Title
Selex infrared sensors for astronomy – present and future

Journal
Adaptive Optics for Extremely Large Telescopes 4 – Conference Proceedings, 1(1)

Authors
Baker, Ian
Maxey, Chris
Barnes, Keith

Publication Date
2015

DOI
10.20353/K3T4CP1131564

Selex infrared sensors for astronomy – present and future

Ian Baker, Chris Maxey and Keith Barnes
Selex ES Ltd, Southampton, United Kingdom, SO15 0LG

Abstract

Many branches of science require infrared detectors sensitive to individual photons. Applications range from low background astronomy to high speed imaging. Selex-ES Ltd in Southampton, UK, has been developing HgCdTe avalanche photodiode (APD) sensors for astronomy in collaboration with ESO since 2008 and more recently the University of Hawaii. The devices utilise MOVPE grown on low-cost GaAs substrates and in combination with a mesa device structure achieve very low dark current and near-ideal MTF. MOVPE provides the ability to grow complex HgCdTe heterostructures which have proved crucial to suppress breakdown currents and allow high avalanche gain in low background situations. A custom device called Saphira (320x256/24µm) has been developed for wavefront sensors, interferometry and transient event imaging. This device has achieved read noise as low as 0.26 electrons rms and single photon imaging with avalanche gains up to x100. It is used in the ESO Gravity program for adaptive optics and fringe tracking and has been successfully trialled on the 3m NASA IRTF, 8.2m Subaru and 60 inch Mt Palomar for lucky imaging and wavefront sensing. In future the technology offers much shorter observation times for read-noise limited instruments, particularly spectroscopy. The paper will describe the MOVPE APD technology and current performance achievements.

1 Introduction

Conventional infrared detectors are limited. The best CMOS silicon multiplexers have a sensitivity around 10 µV/photon. At typical clock rates the read noise is around 100 µV rms so 10s of photons are required to obtain a statistically valid signal from one frame. Even then the instrument is said to be read noise limited. In natural guide star wavefront sensors many thousands of frames per second are needed providing even more photon-starvation. Electronic amplification methods all have serious drawbacks in small-pixel focal plane arrays so engineers have turned to avalanche multiplication for future astronomical sensors. Many low background spectroscopic instruments are read noise limited and require long observations to average down the noise to a level controlled by 1/f noise and the electronics stability. Avalanche gain promises to achieve photon-limited performance in much shorter observation times and avoid 1/f noise and stability limits. The ultimate goal is single photon-level imaging.

The defence and security sector first recognised the importance of single photon imaging in programs starting in 2001. The ability to perform detection, recognition, identification and intent over long ranges, day and night, is an essential modern requirement, and it stimulated the development of sensitive detectors for laser-gated imaging (LGI) or burst-illumination LIDAR (BIL), Baker *et al*, 2004. The HgCdTe avalanche photodiode arrays (e-APDs) emerging from these programs had particular characteristics including very high avalanche gain and fast response to be sensitive to 10ns laser pulses. The technology was based on Liquid Phase Epitaxial (LPE) growth of HgCdTe and simple homojunction device architectures. When ESO first explored these arrays in 2008 for astronomy they clearly showed promise but were not optimised for long integration times and low dark current. Arrays were manufactured but needed cooling to 40K and had gains limited to x20 and integration periods limited to 10s of milli-seconds. However astronomy requirements are far less stringent on response time and it became practical to use 3rd Generation technology for e-APDs. The benefit of bandgap engineering was seen immediately with operation at temperatures up to 100K, gains up to x60 and few defects in integration times of seconds.

