New developments of near-infrared eAPD technology for wavefront sensing at ground-based telescopes, on-sky performance verification with GRAVITY and the potential of eAPDs for improving the sensitivity of large format science arrays and for deployment in space

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ABSTRACT

Ground-based near-infrared adaptive optics as well as fringe tracking for coherent beam combination in optical interferometry has required the development of high-speed sensors. Because of the high speed, a large analog bandwidth is needed. The short exposure times result in small signal levels which require noiseless detection. Both of these conflicting requirements cannot be met by state-of-the-art conventional CMOS technology of near-infrared arrays as has been attempted previously. The HgCdTe electron avalanche photo diode (eAPD) technology is the only way to overcome the limiting CMOS noise barrier of near infrared sensors. Therefore, ESO funded the development of the near infrared SAPHIRA 320x256 pixel e-APD arrays at LEONARDO [1][2]. With their unprecedented performance SAPHIRA arrays have now become the devices of choice for control loops as demonstrated by the four wavefront sensors and the fringe tracker deployed in the VLTI instrument GRAVITY, which set a new sensitivity standard in infrared interferometry[3]. These APD arrays also have extremely low dark current (1E-3 electrons/s/pixel) and may outperform conventional CMOS arrays for 100 second integrations when operated with moderate APD gains. Currently, a 512x512 pixel SAPHIRA array with 64 parallel video outputs optimized for pyramid wavefront sensing is in development. The SAPHIRA array has successfully passed radiation hardness testing and may soon be used for future instruments in space with the SIDECAR ASIC.

Keywords: eAPD, near infrared array, CMOS noise barrier, readout noise, excess noise, APD gain, cryogenic amplifier, infrared, wavefront sensor, fringe tracker, LmAPD

1. INTRODUCTION

Applying the noiseless HgCdTe electron avalanche photodiode (eAPD) gain is the only possibility to meet the speed and sensitivity requirements of the fringe tracker and the four wavefront sensors of the VLTI instrument GRAVITY, which cannot be met by conventional IR arrays without APD gain because they are limited by the readout noise of the CMOS ROIC. After several development cycles of solid-state engineering labeled by Mark#n which are facilitated by the chosen growth technology of metal organic vapour phase epitaxy (MOVPE), the eAPD arrays have matured and resulted in the SAPHIRA Mark14 arrays with a format of 320x256 pixels and a pitch of 24 μm. The arrays now offer an unmatched combination of sub-electron read noise at 1KHz frame rates. The ROIC of the SAPHIRA has 32 parallel video outputs operating at a pixel rate of 5 MHz. To optimize the windowed readout, the 32 outputs are organized in such a way that they read out 32 adjacent pixels in a row at the same time. Hence, the windowed readout also benefits from the multiplex advantage of 32 parallel channels. The unit cell of the ROIC is a state-of-the-art low noise source follower, which allows multiple nondestructive readouts and Fowler sampling to further minimize the readout noise, which is as low as 0.15 electrons rms at a frame rate of 1 KHz for two Fowler pairs and an APD gain of 299 in the CIAO wavefront sensor of the GRAVITY AO system.

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2. ELECTRON APD DIODE STRUCTURE

The arrays are mesa heterojunctions grown by metal organic vapour phase epitaxy (MOVPE) on a cheap GaAs substrate, which is then removed by a chemical etch. The top layer is a CdTe seed layer which is opaque at wavelengths $\lambda<0.8$ µm. A thick wide bandgap buffer layer is used to cope with the lattice mismatch of GaAs. This buffer layer limits the spectral response of Mark3 arrays to wavelengths $\lambda>1.3$ µm on the short wavelength side. Photons are absorbed in the p-type absorber. The photon-generated charge diffuses to the p-n junction and is then accelerated in the electric field of the multiplication region to start the multiplication process by impact ionization. To boost the avalanche gain, the multiplication region is made of narrow bandgap material corresponding to a cutoff wavelength of $\lambda c=3.5$ µm[5]. The Mark3 diode arrays on the left side of Figure 1 below are currently deployed in the GRAVITY instrument at the VLTI.

