Developments in MOVPE HgCdTe Arrays for Passive and Active Infrared Imaging

Ian Baker, Chris Maxey, Les Hipwood, Harald Weller and Peter Thorne

SELEX Galileo Infra-Red Ltd, Southampton, SO15 OLG, UK

ABSTRACT

SELEX Galileo Infrared Ltd has developed a range of 3rd Generation infrared detectors based on HgCdTe grown by Metal Organic Vapour Phase Epitaxy (MOVPE) on low cost GaAs substrates. There have been four key development aims: reducing the cost especially for large arrays, extending the wavelength range, improving the operating temperature for lower power, size and weight cameras and increasing the functionality. Despite a 14% lattice mismatch between GaAs and HgCdTe MOVPE arrays show few symptoms of misfit dislocations even in longwave detectors. The key factors in the growth and device technology are described in this paper to explain at a scientific level the radiometric quality of MOVPE arrays. A feature of the past few years has been the increasingly sophisticated products that are emerging thanks to custom designed silicon readout devices. Three devices are described as examples: a multifunctional device that can operate as an active or passive imager with built-in range finder, a 3-side buttable megapixel array and an ultra-low noise device designed for scientific applications.

KEYWORDS: SELEX, HgCdTe, MOVPE, ROIC,

1. INTRODUCTION

Infrared focal plane arrays (FPAs) for the higher end of the thermal imaging market are based on three basic technologies. In order of market penetration these are: indium antimonide (InSb), HgCdTe based mostly on liquid phase epitaxy (LPE) but increasingly on vapour phase epitaxy and quantum detectors using the III-V material system. The InSb and LPE HgCdTe processes are often called 2nd Generation technology and have successfully serviced tens of thousands of high performance thermal imaging cameras. The challenges for 3rd Generation technology include the following:

1. Larger and higher pixel count arrays with no increase in cost or reduction in sensitivity.
2. Higher operating temperature performance for lower camera power consumption.
3. Longwave (8-12 µm) and dual-waveband detectors for better smoke and dust penetration.
4. Multifunctional and highly flexible focal planes arrays (FPAs) to reduce the cost and complexity especially in steerable platforms.

HgCdTe can in principle satisfy all the needs of future IR detectors. This stems from low cost, large area manufacturing methods, the flexible control of bandgap and doping levels, high optical absorption coefficient and well-developed efficient device structures. The perceived disadvantages centre on the low binding energies, ionic bond nature and open lattice of HgCdTe which makes crystal growth and device processing more difficult and reliability less certain. This paper attempts to explain the technological approaches used by SELEX so that a proper comparison of the candidate 3rd Generation technologies can be made.

In the UK the 3rd Generation technology is based on metal organic vapour phase epitaxy (MOVPE) of HgCdTe grown on GaAs substrates [1, 2]. MOVPE was originally developed by the MOD in RSRE Malvern in conjunction with the Philips Research Labs in Redhill. It has been in continuous development at SELEX-Galileo Infrared in Southampton for 25 years including 10 years devoted to growth on GaAs. It is broadly recognised that growth on a lattice matched substrate, such as CdZnTe, results in better device performance than growth on a mismatched substrate. However the generation and propagation of misfit dislocations in MOVPE growth can be mitigated and the detector design can also contribute to a reduction in the effect of any crystal defects. The ultimate test is the device quality especially at longer wavelengths and MOVPE on GaAs typically results in arrays of long wavelength, medium wavelength and dual band devices with

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low defect levels and low dark current. Also recent imaging comparisons have shown MOVPE arrays to have much better sharpness and thermal contrast in side-by-side camera trials with 2nd Generation detectors [3, 4]. Operating focal plane arrays at higher temperatures is a key modern requirement and the status of MOVPE arrays has been described [5, 6]. Operating temperature clearly depends the optics, scene temperature, wavelength and performance specification. Standard MOVPE products operating in the 3.7 to 5.0 μm band with an F/4 optic and viewing a 293K scene temperature show background limited sensitivity up to 155K with a modest increase in defective pixels. Very acceptable imaging has been obtained up to 210K under certain conditions [5, 6]. Programmes are currently underway to design specific MOVPE device structures for even higher operating temperature and this has far-reaching consequences on the size, weight, power and cost of future thermal imaging systems.

