NIR HgCdTe
Avalanche Photodiode Arrays for Wavefront Sensing and Fringe Tracking
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ABSTRACT

The application of noise free electron avalanche gain of HgCdTe to near infrared wavefront sensing and fringe tracking has resulted in a technological breakthrough at SELEX ES. At frame rates of 1 kHz, subelectron readout noise is demonstrated. After several predevelopment studies on early prototypes a new ROIC was developed, called SAPHIRA. This ROIC has a format of 320x256 pixels with 32 parallel video channels, each operating at 5 MHz. Novel readout options are implemented using the full multiplex advantage for reading small sub-windows and dispersed fringes. This design is well matched to further reduce the readout noise of sub-windows using multiple sampling techniques at frame rates >1kHz. The first devices were LPE grown, having a cutoff wavelength of 2.5 micron, and they proved to have good cosmetic quality at high APD gain when they are cooled down to a temperature of 40K. These SAPHIRA arrays are now being deployed in the four wavefront sensors and in the fringe tracker of the VLTI instrument GRAVITY.

Recently, the growth technology of LPE loopholes was replaced by MOVPE, which allows the application of solid state engineering techniques. Heterostructures with separate optimization of the absorber and gain regions resulted in perfect devices of superb cosmetic quality at APD gains as high as 80 and at operating temperatures of 85K. Sub-electron readout noise is achieved for full frame readout with simple DCS. Further improvements of the quantum efficiency and the noise figure are expected for devices with lower Arsenic doping and thicker absorber layers.

1. INTRODUCTION

The noiseless gain mechanism offered by the avalanche effect of HgCdTe photodiodes at high bias voltages is the only way to overcome the CMOS noise barrier at the high frame rates (>1kHz) required for wavefront sensing.

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applications to minimize wavefront distortions caused by the turbulent atmosphere [1][2]. Typically, CMOS sensors read out with 5 Mpixel/channel operate at noise levels between 60 and 100 electrons rms. The avalanche gain has already successfully been used to enhance the sensitivity in laser gated imaging applications. The cut-off wavelength of the HgCdTe material used for these applications is 4.5 μm to achieve high APD gain. This is possible because the integration times for laser gated imaging are in the nanosecond range whereas wavefront sensing requires integration times of 1 ms. In order to reduce the dark current, first prototype arrays have been made with a cutoff wavelength of λc ~2.5 μm. First tests on an existing multiplexer demonstrated that the dark current is sufficiently small for integration times of 1ms [3]. It then became evident that a special ROIC had to be designed to meet the needs of fringe tracking and wavefront sensing. This ROIC is called SAPHIRA. Initial LPE grown devices did not reproduce the performance of the prototypes. Widening the depletion region delivered good LPE SAPHIRA devices, which operate best at temperatures of T=45K. The major technological breakthrough in terms of cosmetics, noise performance and operating temperature was achieved by switching the growth technology from LPE (Liquid Phase Epitaxy) to MOVPE (Metal Organic Vapor Phase Epitaxy) using optimized heterostructure designs with a wide bandgap absorber region and a narrow bandgap gain region. The development is still ongoing, targeting to high quantum efficiency, low dark current and panchromatic response.

2. SAPHIRA MULTIPLEXER AND ESO TEST RIG

Even though early results were obtained with λc=2.5μm NIR eAPD prototype arrays on the SWALLOW ROIC developed for laser gated imaging, the special requirements of adaptive optics and interferometry with multiple windows and low readout noise at high frame rates could only be met by developing the new SAPHIRA ROIC, which is described in more detail in a previous paper [4]. The SAPHIRA ROIC has a format of 320x256 pixels and 32 parallel video outputs operating at 5 MHz. The 32 outputs are organized in such a way that they read out 32 adjacent pixels in a row at the same time. The readout time of a full frame is 500μs allowing frame rates of 1 kHz for single double correlated sampling. With this readout topology, windowed readout schemes benefit from the multiplex advantage of 32 parallel channels. This is one of the key features of the SAPHIRA ROIC which helps to achieve the lowest readout noise. Depending on the size of the window many frames can be read out nondestructively with typical integration times of 1 ms, to reduce the readout noise with Fowler sampling. A 10 MHz 32-channel ADC board in the NGC detector front end electronics allows digital filtering and Fowler preprocessing in the FPGA of the ADC board to limit the bandwidth of the fiber link to the real time computer.