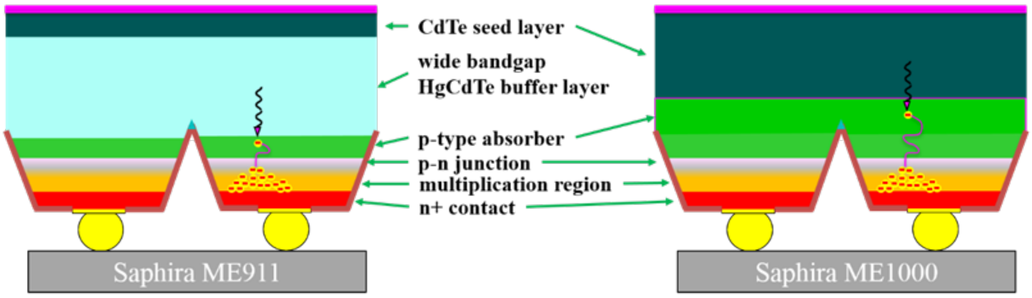

Figure 1. Left: Mark3 MOVPE diode design with wide bandgap buffer layer limiting short wavelength response to $\lambda>1.3$ µm. Right: Mark14 MOVPE diode design without wide bandgap buffer layer sensitive from 0.8 to 2.5 µm.

3. TEST RIG

In our setup the 32 parallel video channels of the SAPHIRA are amplified directly at the cold focal plane by the detector board with commercial off-chip cryogenic preamplifiers as shown at the top of Figure 2.

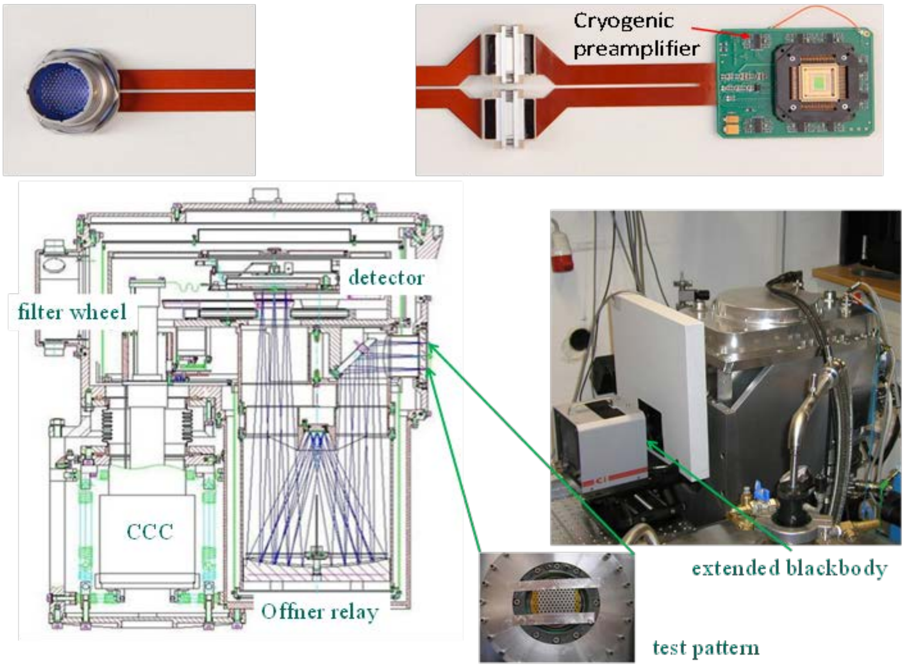

Figure 2 Top detector in LCC socket on detector board with cryogenic preamplifiers and flexible boards, connectors for radiation shield and hermetic connector. Bottom: cryogenic camera with Offner relay Offner and two filter wheels. Right: extended blackbody and test pattern on entrance window in image plane of detector.

