International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

Infrared Detector Developments at Teledyne e2v for Current and Future Missions

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 12777, 1277760 · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2691107

Infrared Detector Developments at Teledyne e2v for Current and Future Missions

Ian Swindells*, Ross Wheeler, Paul Jerram, Jeremey Kendall, Iain Read
Teledyne e2v, 106 Waterhouse Lane, Chelmsford, CM1 2QU, UK

ABSTRACT

There is increased interest in hyperspectral imaging space missions as a powerful remote sensing technique for Earth observation. The Teledyne HgCdTe FPA and digital ROIC technology enable Teledyne e2v to provide wide bandwidth, high frame-rate detector solutions that are enabling a simplification in hyperspectral instrument design for both institutional large scale missions and for future commercial constellations. In parallel Teledyne e2v are developing III-V technology for surveillance applications that could find use in future generations of space based instruments.

Keywords: Infrared, Hyperspectral, HgCdTe, Ultraviolet, SWIR, III-V, MWIR, Unipolar Barrier, T2SL

1. INTRODUCTION

Teledyne's HgCdTe detector growth technology and backside processing with substrate removal techniques enable production of large format, low dark signal detectors with high quantum efficiency across the full wavelength band. Combined with fully digital multi-functional CHROMA-D ROICs, Teledyne is producing hybrid sensors able to meet the full hyperspectral performance needs across the whole UV-SWIR wavelength band, eliminating the need for separation of the visible, VNIR and/or SWIR channels in the instrument design. CHROMA-D ROIC based sensors have 18 micron pixels and a scalable architecture from 1052x512 up to 3072x3072 pixels. Frame rates up to 275 Hz / 144 Hz are achieved for 512/1024 row formats in full frame, with much higher frame rates possible by using the 8 independently programmable row selection windowing functionality to ignore unwanted parts of the spectrum. High quantum efficiency (QE) is achieved across the spectral range, with 80 % in the NIR/SWIR, 60 % in the Visible and >50 % in the near-UV. Each pixel has high and low gain, selectable per row to match to changes in irradiance with wavelength. A Teledyne e2v manufactured 3Kx512 CHROMA-D SWIR detector is selected for the Vis-SWIR hyperspectral instrument for the Copernicus CHIME mission, with a 2Kx1K format also baselined for the planned ESA TRUTHS mission.

Teledyne e2v have been developing III-V based IR detectors for surveillance applications. The new generation of unipolar barrier detectors in the III-Sb material system provide a promising alternative to HgCdTe, offering comparable performance, tailorability and volume manufacture processing. Unipolar barrier structures can sufficiently suppress dark current for operation in the so-called HOT (Higher Operating Temperature) regime to be achieved. T2SL (Type-II Super Lattice) or SLS (Strained Layer Superlattice) absorbers can be employed which then allow tailorability of the spectral sensitivity from SWIR out to VLWIR wavelengths in a similar manner to HgCdTe. Detailed information on III-V barrier detector design, operation and manufacture is described extensively in the literature [1], [2], [3]. For future space applications, III-V based IR detectors could offer large format arrays with an alternative material processing supply chain to HgCdTe based detectors. In this paper, we will present a summary of III-V IR detector development at Teledyne e2v. MWIR Unipolar barrier-based single element detectors have been manufactured and tested to compare the tolerance of different structures to radiation. As a vehicle to verify the detector manufacturing supply chain, MWIR VGA format FPA detectors utilizing a Teledyne FLIR ISC0403 ROIC have been manufactured and their performance characterized. These developments are providing the necessary building blocks for manufacture of III-V IR detectors for space in the future.

2. CHROMA-D HGCDTE SWIR DETECTORS

DETECTOR OVERVIEW

The CHROMA-D18 ROIC is an 18 micron pixel digital readout integrated circuit manufactured using a 180 nm foundry process. The mask design incorporates stitch blocks enabling detector sizes in multiple formats that scale in blocks of 1024 columns by 512 rows. Each 1024 column block has 2 primary high speed current mode logic (CML) differential output drivers used for the data output, running a 1.6 Gbps. Nominal sizing options with the associated number of outputs are shown in Table 1. The primary focus of the current activity detailed in this paper is for the single sided 3Kx512 and 2Kx1K formats baselined for upcoming CHIME and TRUTHS hyperspectral missions respectively.

