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## *Advances in SELEX ES infrared detectors for space and astronomy*

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## ADVANCES IN SELEX ES INFRARED DETECTORS FOR SPACE AND ASTRONOMY

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### I. INTRODUCTION

Selex ES produces a wide range of infrared detectors from mercury cadmium telluride (MCT) and triglycine sulfate (TGS), and has supplied both materials into space programmes spanning a period of over 40 years. Current development activities that underpin potential future space missions include large format arrays for near- and short-wave infrared (NIR and SWIR) incorporating radiation-hard designs and suppression of glow. Improved heterostructures are aimed at the reduction of dark currents and avalanche photodiodes (APDs), and parallel studies have been undertaken for low-stress MCT array mounts. Much of this development work has been supported by ESA, UK Space, and ESO, and some has been performed in collaboration with the UK Astronomy Technology Centre and E2V.

This paper focuses on MCT heterostructure developments and novel design elements in silicon read-out chips (ROICs). The 2048 x 2048 element, 17 $\mu$ m pitch ROIC for ESA's SWIR array development forms the basis for the largest cooled infrared detector manufactured in Europe. Selex ES MCT is grown by metal organic vapour phase epitaxy (MOVPE), currently on 75mm diameter GaAs substrates. The MCT die size of the SWIR array is 35mm square and only a single array can be printed on the 75mm diameter wafer, utilising only 28% of the wafer area. The situation for 100mm substrates is little better, allowing only 2 arrays and 31% utilisation. However, low cost GaAs substrates are readily available in 150mm diameter and the MCT growth is scalable to this size, offering the real possibility of 6 arrays per wafer with 42% utilisation.

A similar 2k x 2k ROIC is the goal of ESA's NIR programme, which is currently in phase 2 with a 1k x 1k demonstrator, and a smaller 320 x 256 ROIC (SAPHIRA) has been designed for ESO for the adaptive optics application in the VLT Gravity instrument. All 3 chips have low noise source-follower architecture and are enabled for MCT APD arrays, which have been demonstrated by ESO to be capable of single photon detection. The possibility therefore exists in the near future of demonstrating a photon counting, 2k x 2k SWIR MCT detector manufactured on an affordable wafer scale of 6 arrays per wafer.

### II. ADVANTAGES OF MOVPE

Selex ES has over 14 years' experience in the MOVPE growth of MCT by the interdiffused multilayer process (IMP) on GaAs substrates [1]. MOVPE allows control of the alloy composition (x) across the entire compositional range between CdTe and HgTe without any changes to the reactor growth conditions, allowing heterostructure and bandgap engineering approaches to achieve innovative device designs, such as the separation of the gain and absorption regions in APDs used in adaptive optics applications, achieving high breakdown voltage while maintaining high gain [2]. Extrinsic doping control over the range  $\sim 10^{15} \text{ cm}^{-3}$  –  $\text{mid} \times 10^{17} \text{ cm}^{-3}$  is achieved using arsenic and iodine as the acceptor and donor dopant respectively. The use of cheap large area growth substrates (compared to cadmium zinc telluride as used in alternative technologies) is seen as a particular advantage for the large format arrays required in many future astronomy and space applications.

The junctions are grown and a mesa technology (combination of dry and wet etching) is used to define the pixels. Optical concentration is achieved by this approach whereby radiation can be funneled from the full pixel area into a reduced volume absorber and junction area [3], thus reducing the noise generation volume and junction leakage. For most applications, near ideal MTF can be achieved as absorber volumes for each pixel are fully isolated, removing pixel-to-pixel electrical crosstalk [4].

### III. NEAR INFRARED (NIR) AND SHORTWAVE (SWIR)

Work in the NIR (0.8 - 1.9  $\mu$ m) and SWIR (0.8 - 2.5  $\mu$ m) was undertaken in response to European Space Agency requirements for large-format arrays, eventually 2k x 2k at 15–18  $\mu$ m pitch. Initial NIR development used a 320x256, 24  $\mu$ m pitch format, moving on to a 1280 x 1032, 15  $\mu$ m pitch format (the largest achievable in

the current 0.35  $\mu\text{m}$  CMOS foundry process with a single reticle). The SWIR development followed on from the NIR with a stitched-reticule ROIC format of 2048 x 2044, 17  $\mu\text{m}$  pitch.