The evaluation of the performance of the eAPD array is made using the IRATEC test camera which consists of a cold f/11 Offner relay with a cold pupil and two cold filter wheels in front of the detector.
The detector can be cooled down to a temperature of 40 K by a two-stage closed cycle cooler. A chopped test pattern in filter H with subelectron flux levels for integration times of 1.17ms can clearly be seen. These tests allow a relative comparison of the performance of different detectors in terms of signal to noise without uncertainties due to issues of absolute efficiency calibrations.

4. ON-SKY PERFORMANCE OF MARK 3 IN GRAVITY

Each of the four 8-meter telescopes of the VLTI is equipped with CIAO, the Coude Infrared Adaptive Optics system, which has a SAPHIRA near infrared Shack-Hartmann wavefront sensor with 9x9 subapertures sampled by 8x8 pixels needing a window of 96x72 pixels. For good seeing and a star of mK=6.5 a Strehl ratio of 60% was measured with CIAO, which still works on guide stars as faint as magnitude 11. In GRAVITY the limiting magnitude for fringe tracking is about mK=11. The electron avalanche photodiodes improved the sensitivity for fringe tracking by more than 2 magnitudes. The limiting magnitude for coherent exposures with GRAVITY is mK~17 – this sets a new sensitivity standard in infrared interferometry, made possible by the deployment of eAPD technology, which is now widely being used in near infrared interferometry and for wavefront sensing. The pericenter approach of star S2 to the massive black hole in the Galactic center has been observed in May 2018, and for the first time the gravitational redshift in the orbit of S2 has been detected and the relativistic Schwarzschild precession of the S2 orbit has been measured[7].

5. DARK CURRENT AND NOISE OF MARK14

To include the astronomically important Y and J bands in the spectral range of eAPDs, the Mark14 diode structure, funded by the University of Hawaii, was developed at Leonardo. To extend the spectral response down to λ=0.8 µm the wide bandgap buffer layer had to be removed as shown in the right image of Figure 1 and the absorber layer is directly grown on CdTe by a pauseless process.

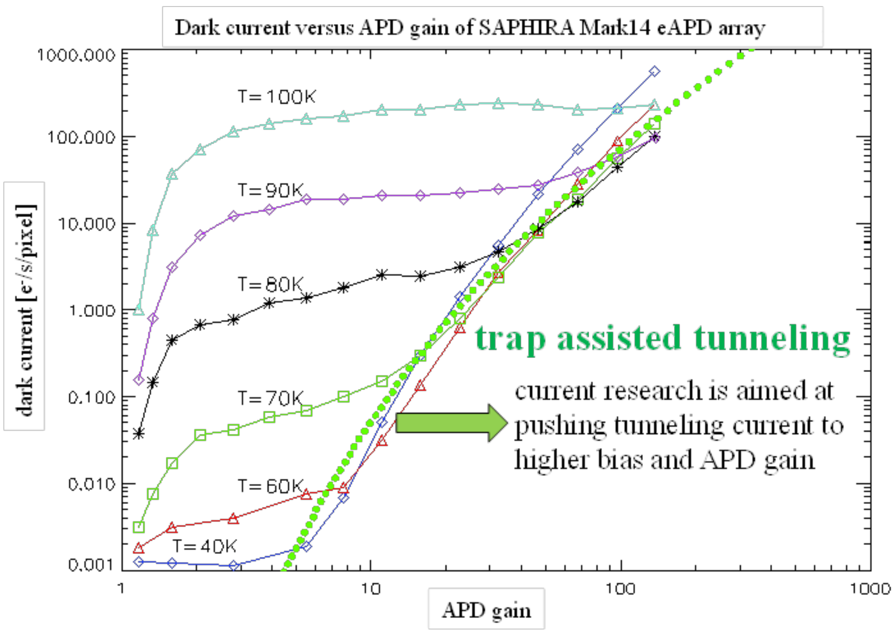

Figure 3 Dark current as a function of APD gain for different detector temperatures. At a detector temperature of T=40K and low APD gain dark current is 1E-3 electrons/s/pixel. At high APD gain dark current is dominated by temperature independent trap-assisted tunneling. Current research is aimed at reducing trap assisted tunneling at higher APD gain.