2. 3rd GENERATION FPA TECHNOLOGY USING MOVPE HgCdTe

There is a dual purpose in developing vapour phase epitaxy technologies for HgCdTe infrared detectors. Firstly, it provides a whole range of new device structures with programmed control of the thicknesses, bandgap and doping levels, and secondly it allows growth on lower cost substrates.

2.1 MOVPE materials growth

MOVPE growth depends on transporting the elements cadmium and tellurium (and dopants iodine and arsenic) at room temperature as volatile organometallics. They react along with Hg vapour in the hot gas stream above the substrate or catalytically on the substrate surface. The drive to lower temperatures and hence lower Hg equilibrium pressures has resulted in the adoption of the Te precursor di-isopropyl telluride, which is used for growth in the 350-400°C range. A key step in the success of this process is to separate the CdTe and HgTe growth so they can be independently optimised. This is called the IMP process for Interdiffused Multilayer Process. The resulting stack of alternating CdTe and HgTe layers relies on the fast interdiffusion coefficients in the pseudobinary to homogenise the structure at the growth temperature. The wavelength of $Hg_{1-x}Cd_xTe$ is determined by the composition x which is in turn dependent on the growth rates during the CdTe and HgTe cycles. The key difference to molecular beam epitaxy (MBE) is that control of HgCdTe composition can be simply accomplished by the length of time the Cd source flows into the reactor for the CdTe part of the IMP cycle. Also since the dopants are incorporated on the CdTe cycle the doping density is relatively independent of composition. Arsenic is used for P-doping (*Tris*-Di-Methyl Amino Arsine) and iodine for N-doping (*Iso*-Butyl Iodide) and are actively incorporated during growth without a requirement for an ex-situ anneal.

Commercial GaAs substrates have a number of attractions compared with alternative low cost substrates such as silicon. They are readily available at low cost, have good crystal quality and an oxide that is easy to remove prior to MOVPE growth. At the end of the process the GaAs substrate is removed by a selective etch. A 76.2mm GaAs substrate costs about $100 some 5x less than GaSb (used in III-V detectors) and about 50x less than CdZnTe used in 2nd Generation processes. Since the substrate is at the front end of the process the cost impact per array is divided by the yield and the number of arrays per wafer. It therefore has a superlinear relationship on the size of the array. The MOVPE on GaAs process has a strong cost impact on larger arrays (over 100 mm^{-2}) and in principle enables the economic manufacture of arrays up to 40x40mm. The preparation of the GaAs surface and the initial nucleation layers are critical to a successful growth. The subsequent CdTe buffer layer plays a role in turning misfit dislocations and blocks Ga diffusion into the HgCdTe. The main morphological risk for MOVPE is the creation of hillocks that can cause a cluster of pixel defects. Particles or other surface roughening features can lead to the creation of these hillock features due to the fast <111> microcrystal growth rates that enhance any surface perturbation. Growth orientations 3-4° off (100) are used primarily to reduce both the size and density of hillocks.

Compositional targeting is of key interest for vapour phase epitaxy processes. For a 5.0 μm cutoff device the wavelength target is 5.55 ±0.25 μm corresponding to an x change of ±0.007. The long term yield against this specification is 74%. At longwave the corresponding yield is 55%. The MOVPE targeting is expected to improve further with higher wafer throughput in future. Special gas injectors and a rotating substrate ensure excellent uniformity of cut-off wavelength across the wafers.

Cadmium is the subject of a number of international protocols concerning its use and disposal. The best 2nd Generation HgCdTe FPAs were based on LPE or MBE grown on CdZnTe substrates. The substrates are mined from sawn up slices taken from large bulk crystal ingots grown by either vertical gradient freezing (VGF) or Bridgman methods. A conservative estimate is that GaAs substrates have reduced the cadmium utilisation by a factor of 100. The MOVPE reactor uses dimethyl cadmium that disassociates into cadmium and harmless gases. Once past the reactor an abatement system uses high temperature cracking furnaces to ensure complete disassociation of any unreacted metal organic compounds and the products are captured in activated carbon filter systems. The environmental impact of HgCdTe grown by MOVPE is therefore negligible complying with our international safety obligations.

