First tests of a 1 megapixel near-infrared avalanche photodiode array for ultra-low-background space astronomy

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ABSTRACT

One of the primary goals of HgCdTe linear-mode avalanche photodiode arrays is to provide a 1kx1k pixels format, @15 $\mu$m pitch, near-infrared (0.9 to 2.5 $\mu$m) detector suitable for ultra-low background astronomical applications and long integration times. Such science goals impose very strict detector requirements, namely a dark current $< 0.001 \ [e^-/pix/sec]$ and a sub-electron read noise. The Institute for Astronomy (IfA), University of Hawaii has partnered with Leonardo Company to develop such devices, using fine control of the photodiode process to enable noise-free amplification of the charge carriers and a readout circuit optimized for minimal glow. We discuss the first results of the tests conducted at the IfA on this new device operated in our cryogenic testbed. We report the values of dark current, read noise and conversion gain, as well as its cosmetic qualities that we have measured at a temperature of 50K. The measured dark current of these devices at low bias voltages is of $\sim 3 \ [e^-/pix/ksec]$ (ksec=1000 seconds). We show that this dark current is dominated by the glow emitted by the ROIC of the detector when it is being read out. The intrinsic dark current of these devices is consistent with zero, with a best estimate of $\sim 0.1 \ [e^-/pix/ksec]$. The glow coming from the ROIC is measured to be $\sim 0.08 \ [e^-/pix/frame]$, or 1 [e-/pix] every $\sim 12$ frames. The read noise of these devices starts around $\sim 10 \ [e^-/pix/frame]$ at a bias voltage of 3V, and decreases by a factor of 1.3 with each +1V increment of the bias voltage, in agreement with theory. It is reduced to $\sim 2 \ [e^-/pix/frame]$ at a bias voltage of 8V.

Keywords: infrared detector, HgCdTe, linear mode avalanche photodiode, photon starved applications

1. INTRODUCTION

The high quantum efficiency (QE), low dark current (DC), and tunable cut-off wavelength of mercury cadmium telluride (HgCdTe) makes it the leading material for astronomical infrared detectors. Superb large format arrays such as the HAWAII family, manufactured by Teledyne imaging systems, are in regular use at observatories around the world, and comprise almost all the detectors on the James Webb Space Telescope. These arrays deliver dark currents of $\sim 1 \ [e^-/pix/ksec]$ and read noise of $\sim 10-15 \ [e^-/pix/frame]$, which may be reduced to 2-3 [e-/pix/frame] by frame averaging. However, for photon starved science such as exoplanet imaging or faint galaxy spectroscopy, such arrays are too noisy. The read noise, in particular, imposes a severe limit, and has not been improved significantly in the three decades, as it is a fundamental limitation of the gate in the MOSFET-based source follower used in each readout pixel node.

There is currently a pressing need for extremely low noise infrared detectors, as the most recent astronomical decadal survey\textsuperscript{3} identified the highest-priority mission as a 6-meter space telescope operating from UV-IR, with exoplanet imaging and spectroscopy of Earth-like exoplanets as the primary science driver. For this science, typical flux rates are about 1 photon per square meter per hour in V-band, and it is well-known that detector noise...
is the most serious obstacle for such missions. In the optical, EMCCDs can meet the detector noise requirements, but in the infrared—where most of the deep biomarker spectral signatures exist—no current detectors can meet the stringent noise requirements of dark current <0.001 $[\text{e-/pix/s}]$ and read noise <0.3 rms $[\text{e-/pix/frame}]$. Ground-based instruments, particularly very high resolution spectrographs, can also benefit from such low noise.

Linear-mode avalanche photodiodes (LmAPDs) offer one potential path to overcoming this readout noise barrier. In these devices, large electric fields cause signal photoelectrons to be multiplied before the readout noise penalty, leading to an “effective” readout noise that is proportionally reduced by the multiplication gain. HgCdTe LmAPDs, developed by Leonardo corporation (formerly Selex) in partnership with ESO and the University of Hawai’i, have found wide use as high speed wavefront sensors, such as in the SAPHIRA detectors. The current generation of SAPHIRA arrays have demonstrated sensitivity from 0.8 to 2.5 mW/m$^2$/sr, offering an unmatched combination of sub-electron effective read noise (as low as 0.1 rms [e-]) at 1kHz frame rate at convenient operating temperatures around 90-100K. While SAPHIRA detectors showed some promise as science focal plane detectors, they have several issues that make them unsuitable for the low-flux science cases discussed above. First, their pixel format (320 x 256) is too small for integral field unit spectroscopy, which is better matched to a 1 megapixel (eg, 1k x 1k) sensor. Second, the lack of reference pixels puts high demands on voltage and temperature stability for long exposures, where drifts in the voltage level manifest as an extra noise source. Finally, when operated at low gain, SAPHIRAs deliver a dark current nearly at the level required, and still likely glow limited. However, when operated at high gain, to minimize read noise, the large voltages cause electrons to tunnel through the band gap, which causes the effective dark current to exponentially increase. In practice, this means that SAPHIRAs cannot deliver low dark current and low read noise simultaneously.