To obtain low dark currents which are plotted as a function of APD gain at different detector temperatures in Figure 3, the operating voltages of the SAPHIRA ROIC were reduced from the nominal values of 5 V to 2.5 V. At higher temperatures the temperature dependence of the dark current is mainly determined by the narrow bandgap multiplication region. At high APD gain the dark current is dominated by temperature-independent trap-assisted tunneling. The green dotted curve shows the model prediction of the trap-assisted tunnel current. Current research is looking for ways to reduce trap-assisted tunneling at higher APD gain[4]. It is remarkable that for low APD gain at a temperature of T=40K the dark current of the SAPHIRA array is in the 1E-3 e-/s/pixel regime, which is as low as the values measured for the best large format 2Kx2K HgCdTe arrays. The spectacular dark current result raises expectations that APD technology will eventually also break the CMOS noise barrier of conventional large format infrared arrays offering also noiseless detection for the most sensitive long-time exposures [6].

To compare the pixel performance of the SAPHIRA Mark14 array with the Hawaii-2RG array for long and faint exposures the readout noise for both arrays is plotted as a function of integration time for Fowler sampling with 64 Fowler pairs for the Hawaii-2RG array and 32 Fowler pairs for the SAPHIRA array in Figure 4. For each data point of the SAPHIRA array a series of exposures with different APD gains has been taken and the data with the APD gain achieving the lowest readout noise is plotted here. For longer integration times the APD gain must be reduced to achieve the best readout noise. The readout noise of the SAPHIRA array is subelectron up to integration times of 3 seconds. The readout noise of the SAPHIRA array is lower than the readout noise of the Hawaii2RG array up to integration times of 1000s. The time to read out 32 nondestructive full frames of the Hawaii-2RG array is 44 seconds but only 0.293 seconds for the SAPHIRA array using subpixel sampling with 8 conversions per pixel. It would be 15 seconds if the SAPHIRA array had to read out 2kx2K pixels, which is still a factor of 3 faster than the readout time of the Hawaii2RG array. Both detectors used the NGC controller and the same type of cryogenic preamplifiers. If an eAPD diode structure can be grown which allows to apply higher APD gain for long integration times it will clearly outperform arrays which do not use APD gain.

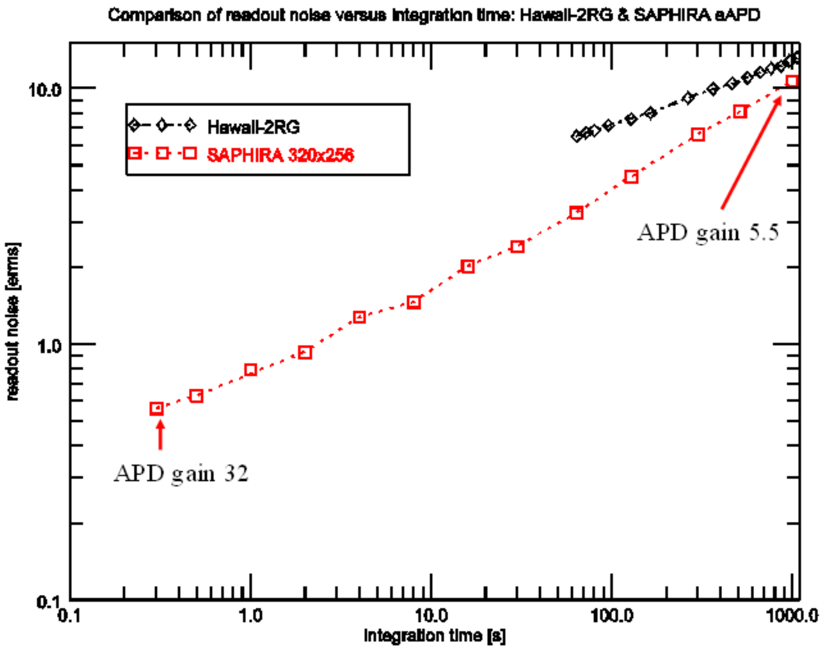

Figure 4 Comparison of readout noise of Hawaii-2RG array and SAPHIRA Mark14 array as function of detector integration time at optimum APD gain.