2.2 Device fabrication and optical efficiency

The device structure is illustrated in Figure 1. Each pixel is electrically isolated by a mesa slot that extends though the absorber to eliminate lateral collection which can often degrade the MTF of 2nd Generation devices. A combination of dry and wet etching is used to ensure the sidewall shape and quality. The sidewalls are then coated with a CdTe layer that is interdiffused 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 heteropassivation and it has a strong impact on the manufacturing yields and long term process stability.

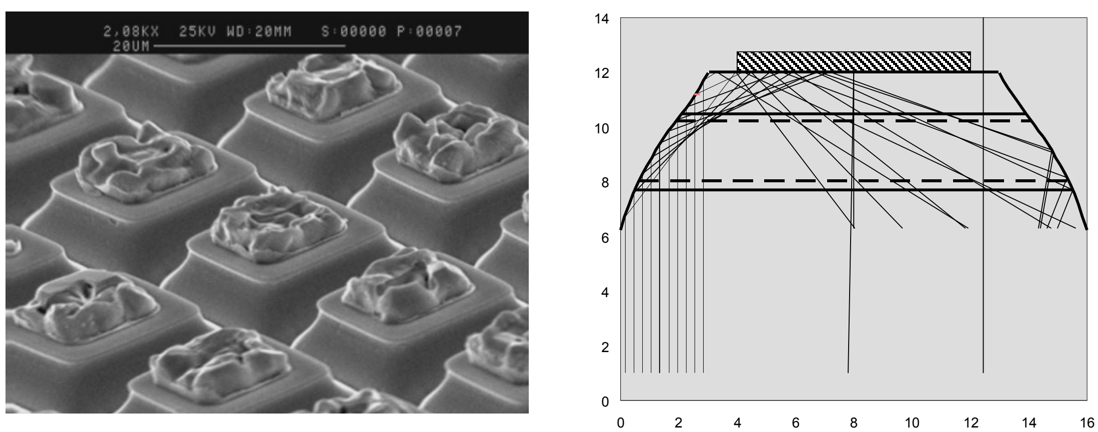


Figure 1 Standard 16 µm pitch structure
– absorption efficiency 0.86, number of photons double-reflected into adjacent pixels (stray light) 3.5%

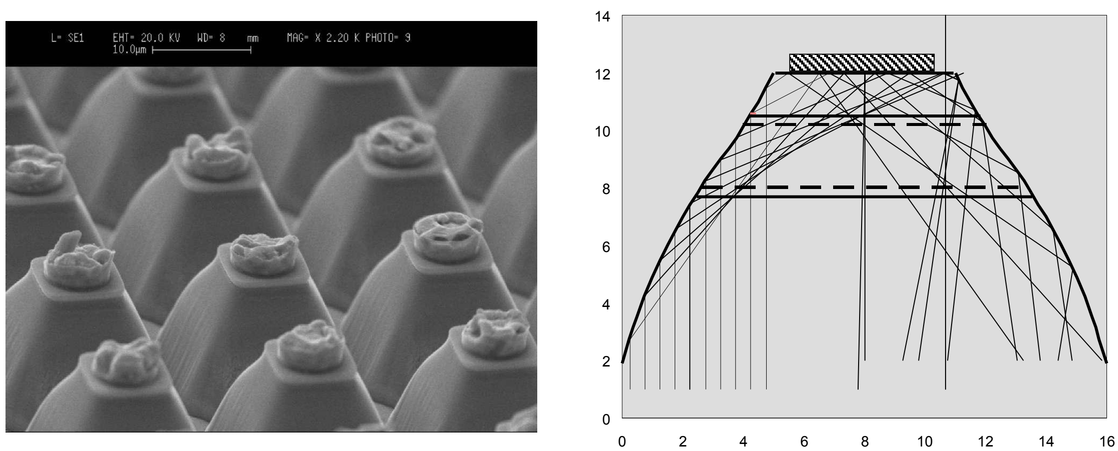


Figure 2 Deep slot structure
– absorption efficiency 0.90, number of photons double-reflected into adjacent pixels (stray light) 2.3%

The main emphasis in the optical design is to ensure that photons are trapped within the mesa cone and completely absorbed. This ensures that stray photons do not scatter and contribute to the background current of other pixels. Stray photons reduce the integration time and have a direct impact on thermal contrast. Figure 1 shows an SEM of a production Hawk array (640x512) with a 16um pitch. It shows the extracted sidewall shape and the ray tracing analysis. The sidewall reflections have skewed paths through the absorber effectively lengthening the absorber by about x3. Using the Chu formula for absorption v wavelength and taking into account the bandgap shape of the absorber gives a total integrated absorption efficiency of 0.86. In combination with the ray tracing data the exported stray light is calculated to be 3.5% which is negligible.

