OPTRO-2014 - 2930312

MULTI-FUNCTION InGaAs DETECTOR FOR SWIR IMAGING

Lior Shkedy(1), Alina Koifman(1), Avihoo Giladi(1), Avi Tuito(2), Elad Ilan(1), Ilana Grimberg(1), Itay Hirsh(1), Leonid Bykov(1), Rahel Elishkov(1), Rami Fraenkel(1) and Shay Vasserman(1)

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

(2) Isreal MOD

KEYWODS: SWIR, Infrared Detector, InGaAs, SNIR, Low Light Level imaging

ABSTRACT:

Imaging in the Short-Wave Infra-Red (SWIR) has some advantages over imaging in the visible spectrum or over thermal imaging in the MWIR or LWIR. InGaAs/InP technology with a cut-off wavelength of 1.7 μm allows for two-dimensional (2D) detector arrays with high electro-optical performance at room temperature. For optimal performance, such detectors can be moderately cooled and temperature stabilized using a Thermo-Electric Cooler (TEC). This results in a small package with low power consumption, and relatively low production costs.

SCD's "Cardinal 640" detector consists of a 640×512/15μm InGaAs array which is coupled to the multi-function SNIR Read-Out Integrated Circuit (ROIC) using Flip-chip bonding. The ROIC has a "high gain" mode with a low readout noise of ~40e$^-$ (including Correlated Double Sampling), specifically designed for typical SWIR signals. The SNIR ROIC also implements several functionalities in each pixel, which traditionally have been implemented at the system level, such as Asynchronous Laser Pulse Detection (ALPD) and 2D Laser Range Finding (TLRF). The Focal Plane Array (FPA) is integrated into a metallic package and is assembled with a low power proximity electronics board, which controls the ROIC and the TEC, and delivers Camera Link output to the system. The overall power dissipation is 1.5W, not including TEC cooling which is required in some applications.

In this work we report on the electro-optical characteristics of the "Cardinal 640" detector. The performance figures are based on measured results from over 150 detectors manufactured by SCD over the last year. The dark current density is typically below 1.5 nA/cm^2 at 280K, the Quantum Efficiency is higher than 80% at 1.55 μm, and the operability is higher than 99.5%.

1. INTRODUCTION AND BACKGROUND

The Short Wave Infra-Red (SWIR) spectral band lies between the visible (VIS) spectral band and the Mid-Wave Infra-Red (MWIR) band and enjoys the benefits of both. On the one hand, the wavelength is shorter than the MWIR and so the spatial resolution is better, and on the other hand the wavelength is longer than the VIS which results in better atmospheric transmission. Another advantage of SWIR imaging over MWIR is its reflected light image rather than an emissive picture, which supports improved identification capabilities. However, a reflected image needs a source of illumination, which would be a problem at night if not for the “night glow” [1].

Taking these advantages into account it is clear why InGaAs detectors are ideal for low Size Weight and Power (SWaP) applications. InGaAs detectors have high resolution with small optics, they do not need significant cooling or high vacuum to reach high performance and the natural "night glow" illumination gives them an advantage over VIS and Near Infra-Red (NIR) detectors for low light conditions. However, in order to exploit the aforementioned advantages to produce a quality image, the detector must have very low temporal and spatial noise, low dark current, small size pixels and large array format. Moreover, to compete with other SWIR solutions, low power consumption of the Readout Integrated Circuit (ROIC) and proximity electronics is crucial.

In this work we present SCD's 640×512, 15 µm pitch InGaAs detector, "Cardinal 640", which meets these requirements. The InGaAs diode array is Flip Chip bonded to the SNIR ROIC, which was described extensively elsewhere [2,3,4]. This is a digital ROIC with very low readout noise and excellent linearity and uniformity. The ROIC also supports special modes like Laser Range Finding (LRF), which eliminates the need for a dedicated LRF sensor and thereby allows for even further miniaturization of the system.

In this paper the electro-optical characteristics of the "Cardinal 640" are presented. The performance figures are based on measured results from over 150 detectors manufactured by SCD over the past year.

