Development of low SWaP and low noise InGaAs detectors

R. Fraenkel, E. Berkowicz, L. Bikov, R. Elishkov, A. Giladi, I. Hirsh, E. Ilan
C. Jakobson, P. Kondrashov, E. Louzon, I. Nevo, I. Pivnik, A. Tuito* and S. Vasserman

SemiConductor Devices, P.O. Box 2250, Haifa 31021, Israel

*** Israel MOD**

ABSTRACT

In recent years SCD has developed InGaAs/InP technology for Short-Wave Infrared (SWIR) imaging. The first product, *Cardinal 640*, has a 640×512 (VGA) format at 15µm pitch, and more than two thousand units have already been delivered to customers. Recently we have also introduced *Cardinal 1280* which is an SXGA array with 10µm pitch aimed for long-range high end platforms [1].

One of the big challenges facing the SWIR technology is its proliferation to widespread low cost and low SWaP applications, specifically Low Light Level (LLL) and Image Intensifier (II) replacements. In order to achieve this goal we have invested and combined efforts in several design and development directions:

1. Optimization of the InGaAs pixel array, reducing the dark current below 2fA at 20° C in order to save TEC cooling power under harsh light and environmental conditions.
2. Design of a new "Low Noise" ROIC targeting 15e noise floor and improved active imaging capabilities
3. Design of compact, low SWaP and low cost packages. In this context we have developed 2 types of packages: a non-hermetic package with thermo-electric cooler (TEC) and a hermetic TEC-Less ceramic package.
4. Development of efficient TEC-Less algorithms for optimal imaging at both day-light and low light level conditions.

The result of these combined efforts is a compact low SWaP detector that provides equivalent performance to Gen III image intensifier under starlight conditions. In this paper we will present results from lab and field experiments that will support this claim.

Keywords: Infrared Detector, Focal Plane Array, InGaAs, low SWaP, low light level

1. INTRODUCTION

In recent years SCD has developed InGaAs/InP technology for Short-Wave Infrared (SWIR) imaging. The first product, *Cardinal 640* with 640x512 format and 15µm pitch, was launched in 2013 and since then more than two thousand units have already been delivered to numerous customers [2-4].

The SWIR technology offers many benefits for a variety of electro-optical systems and applications: the image is reflective and thus more natural and intuitive compared with thermal. It penetrates fog and haze much better than CCD or CMOS detectors, especially for long range distances. For low light level conditions it can utilize the night glow phenomenon and unlike standard image intensifiers it can address the full intensity spectrum (from daylight to overcast). Another important advantage is the capability to perform active or gated imaging with "eye-safe" laser source [5].

However one of the big challenges facing the SWIR technology is its proliferation to widespread low cost and low SWaP applications. Specifically hand held (HH) platforms, Low Light Level (LLL) and Image Intensifier (II) replacements. In order to achieve this goal one needs to address a few key issues:

- Minimize battery power dissipation for both detector and video engine. The treatment of the video engine is beyond the scope of this article, but for the detector level we need to optimize the ROIC and save TEC cooling power.
- Improve the sensitivity specifically for harsh and low light level scenarios. In this context it is imperative to reduce the ROIC floor noise as much as possible since it sets the ultimate SNR limit.
- Implement compact and low cost packaging solutions in similar manner to uncooled μ-Bolometer applications such as hand-held or TWS systems.
- Maintain high image quality with minimal spatial or residual non-uniformity (RNU) effects.

Facing this challenge SCD has invested efforts in recent years in several design and development directions:

1. Optimization of the InGaAs pixel array, reducing the dark current below 2fA at 20° C in order to save TEC cooling power under harsh light and environmental conditions.
2. Design of a new "Low Noise" ROIC targeting 15e floor noise and improved active imaging capabilities
3. Design of compact, low SWaP and low cost packages: a non-hermetic package with thermo-electric cooler (TEC) and hermetic TEC-Less ceramic package.
4. Development of efficient correction algorithms for optimal imaging at both day-light and low light level conditions.

The result of these combined efforts is a compact low SWaP detector that is intended to provide equal or even better performance than Gen III image intensifiers under starlight conditions for various hand-held applications.
The paper is organized as follows: In section 2 we describe the performance of the new low dark current pixel array. This is followed with the description of the "Low Noise" ROIC in section 3. In section 4 we elaborate on our low SWaP packaging solutions. Finally in section 5 we present electro-optical characterization results.

2. OPTIMIZATION OF THE PIXEL ARRAY

The new design is based on the mature 15μm P-i-N pixel technology that was developed a few years ago. The main challenge facing us was the reduction of the dark current without hampering the other essential attributes such as quantum efficiency (QE), Cross Talk (XT), uniformity and operability.

Figure 1 shows the dark current map and histogram distribution for a typical FPA. The average value is 1.5fA at 20° C with narrow distribution. Despite the lower dark current the uniformity and operability are still very high similar to our standard production line.