Figure 2 shows a deeper slot used for dual waveband detectors. The ray tracing graph illustrates the optical concentration effect and a substantial reduction in the absorber volume. The electrical properties of MOVPE mesa diodes actually improve with reduction of the absorber volume possibly due to a gettering effect from the interdiffused sidewall. So optical concentration has an impact on dark current, operating temperature and for space applications radiation hardness.

A comparison of cameras using 2nd Generation detectors and the SLX Hawk camera has been possible thanks to HOTSPOT produced by Australian company BBG Sports[3, 4]. Previous 2nd Generation cameras based on InSb and LPE HgCdTe used integration times of over 10ms and could not resolve the ball which can move 25cm in this time. The SLX Hawk camera uses an F/4 optic and an integration time between 0.5 and 1ms therefore having over an order of magnitude less photon flux. Figure 3 shows a typical image with the 90km/hr ball frozen between the batsmans pads. The contact of the ball on the edge of the bat is revealed by a warm friction burn which remains for a fraction of a second. Note also the hairs on the batsmans arms resolved from 80m. The high thermal contrast and resolution of these cameras compared to 2nd Generation is due to the optical design features described above together with low parasitic capacitance in the mesa diode and ROIC.

Figure 3 Image from SLX Hawk camera used in HOTSPOT technology
Courtesy of BBG Sports

2.3 The role of misfit dislocations in MOVPE

The electrically active nature of dislocations and other crystal defects in HgCdTe has been well reported in LPE HgCdTe since the 1980s [7, 8, 9, 10, 11]. The reverse-bias characteristics and 1/f noise of HgCdTe diodes is known to depend strongly on dislocations intercepting the junction. The physics of crystallographic defects in HgCdTe is complex because dislocations tend to manifest as n-type pipes with strain dipoles and also getter impurities that can act as active trap centres. The combination of bandgap narrowing, high junction fields and the presence of traps provides an environment conducive to trap-assisted tunnelling currents (TAT), and we find this the ubiquitous dark current source in defective diodes from both LPE and MOVPE. Dislocations are revealed by the etch pit densities (EPDs) after chemical etches such as the Chen, Hahnert and Schenke and Shaarky etches and in <111> LPE show as strong triangular features. EPDs of $<3\text{-}7\times10^4$ cm^{-2} are required for long wavelength arrays and only LPE grown on lattice matched CdZnTe substrates met this requirement. However LPE is grown at 500ºC and threading dislocations, emanating from the substrate and possibly decorated during growth, are the most potent forms. MOVPE material on (100) orientation displays a totally different behaviour in terms of the type of dislocation and the way dislocations interact with the device currents.

In MOVPE standard etches produce a faint pattern of etch pits that increase with time and depend on the composition (bandgap). There appears to be an absence of the strong types of features in LPE but a indication of many small features perhaps reflecting a mosaic-like growth. There has been very little experimental investigation of the evolution of crystal defects during the MOVPE growth on (100) GaAs substrates. Transmission electron microscope analysis of the CdTe buffer layer has shown misfit dislocations turning into the plane of growth and from work in the III-V area this is expected to persist in the superlattice phase. Structural analysis techniques are indecisive when applied to MOVPE HgCdTe so we have concentrated on device results to provide data. The clearest evidence is the inverse relationship between the array defect level and the proximity of the junction to the growth substrate. For example in two-colour detectors where there is a LW absorber on top of a MW absorber we often see lower defect levels in the LW array than the MW which is substantially nearer the growth interface. There is also no correlation of defects in the two bands despite the junctions only being a few microns apart establishing that there are no active threading dislocations in MOVPE.

Earlier work on MOVPE arrays grown on GaAs/silicon wafers, where the mismatch and strain was much higher, revealed the importance of the mesa delineation in strain relief. Here there was significant dislocation generation at the base of the mesas. Without mesa definition this strain would continue to reside in the absorber and possibly create problems after temperature cycling. The process has been evolved to allow the mesa pillars to relax and isolate any dislocation rafts to electrically inactive parts of the structure.

