

Leonardo UK Short and Mid Wave Avalanche Photodiode Development for Low Flux Detection in Astronomy Applications

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ABSTRACT

Detecting and tracking weak infrared signals in space and astronomy can be extremely challenging. The benefits of Avalanche Photo Diodes (APDs) operating in the Short-Wave Infrared (SWIR) waveband have been demonstrated for many years. Such APDs allow the detection of signals down to a few photons without amplifying noise.

Leonardo is developing Mid Wave Infrared (MWIR) APD technology. APD gain may be set high for photon counting sensitivity with high signal to noise ratio, or to more moderate levels to improve sensitivity for more standard imaging without saturating the array.

Leonardo has engineered its SWIR APD technology for use in the 3 – 5 μm mid wave band region. Mercury cadmium telluride (MCT) material developed using Metal Organic Vapour Phase Epitaxy (MOVPE) grown on low-cost gallium arsenide (GaAs) substrates has been designed by engineering the band gap of the MCT heterostructure, crucial in APD designs to minimise excess noise. An absorber region was designed with band energies corresponding to MWIR wavelengths. 320 x 256 pixels with 24 μm pitch Focal Plane Arrays (FPAs), created by hybridising the MCT to a readout integrated circuit designed for high-speed SWIR APDs. Electro-Optical (EO) and dark measurement tests were carried out at operating temperatures of 80 – 130K. The full dynamic range of the ROIC has been utilised by assessing the gain-bias characteristics of the FPA with varying source temperatures. High APD gain with a spectral responsivity covering the 3 – 5 μm range has been achieved in initial trials. Blind measurements have been captured to assess dark current and comparison made to models predicting performance based on the MCT heterostructure.

Keywords: Mercury Cadmium Telluride, Avalanche Photo Diodes, Mid-wave infrared, low flux detection, Focal plane arrays

1. INTRODUCTION

Leonardo UK has been at the forefront of MCT infrared detector technology for more than five decades, developing advanced detector solutions for defense, space and scientific applications. Using proprietary MOVPE growth processes on GaAs substrates, Leonardo has established the capability to engineer MCT material properties across a broad infrared spectral range, extending from the SWIR [1] through to the Very Long Wave Infrared (VLWIR) [2]. This flexibility in material design has enabled the development of high-performance FPAs, multi-band architecture and APD technologies tailored to demanding operational environments [3,4].

Among these technologies, APDs have emerged as a key solution for applications where conventional photodiode detectors become limited by readout noise and insufficient signal levels. By providing internal gain within the detector structure, APDs enhance sensitivity under photon-starved conditions while maintaining low excess noise characteristics. These advantages are particularly valuable in astronomical instrumentation, where extremely low photon arrival rates often define system performance limits.

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Historically, Leonardo's APD development activities have focused on SWIR MCT devices that combine high avalanche gain with low noise operation. These detectors have demonstrated suitability across a range of applications including adaptive optics wavefront sensing, astronomical fringe tracking, rapid time-domain astronomy, optical communications and laser ranging systems. Large-format SWIR APD arrays have been successfully developed with avalanche gain exceeding two orders of magnitude under cryogenic operating conditions. Continued optimisation of device architecture has also enabled significant reductions in dark current, making these detectors increasingly attractive for ultra-low flux astronomical observations. Collaborative programmes with the astronomy community have further demonstrated detector performance at photon flux levels approaching those required for next-generation scientific instruments.

The success of SWIR APD technology has subsequently provided the foundation for extending avalanche multiplication into the MWIR spectral region. Achieving low-noise avalanche gain at longer wavelengths presents additional challenges due to the narrower material bandgap and associated increases in dark current generation mechanisms. Nevertheless, advances in MCT bandgap engineering, heterostructure design and device processing have enabled the development of MWIR APD architectures capable of operating with measurable gain while preserving favourable noise characteristics. These developments create new opportunities for low-flux imaging and sensing in astronomical applications, where observations in the MWIR can provide access to important scientific signatures unavailable at shorter wavelengths.

Astronomy remains one of the most demanding application areas for infrared detector technology. Future ground-based and space-based observatories require sensors capable of detecting extremely weak optical signals while maintaining high spatial resolution and low false-event rates. Detector parameters such as dark current, avalanche gain, excess noise factor and overall signal-to-noise ratio are therefore critical. Progress toward lower dark current operation and higher usable gain is essential for enabling faint-object imaging, interferometry and, ultimately, photon-counting capability.