2 HgCdTe Electron Avalanche Photodiodes (e-APDs)

The concept for avalanche photodiode arrays (e-APDs) dates back to the 1980s (Elliott *et al,* 1990) and the first e-APD arrays were produced in the early 2000s (for instance Beck *et al*, 2001). The solid state mechanisms for avalanche gain in HgCdTe have been well described and three recommended papers are Rothman *et al*, 2011, Beck *et al,* 2011 and Kinch and Baker, 2011 and the references therein. Figure 1 shows a potential energy schematic for a typical photodiode and it illustrates the single-carrier, cascade-like gain mechanism, together with the history-dependent behaviour that leads to the observed low noise figures. The heavy hole mass is ~ $0.55m_o$ across the entire HgCdTe composition range, resulting in low hole mobility values, and a significant degree of optical phonon scattering. Thus the heavy hole acquires energy from applied fields very inefficiently, and readily loses what it does gain to optical phonons. The effective mass of the electron, on the other hand, is very small, $m_e^*/m_o \sim 7\times10^{-2}E_g$ [8], where E_g is the bandgap in eV. Its mobility is high, particularly at low temperatures, and scattering by optical phonons is weak, which results in significant energy gain at even modest applied fields. The conduction band of HgCdTe is also devoid of any low-lying secondary minima, which allows for large electron energy excursions deep into the band, and hence the high probability of impact ionization, with the generation of electron–hole pairs. In HgCdTe this is an electron gain mechanism so the absorber must be p-type, which dictates an n-on-p structure. Theoretical studies indicate that there is an optimum width for the depletion region (multiplication zone) of 1.5 to 2.5 µm; at the lower end is a risk of gain saturation and tunneling currents; and at the upper end, alloy or phonon scattering starts to impact the ionisation threshold voltage. One of the reasons e-APD arrays have matured so quickly is that these conditions are easily met using near-standard manufacturing processes.

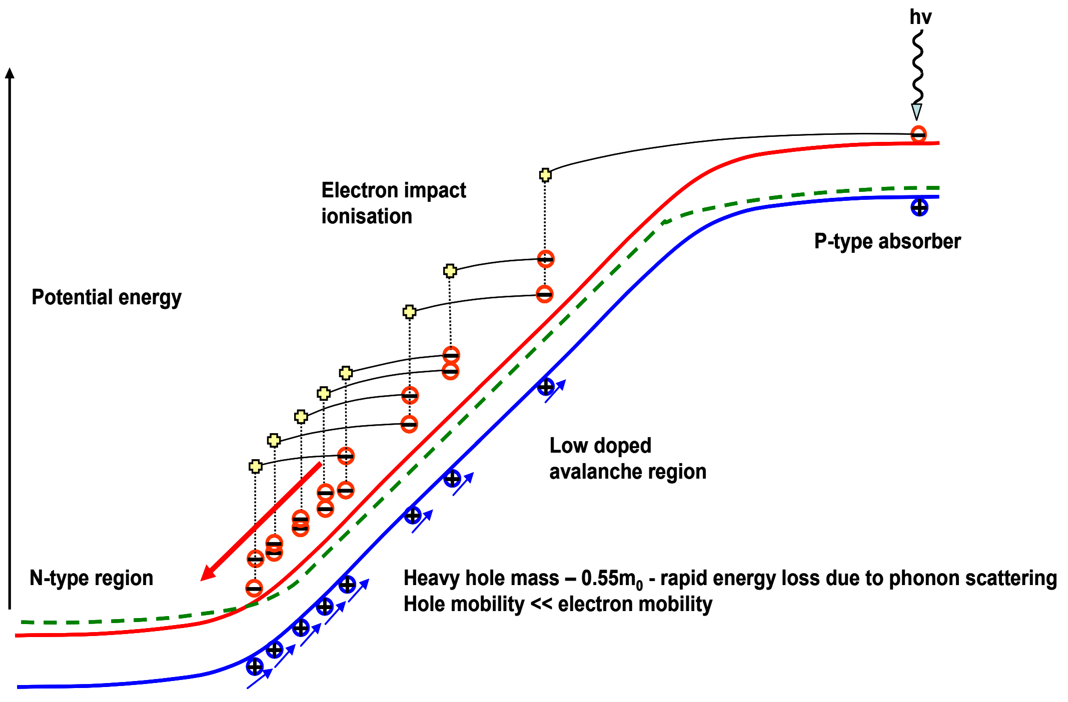


Figure 1 ***Potential energy schematic – illustrating history-dependent avalanche gain in HgCdTe***

In fact, the e-APD offers an extraordinary amplifier specification: voltage controlled gain at the point of absorption, electron gain values up to 1000×, virtually zero power consumption, bandwidths to GHz, high stability, high uniformity, no impact on the silicon pixel design and negligible added noise. On the cautionary side the noise figure of HgCdTe e-APDs is often quoted as being negligible but APD noise figures only describe the gain fluctuation. Noise due to dark current is not included and can be significant particularly as it is gain-amplified in many devices. Most photon starved applications can exploit avalanche gain but some care needs to be taken with dark current.