Most 2nd Generation FPA processes have broad absorbers, so-called lateral collection devices, where the quantum efficiency depends on the diffusion of photogenerated carriers to the junction. One of the mechanisms for dislocations to affect the device performance has been explained as the modulation of the absorber volume by trapping events on dislocations [12]. In the MOVPE process the absorber volume is an order less than that of planar or via-hole devices and the absorber thickness is low compared with the diffusion length. We would therefore not expect dislocation modulation of the photocurrent or diffusion current and this type of noise mechanism is completely excluded in MOVPE arrays.

There is evidence for the presence of weak electrically active dislocations in the absorber from studies on random telegraph signal noise (RTS), a noise type that presents as a binary fluctuation in dark current in a few pixels. This is caused by a single trapping event and in our model is associated with filamentary dislocations that are connected and disconnected to the N-region by a nearby slow trap. By studying these pixels we have been able to show that processes and anneals can strongly effect the activation. This has provided the first evidence to our knowledge that the activity of dislocations can be reduced by proprietary high temperature anneals.

MOVPE HgCdTe growth takes place in an overpressure of hydrogen and there is evidence of significant incorporation in the lattice where it is presumed to reside interstitially. Hydrogenation is a well known process for reducing surface state densities in silicon. At present it is conjecture that it has a similar effect in HgCdTe but it is a factor that separates MOVPE from other processes and may have a role in the deactivation of dislocations.

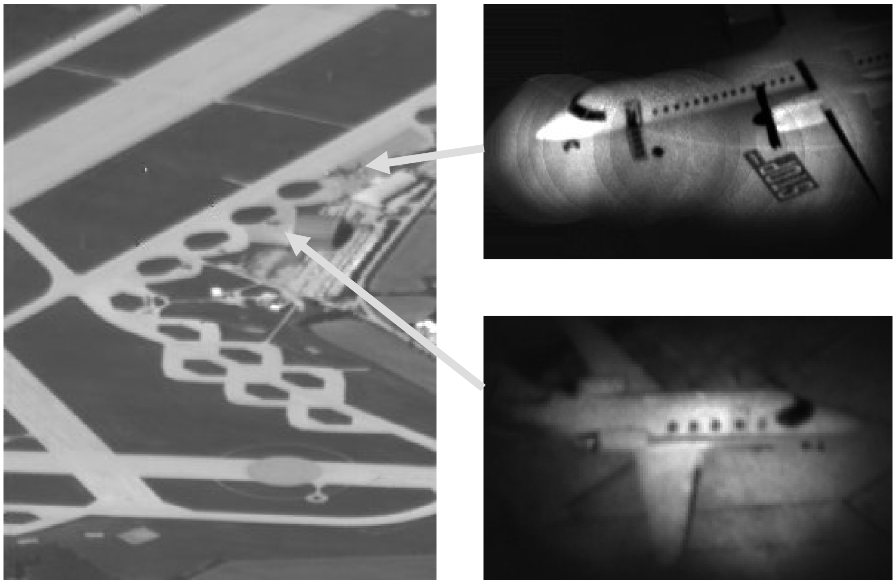
In summary the MOVPE/GaAs growth system combined with the mesa photodiode process has significant differences compared to 2nd Generation technology and perhaps to MBE-based technology. The picture emerging is of a background of very weak dislocations in the absorber possibly associated with mosaic boundaries but in general no threading or other strong crystal defects. The absorber is only a few microns thick and trapping events on dislocations create much less excess noise in the photocurrent or thermal current than in 2nd Generation devices. Dislocations in the junction would be expected to contribute significant TAT current but in MOVPE devices the junction is routinely placed up the composition grade into a wider bandgap area and the thermal step in the TAT process is much reduced. The main cause of excess noise in defective pixels appears to be due to the modulation of TAT current by nearby slower trapping events.

3. RECENT ADVANCED DETECTOR DEVELOPMENTS

Three examples have been selected to illustrate the trends in modern detectors. A crucial element is the readout integrated circuit or ROIC which continually evolves as more advanced mixed digital/analog options become available.