The test setup used to evaluate the eAPD arrays was also described in an earlier SPIE paper [3]. A test camera cooled by a closed cycle cooler allows operation of the detector at temperatures of 40K. The telescope focus is in front of the
entrance window outside the camera at room temperature. Therefore, a test pattern such as a grid of holes illuminated by an extended blackbody can be used to generate a pattern of calibrated flux on the detector. The test pattern is imaged by the cryogenically cooled f/11 Offner relay onto the detector. Two cold filter wheels inside the camera are equipped with band-pass and neutral density filters.

3. **LIQUID PHASE EPITAXY eAPD ARRAYS**

The first near infrared (NIR) eAPD arrays grown by Liquid Phase Epitaxy (LPE) on a prototype multiplexer (SWALLOW) have demonstrated the feasibility of electron avalanche multiplication to break the CMOS noise barrier. The dark current scales with the width of the bandgap. Reducing the cutoff wavelength from $\lambda_c = 4.5 \, \mu m$ to $2.5 \, \mu m$ brought the dark current down to levels which are negligible at frame rates of 1 kHz. For collecting avalanched electrons n-on-p structures are required. The LPE arrays are annular structures which operate with lateral collection of charge generated by photons in the p-type absorber region. The charge collected by diffusion is then amplified in an annular gain region around the n side of a metalized hole making the contact to the multiplexer. The hole in the center of the pixel is metalized to make the contact to the ROIC. The so-called LPE loophole structure is shown on the left side of Figure 1, this is compared to MOVEPE/mesa structure, also shown and described in chapter 4.

![Diagram of LPE and MOVPE structures](image)

*Figure 1 Left: Diode structure of liquid phase epitaxy (LPE) array. Right: Diode structure of metal organic vapour phase epitaxy (MOVPE)*

Early results with LPE arrays on a prototype multiplexer were encouraging. However, the first LPE arrays hybridized on the SAPHIRA ROIC did not meet the expectations raised by the prototype results. The number of noisy pixels and the
nonuniformity increased rapidly above 6V bias even when cooling down the array to temperatures of 40K. The bottom left side of Figure 2 shows a noise map at an operating temperature of 40K with an APD gain of 25.

Figure 2 Top: Band diagrams of LPE eAPD arrays. Bottom: Noise maps with cut levels 0 to 20 electrons at integration time 575 μs, APD gain of 25 and operating temperature of T=40K. Top left: Narrow depletion width with large electric fields and narrow potential barrier favouring trap assisted tunneling defects. Bottom left: Corresponding noise map. Top right: Wide depletion width with reduced electric fields and wide potential barrier for reduced trap assisted tunneling. Bottom right: Corresponding noise map.

The cut levels of the noise maps at the bottom of Figure 2 are 0 to 20 electrons rms. The large number of noisy pixels probably reflects a high dislocation density. Analysis showed that the bad pixels are mainly caused by trap-assisted tunneling (TAT) and originated around the junction region. Since the tunneling probability decreases exponentially with the height and the width of the potential barrier, an increase in the width of the depletion region where the APD gain occurs reduces the probability of trap-assisted tunneling. This is schematically shown by the top two energy band diagrams of Figure 2. The corresponding noise maps at the bottom of Figure 2 show the dramatic reduction of noisy pixels for the larger depletion width at high APD gain. LPE arrays with large diodes on the SAPHIRA
multiplexer present a technological breakthrough and achieve the expected results of 2.5 electrons readout noise for the full frame with double correlated sampling and 0.8 electrons rms with Fowler-8 for a 96x72 pixel subwindow. However, the arrays have to be cooled to operating temperatures of 40K for achieving this performance.

4. **Metal Organic Vapor Phase E-APD Heterojunction Arrays**

The LPE loophole structure is the most mature technology for APD arrays. The technology has some merits such as low doping levels, panchromatic spectral response and a beneficial geometry for avalanching. However, diodes become leaky at high bias voltages and require deep cooling down to 40K. Currently Selex is replacing LPE by Metal Organic Vapour Phase Epitaxy (MOVPE) grown on GaAs substrates, because MOVPE allows the band structure and doping to be controlled on a 0.1µm scale and provides more flexibility for the design of diode structures. The bandgap can be varied for different layers of Hg(1-x)Cd,xTe by varying stoichiometry x of the alloy during the growth process. So it is possible to make heterojunctions and apply solid state engineering techniques. The mesa structure of an MOVPE diode is shown on the right side of Figure 1. Pixels are separated by trenches and the n-side of the diode is connected to the ROIC by Indium bumps. The absorber and the gain region can be optimized separately to maximise the quantum efficiency, breakdown voltage, and the APD gain.