		Number of columns		
Readout mode	**Number of rows**	**1024 (1K)**	**2048 (2K)**	**3072 (3K)**
Single side	**512 (0.5K) 1024 (1K) 1536 (1.5K)**	2 primary outputs	4 primary outputs	6 primary outputs
Dual sided	**1024 (1K) 2048 (2K) 3072 (3K)**	4 primary outputs	8 primary outputs	12 primary outputs

Table 1: Available combinations of column and row formats of the CHROMA-D18 ROIC and associated number of outputs. The labelling in brackets is the shorthand sizing terminology "1K", "2K".

Pixel signal conversion is via column parallel ADC operating in single slope (SS) configuration, where a line rate saw-tooth waveform generated on-chip (ramp signal) is compared against the analogue input (output of the selected pixel) by a comparator. The time for the waveform to exceed the input voltage is measured by a high speed digital ADC counter. This counter value is stored in a per column 14 bit memory cell before being sequentially multiplexed out of the ROIC. The line time is dominated by the ADC read time, which at 14 bit is 10.94 µs. Reduced line times and thus higher frame rates are available by operating with a reduced ADC bit rate, down to a minimum of 6.45 µs at 13.168 bit in single slope mode. The pixel timing sequence starts with reset period followed by the in pixel correlated double sampling (CDS) operation, which together give a dead time of 140.5 µs per frame where each pixel is not available for integration. The minimum integration time in default mode is 320 µs, with a maximum integration time equal to the frame period minus the pixel dead time. The maximum frame rate is therefore derived from a combination of ADC line time and the number of rows, plus the overhead time known as the vertical blanking time where no data is being output from the ROIC. The maximum available frame rates for the 512 row and 1024 row formats are listed in Table 2. Running at the highest full-frame frame rate, the ROIC power dissipation is approximately 600 mW to 700 mW for both formats.

Maximum full-frame frame rate (Hz) At MCLK=80 MHz and dead time = 140.5µs			
Readout Mode	**Number of Rows**	**ADC Resolution**	
		SS 14 bit	**SS 13.168 bit**
Single side	512	168.5	275.4
Single side	1024	86.7	144.2

Table 2: Maximum available frame rates as a function of number of rows and ADC bit resolution for the 512 row and 1024 rows single sided ROICs.

Each pixel has a Capacitive Transimpedance Amplifier (CTIA) pixel design with dual high and low gain mode, selectable on a row by row basis. Various combinations of high and low gain well capacity are available, the default for the CHIME hyperspectral mission being set at with high gain full well of ~100 ke- and low gain full well of ~ 600 ke-. The corresponding median read noise is ~35 rms e- and ~100 e- rms respectively at 175 K operating temperature. A high gain full well of 180 ke- and low gain full wells of 1.0 Me- and 2.6 Me- have also been manufactured, with the values being able to be customised within this range by a metal mask change if required by the mission.

Teledyne e2v packaged detectors incorporate a package consisting metal base plate for thermal and mechanical interfaces, which is gold coated to reduce emissivity, with a ceramic pcb interconnect and integrated flex circuit with connector for the electrical interface. There exists provision for attachment of a window or filter above the image area. The current design for the 3Kx512 and the 2Kx1K formats are shown in Figure 1.