2. InGaAs FOCAL PLANE ARRAY

The SWIR sensing array consists of a typical *p/n* InGaAs on InP heterostructure. The *p/n* junctions are fabricated by diffusion process through InP windows and the passivation layers ensure high stability and reliability. The diode array is hybridized to the SNIR ROIC using SCD's mature 15 µm pitch Indium bump and Flip-Chip processes that were originally developed for the Pelican and Pelican-D InSb detectors [5]. Some modifications of the transition metals and hybridization parameters were needed and implemented accordingly. Backside illuminated InGaAs detectors are usually sensitive in the 0.9 to 1.7 µm region where the cut-on wavelength is due to absorption by the InP substrate. We have developed a thinning process of the InP substrate, thus opening the detector to response in the NIR and VIS regions as can be seen in Fig 1. In this Figure the spectral response of a typical InGaAs detector is presented. The response in the VIS spectral band is reasonable although inferior to the response in the SWIR band. The integral Quantum Efficiency (QE) over the spectral band of 0.9 to 1.6 µm is larger than 75% while the dark current density is below 1.5 nA/cm^2 at 280K. In Fig. 2 we present a histogram (left) and a 2D map (right) of the dark current in a typical InGaAs detector at ambient temperature (30 °C). The dark current has a mean value of 8 fA. As can be seen from the histogram, the distribution is narrow with a FWHM of less than 2 fA, and the map shows that the dark current is uniform over the array. This low and uniform dark current enables the detector to work at relatively high temperatures and reduces the cooling requirement. The dark current is diffusion limited and can be reduced by further cooling using the TEC for Low Light Level (LLL) imaging applications. Fig. 3 shows the median dark current at 10 °C for more than 150 FPAs produced over the past year. The small distribution of dark current over the FPAs emphasizes the controlled manufacturing process of the detector.

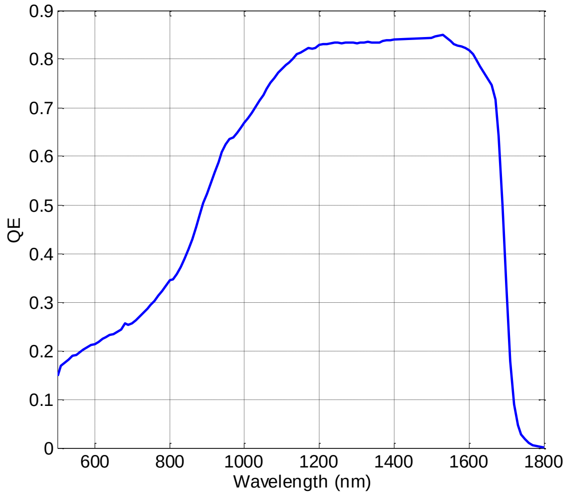


Figure 1: Quantum Efficiency (QE) vs wavelength for an InGaAs detector with the InP substrate removed

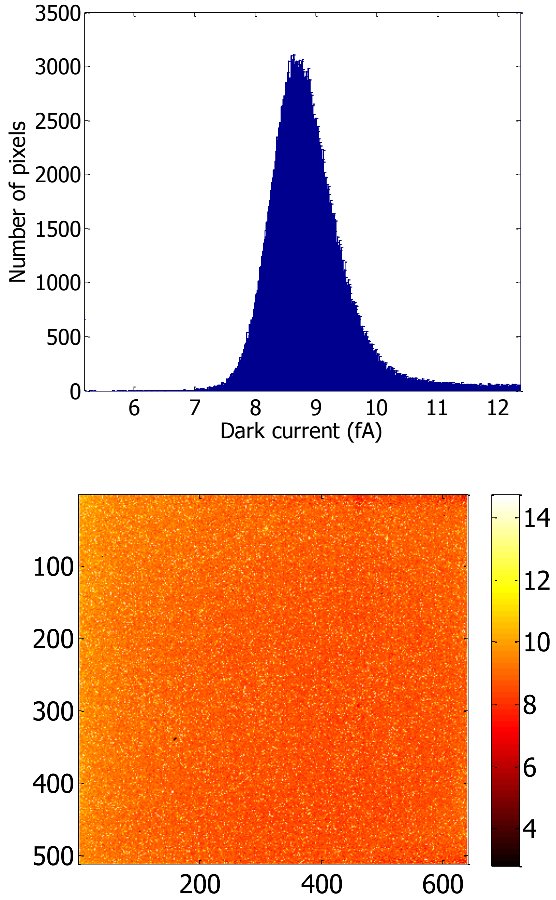


Figure 2: Up, a typical histogram of the dark current distribution at ambient temperature (30 ℃). Down, a 2D map of the dark current from the VGA array (scale in fA).