Motivated by the SAPHIRA results, the University of Hawai’i has partnered with Leonardo corporation and several other industrial partners to develop an LmAPD device suitable for ultra-low background infrared science, with the goals of a dark current <0.001 $[\text{e-/pix/s}]$ and an effective read noise <0.3 rms $[\text{e-/pix/frame}]$. The main differences from the SAPHIRA will be a larger format (1k x 1k with 15 $\mu$m pixels), a design including reference pixels to improve overall stability, and careful bandgap engineering to move the onset of tunneling current to much higher voltage, so low read noise and dark current can be simultaneously achieved. Our development plan includes maturing these sensors to technology readiness level (TRL) 5, including detailed laboratory testing in a realistic space-like environment, on-sky testing, and characterization of performance after irradiation to space-like levels.

This paper presents the results obtained from the first engineering-grade versions of this new 1kx1k detector design. The engineering-grade detectors represent a first attempt at fabricating the megapixel detector with reference pixels. However, the engineering-grade detectors have a different bandgap structure than the science-grade design, more similar to the SAPHIRAs, so the lower tunneling current at high bias voltage cannot yet be obtained. Additionally, a contamination introduced during the manufacturing process caused the number of defective pixels to be far higher than expected, and the QE to drop at low bias voltages. Regardless, the results from the engineering grade device are very encouraging, showing essentially no dark current (glow-limited) and a decreasing read noise with bias voltage in good agreement with theoretical expectations.

This paper is organized as follows. Sec. 2 gives a detailed description of the LmAPD technology and of the design of the photodiode structure optimized to reach the performance cited above. The features of the ROIC are also discussed. Sec. 3 covers the testbed implemented to read out and characterize the detector. Sec. 4 presents our measurement methods of the conversion gain, read noise and dark current, as a function of the APD gain, as well as our results and their interpretation. Sec. 5 also reports on other effects observed with this detector. Sec. 6 gives a summary of our results and discusses the next steps planned in the development and characterization of this detector.

2. DETECTOR DESIGN

2.1 HgCdTe material and avalanche process

HgCdTe is unique amongst avalanche semiconductors for three reasons. First, only electrons participate in the avalanche process, because the holes have very low mobility due to their high effective mass and low
ionization efficiency. Second, the multiplication process is ballistic because the electrons do not experience phonon interactions or scattering, resulting in nearly noiseless amplification and deterministic APD gain as a function of bias voltage. Finally, there is no breakdown effect in HgCdTe at high bias voltages/APD gains. The signal multiplication occurs before the readout noise penalty, so we speak of an “effective” read noise which is the read noise divided by the multiplicative gain. The penalty for this is a reduction in full well depth, which is irrelevant for low-flux applications.

The arrays are grown by Metal Organic Vapour Phase Epitaxy (MOVPE), which allows for a precise control and variable profiles of the thickness, so complex bandgaps and doping concentrations can be used to define the structure of the diode. The diode and its mesa cone form a mesa heterojunction. The MOVPE LnAPD array is hybridized to the silicon ROIC via the contact pads and indium bumps embedded at the tip of each pixel mesa cone.

The top layer of the photodiode is a CdTe seed layer opaque at $\lambda<0.8 \mu m$, see Fig. 2. Photons of $\lambda \leq 2.5 \mu m$ are absorbed in the p-type absorber directly grown on CdTe and are converted into electrons. 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. In general, the multiplication region is made of narrow bandgap material in order to boost the APD gain relative to a given bias voltage. The absorber and the gain region are therefore decoupled so each can be optimized separately. It is possible for photons with longer wavelengths ($\lambda>2.5 \mu m$) to penetrate the absorption layer and the junction to be absorbed directly in the multiplication layer.

