in the vertical direction and flipping the horizontal and vertical readout directions. The Blackbird ROIC's high functionality and autonomy along with its standard communication and video output allows integration to the system without a proximity electronics board. However such a board is present in the current application to act as a buffer to protect the ROIC.

3. DIODE ARRAY

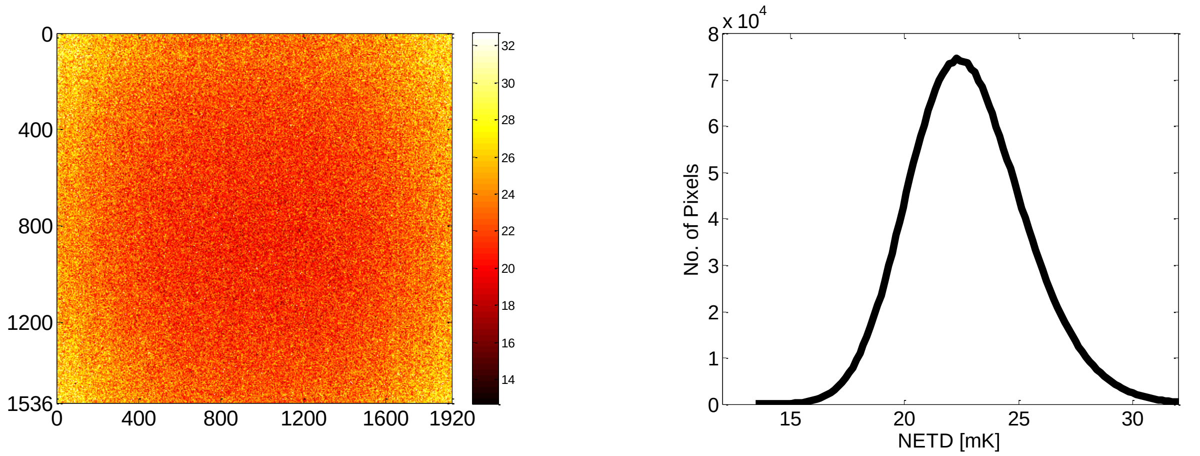
A fundamental building block of the Blackbird detector is the InSb diode array of 10x10 μm^2 InSb pixels based on the matured planar technology developed over the years at SCD [3]. The scale down of the 15μm pixel to 10μm pixel is not trivial. The increased ratio of surface to volume imposes new design rules to maintain key parameters such as high External Quantum Efficiency (QE) and low Dark Current ($I_{\mathbf{dark}}$). These parameters (and others) are also affected by the thickness of the active layer which, in its turn, needs to be controlled in order to achieve a small crosstalk between neighboring pixels. The InSb array is integrated to the ROIC using Flip-Chip technology by means of indium bumps, and those bumps are now smaller than the ones used for the 15μm pitch FPA. All those challenges are addressed and resolved in the Blackbird detector so that a high FPA performance with QE >80% and I_{dark} <1.3pA at 77K have been achieved.

4. ELECTRO OPTICAL PERFORMANCE

The performance of an array detector is determined by several key properties characterizing its sensitivity, homogeneity, and linear response. The sensitivity is normally defined by the Noise Equivalent Temperature Difference (NETD). The spatial fixed noise following a Non Uniformity Correction (NUC) procedure defines the Residual Non Uniformity (RNU). Usually the NUC is calculated linearly from two different signal levels. It is thus related to residual deviations from linear response in the FPA.

NETD & READOUT NOISE

The NETD is a key parameter in the evaluation of an IR detector. It is a measure of the detector's ability to register a temperature difference which causes a signal larger than the detector's noise. Due to the low readout noise and low dark current the NETD is background limited (BLIP) even at low well fill (low signal). However, at very low signal level the NETD is dominated by the readout noise (floor level noise), which is the temporal noise of the signal recorded at zero integration time. At null integration time there is no charge from the photodiodes in the integration capacitors, so the readout noise is a property of the ROIC, and is independent of the InSb diode. The readout noise is dominated by Johnson-Nyquist noise of the equivalent readout circuit [8]. Blackbird exhibits very good noise characteristics as can be seen in Table 1. The NETD is usually calculated at an averaged signal, corresponding to median well fill. In Fig 3(a), a map of the FPA NETD (per pixel) at 50% well-fill is presented for the 2.5 Me^- integration mode. As can be seen in the image, there are no spatial features in the temporal noise, indicating no additional noise mechanisms aside from the shot noise. In Fig. 3(b) the smooth Gaussian like histogram of the NETD is shown.