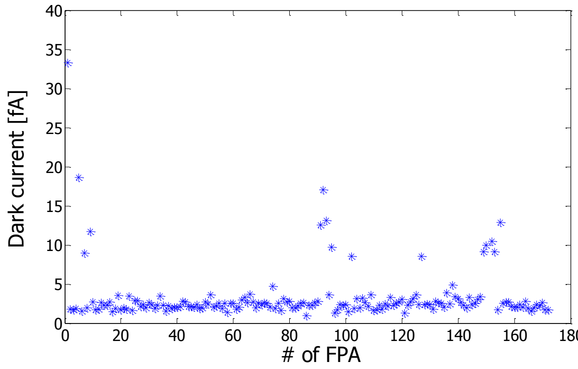


Figure 3: Average dark current of 170 FPAs produced over the last year. The dark current was measured at an FPA temperature of 10 ℃

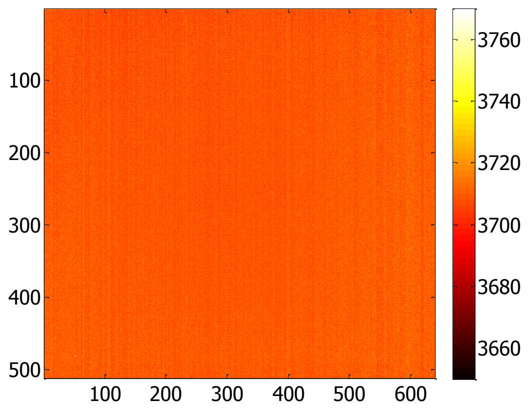
The SNIR ROIC offers the following advantages:

- Low power Analogue to Digital Converters (ADC) on chip. The overall ROIC power dissipation is less than 100 mW at 60 Hz, and requires no additional power of ADC at the system level.
- High frame rate of more than 350 Hz (full frame) at room temperature.
- Snapshot readout with low temporal noise.
- Excellent linearity of better than 0.1% of the Dynamic Range (DR) over almost the whole DR. Following a 2 point Non-Uniformity Correction (NUC), this reduces the spatial noise and allows for operation at continuous integration time, which is important for reflective scenery.

The ROIC supports several unique modes of operation [6] which are well adapted to the various SWIR applications:

- Standard IR Imaging (SIM)
- Low Noise Imaging (LNIM)
- Active LNIM
- Asynchronous Laser Pulse Detection (ALPD)
- Two Dimensional Laser Range Finding (TLRF)

The Standard Imaging Mode is similar to other SCD detectors that are open in the MWIR, and is suitable for high flux conditions that exist in the SWIR during daylight operation. The pixel signal is read via a Direct Injection (DI) readout circuit to an internal capacitor. Two readout capacitors are available in this mode and are selectable via serial communication. In Fig. 4, we present a 2 point corrected image in front of a uniform illumination from an integration sphere (left), and the Residual Non-Uniformity (RNU) as a percentage of the DR versus the capacitor well fill (right). The blue line represents the global RNU, which is the standard deviation (*std*) over all non-defective pixels, and the green line is the local RNU, which is the average over the whole array of the *std* for non-defective pixels in 15×15 pixels' regions. The quality of the image after correction is clear and without spatial patterns, and is maintained over most of the DR.



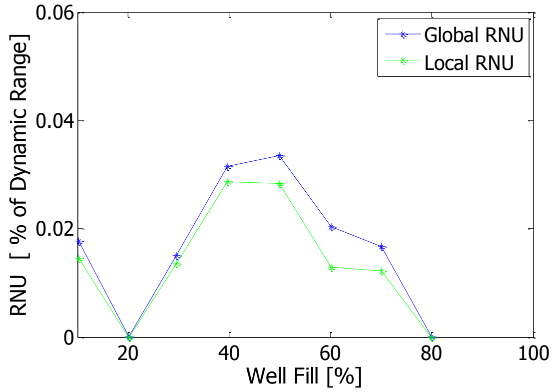


Figure 4: Up, a 2 point corrected image in front of a uniform illumination from an integration sphere at 50% of the full capacitor size. The scale is in Digital Levels (DL). Down, a W-curve of the RNU versus integration capacitor well-fill.