The mesa cones on the back of the device fulfill several critical functions. Their slots extending through the absorber layer allow for complete electrical isolation between pixels to eliminate lateral charge collection. Their shape maximizes photon trapping within the pixel and prevents stray photons from scattering into neighboring pixels. This leads to near-ideal MTF (Modulation Transfer Function) and crosstalk. Together with a continuous absorber layer, this photodiode layout provides complete photon absorption within the pixel, and ensures every

*For example, if a 10 e- signal is multiplied by a gain of 20 to 200e- with an underlying read noise of 10e-, (SNR = 200/10=20), it is the same effective noise as if the 10e- signal sees a readout noise of 10e-/20 = 0.5 e- (SNR = 10/0.5 = 20)
photoelectron receives the same APD gain independent of the position where the photon is absorbed in the pixel so that no microlenses are needed.

Figure 2: The single-carrier electron avalanche process is illustrated on the left. The bias voltage is applied across the multiplication and junction regions. On the right, it is shown a schematic of the APD heterostructure grown by MOVPE. More information in the text. The red circles represent the electrons experiencing the avalanche process in the semiconductor, and the blue circles, the holes. The “yellow spheres” represent the indium bumps that are necessary to hybridize the pixel nodes to the silicon ROIC. (Original figure courtesy Leonardo)

2.2 Diode structure design for low dark current
At temperatures $>60K$, the temperature dependence of dark current is mainly determined by the narrow bandgap multiplication region. At high APD gains, dark current is dominated by trap-assisted tunnel current. During this process, two mechanisms are involved: an electron tunnels (tunnel-tunnel current) or is thermally excited (thermal-tunnel current) into a trap before tunneling to the conduction band. At temperatures $\leq 60K$, only tunnel-tunnel current is significant. When the devices are operated at high bias voltage (and hence low read noise), this also causes the onset of tunneling current after a point, which can raise dark current to unacceptable levels. As seen in Fig. 1, for a given temperature and bias voltage $>2V$, the measured dark current first exhibits a moderate increase as a function of bias voltage. Then, after the voltage threshold is crossed, the tunneling current becomes the dominant component of the dark current. It increases very steeply in agreement with the exponential increase predicted by theory, as shown by the light green dotted curve.

The design of this detector was optimized for long integration times expected for low-flux science and has two differences from the earlier SAPHIRA design: a wider and graded bandgap structure in the multiplication region. This design should allow the thermally generated dark current to experience much lower APD gain and APD gains of several tens before the onset of trap-assisted tunneling current occurs. The engineering-grade device under consideration here only has one change, the wider structure, while future science grade devices will also have the graded bandgap.

2.3 Characteristics of the ME1070 ROIC
Leonardo ME1070 1kx1k ROIC is a low-voltage multiplexer (nominal operating voltage of less than 3.5V) designed for use with avalanche photodiode arrays. A small integration node capacitance per pixel of about 27 fF is implemented to limit read noise. All of its I/O pads are on the one side in order to make the arrays 3-side buttable. Many user-tunable options are controlled via a serial programmable interface to set the array up in the lowest noise configuration.

The device has 16 analog video outputs able to run at a pixel clock up to 1MHz resulting in a maximum full-frame readout speed of about 15 frames per second (FPS). The ROIC topology offers flexible readout schemes. It preserves the multiplexing advantage of 16 parallel video channels, organized in such a way that they read
out 16 adjacent pixels simultaneously with a single ADC (Analog to Digital Converter) conversion strobe, so that windowing can be as small as 1 row by 16 columns. ME1070 provides scanning modes allowing for multiple digitization strobes per pixel or on a row by row basis. This facilitates multiple non-destructive readouts and Fowler sampling to further minimize the read noise. The detector can be read using the readout scheme called integrate then read (ITR) in conjunction with up-the-ramp (UTR) sampling; an external strobe to reset the full array is applied at the start of each new exposure. The readout scheme called read-reset-read for efficient correlated double sampling is also available.

The ROIC architecture has 4 reference rows which can be configured in interlaced mode. Reference pixels in NIR arrays require replacing the HgCdTe photodiode with a matching capacitor to the same bias voltage. Reference rows are commonly used to correct for settling and compensate for voltage and temperature drifts over long exposure times. It will be extremely useful for measuring very low dark current over periods of several hours. The ROIC architecture also has 4 reference outputs coupled to a row of 256 reference pixels for further compensation, especially electromagnetic interference.

ME1070 is specifically designed for low IR on-chip self-emission circuitry. It is supplied by lower voltages and the whole top surface of the silicon ROIC has a continuous metal coverage to further exclude any glow photons.

3. LABORATORY SETUP

3.1 Cryostat and sensor chip assembly

The evaluation of the performance of the arrays is made using the ULBcam (Ultra-Low Background infrared camera) instrument (Fig. 3a), which functions as both a lab testbed and on-sky camera. The cryostat chamber vacuum is pumped to <10e-6 Torr and can be cooled down to a temperature as low as 40K, with milliKelvin stability over week-long periods. The internal focal plane assembly is shown in Fig. 3b, on the upper-right (see the description in the legend).

