Next-generation performance of SAPHIRA HgCdTe APDs

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ABSTRACT

We present the measured characteristics of the most recent iteration of SAPHIRA HgCdTe APD arrays, and with suppressed glow show them to be capable of a baseline dark current of 0.03e$^-$/s. Under high bias voltages the device also reaches avalanche gains greater than 500. The application of a high temperature anneal during production shows great improvements to cosmetic performance and moves the SAPHIRA much closer to being science-grade arrays. We also discuss investigations into photon counting and ongoing telescope deployments of the SAPHIRA with UH-IfA.

Keywords: HgCdTe, mercury cadmium telluride, MCT, near infrared, NIR, MOVPE, avalanche photo diodes, APDs, tip-tilt, natural guide star, adaptive optics, lucky imaging

1. INTRODUCTION

Since their first deployments, mercury cadmium telluride (HgCdTe) CMOS detectors have become the devices of choice for astronomical NIR imaging primarily due to their extremely low dark current, high quantum efficiency, and the availability of large format arrays e.g. in the HAWAII series.[1–4] Investigations into the properties of HgCdTe found that as an avalanche photodiode (APD) the material exhibited a virtually noiseless amplification attributed to a unique single-carrier avalanche,[5,6] well-suited for development as a linear avalanche photodiode.[7,8]

Initial development of HgCdTe APD arrays focused on high-background fast time-resolution (100+MHz) devices for defense applications, e.g. as LIDAR receivers. Working from those devices and at the direction of ESO, Selex ES (soon to be Leonardo) created the Selex Avalanche Photodiode for High-speed Infrared Arrays (SAPHIRA) with the goal of creating a wavefront sensing and fringe tracking NIR detector for astronomy.[9] The first arrays showed impressive results in gain, dark current, and excess noise.[10,11]

Dark current being closely tied to material quality, Selex's use of metal organic vapor phase epitaxy (MOVPE) permits the growth of HgCdTe with much lower dark currents than comparable liquid phase epitaxy devices. Although molecular beam epitaxy (MBE) has been used successfully for decades to grow conventional HgCdTe devices, multiple efforts initiated by the University of Hawai'i Institute for Astronomy (UH-IfA) to grow via MBE the n-on-p HgCdTe necessary for APD arrays failed to produce functional devices.

Building on the promising ESO results, UH-IfA partnered with Selex to further develop the SAPHIRA as a wavefront sensor and photon-counting device. UH received a Mark 3 SAPHIRA in late 2013, and conducted the first on-sky deployment of a HgCdTe APD array at the 3-m NASA Infrared Telescope Facility on Maunakea over two nights starting 29 April 2014.[12] SAPHIRA was then redeployed May-September 2014 to the Palomar 1.5-meter telescope to add tip-tilt guidance capability and simultaneous NIR imaging to the Robo-AO instrument there.[12,13]

The Selex-UH-ESO partnership has continued to iterate and improve on the SAPHIRA detector since, working toward science-grade arrays. We present here the performance improvements of new bandgap structures and HgCdTe manufacturing techniques (with iterations denoted by mark number), as well as results obtained by improved characterization techniques.

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2. SAPHIRA

The SAPHIRA is a 320x256x24μm HgCdTe APD array, initially targeted for use as a wavefront sensor in VLT/GRAVITY.[10, 11] The MOVPE process is used to grow HgCdTe for the arrays, and benefits from both a relatively low defect/trap density (necessary for low dark current) and fine control over the material's bandgap architecture (i.e. change in bandgap with material depth). In keeping with the original wavefront sensor application it is designed for rapid readout, with a designed maximum pixel rate of 20+MHz and 32 outputs. All 32 outputs may be used during subarray/windowed readout.

The bandgap structure of the SAPHIRA consists of three primary regions: an absorber, a multiplier, and a junction between the two. The absorber region ($\lambda_c = 2.5\mu$m) initially absorbs the photon, freeing an electron into the conduction band, which is then accelerated as it moves through the remaining absorber and interstitial buffer region. The avalanche effect occurs as it travels through the relatively multiplication region, which possesses a narrower bandgap ($\lambda_c = 3.5\mu$m) to enhance avalanche gain.