The LNIM is a low noise, high gain mode designed for LLL imaging applications in the SWIR. In this mode the diode current feeds a Capacitive Trans-Impedance Amplifier (CTIA) stage. The CTIA stage enables the use of a very small integration capacitor (12 Ke$^-$) with a noise down to 40 e$^-$ after Correlated Double Sampling (CDS), and provides a stabilized diode bias. The LNIM mode can also be useful for active imaging or gated imaging, where the target is illuminated by a high flux source and the integration time duration is short and centered at the distance to the desired target. In Fig. 5 the LNIM spatial and temporal noise in electrons of more than 150 FPAs produced in the last year are shown. The floor noise in the LNIM mode is shown in black, the global RNU is shown in red and the local RNU is shown in blue, respectively. As can be seen the difference between the global and local RNU is small and they are both lower than the readout noise for the LNIM mode. In Fig. 6 we present the number of defect pixels in these detectors. The small variations in the dark current (Fig. 3) and in the spatial and temporal noise (Fig. 5) between different detectors, as well as the relatively low number of defects (Fig. 6), demonstrates the high manufacturability of this detector.

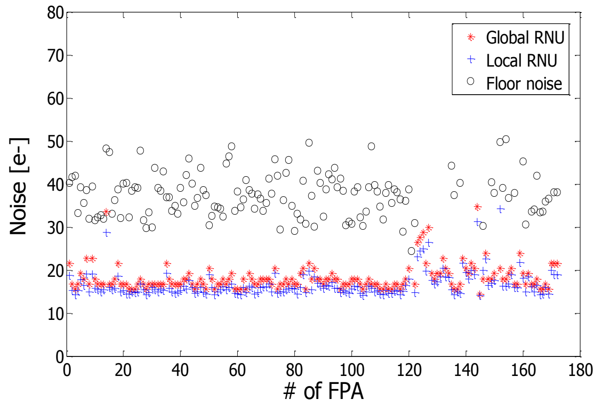


Figure 5: LNIM spatial and temporal noise (in electrons) for 170 FPAs produced over the last year.

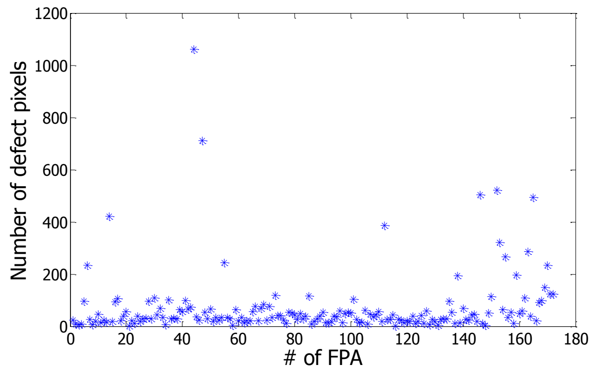


Figure 6: Number of defect pixels in 170 FPAs produced over the last year.

The InGaAs diode signal in the ALPD mode is read to an internal capacitor via a Buffered Direct Injection (BDI) circuit. The BDI circuit enables improved diode bias stabilization compared to a DI readout. It is especially important in cases of abrupt changes in the flux, which is common in SWIR applications. In this mode, on top of the standard imaging in two different gains, there is an additional bit at each pixel that designates asynchronous laser pulse detection during the frame time, independent of the integration time.

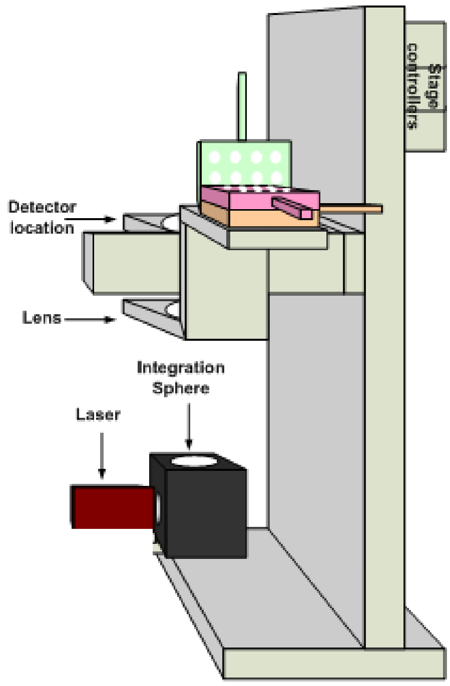


Figure 7: Schematic depiction of the active modes characterization setup. The detector is placed on an XYZ stage. A pulsed Laser goes through an integrating sphere and is imaged on the detector using a lens.