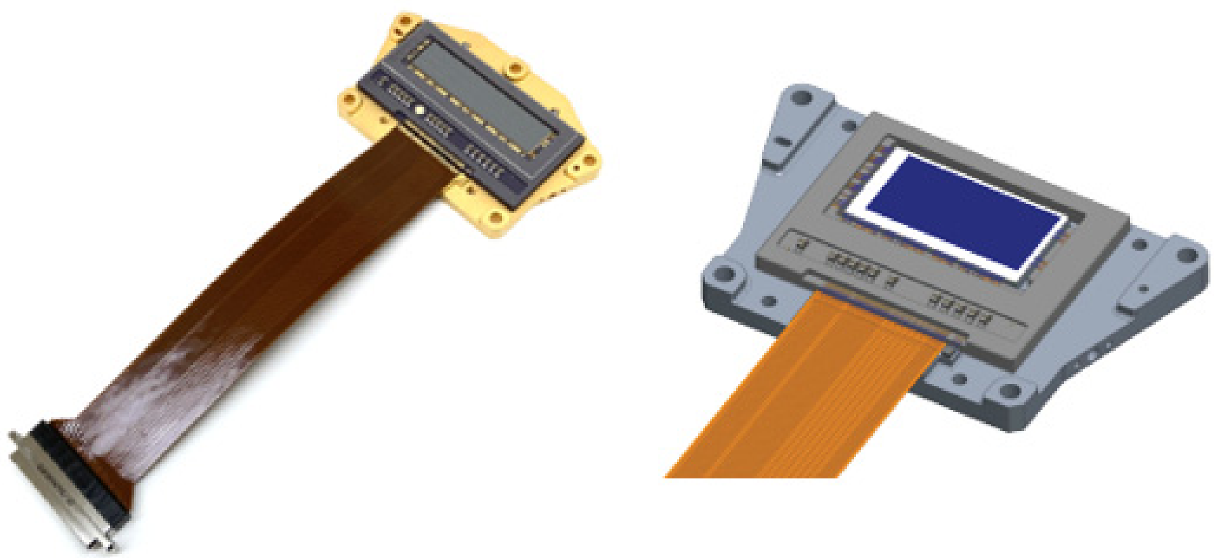

Figure 1: Teledyne e2v package for the 3Kx512 CHROMA-D SWIR detector (left) and the design for the 2Kx1K CHROMA-D SWIR detector (right). The 2Kx1K package design will also accommodate a 2Kx512 detector without any changes needed.

LAG PERFORMANCE

Lag performance has been measured on a CHROMA-D 18 μm ROIC that has high gain full well of 100 ke- and low gain full well of 1.2 Me-. The test sample was a substrate removed, AR coated, standard process HgCdTe detector with SWIR 2.5 μm cut-off operating at 150 K. Lag was measured in full frame mode by pulsing on and off a cooled 1650 nm LED as shown in Figure 2. Measurements were made at various signal levels and frame rates in both high and low gain modes as shown by the results in Figure 3. Lag is defined as the signal level in the OFF frame as a percentage of the signal in the last ON frame (TFoff), after subtraction of the average signal level in the last 3 off frames of the sequence. Measurements showed no lag measured in the second off frame, and a lag in the first off frame of -0.2 % for high gain mode and -0.35 % for low gain mode across ~90 % of the signal range of the CTIA. Lag remained constant over frames rates from 45 Hz to 230 Hz. There was also no impact on the lag results of pixel reset time from 12 ms down to 30 μs and no difference between IWR and ITR modes. The negative lag is attributed to capacitive cross talk within the read out circuit.

IMPROVING UV QE

The capability to manufacture HgCdTe with both optical and infrared response has been established at Teledyne for many years through the process of substrate removal and anti-reflection coating application to the back surface. Recently, Teledyne have undertaken a development activity to establish a process with higher UV QE down to 300 nm. This involved back surface process optimization and modification to the anti-reflection coating application to the back surface.

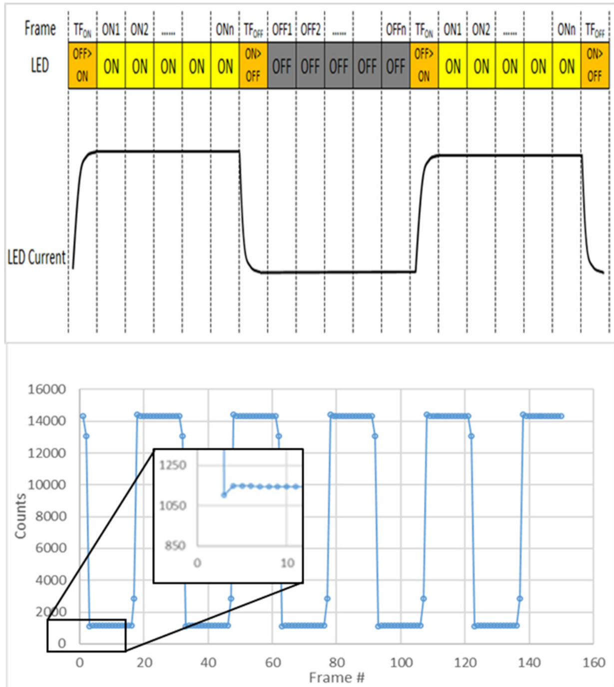

Figure 2: - Schematic representation of the frame and LED sequence (top) for lag testing. ON frames have the LED fully on, OFF frames have the LED fully off. There are two transitions per cycle where the LED is ramping down or up, as can be seen in the real data capture signal levels (bottom). The zoomed view (bottom) shows the first dark image negative signal level that returns a negative lag value.