To characterize the detectors, we operate ULBcam in a testbed configuration, where a light-tight cover replaces the field lens to minimize thermal background. A cryogenic integrating sphere is placed in front of the detector, providing flat illumination with LEDs of 1.05, 1.30 (J-band) and 1.70 (H-band) µm, each with 10% spectral bandwidth, see Fig. 3c. It was found that the integrating sphere did not provide a perfectly light tight seal, with photoelectrons being detectable at the level of a few electrons per pixel per hour. To mitigate this, we installed a mask ∼1mm above the sensor, see Fig. 3d. This mask is at the same temperature as the detector and has minimal thermal emission in wavelengths of interest. It has a rectangular opening in the center leaving about 10% of the sensor surface exposed. This allows measurements requiring both partial illumination and dark conditions to be made with the same system.

3.2 Readout chain and data acquisition

All the hardware components of the readout chain from the detector to the computer are shown in the block diagram in Fig. 4. The detector is controlled by a SIDECAR ASIC14 via an interface rigid flex cable supplied by Hawaii Aerospace. The SIDECAR is a TRL-9 microcontroller-based system-on-a-chip that comprises low noise analog circuits, detector output conditioning, and 36 parallel ADC channels for 16-bit signal digitization. It can be operated both at ambient temperature and at cryogenic temperatures down to 40K. The SIDECAR interfaces to our control computer via a MACIE (Multi-purpose ASIC Control and Interface Electronics) controller card. We developed custom firmware and software to read out the detectors via the SIDECAR and MACIE card, including a custom Python wrapper to the MACIE C library to simplify automation and testing, which we intend to release in the near future, as it is compatible with any detectors using SIDECAR or ACADIA15 ASICs. Finally, an external negative voltage supply is used to bias the detector and control the gain.

To validate our readout chain, we first operated ULBcam in the standard astronomical camera configuration with the field lens in place, then installed some foreoptics to create an image on the focal plane. Fig. 5 shows the first light image we took with our first engineering-grade device, showing good cosmetic quality overall.
Figure 3: Pictures showing the main components of our test system ULBcam and how the assembly of the detector to be characterized is mounted inside the cryostat dewar of ULBcam.

(a) View of the test dewar with the safety cover removed showing the detector mounting site. The MACIE card secured to the metal plate in the foreground of this picture, and the flex cable to which the MACIE card is connected, are visible. The flex cable is routed through the cryostat wall to the ASIC SIDECAR.

(b) View of the inner detector housing and mounting structures. An engineering-grade sensor is integrated on its carrier and connected to the flex cable plugged to the ASIC SIDECAR located underneath the mounting site.

(c) Golden integrating sphere mounted on top of the detector. The LEDs are fitted in the ports of the integrating sphere.

(d) On this picture, the black matte mask is installed above the detector. There is a rectangular window visible in its center.
Figure 4: Block diagram of the readout system for testing.

Figure 5: First light image taken (2021/07/15) with our 1st LmAPD engineering-grade device. A poor-quality USAF test target printed out from our office printer was imaged on the sensor.
4. CONVERSION GAIN, READ NOISE & DARK CURRENT

Unless otherwise stated, all the results presented in this section were obtained with the same engineering-grade detector, cooled down to a temperature of 50K, and set up in source follower mode, with its minimum operating voltages.

4.1 Conversion gain and read noise

The conversion gain and the read noise are estimated using the photon transfer curve (PTC) method.\textsuperscript{16} The standard deviation (STD) of the signal measured with the detector is plotted against the mean signal by scanning an increasing level of incident flux. The PTC method requires that the received illumination is uniform within the averaged pixel region. The detector is illuminated by the integrated sphere with a constant flux emitted from the LED and the collected signal is UTR-sampled, see Fig. 6. STD and mean signal are computed by spatial averaging over the pixels and are expressed in [ADU] (for Analog to Digital Unit, also called Digital Number [DN]). In fact, two data cubes are produced. The two resulting datasets are first subtracted from their respective bias frame in order to remove the kTC noise. Each individual frame is subtracted from the median of its four reference rows at the column level. The mean signal is computed using the sum of the two datasets frame by frame, then divided by two. The standard deviation is computed using the difference of the two datasets, then divided by \( \sqrt{2} \). This last operation has the advantage of mitigating the impact on the variance of a possibly slightly non-uniform illumination. \textit{This also means that the measured read noise is defined as the CDS read noise.}