MTF measurements for various pixel designs are presented in Figure 2. The measurements were performed using Point Spread Function (PSF) measurement setup with a cavity Black Body (BB) set typically to 1000° C. The radiation is passed through a filter wheel with a selected narrow-band filter at 1.5μm and diffraction limited SWIR lens optics. The FPA is set on a translation stage which is controlled by a precision DC motor controller. The pixel's net spatial photo-response is calculated by de-convoluting the measured 2D spatial response with the theoretical diffraction limited beam. The extracted MTF is higher than 0.4 at Nyquist frequency for all combinations. The ideal curve for a 15μm pitch is added for reference.

Quantum Efficiency (QE) measurements were performed with a halogen/tungsten lamp, passed through a 1550nm bandpass filter and integration sphere. The illumination intensity is measured independently and controlled by a sphere-optics variable aperture setup. Our measurements show that the new design preserves the existing QE and responsivity values.

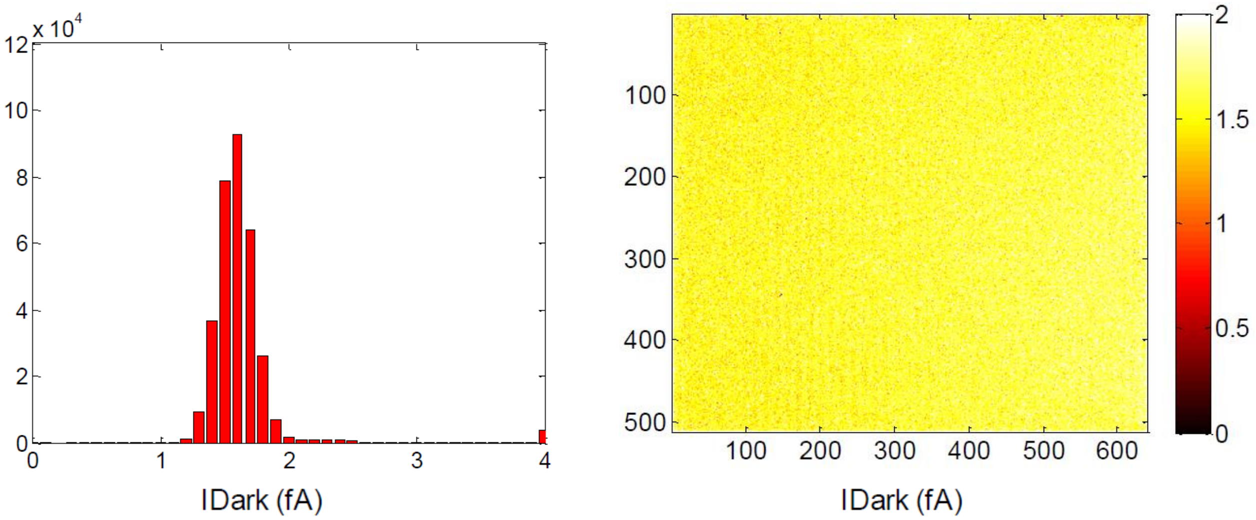

Figure 1: Dark current histogram distribution (left) and map (right) of the FPA. Measurement temperature is 20° C.

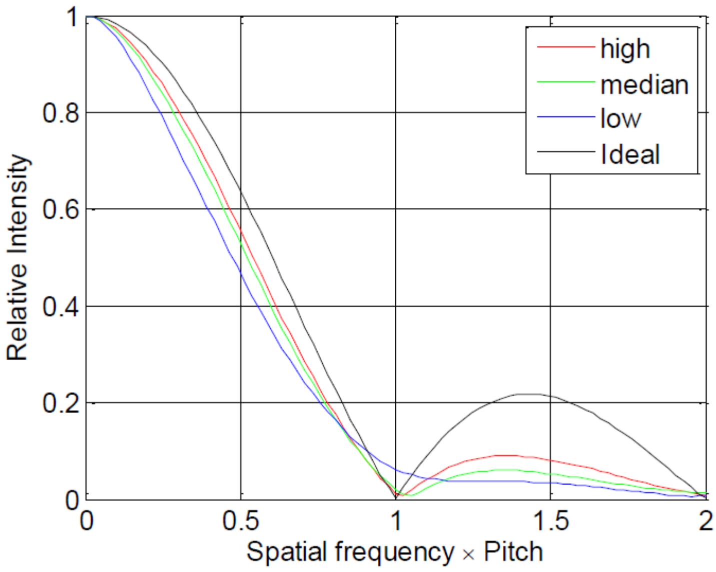

Figure 2: Extracted FPA pixel MTF for various pixel designs. (Ideal curve is added for reference)