This paper presents the status of Leonardo UK's short-wave and mid-wave MCT APD developments targeted at low-flux astronomical applications. The work builds upon established SWIR APD technology and recent advances in MWIR APD design, fabrication and characterisation. Device architectures, measured performance and ongoing technology improvements are discussed.

2. MOVPE GROWN MCT TECHNOLOGY

A significant advantage of the Leonardo manufacturing approach is the use of a single mature production line for both high-volume infrared imaging products and specialised scientific detectors. Consequently, the fabrication processes, quality controls and yield improvements developed for commercial production directly benefit astronomy-grade detector devices.

The flexibility of the MOVPE process enables precise control of both composition and doping throughout the epitaxial structure. One of the key strengths of MOVPE-grown MCT is the ability to engineer bandgap profiles with sub-micron precision. This capability is particularly important for avalanche photodiode structures, where carefully designed heterojunctions can suppress unwanted dark-current generation while maintaining efficient avalanche multiplication. Strategic widening of the bandgap in critical regions of the device can significantly reduce thermally generated carrier currents, thereby improving sensitivity for low-flux detection applications.

Although MCT is grown on GaAs, despite a lattice mismatch of approximately 14%, the substrate provides several important advantages over alternative materials such as CdZnTe. GaAs substrates are available from multiple suppliers in large wafer diameters, exhibit excellent mechanical robustness and are substantially lower in cost. In addition, their high crystalline quality and low contamination levels make them well suited for reproducible detector manufacturing. Following hybridisation, the GaAs substrate can be selectively removed, reducing thermal stress within the detector assembly and eliminating substrate-related optical effects.

Accommodation of the lattice mismatch is achieved using engineered buffer layers, which effectively manage the transition from the substrate to the active device region. Subsequent material analysis reveals low defect densities and an absence of significant threading dislocations within the detector layers. This material quality is particularly important for large-format focal plane arrays, where individual crystal defects can otherwise manifest as defective pixels and reduce operability.

Most detector structures are grown on 100 mm diameter GaAs wafers with a slight off-axis orientation from the (100) crystal plane. The MOVPE process employs alternating CdTe and HgTe binary layer deposition, with the final alloy

composition determined by the relative layer thicknesses and subsequent interdiffusion during growth. N-type and p-type doping species are incorporated independently of alloy composition, using iodine as a donor and arsenic as an acceptor.

Detector pixel definition is achieved through mesa isolation technology, whereby each pixel is electrically separated by etched mesa structures. For APD devices, the multiplication region is confined within the mesa geometry, allowing the active low-bandgap volume to be minimised. This architecture contributes to reduced dark current while maintaining efficient avalanche gain. Figure 1 shows etched mesa profile of MCT focal plane arrays with indium deposited on the mesa tops for hybridisation. These characteristics are particularly advantageous for low-flux astronomical observations, where both detector sensitivity and spatial fidelity are critical performance parameters.

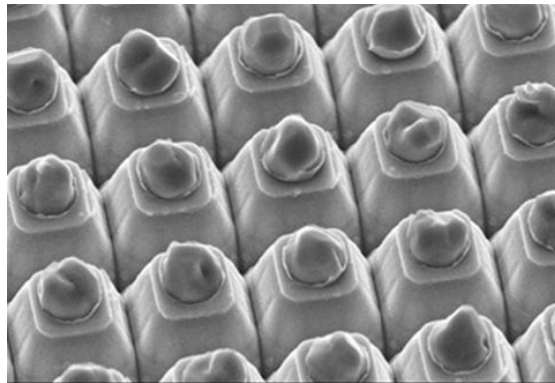


Figure 1. SEM image of etched CMT mesa with indium deposition

The combination of precise bandgap engineering, low-defect epitaxial growth, advanced mesa isolation and mature high-volume manufacturing provides a robust technological foundation for the development of both SWIR and MWIR MCT APD arrays targeted at next-generation low-flux astronomy instruments.

3. SWIR APD CMT DESIGN AND CHARACTERISATION

The SWIR APD architecture reported in this work represents a further optimisation of Leonardo's established detector platform, guided by an updated tunnelling current model developed from experimental characterisation data. The design objective was to simultaneously minimise dark current and maximise avalanche gain through careful bandgap and electric-field engineering. Tunnel current and persistence effects were reduced by engineering the bandgap to maintain ionisation efficiency and depletion width whilst reducing electron heating effects.