Avalanche gain has an exponential dependence on applied voltage but the exponent and ionisation threshold voltage are dependent on device level parameters such as the electric field distribution and the composition through the depletion region. Rothman *et al*, 2012 has developed a local field impact ionisation and gain model for SW e-APDs that takes into account gain saturation and phenomenological expressions for the local impact ionisation. Equation 1 is a good baseline for illustrating the behaviour of avalanche gain with voltage, composition and depletion layer width.

$$M = e^{\{\propto Eg^{-1} V^{c} W^{1-c} Exp(-\frac{bW}{V})\}} \tag{1}$$

Where M is the avalanche gain, α, b and c are fitted constants taken here as 22.6, 32500 and 0.6 respectively, V is the applied voltage and W the depletion layer width in cm.

At first sight it would appear to be beneficial to always use narrow bandgap compositions but in practical systems there is a risk of increased dark current and stray light. In this case the noise equivalent photons (NEPh) can be calculated as a function of the e-APD parameters and extra noise. The derivation involves the solution of a quadratic and a useful form is shown in Equation 2.

$$NEPh = \frac{F}{2.Q}\left[1+\left[1+\left(\frac{2.FN}{F.T.M}\right)^{2}\right]^{0.5}\right] \tag{2}$$

Where F is the noise figure, Q is the quantum efficiency, FN is the fixed noise and T is the transfer function (gain from pixel to output – typically in the region of 0.7).

3 MOVPE e-APD design and technology

Three technologies are currently reported in the literature for e-APDs. Planar diffused and via-hole processes are essentially homojunctions where the bandgap is constant throughout the device structure and the depletion width is determined the doping conditions. Mesa heterojunctions on the other hand allow the doping and bandgap to be varied freely through the device structure and the depletion region is a tightly controlled width determined at the material growth stage. Selex has developed the Metal-Organic Vapour Phase Epitaxy (MOVPE) growth of HgCdTe on low cost, three inch GaAs substrates for mesa heterojunctions.

MOVPE growth provides full control over the bandgap and doping profile with arsenic used as the acceptor and iodine used as the donor. For APDs it allows the absorber, p-n junction region and multiplication region to be independently optimised. More details on the process are described in Maxey *et al*, 2003. Initially it was believed that MOVPE would be unsuitable for e-APDs because of potentially high levels of misfit dislocations that are usually associated with junction breakdown currents. However any potential junction-related breakdown currents such as trap-assisted tunnelling or trap-related thermal current can be switched-off by bandgap engineering around the p-n junction and a properly optimized device design.

The multiplication region is made narrow bandgap to give high gain per volt but a compromise is needed to avoid too much stray light or dark current. Figure 2 shows a schematic of the device structure.

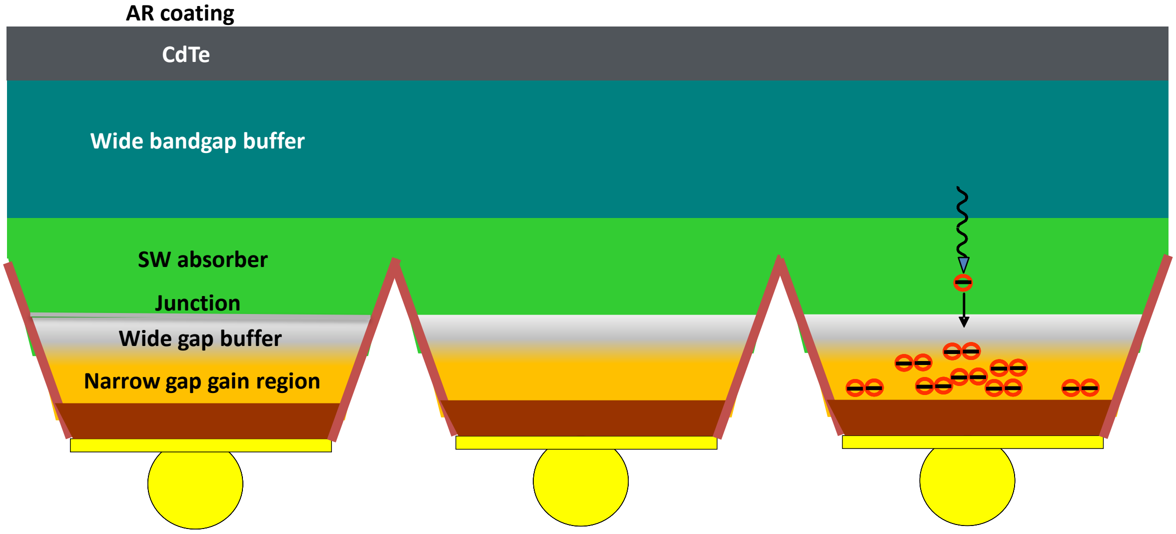
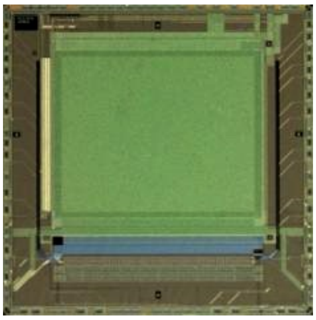