![Band diagram of MOVPE heterostructure eAPD array. Wide bandgap in absorber region and the junction on the right side. Narrow bandgap in gain region for maximum APD gain at small bias voltages.](image)

The first MOVPE arrays were homojunctions with a uniform cutoff wavelength which put into place the required processes needed to manufacture MOVPE
devices such as the photolithographic masks and indium bumped SAPHIRA wafers. The breakdown voltages, defect levels, and the dark current of MOVPE homojunctions were not as good as the best LPE arrays. In a second step heterojunctions were manufactured. The band diagram of the MOVPE heterojunction is shown in Figure 3. The absorber region and the junction are made of wide bandgap material (λ_c = 2.5 μm) to maximize the breakdown voltage. The gain region is narrow bandgap material (λ_c = 3.5 μm) to maximize the APD gain. Doping profiles are optimized for high breakdown voltage, quantum efficiency and APD gain.

The first MOVPE heterostructure array has to be operated at temperatures of 85 K. Below 55K the video response gets slow with rise times of 50ms. To our surprise, even at a temperature of 85K the cosmetic quality of the MOVPE heterostructure is stunning. The widening of the bandgap at the junction and the separate optimization of the absorber and the gain region very effectively suppressed the number of defects caused by trap-assisted tunneling. This is shown in Figure 4, where the flat-fields of the best LPE array and the first MOVPE heterojunction are compared. At the maximum bias voltage of 12.1 V, when the APD gain in K-band is 79, there are only 20 pixels on the heterostructure shown in the right image of Figure 4, which have a signal which is 30% larger or smaller than the mean signal.

![Figure 4: Flatfields in K-band. Left: LPE eAPD array at APD gain of 16.6 and operating temperature of T=45K. Right: MOVPE heterostructure at APD gain of 59 and operating temperature of T=85.](image)

The transfer gain of the SAPHIRA ROIC, defined as the ratio of the voltage change at the video output and the integrating node of the unit cell, was measured to be 0.62. The capacitance of the integrating node at a moderate bias voltage of 2.61V was derived from the variance versus signal method. With a gain of 11.22 electrons/ADU derived from the photon transfer curve and 3.81 μV/ADU, back referred to the integrating node in the unit cell of the pixel, then its total capacitance is derived to be 29.4 fF. This is equivalent to a voltage change of 5.44 μV per electron without APD gain at a bias voltage of 2.61V. The capacitance increases to 49.4 fF at a bias voltage of 0.62V.

It is difficult to disentangle the effect of the voltage dependence of the nodal
capacitance and the avalanche effect, on the gain at moderate bias voltages. At higher bias voltages when the diode is fully depleted the gain is entirely due to the avalanche effect. The APD gain shown in Figure 5 was normalized to one at a bias voltage of 0.62V. The APD gain is higher in H band than in K band due to the partial APD gain of long wavelength photons, as explained below when describing the noise figure.

![APD gain versus bias voltage for MOVPE array in H (diamonds) and K band (squares). APD gain of LPE array in K band (triangles).](image)

The quantum efficiency was measured in H and K band at a bias voltage of 2.61 V without APD gain. The integration time was kept fixed and the flux was changed by changing the blackbody temperature. The quantum efficiency is derived from the slope of the regressional fit to data points plotted in Figure 6, which show the number of electrons versus the number of photons arriving at the detector.