The new mark 13/14 SAPHIRA arrays exhibit sensitivity from the absorber cutoff wavelength $\lambda_c = 2.5\mu m$ down to 0.8 μm, a wider bandgap than previous iterations achieved by removing the short-wavelength buffer region. Responsivity over the full wavelength range of these devices has been measured at ESO and found to reach over 70%.[14]

2.1 Readout Update

The original ME911 SAPHIRA Read Out Integrated Circuit (ROIC) used allowed the detector to be read out in the standard integrate-then-read (ITR) mode, wherein the detector is reset and then read out for the requested number of frames, with either externally or internally triggered resets. The ME1000 ROIC, the first article of which was received by UH in November 2015 as a mark 14 array, maintains this functionality but adds an additional mode: read-reset-read. This new operating mode runs the detector row-by-row (rather than frame-by-frame), allowing it to be read out, reset, and immediately read out again. The duty cycle of each pixel is then optimized, making use of the full integrating time from one reset to the next. The ME1000 has been introduced and hybridized with a subset of the mark 13/14 arrays.

3. DARK CURRENT

3.1 Glow Reduction

Initial measurements of the SAPHIRA's baseline dark current were glow-limited, i.e. emission from the ROIC was the dominant source, rather than thermal current (or tunneling) in the detector itself. Although some degree of glow is expected from the output amplifiers, the observed glow was brighter than expected. We were initially unable to locate the source in images as it presented a largely flat distribution across the array surface, suggesting that the light on the detector was reflecting from the inside of the cryostat (see Fig 1).

A mask was designed and manufactured to shield the outer array from the glow, with a μm-scale clearance above the detector surface, and a distinctively shaped milled aperture to assist discrimination of background/glow from the detector's native dark current. The installation of the mask produced rays extending across the detector from an unknown and very bright point source to the lower-left of the array. These images indicated the position of the offending point source, which was then precisely located by imaging a SAPHIRA device onto a HAWAII-4RG array. Selex was then able to link it to a mask error causing a FET gate in the ROIC to be left in an undefined state, conducting a great deal of current. The error is being corrected in the remaining (to date unfinished) ME1000 ROICs.

3.2 With Bias Voltage

For SAPHIRA arrays the generated electrons also experience avalanche gain in the multiplication region, though as they are generated at varying depths throughout both the absorption and multiplication regions they may not experience the full avalanche gain.

Our measurements are shown in Fig 2, and reveal a baseline dark current of $0.03e^{-}$/s. Dark measurements have been adjusted for gain, revealing the interesting effect that the dark current drops with bias voltage up to a