There have also been investigations of the potential of the SAPHIRA e-APD arrays for photon counting in the near-infrared[8][9].

6. MARK 20 FOR FAINT EXPOSURES OF SCIENCE FOCAL PLANES

For faint exposures with long integration times the application of APD gains > 5 is limited by the onset of dark current due to trap-assisted tunneling. Diode structures must be optimized for the specific applications. For AO applications the absorber region has a bandgap of λc=2.5µm and the gain region a narrow bandgap with λc=3.5µm, which ensures high APD gain of the Mark14 structure to achieve subelectron noise for the large bandwidth needed to achieve high frame rates. The Mark20 structure is optimized for longer integration times having a wider graded bandgap of λ_c=3.3µm in the gain region. It is expected that its graded bandgap minimizes the APD gain of the dark current. The wider bandgap should allow APD gains of >10 without the onset of trap-assisted tunnel current to get lower noise at long integration times.

The Mark20 array was grown with an improved interdiffused multilayer process with thinner HgTe and CdTe layers, which are better interdiffused to minimize the slight bandgap modulation of the absorption layer. This modulation was assumed to be responsible for slowing down the response of the detector at temperatures below T=90K. The speed of response of Mark20 at low temperatures was measured with infrared LED emitting at λ=1.55µm. It is a factor of 5 faster in comparison to Mark14 array at a temperature of T=60K as shown by Figure 5.Currently it is investigated whether the slower speed at lower temperatures is caused by the indium contact of a guard ring applying the high voltage for high APD gain to the p-type absorber region of the diode structure.

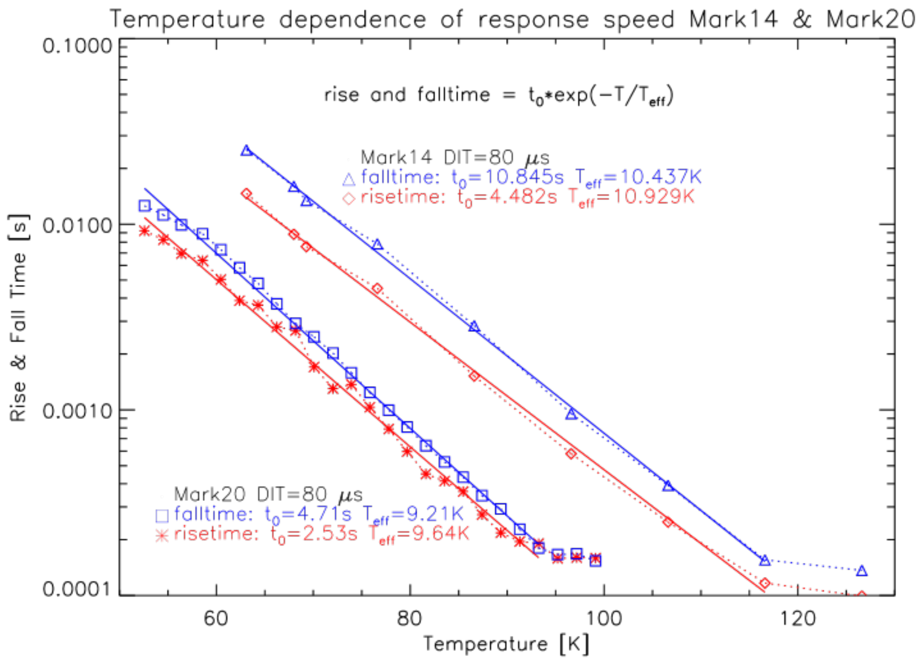

Figure 5. Comparison of rise and fall times of Mark14 and mark 20 arrays as a function of temperature.