The target parameters to be determined, namely the conversion gain and read noise, are obtained by fitting the function in Eq. (1) to the data of the PTC. Eq. (1) has three terms under the square root: the read noise (here in [ADU]) corresponding to the intercept of the PTC, the conversion gain corresponding to the inverse of the slope of the linear part of the PTC, and the fixed pattern noise (FPN) corresponding to the coefficient of the quadratic, or non-linear, part of the PTC. This last term is usually introduced in particular for CMOS sensors in order to take into account that the response between individual pixels may vary. The conversion gain depends on the charge gain \( g \), the APD gain \( G_{\text{avl}} \), and the excess noise factor (ENF). As discussed in Ref. 8, it is expected that under the operating conditions of the detector, i.e. at a temperature of 50K, and at relatively low bias voltages, the ENF is close to 1 and constant over the considered range of bias voltages. This is verified by measuring the conversion gain as a function of bias voltage. The normalized dark current and the effective read noise are directly derived by multiplying their raw value measured in [ADU] by the conversion gain, in order to convert them into \([e^-]\) and correct them for the APD gain.

\[
\sigma_{\text{[ADU]}} = \sqrt{(\text{readnoise})^2 + \frac{1}{G_{\text{conv}}} \cdot N_{\text{[ADU]}} + (\text{FPN} \cdot N_{\text{[ADU]}})^2}, \quad \text{with } G_{\text{conv}} = \frac{g}{G_{\text{avl}} \cdot \text{ENF}} \tag{1}
\]

PTC method can give inconsistent results when used with different sub-regions of the detector, different illumination, etc. We developed a Gaussian process based fitting method that accounts for these correlations and returns reliable uncertainties on the target parameters \{readnoise, G\textsubscript{conv}, FPN\} sampled using an MCMC sampler. At the end of the procedure, each parameter is defined by a distribution of samples. The median of the distribution is the adopted value of the parameter, and its width from the 16th to the 84th percentile is the uncertainty on the parameter. We plan to release this version of the PTC method.

It is known that CMOS sensors are affected by the interpixel capacitance (IPC) effect. This is a deterministic effect that can be corrected. It comes from the coupling between neighboring pixels’ capacitance when pixels accumulate charges and results in a reduction of the variance computed by simple spatial averaging. As a consequence, the linear slope of the PTC is reduced, which leads to an overestimation of the conversion gain and hinders the accurate estimation of other quantities that depend on it. Even a very small coupling coefficient of the order of the sub-percent can already induce an error of the order of percent on the conversion gain. We characterized the interpixel capacitance using the method described in Ref. 17. The total variance can be recovered using the autocorrelation function. We derive a first measurement of the coupling coefficient of the order of 0.7%, which leads to a systematic error of \(~5\%\) on our conversion gain. We have not corrected for this effect yet, as it is minor.

Our PTC measurements at different bias voltages are reported and discussed Sec. 4.3.
Figure 6: On the left, example of photon transfer curve obtained for bias voltage=4.0V. The standard deviation of the signal is plotted against its mean. The signal is measured in the central portion of the sensor exposed through the window of the mask covering the sensor to the illumination output from the integrating sphere. On the right, the exact sub-region selected is indicated by the green rectangle overlaid on one of the frames included in the UTR-sampled data used for the PTC. The illumination within this sub-region of \(\sim 110 \times 110\) pixels is uniform. The flat field image on the right corresponds to a data point in the PTC with an average signal of \(\sim 1500\) [DN]. The fitted function shown in the plot title is decomposed into its three color-coded components. The values of the three target parameters (readnoise\( (RN)\), \(G_{conv}\), FPN) of the fitted function are also given in the legend. Note that in all rigor, the term read noise in the equation is in fact in [ADU]. However, the final result given in the legend is already converted in [e-].
4.2 Dark current

The baseline method used to measure the dark current consists of 2h-long integrations taken in dark conditions. The detector is continuously UTR-sampled at regular time intervals of 20s. In total, the resulting data cube is made up of 360 read frames. The dark current estimate is obtained by subtracting the median at the pixel level of a stack of 60 consecutive read frames taken at the end of the integration, minus the median of a stack of 60 read frames taken at the beginning of the integration, the difference being then divided by the effective integration time. The first 20 frames are discarded in order to avoid settling effects that may occur at the beginning of the acquisition. The “mean” dark current value reported is given by the peak of the pixel distribution and the uncertainty $\sigma$ on this value is given by the median absolute deviation of the distribution around the dark current peak. The pixels outside dark current $\pm 3\sigma$ are rejected as outliers. Our dark current measurements at different bias voltages using the baseline method are reported and discussed Sec. 4.3.