3.1 Multifunctional detector – Swallow MF

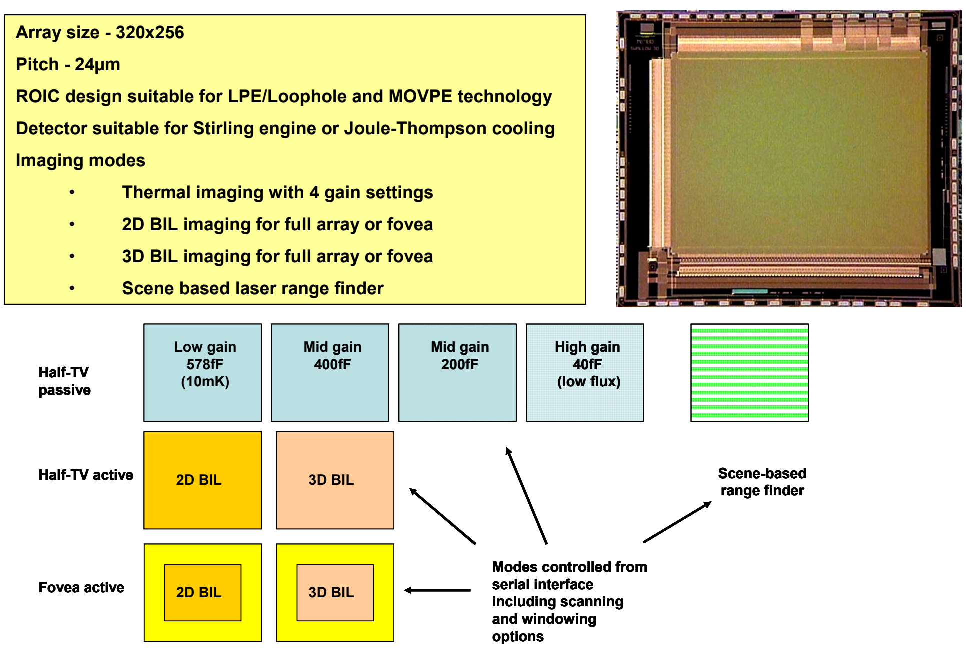
A multifunctional ROIC named Swallow MF has been developed for the Burst-Illumination LIDAR (BIL) market [13, 14, 15] which employs HgCdTe avalanche photodiodes (APDs) to achieve a SW sensitivity down to 10 ph rms. At present the interest is for advanced targeting pods and turrets for airborne applications and is dominated by upgrades to existing equipments. Size, power and mass are critical. In fact it is often impossible to add more optical apertures, sensors and electronics so the only practical option is to upgrade existing thermal imaging detectors within pods with more sophisticated detectors. So-called multifunctional detectors can share optical apertures and electronics, and simplify alignment and data fusion.



An example of airborne BIL imagery from 13,000ft is shown in Figure 4. On the left is a wide field of view thermal image showing an airfield captured using an F/4 camera in the 3.7-5.0 μm band. The thermal image is used to cue potential targets which are then illuminated by a 1.55 μm pulse laser. The BIL detector has a range gate to limit the response to the aircraft only. A combination of the long focal length optic and the shorter wavelength provides the resolution improvement. The avalanche gain in the sensor provides the sensitivity. In this example an older BIL sensor was used with an avalanche gain of x60.

Figure 4 **Example of airborne BIL imagery cued from a thermal image**

Figure 5 illustrates the main features of the SWALLOW MF ROIC.



The complex pixel design required an innovative step called topomorphic design. The pixel can be switched into a number of modes under the control of a serial interface. The BIL modes have a 2D or 3D option. The 3D option produces two frames of data for each laser pulse, the first contains range information and the second intensity information on a pixel-by-pixel basis. With 3D data automatic target recognition is greatly improved and is essential to interpret complex BIL images particularly in the presence of scintillation and camouflage.

Figure 5 **Schematic of SWALLOW multifunctional array with imaging modes**

The laser range finder is a scene-based function which measures the distance to each part of the scene and enables a range gate to be dropped around the target of interest for detailed observation. This then avoids the need to use a separate laser range finder and the computation that is required to set the range gate delay. The thermal imaging mode has 4 gain options and has a similar performance to a dedicated thermal imaging detector.

Swallow MF is a general purpose ROIC that can be used in any active imaging application. The nature of the business is for relatively small numbers of detectors over a long period of time and servicing these requirements with one ROIC leads to savings in support, electronics and cryogenics.