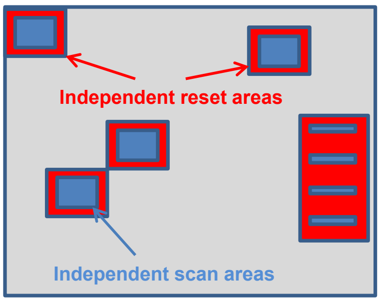
Figure 2 Schematic of MOVPE heterostructure eAPD array. (Note the vertical axis is amplified a factor of 3 for the 24 µm pixel used in Saphira e-APDs).

Each pixel is electrically isolated by a mesa slot that extends though the absorber to eliminate lateral collection and blooming. The optical crosstalk, MTF and pixel inter-capacitance of MOVPE arrays are very favourable for astronomy. The sidewalls are coated with a CdTe layer that is inter-diffused at high temperature. The widening of the bandgap around the edges of the absorber effectively separates carriers from surface states and minimises junction currents where the junction intercepts the sidewall. The high temperature anneal also promotes long term stability and immunity from life at high operational temperatures. HgCdTe is the only infrared material that permits so-called hetero-passivation and it has a strong impact on the reverse-bias breakdown in e-APDs.

4 Saphira – custom designed ROIC for wavefront sensing

In a partnership with the European Southern Observatory, ESO, Selex ES has developed a full-custom silicon ROIC known as SAPHIRA (Selex Advanced Photodiode array for High speed Infrared Arrays). This 320 x 256, 24 µm pixel pitch array has been designed specifically for wavefront sensors and interferometry applications in astronomical telescopes. The requirement is for high frame rates and for low noise at the corresponding bandwidth. The high frame rate is achieved through the use of 32 parallel analogue ROIC outputs, and a windowing function to limit the readout area to regions of interest (as illustrated in Figure 3).





- Fully flexible 'Region of Interest' architecture
- 32 outputs and optimum pixel mapping for high frame rate in multiple windows
- Non-destructive readout
- Very low noise
- Designed for HgCdTe APDs

Figure 3 Saphira ME1000 ROIC summary

In a typical wavefront sensor setup the frame rate can exceed ten thousand frames per second. To minimise the readout noise the SAPHIRA ROIC design was optimised to reduce noise from the analogue output chain. Non-destructive readout is provided to allow multiple frame averaging techniques to reduce readout noise. 32 adjacent row pixels are mapping onto the outputs simultaneously to provide the fastest frame rate so a 32x32 window only requires 32 clocks.

The first Saphira ROIC was designated ME911 and has now been up-graded following funding from ESO. Saphira ME1000 has an optimised analogue chain and additional functionality to permit more flexible readout modes. Specifically the row advance is under external control so that rows can be read many times to reduce noise and allow more efficient correlated-double-sampling.

5 Performance status of e-APDs for H and K band

The bandgap of the multiplication layer can be optimised for each application but standard Saphira arrays use a bandgap equivalent to a cutoff of 3.5 μms. This wavelength is a compromise to allow the highest gain without incurring excessive dark current or providing a problem excluding stray thermal background. The avalanche gain of this configuration is shown in Figure 4 and the corresponding dark current in Figure 5.