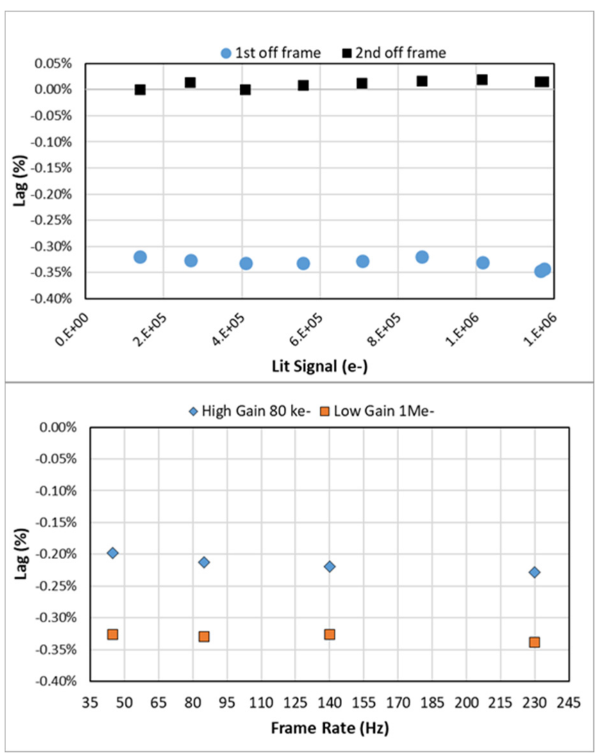

Figure 3: Measured lag test results versus signal level in low gain mode for the first and second off frames (top) and lag in the first off frame versus frame rate for both high and low gain (bottom).

Recently, Teledyne have undertaken a development activity to establish a process with higher UV QE down to 300 nm. This involved back surface process optimization and modification to the anti-reflection coating layers to reduce UV reflectance and have higher UV transmission compared to the standard SWIR anti-reflection coatings. The new coating process has been manufactured on two large area SWIR detectors and the QE measured at 150 K operating temperature. Significant improvement in the UV has been achieved with > 75% QE at 325 nm. As a result of the shift to preferential UV QE, the performance in the SWIR region is impacted with 60-70 % QE between 1500 nm and 2400 nm compared to the SWIR standard coating values of 80-90 %.

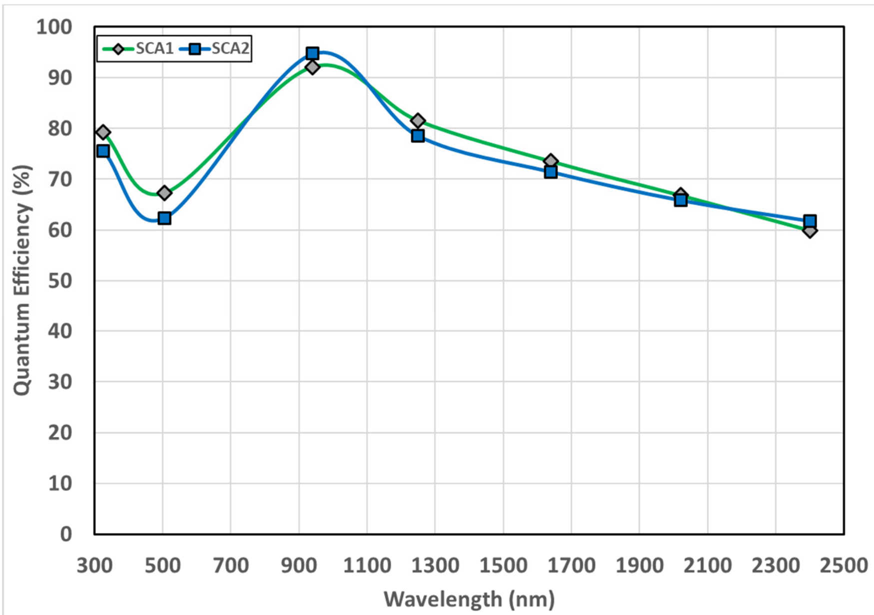

Figure 4: Measured array median QE at 150 K of two large area HgCdTe CHROMA-D detectors with UV improved coating process. The measurements below 1000 nm used LED sources and the measurements above 1000 nm used a broad band source with narrow band filters.