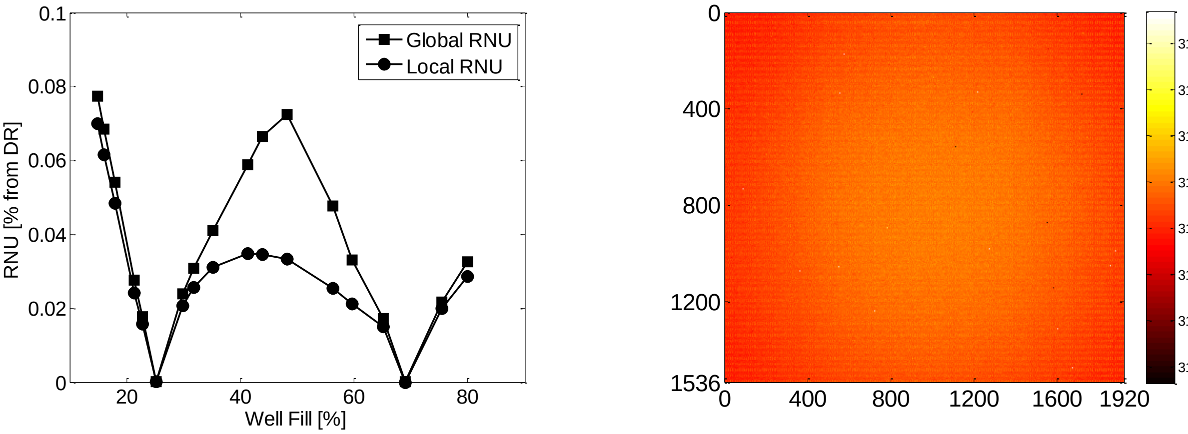


(a) (b)

Fig. 3 (a) NETD image at 50% well-fill, F/4, 77 K. The color scale is in mK. (b) NETD histogram of the data in Fig 3(a). The average NETD is 22.5 mK and the standard deviation is 2.5 mK.

RNU

The second key parameter with respect to the performance of two dimensional arrays is the uniformity of the pixels in the array. The uniformity is evaluated from an analysis of the corrected image after NUC [9]. Here we present the results for the standard linear 2-point NUC. Fig.1 demonstrates the excellent linearity of the ROIC over almost the entire dynamic range (DR) of the detector. Such high pixel linearity and its narrow distribution naturally yield a low RNU as can be seen in Fig.4.



(a) (b)

Fig. 4 (a) RNU as a function of well-fill at F/4, 77 K. The signal is varied by changing the black-body target temperature at constant integration time. (b) An image of a uniform target at 50% well-fill. The color scale is in digital levels. No Bad Pixel Replacement (BPR) was applied.

The measurement and analysis procedure for the RNU is as follows. The detector is placed in front of a uniform extended black-body and then a set of signal measurements is recorded for different blackbody temperatures, while the integration time is kept constant. Each signal measurement is an average of 64 consecutive frames in order to reduce the effect of the temporal noise on the spatial correction. The measurements at about 25% and 75% well-fill capacity are used to calculate the linear 2-point NUC coefficients. These coefficients are then used to correct all the other measurements. The quality of the correction is determined by the spatial standard deviation of all non-defective pixels in the FPA after the correction is applied, and is termed the RNU (at the correction points the RNU is zero by definition). When calculated for all pixels in the array the RNU is termed "Global RNU" and is affected by both low and high spatial pattern frequencies in the recorded image. The low frequency spatial patterns are dominated by the illumination effect caused by the cold shield shadowing of the uniform target ($\cos^4\theta$ effect). Due to this effect, when the averaged raw signal is around 85% well-fill, the central pixels are almost saturated (99% well-fill) and the pixel signal at the periphery is about 75% well-fill (for uniform illumination). This effect has a dramatic contribution to the global RNU. On the other end, the high frequency patterns usually originate from inhomogeneities in the FPA pixels. They are related to variance in the parameters of the individual pixels in both the ROIC and InSb arrays and can be traced back to the fabrication process of the two. This type of non-uniformity has white noise characteristics and it is local in nature and thus determines the ability of the detector to distinguish targets from their close environment. It is therefore useful to discriminate the high frequency spatial patterns from the low frequency patterns. To that aim we define the local RNU as the StD calculated over the 15×15 neighboring pixels of each pixel in the corrected image. As can be seen in Fig. 4 it is lower than the global RNU since low frequency patterns are filtered out. In Fig. 4(a) the RNU of the Blackbird is plotted, and it can be seen that the global (local) RNU of the Blackbird FPA is less than 0.08% (0.04%) StD/full span for a range of signals between 5-85% well fill capacity (the full capacity is 2.5 Me-) indicating the high quality of the array. In Fig. 4(b) an image of a uniform target is presented after non-uniformity correction. As can be seen, there is a dominant low spatial frequency residual non-uniformity, which is related to the residual illumination effect, and a lower random distribution of values which indicates white spatial noise. This result demonstrates that a high quality image is achieved for a wide range of signal with a high level of linearity, as already presented in Fig 1.