Signal uniformity was improved by modifying the absorber cut off wavelength characteristics, supported by results from earlier device measurements. The resulting structure was further optimised by adjusting the iodine doping level through the structure. Spatial response uniformity was improved by developing the mesa array processing which is also expected to suppress speckle related non-uniformity effects across the array.

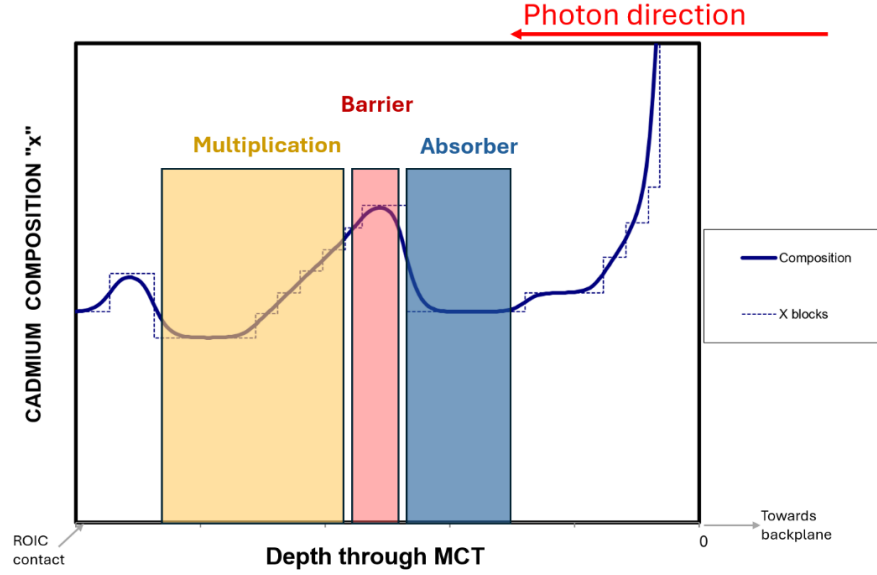


Figure 2. Representative design of SW APD structure

Spectral, EO and dark current results will be presented in the final draft of this paper in October 2026.

4. MWIR APD CMT DESIGN AND CHARACTERISATION

The array being assessed for this paper builds upon the established Leonardo SW-APD design reported in [5] and MW-APD design reported in [6,7]. Unlike a conventional Separate Absorption and Multiplication (SAM) APD optimised for MWIR operation, this is a modified structure that extends the mid-wavelength cut-off into the avalanche gain region as reported in [7]. This bandgap-engineering strategy enables sensitivity to MWIR photons while retaining much of the underlying SW-APD architecture and its demonstrated low-noise avalanche characteristics. In the band structure diagram shown in Figure 2, the parameter x denotes the cadmium fraction in the $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ alloy. The alloy composition directly determines the material bandgap, with lower cadmium concentrations producing narrower bandgaps and therefore extending the spectral cut-off to longer wavelengths. Consequently, regions designed with reduced x values can absorb lower-energy photons and generating photoelectrons at MWIR wavelengths.