Common to both these requirements is response down to 0.8  $\mu\text{m}$  which presented a challenge compared to designs targeting longer wavelengths. For example the latter would use a higher Cd mole fraction MCT common layer as a window but this approach would necessarily restrict the wavelength range for full quantum efficiency to above about 1.3  $\mu\text{m}$ , owing to a drop-off in activation of the dopants in Cd rich MOVPE-grown MCT leading to progressively lower quantum efficiency at shorter wavelengths. Instead the MCT is thinned to within approximately a diffusion length of the junction, followed by back-surface passivation. Fig. 1. shows the evolution of the short wave response on a test array as a function of thinning stages.

Device assessment was performed by the UK Astronomy Technology Centre. Fig. 2 and 3 shows the achieved dark current and H-band (1.65  $\mu\text{m}$ ) quantum efficiency respectively. Stray radiation is believed to have limited the dark current at temperatures below 110K. Above this temperature the dark current is diffusion limited.

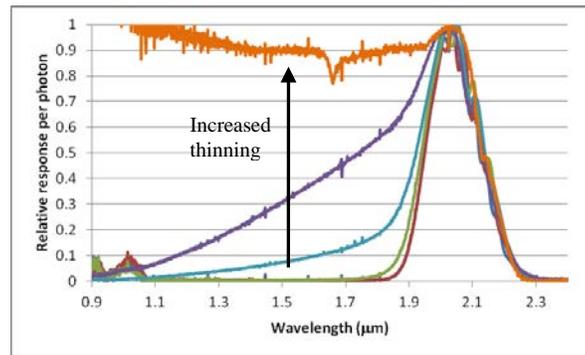


Fig. 1. Evolution of the spectral response as the MCT is thinned in stages.

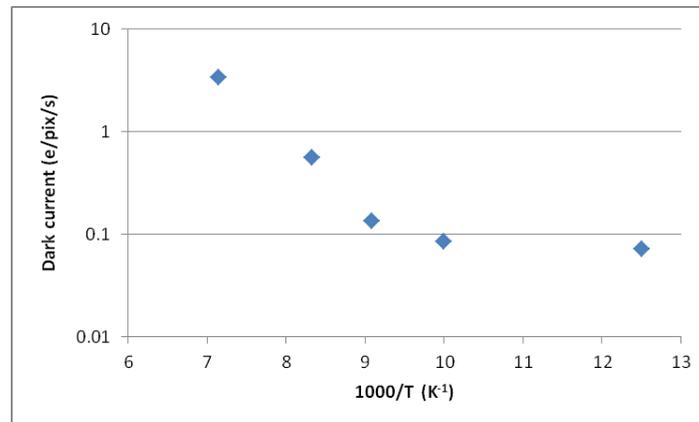


Fig. 2. Dark current for NIR array against inverse temperature.

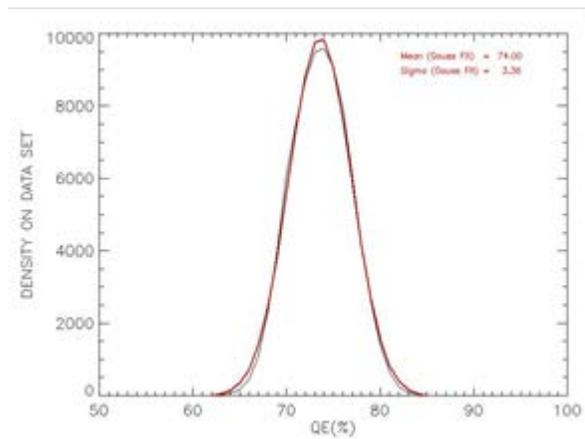


Fig. 3. H-band quantum efficiency histogram.

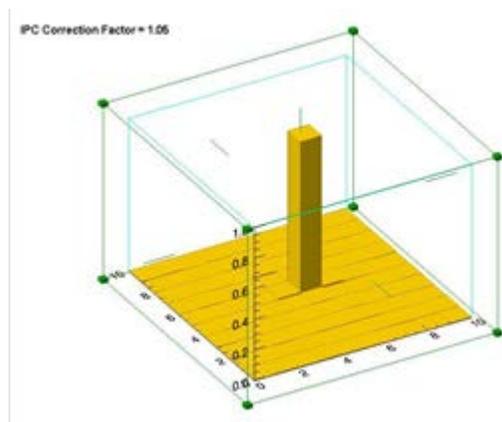


Fig. 4. 2D autocorrelation image showing low-level interpixel capacitance coupling.