3.2 SAPHIRA - SELEX Avalanche Photodiode array for High-speed Infra-Red Arrays

SAPHIRA is a low noise ROIC designed specifically for the European Southern Observatory, ESO, for wavefront sensors and interferometry applications in astronomical telescopes. The waveband of interest is from 1.0 to 2.5µm - mainly J, H and K band. The requirement is for a sensitivity <3e rms at a frame rate exceeding 10K frames per second. Detectors without avalanche gain typically achieve 120e rms at these frame rates so this application represents an extreme challenge for a detector, particularly in view of the long integration times used in these instruments.

To achieve the high frame rates it is necessary for the ROIC to operate with unlimited multiple windows each with independent reset. The device has 32 parallel outputs to fulfill the frame rate requirements and noise floor. It can also work with 16, 8 and 4 outputs. The full array is 320x256 on 24 µm pitch. The floating source follower pixel design was based on test devices to give an optimum sensitivity/noise compromise and this resulted in a very small integration node of 15 fF. It includes glow protection for multiple non-destructive readout frames and also has a voltage clamp to minimise the voltage range for strongly illuminated pixels to reduce persistence. The device has numerous scanning modes and windowing options, all of which are controlled by a simple serial data bus.

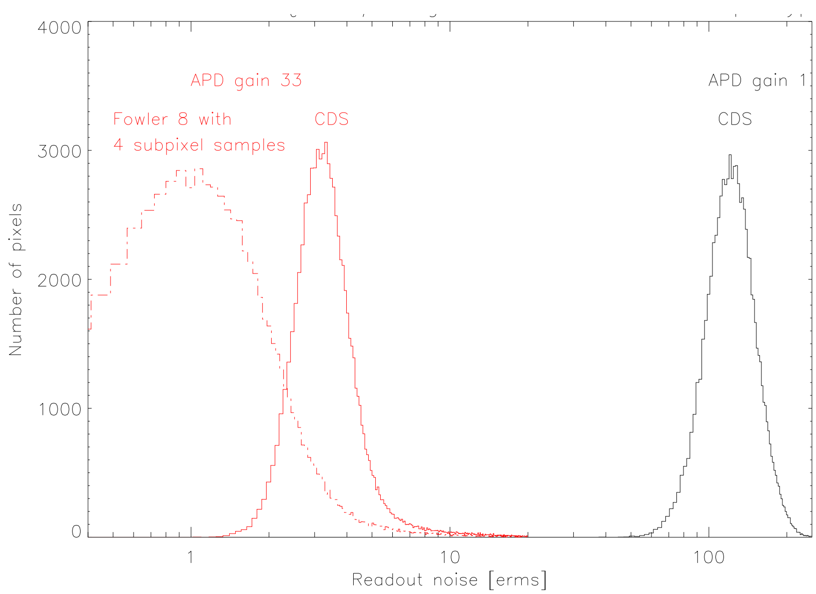


Figure 6 illustrates a typical sensitivity graph for a 2.45 µm cutoff device at 5 MHz clock rate and 40 K. Note that the unity-gain sensitivity is 120 e rms. At an APD gain of x33 and with correlated-double-sampling (CDS) it improves to 3.5 e rms. With Fowler sampling it improves further to 1 e rms. Figure 6 uses data from a previous generation of ROIC with a much higher integration capacitor than SAPHIRA. This remarkable step in sensitivity will enable many new applications in the field of spectroscopy, interferometry, photon counting and wavefront sensing.

Figure 6 Effect of avalanche gain of the sensitivity of a low background flux, SW array

SELEX is contracted to supply the sensors for the GRAVITY instrument in the ESO Very Large Telescope Interferometer (VLTI). The VLTI will optically link four 8.2m Unit Telescopes (UTs) to ultimately achieve an angular resolution equivalent to a 200m telescope. Each UT uses a 96x96 APD window operating at >10K frames per second for simultaneous, first order, wavefront corrections (tip-tilt) to correct the atmospheric distortion. The sensitivity of SAPHIRA is needed to reference on dim stars in the field of regard. The GRAVITY instrument will provide high precision narrow angle astrometry with an accuracy of <10 micro-arcseconds, and phase-referenced interferometric imaging in the astronomical K-band (2.2 µm). The imaging resolution is expected to be milli-arcseconds. Another SAPHIRA array is used as a fringe tracker to stabilise the fringe phase in the VLTI beam relays.