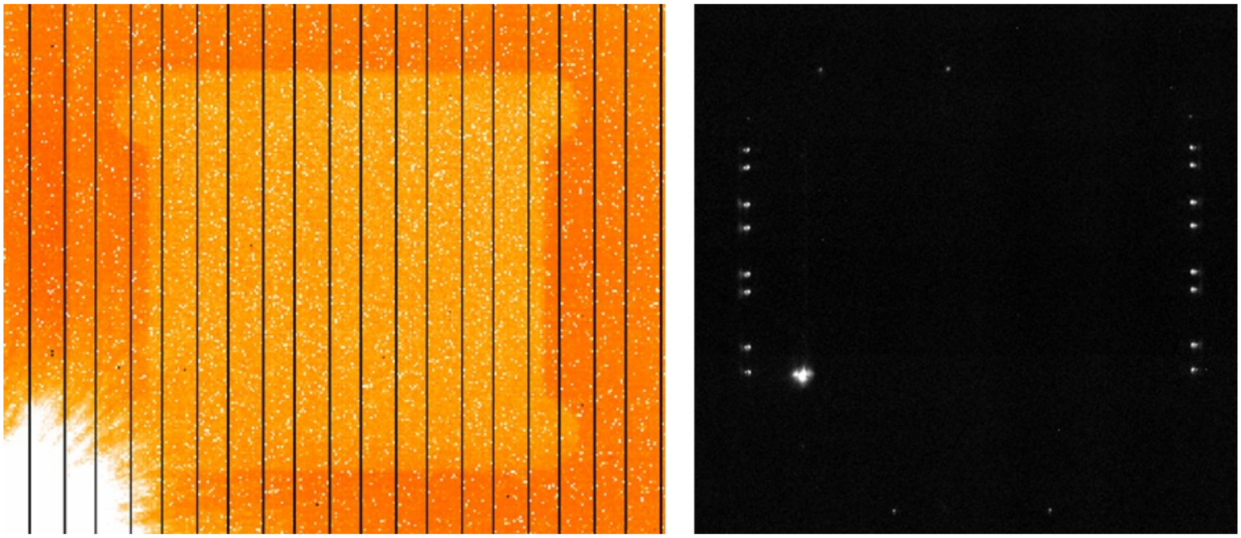

Figure 1. Glow on an ME911 Mark 3 SAPHIRA detector, imaged in J-band on an H4RG (*left*). The array is powered on, and the bright source in the lower left of the image is the noted defect source, while the smaller sources seen on the H4RG image are output amplifiers. Also shown is the glow as seen by the SAPHIRA itself with the mask in place(*right*), showing the rays originating at the defect. The shape in the center of the image is the mask aperture, illuminated by reflected glow on the interior of the cryostat.

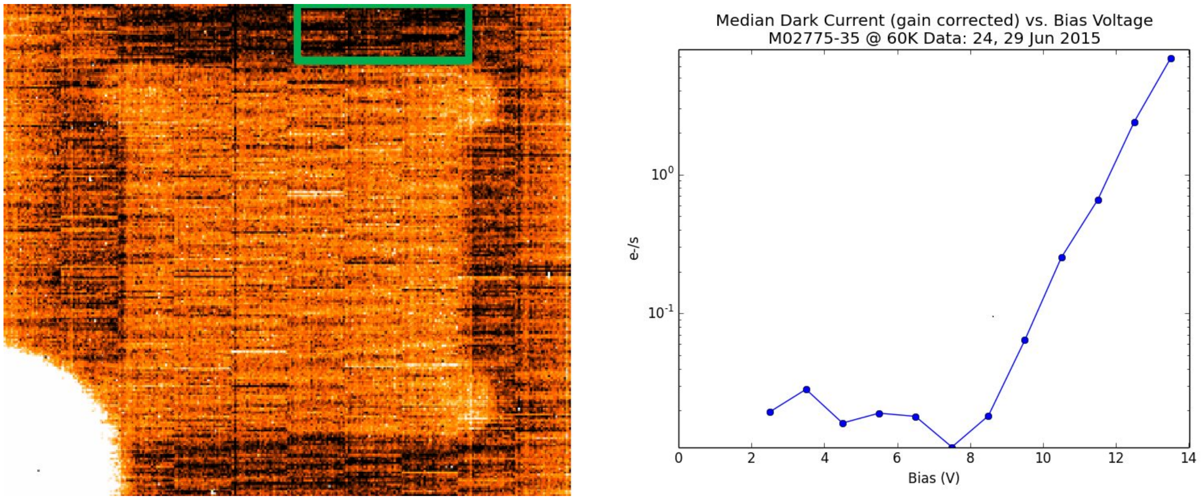

Figure 2. The selected subarray used to measure dark current limits of the SAPHIRA device in the top-center region of the glow-suppressed array (*left*), and measured dark current (corrected for avalanche gain) of the subarray on the mark 3 SAPHIRA detector M02775-35 with as a function of bias voltage (*right*). Note the slope of the line past 8 volts, which we tentatively attribute to the onset of tunneling current.

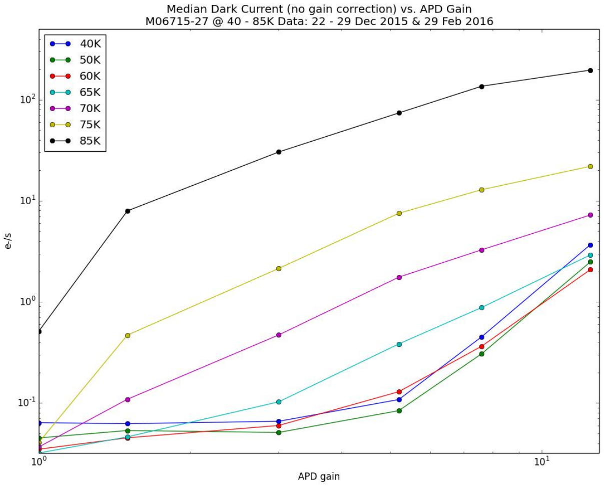

Figure 3. The mean dark current across the mark 14 SAPHIRA detector M06715-27 as a function of avalanche gain and temperature. No gain correction is applied.

value of ~ 8.5V. The decreasing dark current with bias is a function of the partial avalanche gain experienced by dark & glow photons. This effect produces a 'knee' in the dark-bias relation where the detector can be optimally run with an avalanche gain of ~ 6 with little downside. After this point, tunneling becomes the dominant dark current source as expected.