The bump-bond technology does not employ a glue infill. One advantage of this approach is that a low value of interpixel capacitance is achieved, Fig. 4. The auto-correlation image indicates an interpixel coupling of only 1.05.

Persistence is an important parameter in astronomy applications and is associated with a change in response as a consequence of trapped charge after excessive illumination, the response gradually recovering with time. A bright spot was imaged on the detector with a flux level chosen to saturate the detector in 5 s. A 10 s exposure was then taken to drive the detector into “double saturation”. Immediately afterwards the shutter was closed and the cold blank filter switched into place. A series of 10 s exposures was then taken to establish if any signal persistence existed. The results are summarised in Fig. 5. These levels are considered to be promising.

*ROIC designs*

The first development was for the NIR with format 1032x1280, 15 micron pitch with 4 to 32 selectable outputs, designed for low flux, long stare time applications, and a clock rate of 100kHz (design target), with >200kHz achieved. The well-established source follower pixel design achieves <35mW in 4 output mode, to <55mW in 32 output mode, with continuous readout. High gain for good sensitivity is demonstrated, helped by the MCT diode design for low capacitance but high optical fill factor. From the photon transfer curves calculated values of the integration node capacitances with and without additional selectable capacitances are 23 and 14 fF respectively.

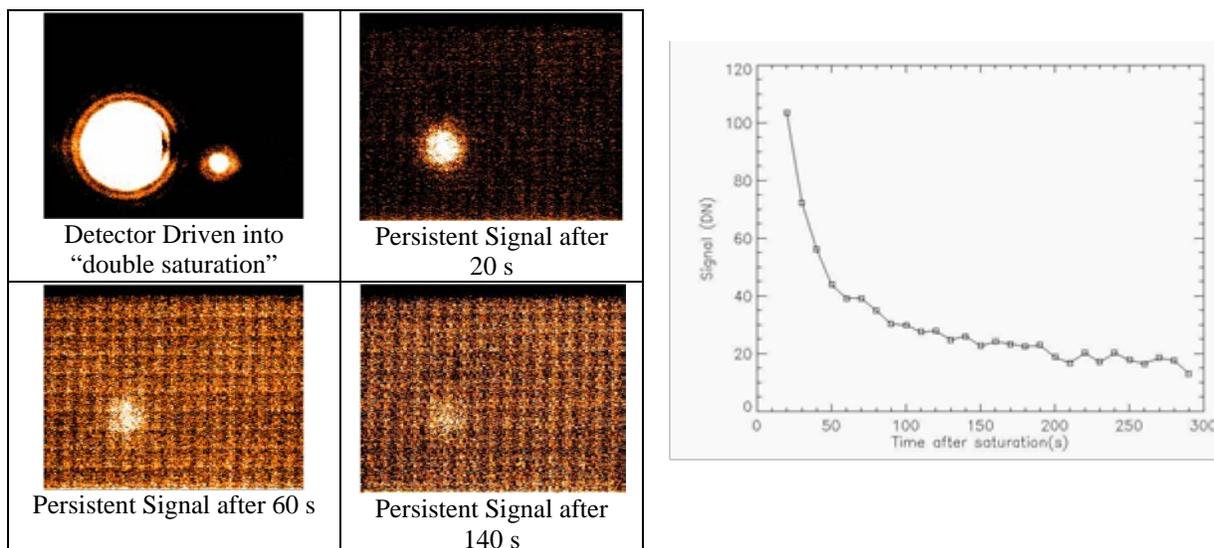


Fig. 5. Detector persistence after being driven into double saturation.

The low MCT junction capacitance improves the overall linearity. Non-linearity is associated with a change of the HgCdTe junction capacitance with a corresponding change in signal level. 3% non-linearity to 75ke- well capacity has been demonstrated. The linearity can be further improved (<1%) if a higher value of switched capacitance or a higher reverse junction bias are used.

Low read noise has also been achieved from a single pair of minimum stare time dark reads (~17e- rms), reduced by up-the-ramp sampling to ~6e- rms with 24 samples.

The same ROIC design techniques including a radiation hard cell library have been incorporated in the large format SWIR (2048 x 2056, 17 $\mu$ m pitch) development for earth observation applications. This device has been designed as a stitched reticule for the silicon foundry. The elements of the stitching allow the foundry to produce larger arrays as multiples of 1024 x 1028, with minimal additional design work. This device is currently undergoing characterisation.