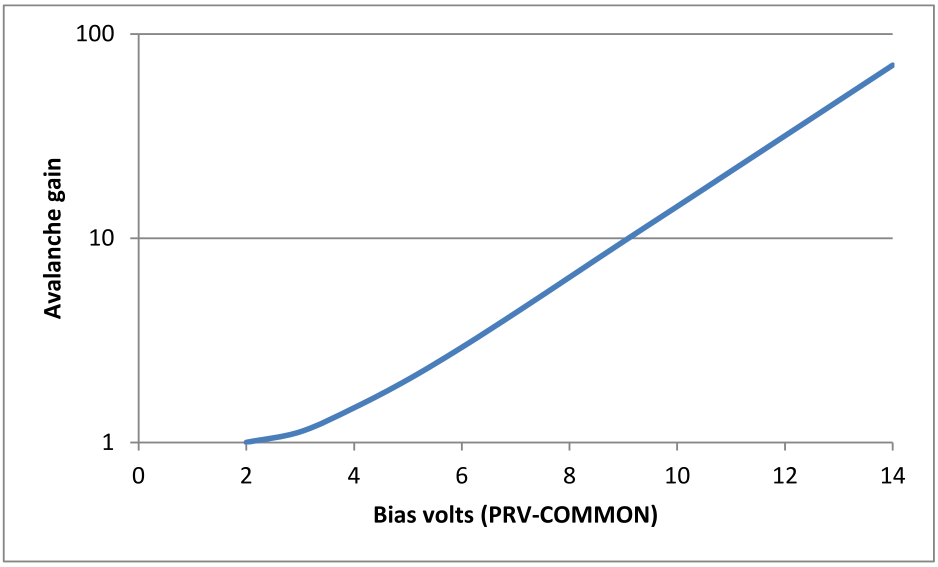


Figure 4 Typical avalanche gain curve

One of the benefits of the heterojunction design is that dark current is generated only in the multiplication region and experiences a fraction of the voltage drop. The difference between 12V and 6V is a factor of x25 so there is a differential in the gain experienced by photons and that experienced by dark current. Future designs could emphasize the differential for photon counting applications.

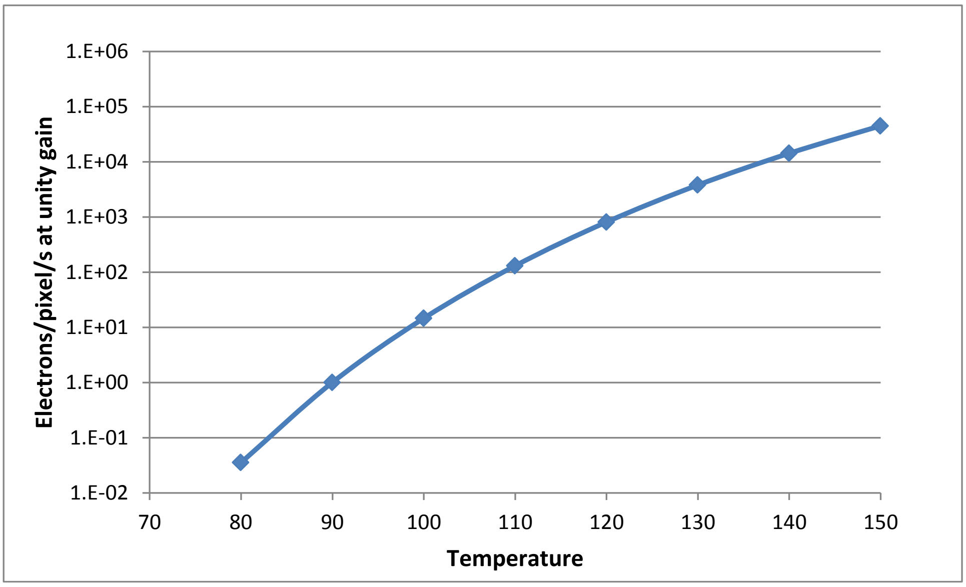


Figure 5 Dark current for 3.5 µm multiplication region

For monitoring QE and signal uniformity a calibrated 1.55 µm laser pulse is employed. The array is flood illuminated through an optical notch filter. Figure 6 shows a typical result for the following operating conditions: bias voltage – 9V (equivalent to a gain of x14), operating temperature – 83K, integration time – 200ms. A feature of MOVPE e-APDs is the uniformity after avalanche gain. The gain is only sensitive to bias voltage and the bandgap of the multiplication region. Other controlling features such as depletion width and doping are tightly controlled by the MOVPE growth process. Signal operability has been 100% in some arrays and is usually counted in a few pixels in science grade arrays. QE varies with temperature and at 100K is around 75% dropping to around 50% at 60K. This variation is now thought to be due the ripples in the bandgap that interfere with electron flow. The cause is probably incomplete interdiffusion of the CdTe and HgTe layers in wide bandgap material where the Hg content is very low.