In order to examine the dependence of the measured dark current on the number of read frames included during the integration, we reproduced the method outlined in the paper Ref. 18. Their method allows us to separate the dark current into two components: a “continuous/per-time” dark current component which is the intrinsic dark current originating from the HgCdTe material, and a “per-frame” dark current component which is in fact due to the glow of the ROIC of the detector radiating in the IR when the acquisition of a read frame is triggered. The latter depends on the sampling frequency of the detector. Two datasets are required: one dataset taken at a given sampling frequency, and a second dataset taken at a different sampling frequency. Then, we can recover the intrinsic and glow-induced dark current at the pixel level simply by resolving a basic system of 2 linear equations. The results are shown Fig. 7, where we report the intrinsic dark current of the device is consistent with zero ($\sim 0.1 \text{[e-/pix/ksec]}$), while the glow is about 0.08 [e-/pix/frame]. These results are from $\sim 93\%$ of active pixels, removing cosmic ray events, hot pixels, and known “problem” areas of the detector (e.g., artifact on the left border). We also repeated this test at 60K for bias voltage=4V, and at 50K for bias voltages={5,6,7,8}V, and got consistent results. Glow photons are arising within the pixel nodes from the source follower MOSFETs. Previous SAPHIRA design had the MOSFETs covered in metal which is not the case for the ME1070 ROIC. As such, a future design path is to redo the wafers with this metal added back in.

There is one important caveat to our dark current results. We identified an increasing number of pixels with anomalously high dark current as we increased our detector bias voltage. The anomalous pixels are primarily comprised of “hot” individual pixels that show dark current several times higher than the background level and are due to the same mechanism as the base tunneling current. These pixel defects were expected to be a problem in these engineering-grade arrays due to a process control issue identified by Leonardo during fabrication, specifically, contamination by silver. As such, the engineering-grade arrays are unsuitable as scientific detectors, but still let us measure the potential of a properly fabricated science-grade array.
Figure 7: Heat maps and histograms of the “per-time” or intrinsic dark current (upper row), and “per-frame” glow (lower row). The light green pixels are the pixels rejected as outliers, their total number is given in the title. The intrinsic dark current is consistent with zero, with a best estimate of $\sim 0.1 \ [e-/pix/ksec]$ (e.g., $\sim 10 \ e-/pix/day$), while the glow is consistent with $0.08 \ [e-/pix/frame]$. The bright “square” in the center is at the location of the hole in our blocking mask, which sees background illumination from the dewar of a few photons per hour. The difference in the top and bottom half of the glow indicates that the glow is higher in the bottom half of the detector, on average $0.015 \ [e-/pix/frame]$ higher. This is thought to be due to the fact that the direct current feeding the electronic components at the origin of this glow is slightly offset in the lower part of the detector.
4.3 Overall performance as a function of bias voltage

Tab. 1 includes all our measurements of conversion gain, read noise and dark current obtained at different bias voltages. Fig. 8 shows the results of our joint analysis of dark current and read noise as a function of bias voltage. They are plotted against the previous best results from the SAPHIRA arrays, which have less than 10% the pixels of the 1kx1k detector. The left axis shows the normalized dark current on a logarithmic scale, and the right axis shows the effective read noise in [e-] on a linear scale. An additional right axis indicates the number of pixels showing anomalous behavior, due to the defects in manufacturing mentioned earlier.

Fig. 8 shows several important effects. First, the read noise behaves exactly as expected, reducing by 1.3x per additional volt of bias, consistent with SAPHIRA. The dark current results are also consistent with SAPHIRA and consist of the glow-limited of ∼3 [e-/pixel/ksec]. This value can be recovered exactly knowing the number of read frames included during the integration and the glow value of 0.08 [e-/pix/frame]. As mentioned in the previous section, the intrinsic dark current is zero. At approximately bias voltage=8V, the tunneling current begins to dominate the dark current budget, and exponentially increases with bias voltage. Finally, we also plot the number of anomalous pixels as a percent of total pixels. In the SAPHIRA devices, the measurements exclude 95% percent of pixels, as the dark current was measured in a single, isolated region of the device. In the 1kx1k detector, the number of defective pixels is low at bias voltage=4V, but increases approximately quadratically up to ∼40%.