#### IV. ELECTRON AVALANCHE PHOTODIODES (eAPD)

In a collaboration with the European Southern Observatory, ESO, Selex ES has developed a custom NIR array with avalanche gain and low noise ROIC (SAPHIRA - Selex Advanced Photodiode array for High speed Infrared Arrays). The ROIC format is 320x256 at 24  $\mu$ m pitch. SAPHIRA was specifically designed as a very sensitive detector for wavefront sensing of guide stars for applications in adaptive optics. Bandgap engineering is made possible with MOVPE and designs separating the absorber, junction and gain regions allow both high gain and high breakdown voltage simultaneously [5]. An example of an eAPD design is shown in fig 6. The junction (and, hence, the peak electric field) is placed in a wider bandgap region (e.g. 2  $\mu$ m absorption edge) to reduce generation and trap assisted tunneling, thus reducing dark currents, increasing breakdown voltage and improving operability. The bandgap reduces into the gain region (e.g. 3  $\mu$ m absorption edge) to reduce the energy required for avalanche multiplication. The design introduces a grade in the heterostructure to avoid potential hole barriers as shown in the figure.

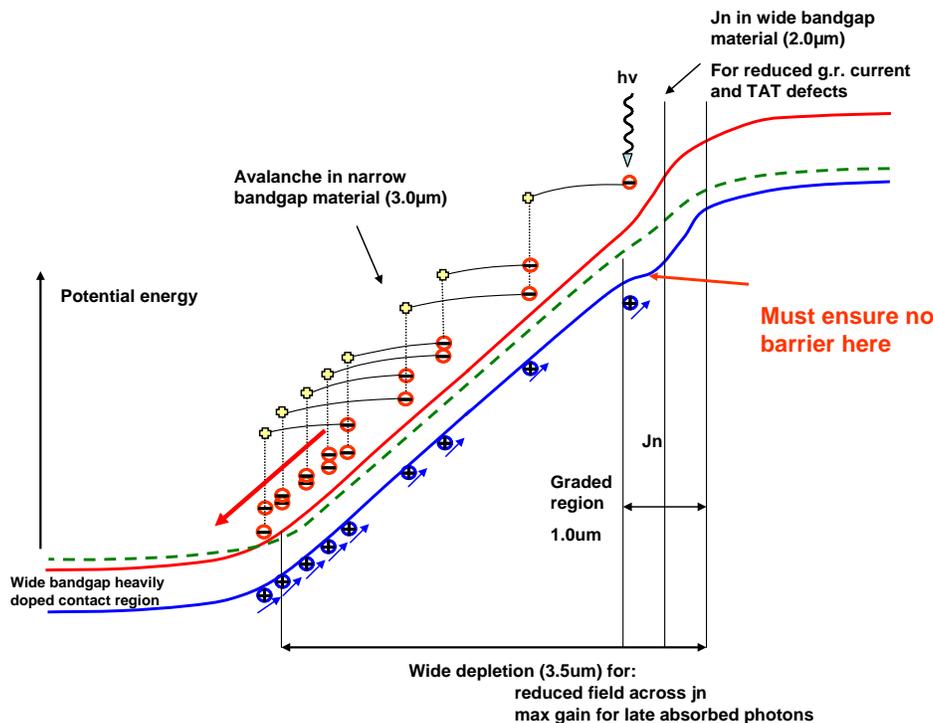


Fig. 6 Illustration of the eAPD band structure

At an operating temperature of 85K multiplication noise figures of approximately 1.2 and 1.3 in the H-band and K-band respectively have been measured at gains of up to 80. These low values compared to, say, typical Si APDs are due to the low electron/hole effective mass ratio in MCT.

The readout noise histogram for single correlated double sampling is shown in fig. 7. No significant high-noise tail is evident and the median value is 0.8 electrons. Measurements by ESO have shown that the readout noise can be reduced to close to just 0.2 electrons rms with 15 Fowler pairs [2].