Table 1 summarizes the typical electro-optical characteristics for the different integration modes of the Blackbird detector.

Integration Capacity [Me$^-$]	**Readout Noise [e$^-$]**	**RNU [%DR]**	**Linearity [%DR]**
4.5	950_{IWR}	0.08_{Global} 0.05_{Local}	0.1
2.5	370_{IWR} 260_{ITR}	0.07_{Global} 0.04_{Local}	0.06
0.6	90_{ITR}	0.07_{Global} 0.04_{Local}	0.06
0.3	60_{ITR}	0.07_{Global} 0.04_{Local}	0.07

Table 1. Radiometric performance of all readout modes in one of the Blackbird FPAs.

5. DDCA CONFIGURATION

When packaged in a Dewar which is integrated with a cryo-cooler and an electronic proximity board the FPA is ready to operate. This Dewar Detector Cooler Assembly (DDCA) makes a compact MWIR detector that generates 13 Bit, 3M pixel images at a frame rate of up to 120 Hz with a total power consumption of less than 30 Watt at 71C. Despite the large format of the FPA, Blackbird has been designed to be integrated into a standard compact "Hercules" package. SCD has adapted its well established rigid Dewar technology from Blackbird's predecessors to fit the current detector. It is based on a rugged Dewar envelope with supporting strings which are connected to the cold finger. The structure and the geometry were optimized to give a high natural frequency. This results in a sub pixel lateral movement of the FPA when subjected to rough vibrations in the frequency range of 5-2000Hz. The resultant heat loads of the Dewar (and cold finger) at an ambient temperature of 71 ºC together with the power consumption of the ROIC at maximum frame rate give a total heat load of ~0.9 Watt. This load is well handled by an "off the shelf" standard 1W cryo-Cooler such as the K543 cooler manufactured by Ricor. The electronics proximity board that was designed for the Blackbird detector is based on the same concept as in the Hercules detector with a single power supply and a standard video output that enables a fast and easy integration of the detector into any system. However since the ROIC of the Blackbird detector is more self-controlled and since it outputs video has Sub-LVDS standard, the proximity board is simpler and has fewer functions to perform compared to the proximity boards in other digital detectors. The proximity board includes an FPGA, a local oscillator, power supplies and Flash memory components (see Fig. 5). A single supply of 5V±10% is supplied to the proximity board with a noise level up to 10 mV rms. The board power consumption is 3 Watt. The core of the proximity board is a Spartan 6 FPGA which serves as a buffer between the ROIC and the system. The FPGA samples the digital data which comes out of the ROIC and performs a simple conversion of the data from sub into normal serial LVDS resulting in a standard channel link interface to the system supporting a video data rate up to 2 Gbit/sec. The system controls the detector with a serial communication command through a standard I^2C protocol. The ROIC self-initiates from a preprogramed set of parameters saved to the proximity board E^2PROM memory. The DDCA comes in one configuration but is available with many modes of operation. This is a direct outcome of the simplicity of the ROIC for configuration changes such as Gain modes. Table 2 summarizes the Blackbird main specifications and Figure 6 presents a picture of the complete DDCA with its proximity electronics. Figure 7 shows image from the new