As glow from the aforementioned sources propagates laterally through the array it can be absorbed in the multiplication region of pixels and thus fail to undergo the full avalanche gain, hence the apparent decrease in dark current before the onset of tunneling current. This supports the idea that despite our glow reduction efforts as documented in the previous section, a fraction of the glow is still reaching the area of the detector under the mask.

3.3 With Temperature

We also measure the dark current of the devices with temperature, and find that the lack of any change in low bias dark current from 60-40K (see Fig 3) indicates that $0.03e^-/\text{s}$ is still a glow-limited measurement, and the actual dark current of the SAPHIRA may be yet lower.

4. CHARACTERISTICS

4.1 High-Bias Performance

The mark 13/14 SAPHIRA arrays have been subjected to higher bias voltages than was previously thought possible without risk of damage, with no adverse effects observed. In previous tests the 250 kHz frequency limit of the ARC controller made it impossible to accurately quantify the SAPHIRA at such levels, but with the PB-32 controller (see below) we have been able to extend measurements of avalanche gain up to nearly 20V of bias, shown in Fig 4. In conjunction with work performed at ESO, we measure a maximum avalanche gain of ~ 600 with a mark 14 SAPHIRA array. Avalanche gain was measured in the KSPEC ultra-low-background cryostat with an H-band ($\lambda = 1.30\mu$m) LED illuminating an integrating sphere in view of the detector. The glow mask is present for these tests, and LED off frames are subtracted to account for background glow and other common effects.

Additionally, in moving toward science-grade arrays, Selex applied a high-temperature anneal to its arrays starting with the mark 12. The high-temperature anneal involves simply 'baking' the device for a number of minutes to eliminate traps in the surface layer. We have observed that this greatly improves the cosmetic performance of the detectors, particularly at high gain (> 20) where previous iterations of the SAPHIRA showed

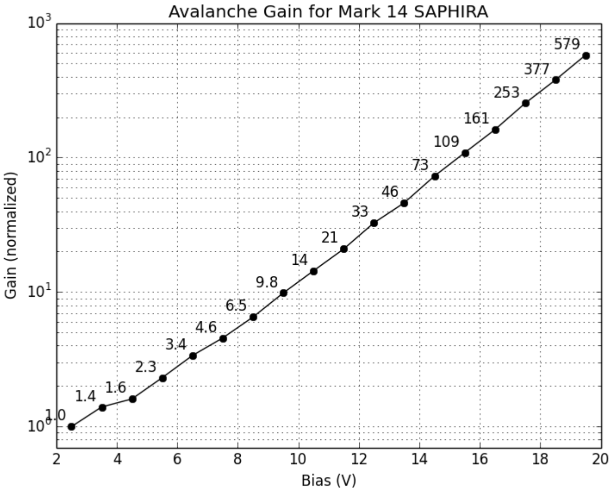

Figure 4. The measured avalanche gain of the mark 14 SAPHIRA detector M06715-27 as a function of bias voltage. Measurements were made in KSPEC at 60K using the PB-32 controller.

Figure 5. Comparative cosmetic performance of the mark 10 (*left*) and mark 13 (*right*) devices, measured as the uniformity of dark current at high bias voltage (14.5V). The mark 13 device receives a 4 minute high temperature anneal during production.

large surface features (see Fig 5). The anneal is thus an integral part of the manufacture of science-grade SAPHIRA arrays.

4.2 The PB-32 Controller

Our characterization with the new PB-32 controller has enhanced our ability to operate the SAPHIRA detector at high-speed with low read noise. The PB-32 is a single-board detector controller with both low- and high-gain modes, the latter providing a charge gain with a SAPHIRA of $\sim 1e^{-}/\mathrm{ADU}$ for enhanced resolution. The new controller's faster readout speed (currently up to 1.5 MHz with the potential for 2 MHz operation) also enhances readout capability and discrimination of pulses.

4.3 Towards Photon Counting

Photon counting is a focus of the SAPHIRA development, and depends on both the overall read noise of the detector and the noise of the avalanche gain process. The unique properties of HgCdTe result in a much higher effective mass and lower ionization coefficient for holes than for electrons, resulting in a single-carrier avalanche that does not experience the susceptibility to phonon scattering experienced by holes. This has been shown to greatly reduce the excess $1/f$ noise $< M >$ that typically increases with gain M in avalanche photodiodes, with some measurements of HgCdTe APD showing it to be completely absent.[7] Without this excess noise, the ability of an NIR APD to distinguish individual photons is enhanced.