7. LARGE SAPHIRA ARRAY FOR XAO

In addition to the deformable secondary mirror of the Extremely Large Telescope ELT the high-resolution Planetary Camera and Spectrograph PCS will have its own extreme adaptive optics mirror with up to 30000 actuators. For a pyramid wavefront sensor which must sample 4 pupil images a 512x12 pixel eAPD array is needed. To achieve a frame rate of 1 KHz for double correlated sampling the sensor will have 64 parallel video outputs which have to be operated at a pixel rate of 8.7 MHz. At this frame rate the APD gain should be high enough for subelectron readout noise. At high APD gain it has been demonstrated with the current SAPHIRA array that subelectron readout noise can also be achieved with uncorrelated sampling, which would allow to increase the frame rate to 2 KHz.

To achieve the high pixel rates without too much intercolumn crosstalk a two-multiplexer A-B architecture has been chosen. This allows time for one multiplexer to blank while the other is downloading the large signal to the output buffers. Because of this design the array will have windowing capability with only a granularity of 64 pixels in the row direction. As for the current 320x256 SAPHIRA array 64 adjacent pixels shall be read out with a single conversion strobe. This readout topology will maintain the multiplex advantage for the readout of subarrays.
It is also crucial for the readout topology of the ROIC to minimize the latency for pyramid wavefront sensing when reading out the 4 subpupils. For this reason, the array is divided into an upper and a lower half with 32 parallel video outputs for each half. The vertical direction of the readout is programmable as shown in Figure 6. For pyramid wavefront sensing the vertical readout direction will be from top to bottom for both the upper and lower half of the array. In this way four subwindows can be read out concurrently in the upper and lower half of the array and calculation of the wavefront errors can already be processed during readout with minimum latency. The calculation of the wavefront can be started depending on the window size, at the latest after the readout of a complete row is finished. This introduces a maximum latency of 3.9 µs for the start of the calculation which is acceptable without affecting the AO performance. Experience has shown a substantial dc offset for the first few rows of a full frame read out. Starting the readout from the top and the bottom edge places this offset at the top and bottom edges of the array where it is less disturbing for a readout of a small window located in the center of the array.
The design takes special care to eliminate multiplexer glow for low dark current. To get the best noise performance for long integration times reference rows will be available for interleaved reference pixel subtraction. This will make the ROIC an excellent device for developing diode structures demonstrating better low noise pixel performance with the help of eAPD gain for the most sensitive exposures with long integration times.
The schematic design of the ROIC is now completed and functional simulations have been carried out. In summer 2019 the ROIC of the large SAPHIRA will be taped out and first devices are expected by the end of 2019.
To keep the cost low the array will be mounted on a custom specific leadless chip carrier for a 124-pin Yamaichi socket as used for the AQUARIUS and Aladdin arrays at ESO. The socket with the detector on the LCC will be mounted on a cryogenic detector board with commercial off-the-shelf linear OPA 354 CMOS operational amplifiers used for symmetric preamplification of the 64 video channels to drive the long cables to the ADC board of the NGC controller. The ESO NGC controller has a 32 channel 10 MHz ADC board. Due to FPGA limitations of the ADC board the pixel rate is currently limited to 5 MHz. However, optimization of the VHDL code should achieve a pixel rate of 8.7MHz. With this optimization, the large SAPHIRA array can be operated at a frame rate of 2KHz with one frontend basic board and two 32-channel 10 MHz ADC boards, requiring minimum hardware development of the ESO NGC controller needed to operate the large 512x512 SAPHIRA array at full speed. The clock speed still needs to be improved to drive the long cables.