3. LOW NOISE ROIC

The New "Low Noise" (LN) ROIC is a successor to the multifunction SNIR [4]. While the periphery and the interface are based on the SNIR architecture, the pixel design and the special operation modes were optimized for low readout noise and improved active imaging which is of great importance in many SWIR applications [5, 6]. The ROIC's main features are:

- Snapshot integration with 13 bit on-chip ADC.
- Improved low light level (LLL) passive imaging with a readout noise design target of 15e-.
- Low gain IWR imaging (0.3Me- capacitance)
- Improved active / gated imaging (< 0.1μsec for a small window size)

- High dynamic range (HDR) mode with consecutive integrations
- 320Hz Maximum frame rate (with IWR mode)

The ROIC basic specification is exhibited in Table 1:

Parameter	**value**		**Unit**
High Gain (ITR + CDS)			
Capacity	15		ke^{-}
RO Noise	15		e^{-}
Maximum Frame Rate	160		Hz
Integration Time	100-100000		µsec
Low Gain 300ke (IWR or ITR + CDS)			
Mode	IWR	ITR +CDS	
Capacity	300		ke^{-}
RO Noise	140	100	e^{-}
Maximum Frame Rate	320	160	Hz
Integration Time	1-100000		µsec
Gated Imaging with CDS			
Response Time (Tau)	100		nsec
Noise	30		e^{-}
Minimum Window Size	64x64		
Active Imaging with CDS			
RO Noise	15		e^{-}
Minimum CDS reference time	10		µsec
Minimum Window Size	160x160		
Minimum Integration time	1		µsec

Table 1: Low Noise ROIC basic specification for different modes of operation

We now elaborate on the various operation modes of the ROIC:

- **Low light level imaging** – the Capacitive Trans Impedance Amplifier (CTIA) "High Gain" mode supports low light level scenarios. The capacitor is 15Ke- per pixel with a readout noise target of 15 electrons (with Correlated Double sampling (CDS)). This is a substantial improvement from a level of 35 electrons in *Cardinal 640.*
- **Low gain daylight imaging** – for daylight imaging the ROIC provides 2 options. Either an Integrate-While-Read (IWR) 0.3Me- capacitor that supports maximum frame rate of 320Hz or an Integrate-Then-Read (ITR) mode. When applying CDS in ITR mode the readout noise is expected to reduce to 100 electrons.
- **Active and gated imaging** – active and gated imaging are implemented in both military and commercial applications [5, 6]. Hence a considerable effort was invested in optimizing these features in the new ROIC. The time constant for various regions of interest are summarized in Table 2. Due to power constraints the lowest time constant is limited to a 64x64 window.

Another important feature is the High Dynamic Range (HDR) mode that extends the IWR capabilities to multiple reads from A & B without stopping integration. This can extend the dynamic range considerably compared with standard integration. The extension on the dynamic range depends upon the number of reads and the time ratio between consecutive reads. For example, reading the image three times with a time ratio x8 between reads extends the dynamic range by 36dB.

The ROIC is currently in final stages of production and we expect to have first samples in the beginning of Q3/17.

Time constant [μs]	Window size [pixels]
0.6	448x448
~0.4	256x192
0.1	64x64

Table 2: Gated imaging time constant for various Regions of Interest (ROI)

4. LOW SWAP PACKAGE

One of the main challenges we faced was to simplify the packaging process which is a major part of the detector cost structure. Traditional SWIR packages include a Thermo-Electric Cooler (TEC), ceramic substrate and a high grade Sapphire window. The package should be vacuum pumped to support the full cooling capability of the TEC (typically ~ 50° C at ambient temperature). As in uncooled μ-Bolometer detectors, the new concepts rely on cheaper bill of material (BOM) and utilize a fully automatic process flow. As a result the cost is reduced remarkably.

We have designed 2 types of packages: a hermetic ceramic "Tec less" package aimed mainly for commercial applications and an adhesively sealed "PCB" type substrate with a TEC for purged cameras and systems. Both designs have a BK7 window, the foot print is 25x20 mm and the weight is lower than 15 grams. Thus they provide an ideal low Size, Weight and Power (SWaP) solution for portable and hand-held systems. These packages are shown in Figure 3.

Figure 3: Image of the InGaAs detector in Ceramic package (left) and in "PCB" type package (right)

Despite the low cost design both packages adhere with the toughest environmental constraints required by military grade systems such as weapon sights:

- -40° C to +70° C for operating temperature range
- -50° C to +85° C for non-operational storage
- Weapon sight vibration and shock profiles

5. ELECTRO-OPTICAL PERFORMANCE

We tested the image quality of the current *Cardinal 640* FPA for "Tec less" performance in front of a uniform integration sphere. The image was corrected with a single gain correction array and two offset correction arrays taking into account both FPA temperature and integration period variations. The results are exhibited in Figure 4 where we present the Residual Non Uniformity (RNU) as a percentage of the dynamic range vs. Well fill: For various combinations of FPA temperature (up to 40° C), illumination levels and integration periods the local RNU (blocks of 25x25 pixels) is bounded by the temporal noise (dashed curve). We can conclude that the non-uniformity correction algorithm is powerful and robust.