The quantum efficiency is 53.4% in K-band and 49.4% in H-band at an operating temperature of 85K. The quantum efficiency is temperature dependent and rises from 42% at 55K to 56% at 120K. This supports the expectation to be able to increase the quantum efficiency by lowering the arsenic doping. In the current device the QE is reduced by recombination with un-ionized arsenic. Calculations show that the arsenic doping must be reduced by at least a factor of 3. It is anticipated that the QE for avalanched photo-electrons will exceed 80% for H and K band with devices from a new wafer run with low doped arsenic.
The noise figure of APDs describes the noise associated with the gain process. If the noise figure is larger than one the noise increases faster than the signal at high APD gain. Hence the signal to noise ratio of the detector is actually degraded by the APD gain. The noise figure can be determined by plotting the inverse conversion gain obtained from the variance versus signal method as a function of reverse bias voltage and division by the APD signal gain. In Figure 7 the MOVPE noise figure is plotted versus APD gain for H and K-band and compared with the noise figure of LPE arrays. Sometimes the excess noise factor is defined as the square root of the noise figure, but the noise figure in Figure 7 was plotted without taking the square root. In all silicon devices with electron multiplication the noise figure is larger than 2. Because of the low noise figure HgCdTe has the potential to outperform silicon detectors. The noise figure of the MOVPE array is 1.23 up to an APD gain of 79 in H-band but in K-band it rises to 1.37 at an APD gain of 59.

This indicates that long wavelength photons penetrate deeper into the diode and are also absorbed in the gain region. Hence the photon generated charge experiences only partial APD gain. Since the absorption is a random process, photons being absorbed at different depths in the gain region experience different APD gains, which contributes to APD gain noise and increases the noise figure. The shorter wavelength photons are absorbed higher in the structure in arsenic doped p-side of the diode junction and must travel the furthest to reach the gain region. They experience the full APD gain which is noiseless. To achieve the optimum performance the noise figure has to be reduced for K-band photons by increasing the thickness of the absorber layer, thus ensuring that these photons experience the full APD gain. This will improve the noise figure in the K-band to values comparable to those of the H-band.
In Figure 8 the noise histogram of a dark exposure taken with a simple double correlated sample is shown. The array was operating at the maximum APD gain which is 59 in K-band and 79 in H-band. The noise histogram peaks at 0.8 electrons rms for K-band photons. The integration time was 1.17 ms. The corresponding noise value for H-band photons is 0.6 electrons rms because of the higher APD gain in H. Figure 9 shows our test pattern which is a grid of holes.
put into the telescope focus which is reimaged onto the detector by the f/11 Offner relay. The test pattern is uniformly illuminated with an extended blackbody at a temperature of 70°C and observed with the H band filter. The flux in the holes of the test pattern is 1.12 photons/ms per pixel or 0.52 electrons/ms per pixel. The integration time is 1.17 ms. The left image of Figure 9 shows a single exposure, and the right image is the average of 12 chop cycles at a chopping frequency of 10 Hz. The left image clearly demonstrates that the sensitivity is sufficient to detect single photons in a single DCS frame at the maximum APD gain.

![Image of Figure 9](image)

*Figure 9: H-band test pattern with signal difference of 1.3 photons or 0.59 electrons in integration time of 1.17 ms. Left: Single exposure. Right: Mean of chopped image.*

The main advantage of the SAPHIRA readout topology only becomes apparent when reading out small subwindows as are often needed for low order AO systems and fringe trackers. For example, the GRAVITY wavefront sensor has 9x9 sub-apertures with 8x8 pixels per sub-aperture [5]. Therefore, a window of 96x72 pixels has to be read out.

Because of the ROIC topology, the number of pixels in the fast readout direction has to be a multiple of 32. In Figure 10 the readout noise is plotted versus the number of nondestructive samples for different APD gains ranging from 25 to 79. The integration time for the data points of Figure 10 having less than 8 nondestructive readouts (4 Fowler pairs) is fixed to 500 μs to limit the number of interrupts for the host computer. For 16 (Fowler-8) and more readouts the integration time is increasing with the number of nondestructive readouts. The integration time is 1.17 ms for 32 readouts (16 Fowler pairs) and 37.5 ms for 1024 readouts. For integration times longer than 19 ms or more than 256 Fowler pairs the readout noise becomes independent of the APD gain. It is dominated by the instrumental photon background in our camera. Since the gain region is narrow bandgap material the detector is still sensitive to thermal radiation up to λ > 3.5 μm, however with low efficiency. The noise data were taken at a detector temperature of 85 K. This measurement will have to be repeated at lower detector operating temperatures and with the detector covered by a cold plate to shield it from the instrumental thermal background. With Fowler-16, an APD
gain of 79 and an integration time of 1.17 ms, the readout noise is 0.2 electrons rms. With this performance the read noise of the GRAVITY wavefront sensor is negligible and single photons can safely be detected.