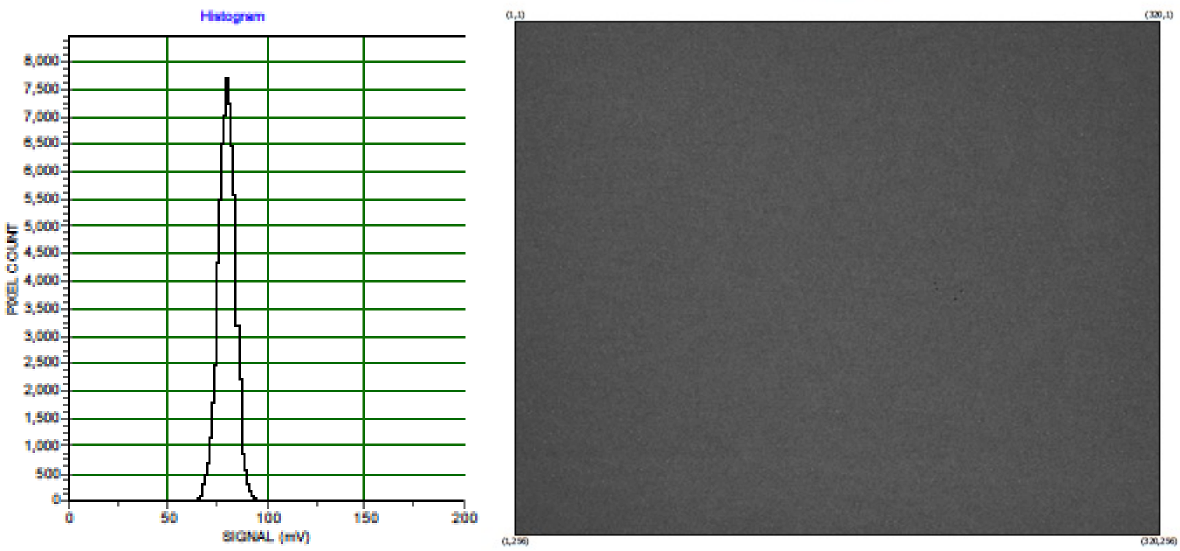


Figure 6 Signal uniformity under avalanche gain

The noise is assessed by running many pairs of frames and subtracting the signals so the integration time is the frame repetition time and the noise is the rms variation. This technique eliminates KTC noise so we call it CDS noise. Our SW test kit has a fixed background of 1e4 photons/second which restricts the length of exposure but typical science grade arrays show few pixels with CDS noise significantly greater than the median noise at our standard test conditions of 83K, 200ms and 9V bias. We rely on specialist centers such as ESO and University of Hawaii for low background and high gain assessment. They report that the very high bias quality varies with the MOVPE wafer which indicates a processing factor. The best arrays can be biased to 14.5V at 85K providing an avalanche gain of x80 and single photon sensing. The best read noise of 0.26 rms electrons has been measured by ESO under these conditions (Finger *et al*, 2013).

The true test of the MOVPE e-APD devices is on-sky imaging and the University of Hawaii (Atkinson *et a*l, 2014) have demonstrated Saphira on the 3m NASA IRTF telescope on Mauna Kea. Two second exposures were performed with an avalanche gain of x30 and frame rate of 1000 frames per second. By selecting the 10% highest contrast frames, centering and averaging the resolution was improved from the seeing conditions of 0.3 arcseconds to 0.13 arcseconds, diffraction limited performance. This is called 10% lucky imaging. In the much worse seeing conditions of Mount Palomar (2 arcseconds on the night), 1% lucky imaging produced near-diffractive limited performance for the first time without using an adaptive optics system. An example is shown in Figure 7.