3. III-V BARRIER IR DETECTORS

RADIATION-HARD INFRARED DETECTORS FOR SPACE

Teledyne e2v were funded through the dstl Space Programme via the DASA Space-to-Innovate Phase 1 competition to develop the first phase of a radiation-hardened III-V barrier MWIR detector for space applications. The development was a collaboration between Teledyne e2v, Amethyst Research Ltd and others. The aim of the programme was to design, manufacture and test a number of different single element MWIR detector designs to assess their performance, these included; a potentially more radiation tolerant design, 2 bulk designs, an SLS design and p-i-n structure for comparison. Specifics of the designs and performance are described in [4].

The radiation tolerance of detectors for space applications is a key attribute as instrument performance needs to be maintained for years at a time to not impact mission goals. Proving the radiation tolerance of IR detectors is challenging as they need to be irradiated at operational temperature as any damage quickly anneals as room temperatures are approached. The Open University at Milton Keynes funded through a UKSA development call have tested some of the devices from the Space-to-Innovate Phase 1 project and successfully managed to verify the performance of an SLS based device pre and post radiation at operational temperature. The devices were exposed to proton irradiation to create displacement damage, the dominant radiation damage mechanism in barrier detectors. Irradiation was performed at 1×10^{10} p/cm^2 at 10 MeV using the beamline at Birmingham University, the dose chosen is typical of standard mission and instrument parameters. The current from the device was measured before and after irradiation, and again following anneal at room-temperature. Measurements were taken in darkness and with illumination from two different wavelength LEDs at the nominal operating temperature of 150 K.

Only a small impact from irradiation was observed with an increase in dark signal of approximately 2 to 3 % and a reduction in sensitivity of less than 3 %, however these change are within measurement error. The result is consistent with the work of Steenbergen et al. [5] who irradiated InAsSb barrier detectors, which showed minimal change in performance for equivalent radiation doses. This is very encouraging and indicates that standard barrier IR detector designs will provide sufficient radiation tolerance at representative levels seen in space.

We hope to build on this work with the Open University in follow-on programs to develop 2D focal plane array detectors. Little if any published work is available on the radiation performance of 2D focal plane array detectors with most focusing on single element detectors. While single element detectors are practical test vehicles to assess performance parameters such as dark current and QE they do not provide any assessment on the spatial effects of radiation, i.e. the creation of defective pixels.

VGA FORMAT MWIR T2SL FPA DETECTOR

Teledyne e2v in collaboration with Amethyst Research Ltd have manufactured VGA format MWIR T2SL FPA detectors. Funded under a DASA Advanced Vision for 2020 and Beyond call, FPA detectors were developed as part of the phase 1 programme to establish and verify a manufacturing route and supply chain.

The MWIR sensitive layer was designed as an InAsSb (Ga-free) SLS with cut-off wavelength > 5 µm at a target operating temperature of 150K. The SLS was hybridized to a FLIR ISC0403 ROIC which has 640 x 512 pixels on a 15 µm^2 pixel pitch. Detectors were produced in both substrate-on and substrate-removed configuration to both understand performance differences and due to availability in the manufacturing process, no AR coating was applied. The hybrid detectors were assembled onto a custom PCB package at Teledyne e2v, see Figure 5.

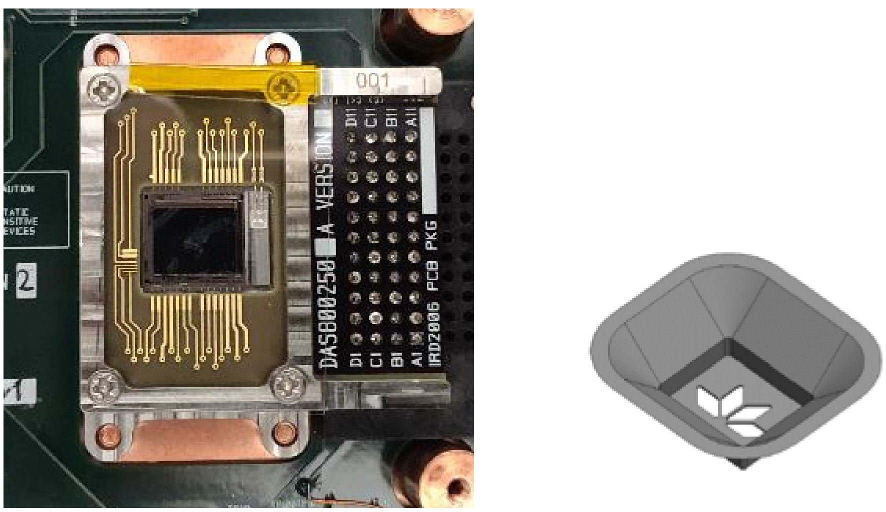

Figure 5: Substrate-on MWIR T2SL FPA detector mounted on the PCB package (left) and proximity mask used in Figure 6 with cut-out projection for Teledyne logo (right)