Our engineering-grade devices were first fabricated without optimizing for the onset of tunneling current, so were expected to perform similarly to SAPHIRA with respect to tunneling current offset, at about bias voltage ∼8V. Theoretical modeling of the device predicted a decrease of about 30% in read noise per volt. At a starting read noise of ∼9 [e-/pix/frame], at bias voltage ∼3V, we achieve a read noise of ∼2 [e-/pix/frame] at bias voltage ∼8V, consistent with theory. Note that this is the read noise achieved without the use of any special reduction method, i.e. for example without taking advantage of some dedicated readout strategies such as Fowler sampling.

Table 1: Summary table for different bias voltages of the conversion gain, raw read noise, and effective read noise determined by PTC method, as well as raw dark current and normalized dark current measured using the 2-hour baseline method. The column “Reduction factor” gives the ratio between the conversion gain of the previous bias voltage and the current one. The number of pixels rejected as outliers in the dark current tests is also reported, as well as the effective full well capacity (Eff. FWC). The Eff. FWC is equal to the theoretical maximum dynamic range per pixel of 16 bits, i.e. 216 levels in [ADU], multiplied by the conversion gain. The read noise cells for bias voltages={8,9,10}V are shaded in gray to highlight that these PTC measurements of the read noise are less reliable due to noisy data.

| Bias voltages [V] | K_{gain} [e-/ADU] | Reduction factor | Raw RN [ADU] | Eff. RN [e-] | Raw DC [ADU/pix/ks] | DC [e-/pix/ks] | #Rejected pixels [%] | Eff. FWC [ke-] |
|-------------------|-----------------|-----------------|---------------|--------------|----------------------|---------------|----------------------|--------------|
| 3.0               | 1.37 ± 0.02     | N.A.            | 6.84 ± 0.25   | 9.35 ± 0.37  | 3.5 ± 0.2            | 4.8 ± 0.3     | 2.0                  | 89.6         |
| 4.0               | 1.02 ± 0.01     | 1.34            | 6.24 ± 0.34   | 6.37 ± 0.35  | 3.4 ± 0.9            | 3.5 ± 0.9     | 4.7                  | 67.0         |
| 5.0               | 0.86 ± 0.005    | 1.19            | 7.20 ± 0.21   | 6.16 ± 0.18  | 4.2 ± 1.2            | 3.6 ± 1.0     | 9.1                  | 56.0         |
| 6.0               | 0.64 ± 0.004    | 1.34            | 6.73 ± 0.34   | 4.31 ± 0.22  | 5.0 ± 1.5            | 3.2 ± 1.0     | 15.0                 | 41.9         |
| 7.0               | 0.49 ± 0.004    | 1.31            | 6.23 ± 0.16   | 3.03 ± 0.08  | 7.0 ± 3.0            | 3.4 ± 1.5     | 23.0                 | 31.9         |
| 8.0               | 0.38 ± 0.003    | 1.29            | 5.58 ± 0.20   | 2.13 ± 0.08  | 10.0 ± 7.0           | 3.8 ± 2.7     | 43.0                 | 25.0         |
| 9.0               | 0.31 ± 0.004    | 1.23            | 3.12 ± 0.63   | 0.97 ± 0.20  | 23.0 ± 30.0          | 7.1 ± 9.3     | 44.0                 | 20.4         |
| 10.0              | 0.21 ± 0.004    | 1.48            | 18.4 ± 0.60   | 3.83 ± 0.14  | 90.0 ± 200.0         | 18.7 ± 41.6   | 42.0                 | 13.6         |
Figure 8: Measured normalized dark current and effective read noise as a function of bias voltage for the 1kx1k detector and compared to best results obtained with SAPHIRA (data collected from Ref. 10,19). The proportion of pixels rejected as outliers in the dark current tests is also reported. The detector is operated at a temperature of 50K, and set up in source follower mode and with its minimum operating voltages. A steep increase of the dark current starts from bias voltage >8.0V due to the onset of the tunneling current.
5. OTHER EFFECTS

While dark current and read noise are the primary objects of this investigation, we have observed several other properties of the detector. During repeated readings under constant illumination, several pixels exhibited what appears to be random telegraph signal (RTS) noise. It is a known effect caused by spontaneous change of the pixel value switching between discrete levels, often only two. It is believed to be caused by random trapping and release of electrons, in general occurring in the readout circuitry of the unit cell of the pixels. In addition, we have evidence of persistence in the detector after bright illumination. We will work to examine RTS and persistence in the coming year. Below, we look at other effects also expected from the engineering-grade devices.