Our investigations into photon counting with the SAPHIRA to date have shown an unexpectedly broad photon avalanche pulse height distribution, inhibiting our ability to register individual photons. By setting a discriminator level to our best ability, and operating a device at high avalanche gain (500+), modeling indicates that we are currently able to register individual photons with approximately 90% confidence and 90% completeness. This would seem to conflict with existing measurements of $< M >$ in SAPHIRA devices at higher photon flux levels.[11, 14, 15] We are still investigating the nature of the electron avalanche in SAPHIRA devices and their respective ability to perform photon counting, and the results of our investigation will be prepared for publication in the next year.

5. DEPLOYMENTS

5.1 Subaru/SCExAO

The UH SAPHIRA team has been working with Olivier Guyon's SCExAO group at the Subaru Telescope to use the SAPHIRA as a speckle nulling imager in the prototypical extreme adaptive optics system. Initial commissioning began in Fall 2014, and in the ongoing deployment the SAPHIRA detector has demonstrated the capability to nullify speckles and isolate atmospheric distortions.[16]

5.2 Kitt Peak/Robo-AO

Following up on the SAPHIRA's previous deployment as a natural guide star sensor with the automated adaptive optics imager Robo-AO at the Palomar 1.5-m telescope in 2014,[12, 13] a SAPHIRA detector (and PB-32 controller) will again be deployed alongside Robo-AO at the Kitt Peak Observatory in late 2016. Advancements in detector performance and the controller upgrade are expected to enable it to perform full-time tip-tilt correction and simultaneous K-band imaging in a search for widely separated exoplanets and brown dwarf companions.[17]

6. UPCOMING DEVELOPMENTS

The planned steps in the SAPHIRA development over the next year are first to create a new bandgap architecture to understand limiting current at high bias voltage and attempt to push back its onset to higher voltages. This improvement should assist in both wavefront sensing and photon counting applications. Second, we will evaluate the performance of 12μm pixel pitch architectures, down from the present 24μm.

7. SUMMARY

Since the presentation of the first MOVPE arrays by ESO and our work with the early mark 3, the SAPHIRA has advanced in great strides. We present the mark 13/14 SAPHIRA devices, which incorporate bandgap changes and a high temperature anneal to enable wavelength coverage from 0.8μm to 2.5μm and greatly improved cosmetic performance, respectively. We also measure a dark current as low as $0.03e^-/$s, and high-bias avalanche gains above 500. In addition to laboratory characterization, UH is continuing deployments of the SAPHIRA at multiple telescopes both inside and outside of Hawai'i.