Parameter	**Typical value**
Format	1920x1536
Pixel Size	10x10 μm^2
Output	Digital 13 bit
Well Fill Capacity And Readout Noise	0.3Me$^-$ / 60e$^-$ .6Me$^-$ / 90e$^-$ 2.5Me$^-$ / 370e$^-$ (260e$^-$ ITR) 4.5Me$^-$ / 950e$^-$
Integration modes	ITR, IWR
Frame cycle control	Free running, System control
Maximum Frame rate	120 Hz (4 video ports) 60 Hz (2 video ports) 30 Hz (1 video ports)
FPA power consumption	400 mW (@ 120Hz) 230 mW (@ 60Hz) 150 mW (@ 30Hz)
Binning mode	2x2 (450Hz)
Cooler power steady state @ 23C	20 W
Weight	700 gr
RNU	0.07 STD/full span
NETD	< 24 mK
Operability	>99.5%

Table 2. Blackbird characteristics

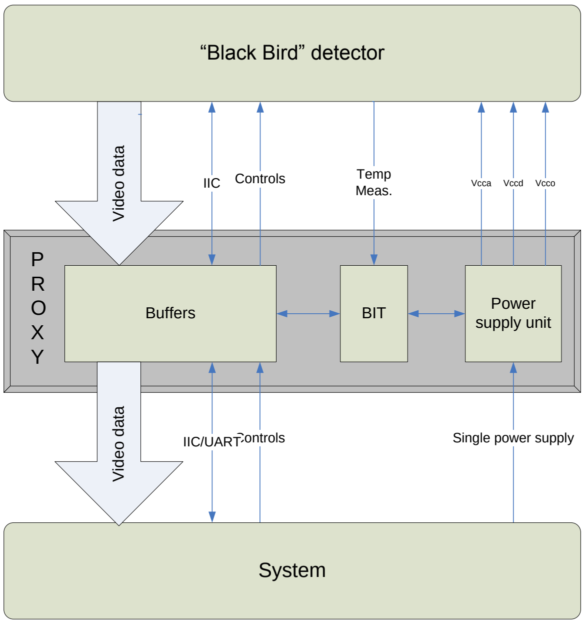


Fig. 5 Scheme of the proximity Electronic Board

Fig. 6 The Blackbird detector**.**

6. SUMMERY

In this paper we present the new Blackbird detector, a unique InSb cooled detector with a 10μm pitch and 1920X1536 pixels, designed for the MWIR spectral range. The development of the new ROIC and InSb diode array is a milestone in SCD's roadmap of cooled MWIR detectors with the aim of meeting the market trend of increased format and pixel shrinkage. The Blackbird detector electro-optical performance makes it a high-end IR detector. Moreover, the detector has relatively low Size, Weight and Power characteristics for such a large array.

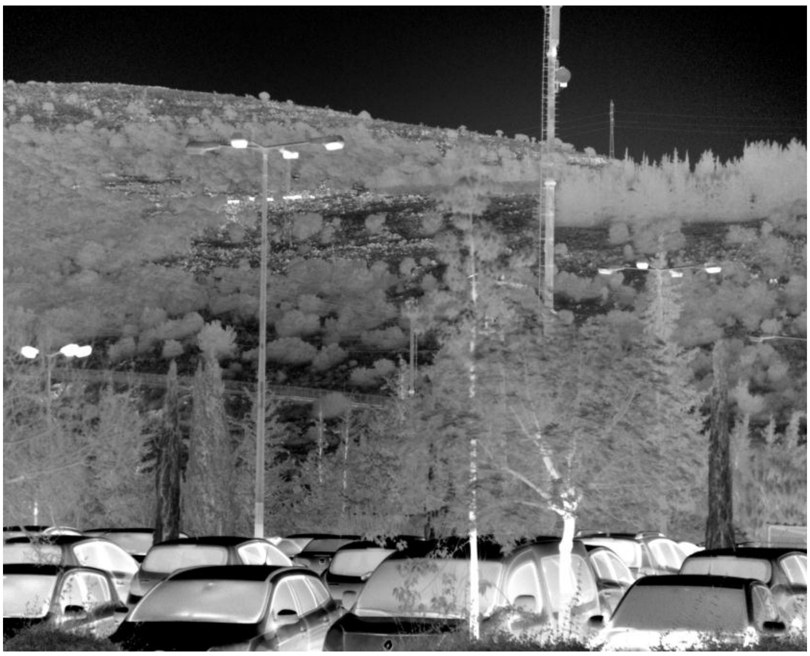


Fig. 7 Image from the Blackbird detector at F/3.