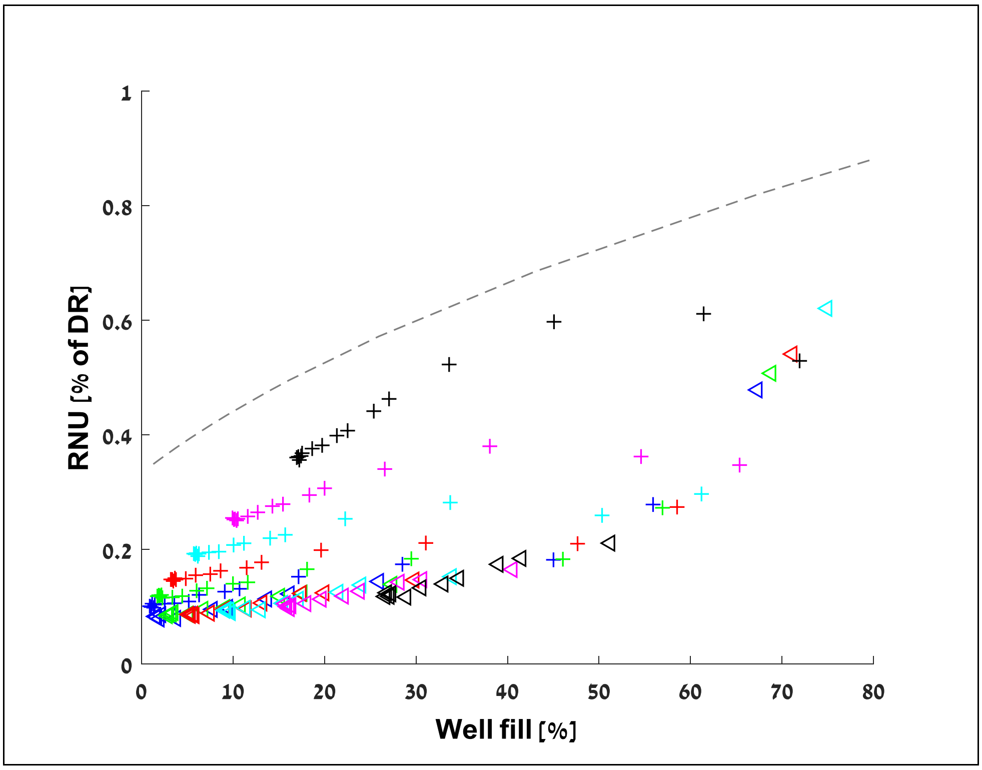

Figure 4: Local RNU vs. Well fill (dashed curve is the calculated temporal noise)

As discussed above, our main goal is the proliferation of SWIR technology to widespread low cost and low SWaP applications. Among these platforms Low Light Level (LLL) and Image Intensifier (II) replacements are the "Holy Grail" with literally hundreds of thousands systems deployed world-wide.

The potential advantages of SWIR cameras over existing II tubes are quite obvious: fully digital video output, day-light and night imaging, higher reliability and support of active and gated imaging. On the other hand they are still considered inferior in terms of power dissipation, resolution, sensitivity and cost. We believe that in the near future as technology advances various ASIC based solutions will provide lower power electronics. Also, high definition formats will become more widespread and affordable. Our innovative packaging solutions will certainly drive the costs down especially for high volume production.

The sensitivity was thoroughly examined with side by side field experiments comparing our SWIR demonstrator camera (based on the *Cardinal 640* FPA) with Gen II and Gen III image intensifiers. These measurements were conducted in remote areas on several moonless nights under starlight conditions. The image was considerably better than Gen II and comparable to the Gen III system. It should be noted that the floor noise was about 35 electrons and we expect to reach even better performance with the new ROIC.

A typical image captured under starlight conditions is shown in Figure 5. The persons are at a distance of 100m and the terrain in the background is very clear. For this setup we used an F/1.5 50mm lens.

Figure 5: SWIR Image (with Cardinal 640 FPA) captured under starlight conditions (F/1.5, 50mm focal length)

6. SUMMARY AND CONCLUSIONS

In this paper we have presented our work and achievements towards the proliferation of the SWIR technology to widespread low cost and low SWaP applications, specifically Low Light Level (LLL) and Image Intensifier (II) replacements. The result of these efforts is a compact detector that provides equal or even better performance than a Gen III image intensifier under starlight conditions.

We believe that with further reduction in power dissipation and improved resolution SWIR technology holds the potential to replace existing II tube based systems.

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