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REFERENCES

1. K.-W. Hodapp, J. L. Hora, D. N. Hall, L. L. Cowie, M. Metzger, E. M. Irwin, T. J. Keller, K. Vural, L. J. Kozlowski, and W. E. Kleinhans, "Astronomical characterization results of 1024 X 1024 HgCdTe HAWAII detector arrays," in *Infrared Detectors and Instrumentation for Astronomy*, A. M. Fowler, ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **2475**, pp. 8–14, June 1995.
2. K.-W. Hodapp, J. L. Hora, D. N. B. Hall, L. L. Cowie, M. Metzger, E. Irwin, K. Vural, L. J. Kozlowski, S. A. Cabelli, C. Y. Chen, D. E. Cooper, G. L. Bostrup, R. B. Bailey, and W. E. Kleinhans, "The HAWAII Infrared Detector Arrays: testing and astronomical characterization of prototype and science-grade devices," *New Astr.* **1**, pp. 177–196, Oct. 1996.
3. D. N. Hall, K.-W. Hodapp, D. L. Goldsmith, C. A. Cabelli, A. K. Haas, L. J. Kozlowski, and K. Vural, "Characterization of lambdac=5 um Hg:Cd:Te arrays for low-background astronomy," in *Optical and IR Telescope Instrumentation and Detectors*, M. Iye and A. F. Moorwood, eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **4008**, pp. 1268–1279, Aug. 2000.
4. K. W. Hodapp, J. Kuhn, R. Thornton, E. Irwin, H. Yamada, M. Waterson, L. Kozlowski, J. T. Montroy, A. Haas, K. Vural, and C. Cabelli, "The HAWAII-2 2048×2048 HgCdTe Detector Arrays," in *Scientific Detectors for Astronomy, The Beginning of a New Era*, P. Amico, J. W. Beletic, and J. E. Belectic, eds., *Astrophysics and Space Science Library* **300**, pp. 501–509, 2004.
5. C. T. Elliot, N. T. Gordon, R. S. Hall, and G. Crimes, "Reverse breakdown in long wavelength lateral collection $Cd_x\ Hg_{1-x}$ Te diodes," *Journal of Vacuum Science & Technology A* **8**, pp. 1251–1253, Mar./Apr. 1990.
6. J. D. Beck, C.-F. Wan, M. A. Kinch, and J. E. Robinson, "MWIR HgCdTe avalanche photodiodes," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, R. E. Longshore, ed., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **4454**, pp. 188–197, Nov. 2001.
7. J. D. Beck, C.-F. Wan, M. A. Kinch, J. E. Robinson, P. Mitra, R. E. Scritchfield, F. Ma, and J. C. Campbell, "The HgCdTe electron avalanche photodiode," in *Infrared Detector Materials and Devices*, R. E. Longshore and S. Sivananthan, eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5564**, pp. 44–53, Oct. 2004.
8. M. A. Kinch, "A Theoretical Model for the HgCdTe Avalanche Photodiode," *Journal of Electronic Materials* **37**, p. 1453, 2008.
9. I. M. Baker, C. D. Maxey, L. G. Hipwood, and K. Barnes, "Leonardo (formerly Selex ES) infrared sensors for scientific astronomy: present and future," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9915**, p. 991504, Aug. 2016.
10. G. Finger, "SAPHIRA: a new NIR HgCdTe Avalanche Photodiode Array optimized for Adaptive Optics and Interferometry," in *Adaptive Optics for Extremely Large Telescopes*, *Adaptive Optics for Extremely Large Telescopes*, May 2013.
11. G. Finger, I. Baker, D. Alvarez, D. Ives, L. Mehrgan, M. Meyer, and J. Stegmeier, "NIR HgCdTe Avalanche Photodiode Arrays for Wavefront Sensing and Fringe Tracking," in *Optical and IR Telescope Instrumentation and Detectors*, *Scientific Detector Workshop*, Oct. 2013.
12. D. Atkinson, D. Hall, C. Baranec, I. Baker, S. Jacobson, and R. Riddle, "Observatory Deployment and Characterization of SAPHIRA HgCdTe Arrays," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, A. D. Holland and J. Beletic, eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9154**, p. 915419, June 2014.
13. C. Baranec, D. Atkinson, R. Riddle, D. Hall, S. Jacobson, N. M. Law, and M. Chun, "High-speed Imaging and Wavefront Sensing with an Infrared Avalanche Photodiode Array," *Ap.J.* **809**, p. 70, Aug. 2015.
14. G. Finger, I. Baker, D. Alvarez, D. Ives, L. Mehrgan, J. Stegmeier, D. N. B. Hall, and C. Dupuy, "Development of the near-infrared eAPD array SAPHIRA achieving sub-electron read noise at millisecond full-frame readout," in *Adaptive Optics Systems V*, *Proc. SPIE* **9909**, p. 990940, Aug. 2016.
15. G. Finger, I. Baker, D. Alvarez, D. Ives, L. Mehrgan, M. Meyer, J. Stegmeier, and H. J. Weller, "SAPHIRA detector for infrared wavefront sensing," in *Adaptive Optics Systems IV*, *Proc. SPIE* **9148**, p. 914817, Aug. 2014.

16. S. B. Goebel, O. Guyon, D. N. B. Hall, N. Jovanovic, and D. E. Atkinson, "Evolutionary timescales of AO-produced speckles at NIR wavelengths," in *Adaptive Optics Systems V*, *Proc. SPIE* **9909**, p. 990946, Aug. 2016.
17. M. Salama, C. Baranec, R. M. Jensen-Clem, R. L. Riddle, D. Duev, S. R. Kulkarni, and N. M. Law, "Robo-AO Kitt Peak: status of the system and optimizing the sensitivity of a sub-electron readnoise IR camera to detect low-mass companions," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9909**, p. 990948, June 2016.