5.1 Quantum efficiency drop at low bias voltages

The silver contamination issue in the engineering devices impaired the original doping and caused the multiplication region in the detectors to be slightly p-type rather than n-type resulting in a widening of the gap at the p-n junction, which significantly affected the QE at low bias voltages. As a consequence, we expected a steep drop in relative QE at low bias voltages. We confirmed this result as shown in Fig. 9 with QE dropping almost linearly by >80% from bias voltage=8V to 4V. The device needs to be biased sufficiently to overcome that barrier, and at higher bias it does not matter anymore. This result is obtained by computing the ratio of the mean signal measured at constant LED flux between two different bias voltages, corrected for the theoretical increase in APD gain, also verified experimentally, as well as for the difference in exposure time.

![Figure 9: This plot shows the drop of the relative QE at low bias voltages (BVs) as expected due to this known problem of contamination in the engineering-grade devices. The purple curve shows the ratio of the QE between two consecutive bias voltages noted $BV_i$ and $BV_{i-1}$. The red curve shows the increase of the ratio taking bias voltage=4V as reference. The QE drops by nearly a factor 9 and quasi-linearly from bias voltage=8 to 4V. Beyond bias voltage=8V, the QE reaches a plateau.](image)

5.2 Cosmic rays

Cosmic ray events (CREs) have been detected in our data, especially during very long integrations such as those used to measure the dark current. As described in Fig. 10, except for this transient effect clearly visible in the...
time series of the impacted pixels, no post-CRE persistence or settling effect has been observed. The affected pixels are filtered out and rejected as outliers in our tests. However, CREs are easy to detect and we plan to correct for them in future analysis.

Figure 10: On the left, time series of an individual pixel UTR-sampled at a regular time interval, every 20 seconds, over a total integration time of 8h. The detector is operated in dark conditions, at bias voltage=4.0V, and at a temperature of 50K. At the beginning of the integration, the time series increases with a constant slope of \( \sim 0.005 \) [ADU/pix/s], determined by the dark current of this pixel. It exhibits around frame \#100 a large jump in amplitude due to the deposit of charges caused by the impact of a cosmic ray occurring between two consecutive read frames. There is no visible persistence effect on the signal measured afterwards, the slope of the signal returns to its initial evolution prior to the CRE. On the right, a sub-region of the dark current heat map includes three CREs indicated by arrows. A CRE usually affects a cluster of pixels and forms a “hot spot”.

6. CONCLUSION AND PATH FORWARD

6.1 Summary of the results

We summarize the above results as follows:

- The engineering-grade sensors are providing a large amount of useful data. However, an identified and now solved fabrication issue caused them to have a large amount of defective pixels, and lose QE at low bias voltage. We can filter out these pixels to provide a baseline for the expected performance of the science-grade devices, due to arrive in August.

- The intrinsic dark current of these devices is consistent with zero, with a best estimate of \( \sim 0.1 \) [e-/pix/ksec]. The “dark current” we measure at low bias voltages, of 3 [e-/pix/ksec], is glow. The glow is measured to be \( \sim 0.08 \) [e-/pix/frame], or 1 [e-/pix] every \( \sim 12 \) frames. The excess glow comes from the source follower MOSFET within the pixel nodes. A future design path to fix this glow is to redo the wafers with the MOSFETs covered in metal.

- The read noise of these devices starts around \( \sim 10 \) [e-/pix/frame] at 3V bias, and reduces by a factor of 1.3 with each additional volt, in agreement with theory.

6.2 Next steps

The next critical step will be evaluating our science-grade arrays which we expect to begin receiving in August. Initial testing at Leonardo indicates they have very low levels of defects now that the contamination problem has
been addressed. The design of the science grade arrays is also such that the onset of tunneling current should be
out at bias voltage $>12$ V, rather than $8$V, so the dark current will remain low while read noise is reduced below 1 [$e-/pix/frame$].

We also plan to examine some effects we observed in our data with the engineering-grade devices, namely
RTS noise and persistence. Our algorithm for detecting and correcting cosmic ray events will be finalized in
order to remove them from our data acquired by UTR sampling during long integration times. Our preliminary
estimate of the level of interpixel capacitance will be confirmed with the science-grade sensors using more data
to increase the accuracy of our measurements. It would also be valuable to get an independent determination
of the charge gain of the detectors by replicating the method by capacitance comparison proposed in Ref. 20.
The unique expected noise performance of these devices holds promise of making them able of photon number
resolving in low flux conditions. We plan to conduct experiments to demonstrate this capability.

Following in-lab characterization of the science grade arrays, our next step will be to take some on-sky data.
We will be able to use our dewar as an astronomical camera, as it was originally designed. Radiation testing
is the final goal. A complete characterization of the detectors will be performed before and after irradiation in
order to investigate what effect the radiation has on different device properties and to assess any degradation in
performance. This will be a crucial milestone to further advance their qualification for space applications.

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