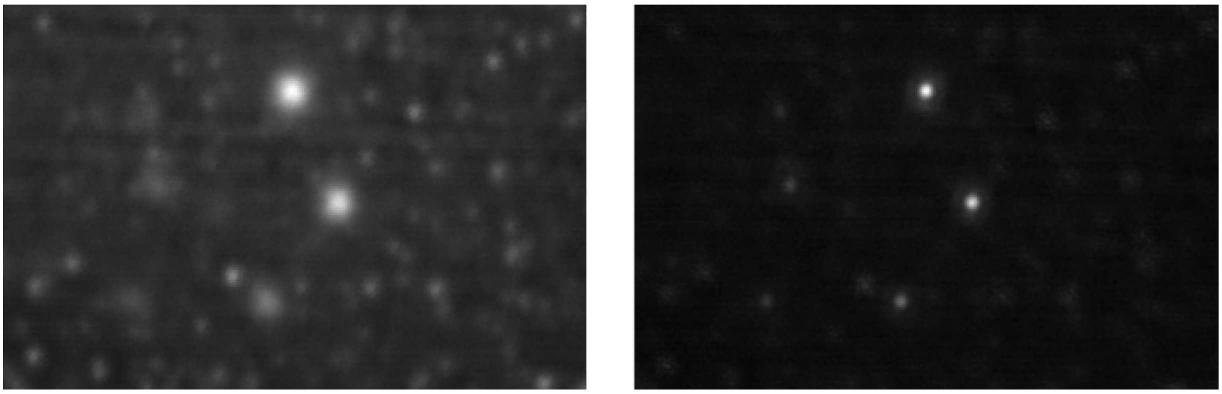


Figure 7 ***Mount Palomar 60 inch telescope. 1 in 100 frame lucky imaging in 2 arcsecond seeing conditions showing near-diffraction limited performance without an AO system. Courtesy University of Hawaii***

6 Performance status of e-APDs for wide spectral response (J, H and K band)

The standard MOVPE process was originally developed for thermal imaging in the long waveband which requires the highest quality HgCdTe. It was found empirically that a thick buffer layer with an equivalent cut-off wavelength of 1.35 µm was very effective at turning over misfit dislocations arising from the crystal lattice mismatch of GaAs. Figure 2 illustrates the buffer layer and clearly it attenuates signal from J band (1.15-1.35 µm) radiation.

There are planned space missions that need panchromatic response and Selex ES decided to invest in modifications to the standard process to allow sensitivity to 0.8 µm. It is not possible to widen the bandgap of the buffer because the surface roughens under growth and this is thought to be a fundamental issue. The strategy chosen was to remove the buffer entirely and grow the absorber directly on the CdTe (which has a bandgap equivalent to 0.8 µm). The key technical issue is to match the growth temperatures and a new CdTe alkyl with a much lower growth rate was used to allow growth at the HgCdTe temperature of 360C. The growth can then be continuous through the interface. CdTe is an insulator and so the mesa slots cannot be allowed to penetrate the CdTe. This leads to a much longer absorber and for high QE the diffusion length must be very long. This necessitates prolonged high temperature annealing to ensure that the CdTe/HgTe layers are fully interdiffused to avoid bandgap ripples that interfere with electron transport in wide bandgap material. The processes were successfully developed independently and the University of Hawaii funded two MOVPE growth runs to assess the APD performance.