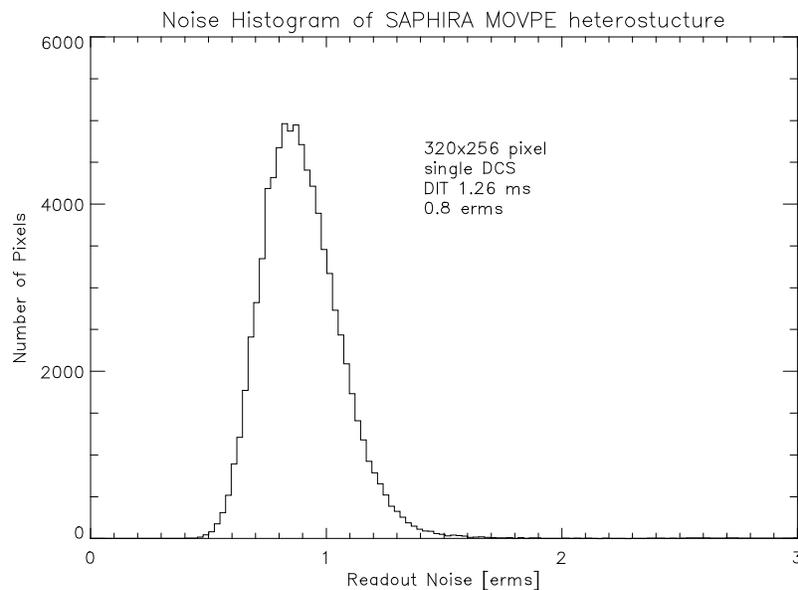
Fig 8 illustrates the exceptional sensitivity that can be achieved with the Selex ES MOVPE HgCdTe eAPD arrays. A test pattern which is calculated to provide a flux contrast of just 1.12 H-band photons/ms/pixel on the array is imaged. This figure clearly demonstrates the detection of single photons.

The breakthrough results achieved with MOVPE grown HgCdTe eAPD arrays hybridised to the SAPHIRA ROIC have shown that single photon detection can be achieved without the need for deep cooling beyond 80 K and with very low defect levels. This performance is well matched to the demanding requirements of wave front sensing and astronomical NIR interferometry.

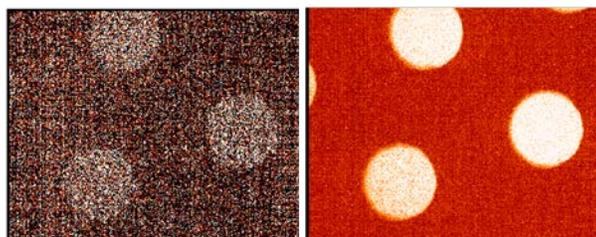
Looking forward, the possibility exists of manufacturing larger APD science arrays on 1k or 2k readout chips, such as the ESA NIR or SWIR chips that are already designed to be compatible with APDs. Selex ES MOVPE growth is currently on 75mm diameter GaAs substrates. The MCT die size of the SWIR array is 35mm square and only a single array can be printed on the 75mm diameter wafer, utilising only 28% of the wafer area. The situation for 100mm substrates is little better, allowing only 2 arrays and 31% utilisation. However, low cost GaAs substrates are readily available in 150mm diameter and the MCT growth is scalable to this size, offering the real possibility of 6 arrays per wafer with 42% utilisation.

## VI CONCLUSIONS

This paper has reported on the recent advances that have been made at Selex ES which enable products exploiting MOVPE grown HgCdTe photodiode arrays to be offered into high performance astronomy and



**Fig. 7** K-band readout noise histogram



**Fig. 8** H-band test pattern with signal difference of 1.12 photons (0.52 electrons) per ms with an integration time of 1.17ms. Left: single exposure. Right: average of 12 exposures

spectroscopy applications. Of note are the exceptional results that have been achieved by developing MOVPE grown HgCdTe eAPDs for low noise NIR imaging applications. Results measured at the European Southern Observatory have shown that the SAPHIRA arrays have a readout noise equivalent to less than one electron rms and that single photon imaging is possible. This makes the technology suited to the advanced applications of wavefront sensing and NIR astronomical interferometry.

The large format NIR and SWIR developments suitable for astronomy and earth observation applications, have incorporated APD enabled ROIC designs with a radiation hard cell library. Development is continuing in these products. VLWIR low dark current is another area under development for potential space applications such as IASI and EChO

These advancements in MOVPE grown HgCdTe mesa arrays and the exploitation of their capabilities through high performance ROIC designs will ensure that this technology remains at the forefront of infrared imaging into the future for formats up to 4Mpixels and beyond.

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