Table 1 specifications of the large format 512x512 SAPHIRA

parameter	**minimum specs**
Array format	512 x 512
Pixel pitch	24 µm
Spectral range	0.8 - 2.45 µm
Number of outputs	64
Frame rate	2 Kf/s uncorrelated
Pixel rate	8.7 Mpixel/s/output
Readout noise DCS	< 0.5e rms at 1 Kf/s
APD gain at bias 17 V	>200
Excess noise factor	<1.3
Quantum efficiency	> 70 % in J, H, K
Fill factor	100%
Dark current back referenced to sense node	< 200 e/s/pixel at T=90 K, bias 16V
Storage capacity	3 E5 e^- at APD gain 1
Uniformity	σ/mean < 20 %
Line driving capability	for 2 Kf/s load of 20pF

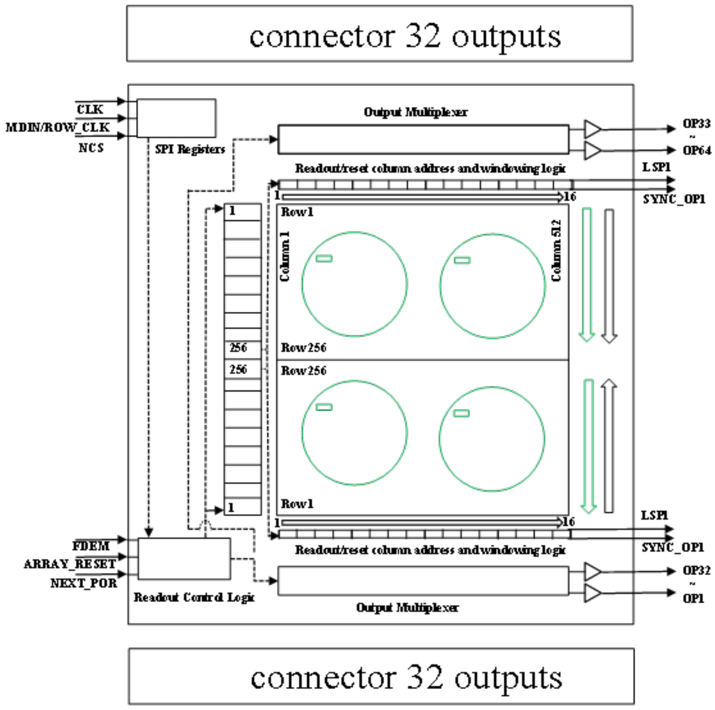

Figure 6 Comparison of readout noise of Hawaii-2RG array and SAPHIRA Mark14 array as function of detector integration time at optimum APD gain

8. TRL OF EAPD TECHNOLOGY FOR SPACE

To qualify the eAPD SAPHIRA arrays for space applications tests of radiation hardness have been carried out. Mark 14 arrays have been irradiated with a dose of 29 krad gamma radiation and with 50MeV proton radiation with a dose of 5.9E10 protons/cm2 without degradation of array performance. No variation in the avalanche process and no long-term degradation of the dark current has been observed so far. Changes to the noise and dark current during proton irradiation still need to be tested. With the low voltage settings for low dark current measurements the operation of the SAPHIRA eAPD array becomes compatible with the SIDECAR ASIC apart from the array common voltage which may be as large as -15V for high APD[10]. This voltage has to be provided by a separate power supply. Unfortunately, the support for the SIDECAR ASIC to operate the SAPHIRA array is no longer available at ESO.

9. CONCLUSIONS

For control loops in the near infrared eAPD arrays have become the devices of choice with unsurpassed performance, as demonstrated by many instruments and also by GRAVITY at the VLTI[3][11]. With the 5 SAPHIRA arrays as wavefront sensors and fringe tracker the gravitational redshift has been observed during the pericenter approach of star S2 to the massive black hole in the Galactic center with a limiting magnitude for coherent exposures of mK~17, setting a new standard in infrared interferometry.
The development of the large SAPHIRA array will meet the ELT XAO requirements. The pixel performance of current SAPHIRA arrays demonstrate that a careful new ROIC design may also allow taking the next step in sensitivity with eAPD technology pursuing subelectron noise for long integration times of large science focal planes.

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