Electro-optical characterization of the detectors has been performed on a Teledyne e2v characterization “camera” modified for testing MWIR detectors. The “camera” features a cryostat with active vacuum pumping and a cooling system which can cool the detector to a minimum temperature of ~ 120 K. The detector is surrounded by a cold shield and optics which gives an equivalent f/# of 1.1. A filter wheel and IR emitter (acting as a pseudo blackbody) is used to provide input illumination. A proximity mask featuring a cut-out of the Teledyne logo can be positioned in front of the detector to project an image and verify correct readout and operation, an example of the projection onto the detector is shown in Figure 6.

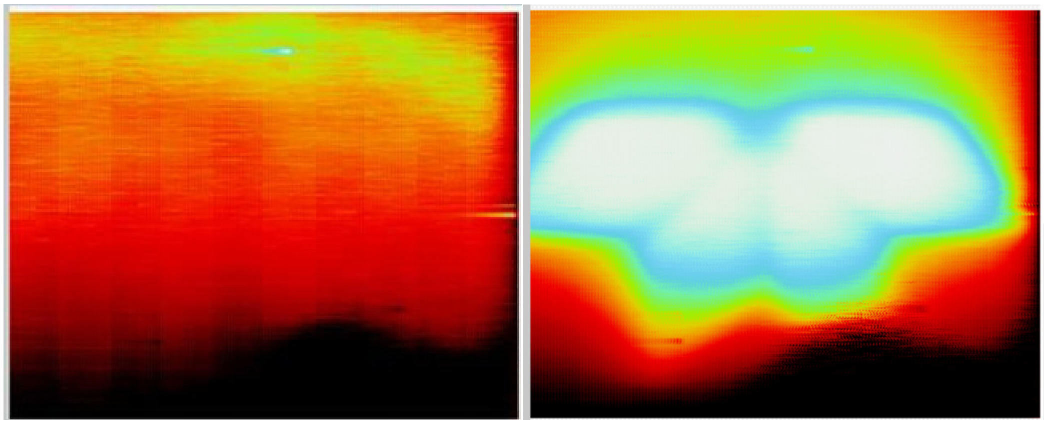

Figure 6: Substrate-on MWIR FPA detector no illumination (left) and substrate-on MWIR FPA detector with mask illumination (right)

Detailed electro-optical characterization has focused on a substrate-removed detector, which had a more uniform response compared to the substrate-on detector. NETD (Noise Equivalent Temperature Difference) is reported in Figure 7 measured against detector operating temperature. The detector was operated at ~ 40 Hz frame rate and bias of -0.2 V, the IR emitter was operated nominally at an equivalent blackbody temperature of 375 K and detector integration time set to ~ 3 ms to achieve the desired signal level on the detector. The measured NETD results are very encouraging and show expected behavior of stable performance until dark current starts to increase at warmer detector operating temperatures and NETD increases. The NETD histograms also show a relatively tight distribution about the median value.

Average dark current versus temperature measurements are shown for the detector in Figure 8. Below about 150K dark current versus temperature starts to plateau, we believe this is due to excess background from the test setup rather than real dark current behavior. The development of these FPA detectors and verification of their functional performance has created the building blocks for the development of III-V barrier detectors for space applications, showing that a viable manufacturing route is possible.