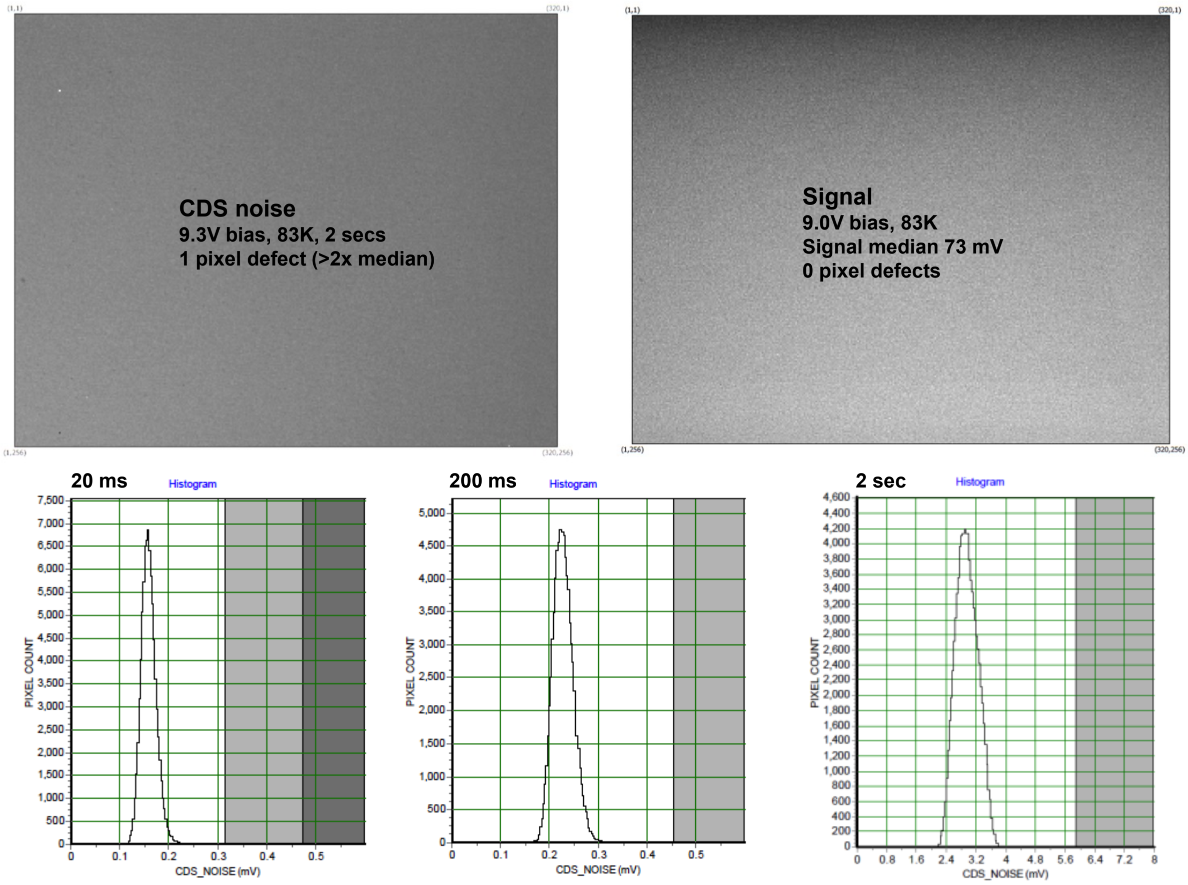


Figure 8 Best array from wide-spectral response batch (Mk 13)

The arrays were sensitive from 0.8-2.5um as expected. The QE was about 20% lower than H, K band devices with values around 60% at 83K due to the longer absorber. The key feature of these arrays was the extraordinary absence of defective pixels which is believed to be a side-effect of the high temperature baking. University of Hawaii show that this situation persists for avalanche gains of up to x100 (work to be published).

7 Conclusions and future e-APD developments

Saphira arrays with HgCdTe e-APDs are fully developed to meet the wavefront sensing market in H and K bands with high QE, fast response and low dark current at convenient operating temperatures around 100K. These arrays have also found application in lucky imaging, fringe tracking and the study of transient events.

The Saphira ROIC has been upgraded to include more flexible readout modes for efficient CDS and the sensitivity improved in a version called ME1000. This will become commercially available once the qualification is complete in Q2 2016.

A wide spectral response e-APD has been trialled in two MOVPE growth runs and shown to give 0.8-2.5 um sensitivity albeit with 20% lower QE than the H, K variants. The use of high temperature anneals on these devices however has resulted in extraordinary low levels of pixel defects even up to x100 avalanche gain. More MOVPE runs are required to bring the QE of the wide-spectral response arrays up to that of the H, K band arrays. So the focus of attention is the technology of the absorber together with longer high temperature anneals.

It is vital this research continues as there is a real prospect that avalanche gain can be applied to very low background imaging applications so in future read-noise limited instruments can be transformed into photon-noise limited instruments and much shorter observation times will be needed.

For ground based astronomy there is interest for a larger version of Saphira in future possibly with smaller pixel size.

REFERENCES

Atkinson D, Hall D, Baranec C. et al, (2014)*Proc. SPIE*, Vol **9154**, 915419Baker I.M, Duncan S. and Copley J, (2004), *Proc. SPIE*, Vol **5406**, p133-144

Beck J.D, Wan C-F, Kinch M.A, and Robinson J.E, (2001), *Proc. SPIE*, Vol **4454**, p188

Beck J.D, Scritchfield R, Mitra P. et al, (2011), *Advanced photon counting techniques,* SPIE Conference Series, 8033

Elliott C.T, Gordon N.T, Hall R.S. and Crimes G.J, (1990), *J.Vac.Sci.Technol.A (USA),* Vol **8** , p1251-1253

Finger G, Baker I.M, Alvarez D. *et al*, (2013), *Optical and IR Telescope Instrumentation and Detectors*, Scientific Detector Workshop, Florence Italy

Kinch M.A. and Baker I.M, (2011), Chapter 21, *"HgCdTe Electron Avalanche Photodiodes"*, Mercury Cadmium Telluride - Growth, Properties and Applications, published by Wiley

Maxey C.D, Camplin J.P, Guilfoy I.T. *et al*, (2003), *J. Electron. Mater.*, **32**, No 7, p656

Rothman J, Mollard L, Bosson S. *et al,* (2012), *Jn. Electron. Mater***,** Vol **41,** No 10, p2928-2936

Rothman J, Mollard L, Gout S. *et al*, (2011), *Jn. Electron Mater*, Vol **40**, No 8,