The TLRF mode is a non-imaging mode that is applied on a sub-window of the array. In this mode the pixel signal value does not indicate the charge collected by the diode, but rather the time registered by a temporal counter between the emission of a laser pulse from the system and the return of the pulse from the target which then stops the counter. The power consumption of the last two modes (ALPD and TLRF) is somewhat higher; however these modes offer wider capabilities over standard imaging.

It is possible to switch between the different modes SIM, TLRF, LNIM, and ALPD on a frame to frame basis. This can support a flexible operating sequence that meets a wide range of applications[3,4].

As part of manufacturing the detector an automatic characterization setup was built. The setup is described schematically in Fig. 7. The detector is placed on an XYZ stage. A pulsed Laser goes through an integrating sphere and is imaged on the detector using a lens. The temperature of the FPA, the position of the detector and the laser pulse characteristics are automatically controlled.

3. PACKAGE & PROXIMITY ELECTRONICS

Design for low SWaP was carried out at the level of the package and proximity electronics board (see Fig. 8). The FPA is integrated into a low size, 30×30 mm^2, vacuum sealed metallic package with a TEC that can cool down the FPA by up to 50°C with respect to the ambient temperature.

The electronics proximity boards include FPGA, local oscillator, power supplies and memory components. A single supply of 5 Volts is provided to the proximity board with a noise level of up to 10 mV RMS. The core of the proximity board is an FPGA which controls the ROIC operation and the data transmission to the system.

The FPGA samples the digital data from the ROIC and performs some basic processing such as pixel remapping and Correlated Double Sampling (CDS). The data is then converted into serial LVDS resulting in a standard Medium Camera Link interface. The system controls the detector with a serial communication command. This concept enables fast and easy integration of the detector into the system. Additionally, the board includes a digital TEC controller where the target FPA temperature can be chosen via a communication command.

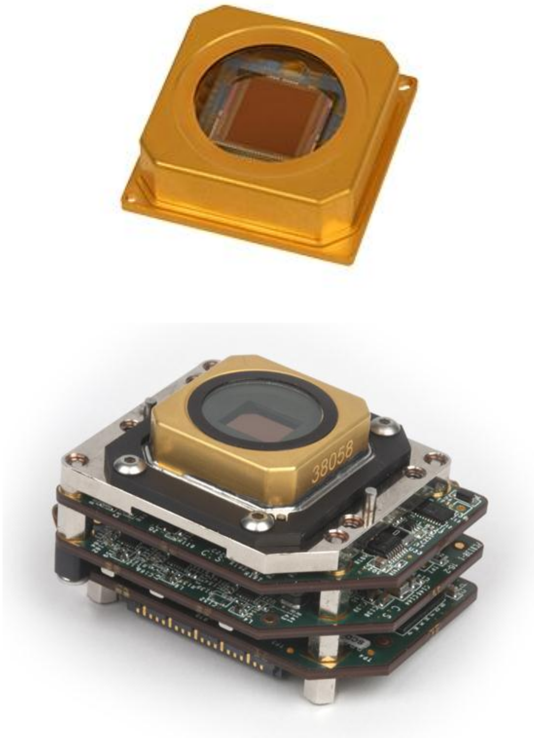


Figure 8: Up, an image of the InGaAs detector. Down, including the proximity electronics boards.

Tab. 1 summarizes the main parameters of the "Cardinal 640" detector.