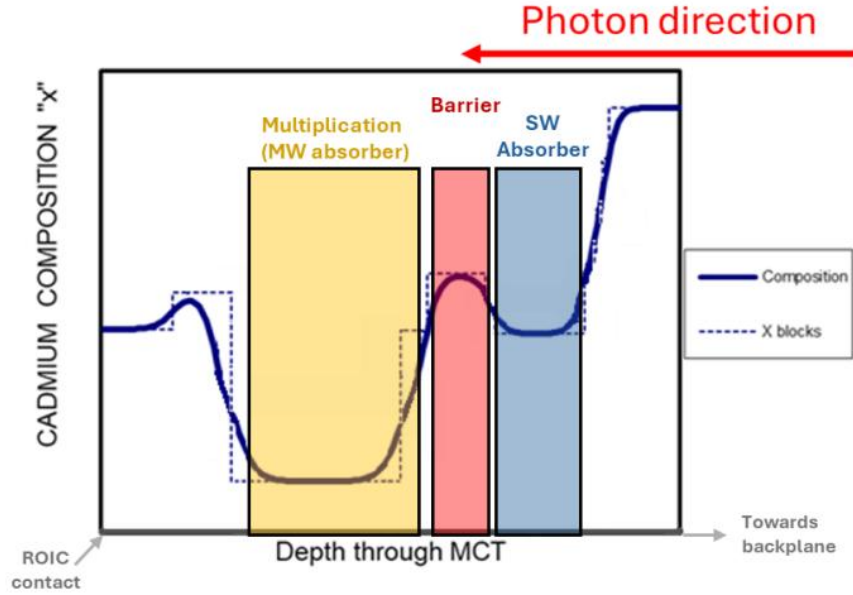


Figure 3. Representative design of SW MW APD structure

The arrays produced using the above design are 320x256, 24 μm pixel pitch hybridized to our Saphira ME1001 ROIC for Spectral and dark current measurement. For dark current measurement, the selected die was coated with 100 nm gold to reduce stray light contribution.

4.1 Spectral

The spectral test was performed using Bruker Fourier Transform Infrared Spectroscopy (FTIR) on test diodes located at the corners of the two arrays at five different temperatures ranging from 71 K to 83 K using a cryocooler. Positive bias was applied while recording the spectral. The normalised spectra for 4 test diodes of an array at a negative bias of 0.5 V is shown in Figure 4. For each temperature, the transmission from all 4 test diodes is corrected for background and window effects and then normalized to 1. The average transmission of all 4 test diodes is plotted in the graph in Figure 4. It was designed for $\sim 5 \mu\text{m}$ cut-off at 80 K, and the measured value is 4.98 μm . It can be observed from the graph that the cut-off wavelength decreases with increase in temperature as expected. Based on 50% spectral response the measured cut-off wavelengths are reported in Table 1 below. The modelled cut-off wavelength values using Brice equation [8] is also noted in the same Table 1. There is excellent agreement between measured and modelled values.

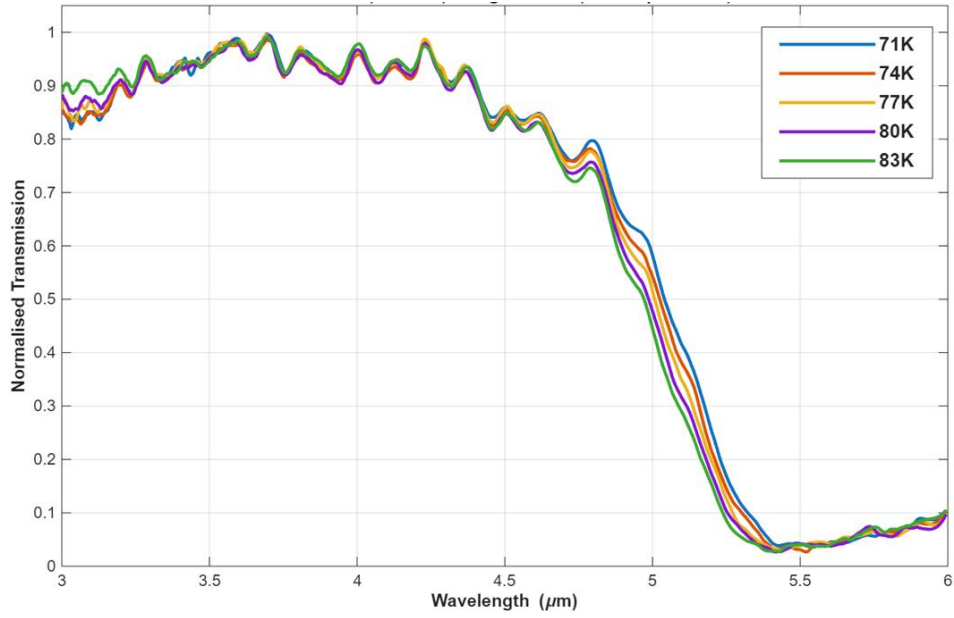


Figure 4. Normalized transmission for MW APD CMT test diodes

Table 1. Measured and modelled cut-off wavelengths of MW APD device

	Measured	Modelled
Array Temperature (K)	Cut-off wavelength at 50% Transmission (μm)	
71	5.041	5.040
74	5.025	5.026
77	5.007	5.012
80	4.987	4.999
83	4.971	4.985

4.2 Dark current

Blind I-V test on test diodes of gold coated arrays using a closed radiation shield was performed at temperatures 80 K, 90 K, 100 K and 110 K using a cryocooler. The result is plotted below in Figure 5.