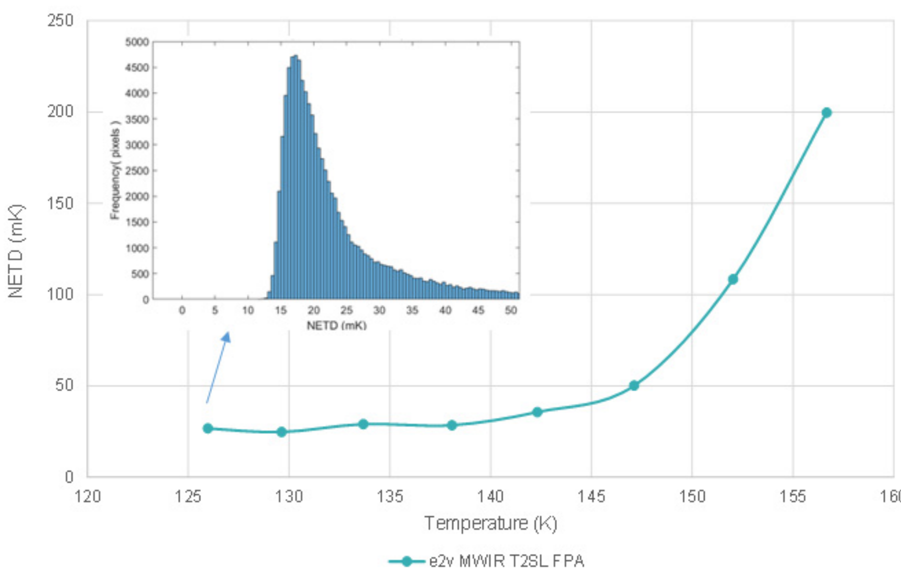

Figure 7: Mean NETD vs temperature for substrate removed MWIR T2SL FPA detector and inset is the NETD histogram at 125 K detector temperature

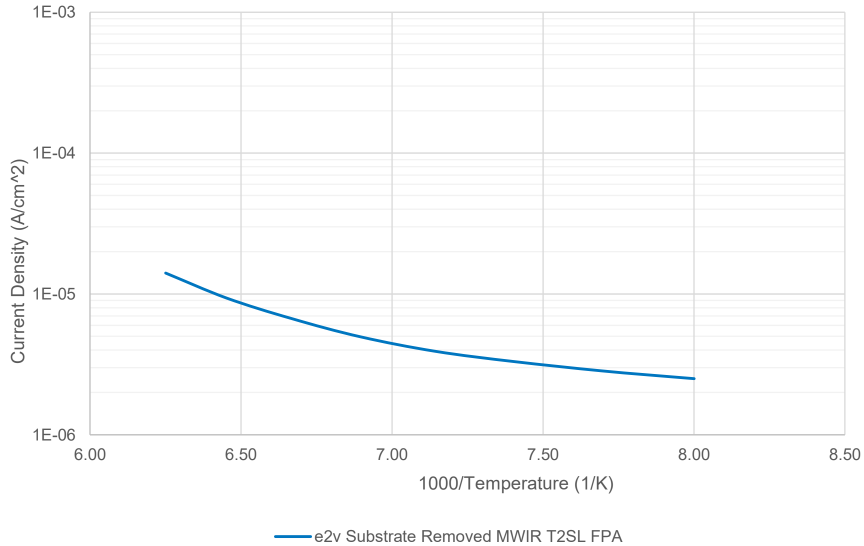

Figure 8: Average pixel dark current density for substrate removed MWIR T2SL FPA detector

4. REFERENCES

[1] Rogalski, A., Kopytko, M. and Martyniuk, P., [Antimonide-Based Infrared Detectors: A New Perspective], SPIE Press, Bellingham, Washington USA, (2018).

[2] A. Rogalski, P. Martyniuk, M. Kopytko, P. Madejczyk, S. Krishna, InAsSb-Based Infrared Photodetectors: Thirty Years Later On. Sensors (Basel). 2020 Dec 9;20(24):7047; doi: 10.3390/s20247047

[3] D. Z. Ting, S. B. Rafol, A. Khoshakhlagh, A. Soibel, S. A. Keo, A. M. Fisher, B. J. Pepper, C. J. Hill, S. D. Gunapala, InAs/InAsSb Type-II Strained-Layer Superlattice Infrared Photodetectors. Micromachines 2020, 11, 958; doi:10.3390/mi11110958

[4] R. Wheeler, I. Mason, P. Jerram, P. Stocken, D. Jordan, M. Willis, M. Carmichael, A. P. Craig, T. Golding, A. R. J. Marshall, "Development of III-V barrier diode radiation-hard infrared detectors for space applications," Proc. SPIE 11537, Electro-Optical and Infrared Systems: Technology and Applications XVII, 115370J (20 September 2020); doi: 10.1117/12.2572933

[5] E. H. Steenbergen, C. P. Morath, D. Maestas, G. D. Jenkins, J. V. Logan, "Comparing II-VI and III-V infrared detectors for space applications," Proc. SPIE 11002, Infrared Technology and Applications XLV, 110021B (30 May 2019); doi: 10.1117/12.2519250