Table1: "Cardinal 640" detector characteristics

Parameter	Typical Value
Dark current density	< 1.5 nA/cm^2 at 280K
Spectral Range	Standard: 0.9 – 1.7 µm (SWIR) Optional: 0.4 – 1.7 µm (VIS-SWIR)
QE	80% at 1550nm
Pixel operability	> 99.5%
Operating mode and well capacity	High Gain (Low Light Level imaging): 12 Ke^- Low Gain (high quality daylight imaging): 0.6Me^-,3Me^-
ROIC noise (typical)	45 e^- at high gain, following CDS

	180 e^- at low gain
Frame rate at full window	Up to 350 frames per second
FPA power consumption	100 mW at 60 Hz
Proximity electronics	Camera link interface Power dissipation < 1.5 W at 60 Hz, 25ºC
Cooling capabilities	-10 ˚C in a 40 ˚C environment

Finally, the "Cardinal 640" detector has successfully passed various qualification tests including accelerated life time tests which are equivalent to more than 10 years in relevant environmental conditions. In Fig. 9 and Fig. 10 we present the number of defects in the LNIM mode and the dark current, respectively, for 5 detectors at the beginning of the life test ('initial') and at the end of the test ('final'). As can be seen there is practically no difference between start and end, indicating no degradation in any detector during the test.

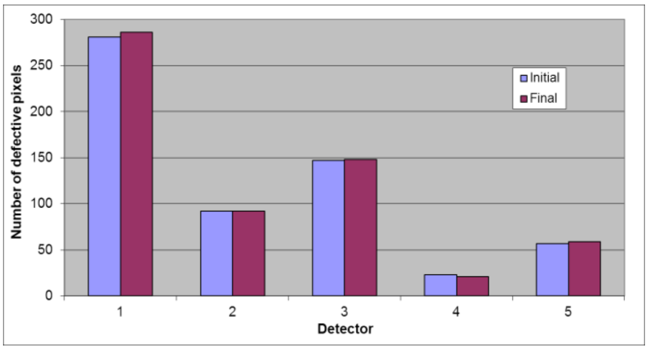


Figure 9: The number of defects for 5 detectors in the LNIM mode at the beginning of the life test ('Initial') and at the end of the test ('Final').

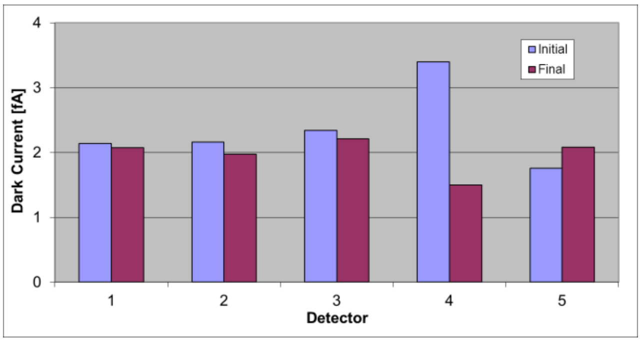


Figure 10: The dark current of 5 detectors at FPA temperature of 10℃ at the beginning of the life test ('Initial') and at the end of the test ('Final').

The "Cardinal 640" also passed successfully other qualification procedures such as thermal cycling and vibration tests according to relevant military standards.

4. SUMMARY

The electro-optical characteristics of the InGaAs "Cardinal 640" detector were presented. The performance figures were based on measured results from over 150 detectors manufactured by SCD over the past year. "Cardinal 640" is now a qualified product with high manufacturability.

ACKNOWLEDGMENTS

This work was supported by the Israeli Ministry of Industry, Trade and Labor (MOITAL) and the Israeli Ministry of Defense (IMoD) through the Hyper-Sensitive Photonics (HYSP) consortium.

REFERENCES

1. Midavaine *et al*. "Solid state low light level imaging from UV to IR, needs and solutions", Proc OPTRO 2010.
2. “SCD's Cooled and Uncooled Photo Detectors for NIR-SWIR”, Rami Fraenkel *et al.*, Proceedings of SPIE vol. 8353, Infrared Technology and Applications XXXVIII Conference, May. 2012, pp 835305.
3. "Advanced multi-function infrared detector with on-chip processing", Lidia Langof *et al*., Proceedings of SPIE vol. 8012, Infrared Technology and Applications XXXVII Conference, April 2011, pp 80120F-80120F-13
4. "Multi-function IR detector with on-chip signal processing", Lidia Langof *et al*., OPTRO 2012, February 2012.
5. "Pelican – SCD's 640×512/15 μm pitch InSb detector" J. Oiknine Schlesinger, *et al*., Proceedings of SPIE vol. 6542, Infrared Technology and Applications XXXIII Conference, July. 2007, pp 654231-1-8.
6. SCD (2011) *Detector pixel signal readout circuit and an imaging method* US Patent US 20120261553 A1 / EP2512125 A2.