It can be observed that below 10 V, the current is below the resolvable limit of the test kit which is $\sim 2\text{E-}11$ A. Ideally, we need to resolve the dark current below 10 V which should then show the trend of thermionic dark current with temperature.

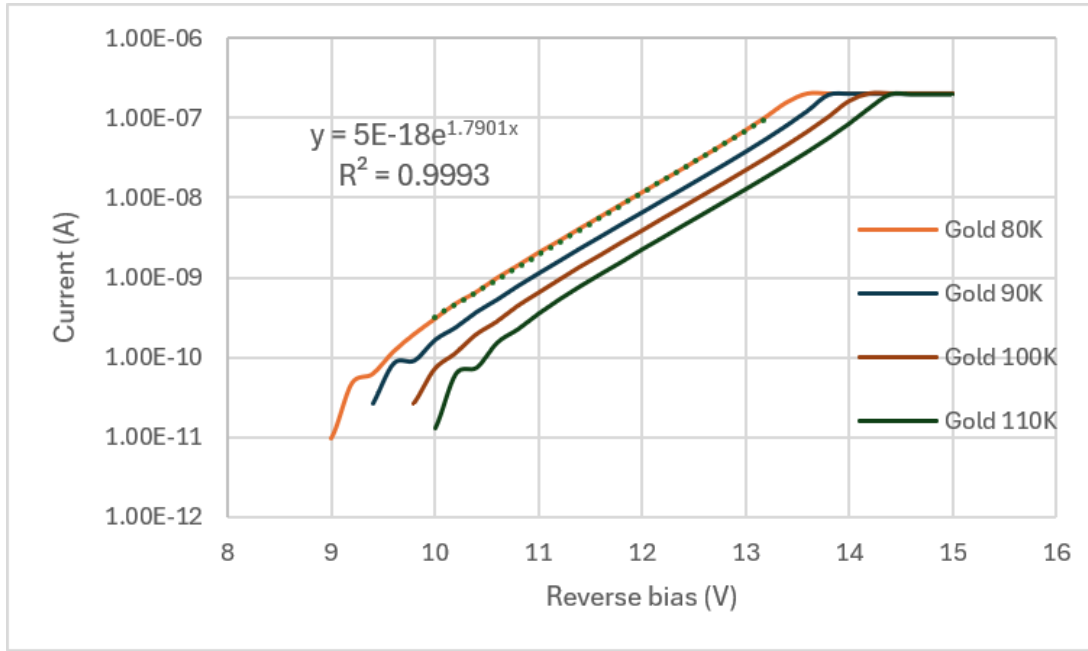


Figure 5. Blind IV characteristics of a gold coated MW APD CMT test diodes

In the testing performed to generate Figure 5, the measurable current limit is higher than the attributed thermionic dark current until ~ 10 V. Above 10 V, the fit on the 80 K curve demonstrates consistency with the expected exponential relationship between band-to-band tunnelling and electric field, which increases via the bias voltage. Importantly, the data illustrates a temperature dependence of band-to-band tunnelling. It shows that as the operating temperature is increased, the current is reduced for a given bias, or that a higher bias is required to generate the same current. From literature [9], we know that the probability (P_T) of a band-to-band tunnelling event is:

$$P_T \propto \exp\left(-\frac{E_g^{3/2}}{E}\right)$$

Where E is the electric field across the barrier, and E_g is the bandgap.

While temperature does not appear to directly influence this probability, it is attributed to increasing the bandgap due to a physical shift in the p-n junction barrier height. Increasing the temperature, and hence bandgap, reduces band-to-band tunnelling probability for a given bias voltage, and less tunnel current is generated as a result. Further work would be required to generate a full model to compare this data to, as well as considering the effects of trap-assisted tunnelling.

A key takeaway from this result is that when the APDs are operated at a higher temperature, a larger range of bias is available before tunnel current dominates the detector output. This means that a higher APD gain can be achieved, but there will be a point beyond which thermal current impacts the viable operation of the device. This can also be inferred by previous work which found SW-APD operation declining somewhere between 140 – 150 K [10].

5. CONCLUSION

Informed by additional results due Sept. 2026.

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