![Figure 10 Readout noise of the 96x72 pixel sub-window of the GRAVITY wavefront sensor with Fowler sampling as a function of the number of nondestructive readouts at different APD gains. Integration time is increasing with the number of nondestructive readouts. The inserted image in the top right corner shows a single 1ms exposure imaging a circular test pattern having a signal of 1 electron/ms/pixel.](image)

5. **OUTLOOK**

Since the noise equivalent number of photons with APDs at high APD gain and negligible readout noise is $F/Q$, the best figure of merit is achieved with the highest quantum efficiency and the lowest noise figure. The heterostructure eAPD array currently under evaluation has a quantum efficiency of 50%. Since the quantum efficiency of the current device is reduced by recombination with un-ionized arsenic, a lower doped p-type region is expected to increase the QE to 80% for H and K band. The optimum absorber thickness is larger for longer wavelengths and has to be compromised for H and K band. The absorber layer can be made thicker than for the current device. Then all K-band photons are absorbed in the absorber layer and will experience the full APD gain, resulting in a low noise figure for both H and K band.

A new wafer run at SELEX has been funded by ESO to implement these improvements and the first devices are expected in 7 months. A revision of the SAPHIRA ROIC is also planned to implement the read-reset-read mode per row.
In this mode during the readout of one row all other rows of the array are integrating photons. This will increase the stare efficiency at the highest frame rate to almost 100%. Some fine-tuning of the unit cell and enhanced output voltage referencing will also be included in the revised design.

The spectral range of the MOVPE eAPD array currently under test is limited to wavelengths between 1.4 μm and 2.5μm. The array is grown on a GaAs substrate with a CdTe buffer layer. The GaAs substrate is then etched off. The top HgCdTe layer is wide bandgap material with a cutoff wavelength of 1.3 μm and the layer underneath is the λ=2.5μm absorber layer. The proposed development steps to extend the response to optical wavelengths are the following. First, increase the bandgap of the wide bandgap HgCdTe top layer to λ=1.0μm to extend the wavelength range to λ=1.0 - 2.5μm. Second, grow the λ=2.5μm absorber layer directly onto a thicker CdTe layer to extend the wavelength range to λ=0.8 - 2.5μm. The CdTe layer absorbs radiation λ < 0.8 μm. The last development step will use a chemical etch to remove the CdTe layer. This will yield panchromatic MOVPE response as for LPE devices. The sensor can then be used for both optical and NIR wavelengths reducing system complexity if both optical and infrared wavefront sensors are needed. Also a broader spectral bandpass with more photons is available if needed.

If the detector dark current can be suppressed to levels below the photon generated current of Zodiacal light between the OH lines in high resolution spectrographs, the eAPD arrays become competitive with NIR science detectors such as the Hawaii-xRG.

6. CONCLUSIONS

Increasing the depletion width of LPE eAPD arrays reduces defects caused by trap-assisted tunneling. Good cosmetic quality can be achieved by cooling them to temperatures of 40K. The readout noise for a full frame using single double correlated sampling is 2.55 electrons rms.

A major breakthrough has been achieved by changing the growth technology to MOVPE, eliminating the need for deep cooling. Devices can be operated at temperatures of 85K with 99.97% of operable pixels. The readout noise for the full frame using DCS is 0.8 electrons rms. For the GRAVITY WFS, the sub-window readout noise can be reduced to the negligible value of 0.2 electrons rms by Fowler-16 sampling at an integration time of 1.17ms. The sensitivity of the array is only limited by the Poisson statistics of the absorbed photons. For negligible readout noise the ultimate figure of merit, the noise equivalent number of photons is F/Q. The measured noise figure in the current device F is 1.2 at the maximum APD gain. However, the recombination of electrons with un-ionized arsenic reduces the QE to 50%.

A next wafer run will attempt to improve the QE by reducing the arsenic doping. Further developments will comprise devices with panchromatic response and dark current levels comparable to flux levels of ~ 1E-2 photons/s/pixel as encountered in high resolution spectrographs. This may render noise free APDs
for large science arrays.

For high speed low noise applications eAPDs already achieve subelectron readout noise and they have advanced to a technical readiness level adequate to deploy them in wavefront sensors and fringe trackers.

7. REFERENCES