7. ACKNOWLEDGMENTS

The development of the Blackbird detector was supported by the Israeli Ministry of Defense (IMOD). The author would like to thank, E. Bogoslavski, Y. Hagbi, M. kinan, A. Zviagintsev, N. Shiloah, S. Elkind, R. Dobromislin, W. Freiman, R. Talmor, M. Regev, A. Liran, E. kuznitzky, I. Nevo, O. Cohen, I. Kogan, Y. Milstain, N. Syrel, S. Vaserman, N. Fishler, T. Schweirz, A. Fruman, K. Rozenshein, G. kabakov E. Teeni, I. Shtrichman for their important contributions to the development of the Blackbird detector.

REFERENCE LINKING

1. Driggers, Ronald G.; Vollmerhausen, Richard; Reynolds, Joseph P.; Fanning, Jonathan; Holst, Gerald C." how low should you go?" Optical Engineering, Volume 51, Issue 6, pp. 063202-063202-6 (2012).
2. O. Nesher and P. Klipstein, "High performance IR detectors at SCD present and future", *Proceedings of SPIE vol. **5957**, Infrared Photoelectronics,* August. 2005, pp 0S1-OS12
3. J. Oiknine Schlesinger, Z. Calahorra, E. Uri, O. Shick, T. Fishman, I. Shtrichman, E. Sinbar, V. Nahum, E. Kahanov, B. Shlomovich, S. Hasson, N. Fishler, D. Chen, T. Markovitz, " Pelican – SCD's 640×512/15 μm pitch InSb detector" *Proceedings of SPIE vol. **6542**, Infrared Technology and Applications XXXIII Conference* July. 2007, pp 654231-1-8
4. O. Nesher; I. Pivnik; E. Ilan; Z. Calalhorra; A. Koifman; I. Vaserman; J. Oiknine Schlesinger; R. Gazit. Hirsh, " High resolution 1280×1024, 15 μm pitch compact InSb IR detector with on-chip ADC" Proceedings of SPIE, Vol. 7298 Infrared Technology and Applications XXXV April 2009
5. Lior Shkedy; Tuvy Markovitz; Zipora Calahorra; Itay Hirsh; Itay Shtrichman, " Megapixel digital InSb detector for idwave infrared imaging". Proceedings of SPIE Vol. 50 Optical Engineering 50(06), 061008 May 2011
6. Shimon Elkind, Amnon Adin, Itzhak Nevo and Arkady B. Marhasev, "Focal plane processor with a digital video output for InSb detectors", *Proceedings of SPIE vol. **4820**, Infrared Technology and Applications XXVIIIConference*, July. 2002, pp 751-757.
7. O. Nesher, S. Elkind, A. Adin, I. Nevo, A. B. Yaakov, S. Raichshtain, A. B. Marhasev, A. Magner, M. Katz, T. Markovitz , D. Chen, M. Kenan A. Ganany, J. Oiknine Schlesinger and Z. Calahorra, " A Digital Cooled InSb Detector for IR Detection", *proceedings of SPIE vol. **5074**, Infrared Technology and Applications XXIX Conference,April. 2003, pp 120.*
8. Elad Ilan, Niv Shiloah, Shimon Elkind, Roman Dobromislin, Willie Freiman, Alex Zviagintsev, Itzik Nevo, Oren Cohen, Fanny Khinich, Amnon Adin, Ron Talmor, Yaakov Milstain," A 3Mpixel ROIC with 10um pixel pitch and 120 Hz frame rate digitaloutput " *proceedings of SPIE vol* 8659, Sensors, Cameras, and Systems for Industrial/Scientific Applications XIV 3 - 7 February 2013
9. SHKEDY L. ; AMIR O. ; CALAHORRA Z. ; OIKNINE-SCHLESINGER J. ; SZAFRANEK I. " Temperature dependence of spatial noise in InSb focal plane arrays" Proceedings of SPIE, the International Society for Optical Engineering ISSN 0277-786X 2000, vol. 4028.