The low noise architecture of SAPHIRA has been the basis of two more recent designs funded by the European Space Agency, ESA. The first is a 1032 x1280 large format array with a 15um pixel aimed at low background flux astronomy applications in the NIR band. The second is a 2Kx2K variant which is aimed at earth observation applications in the SWIR band. Both arrays are enabled for avalanche gain and have the same windowing and variable output configuration architecture.

3.3 FALCON - Megapixel ROIC

FALCON is an HD1920 x 1080 format with a 12µm pixel. The readout and addressing circuits are all implemented on the bottom edge to enable devices to be 3-side buttable. The device and its architecture are illustrated in Figure 7.

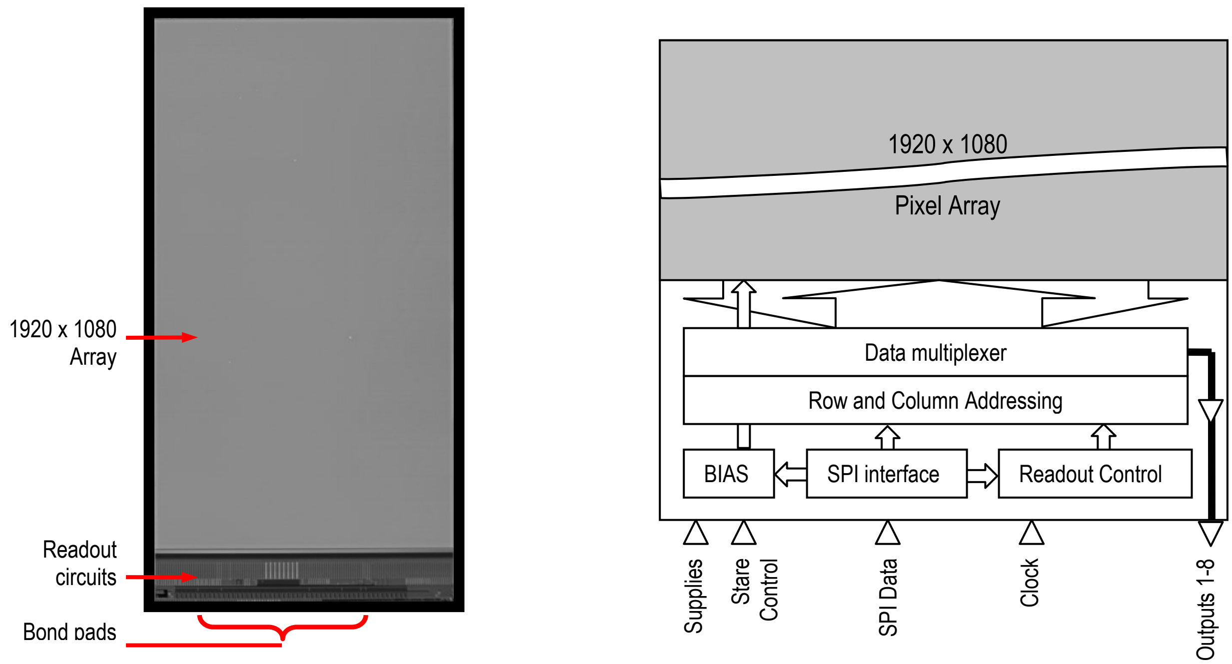


Figure 7 Photograph and architecture of FALCON HD

The readout logic is implemented using counters and address decoders to provide a compact design. The ROIC includes an on-chip digitally programmable reference voltage generator that is used to provide a stable bias voltage to operate the MCT detector diodes. The ROIC readout logic implements progressive scan whereby all rows are readout in sequence. The ROIC may be operated in Integrate Then Read (ITR) or Integrate While Read (IWR) modes for the full frame or for selected windows. The ROIC is configured and controlled using a high speed 3-wire SPI compatible digital interface. Notable is the very low power consumption.

Parameter	**Measured Specification**
Output Dynamic Range	2V min
Non Uniformity Error	1% max, 0.7% typ
Non Linearity Error	+/-0.5% max
CHC	3.5Me- (ITR), 2.8Me- (IWR)
Average power dissipation	15mW
Clock speed	12.8MHz
Frame rate	50Hz

Table 1 Typical ROIC performance values

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