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SPACE-QUALIFIED INFRARED FOCAL PLANE ARRAYS – A CRITICAL TECHNOLOGY FOR PLANETARY DEFENSE

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ABSTRACT

The Near Earth Object Surveyor (NEO Surveyor) project will provide the most comprehensive survey of potentially hazardous objects ever completed. A critical enabling technology for NEO Surveyor is its Infrared Focal Plane Arrays (FPAs), particularly the long-wave infrared (LWIR) detectors, which operate at temperatures achievable in space via passive cooling. Passive cooling reduces the cost and complexity of the mission while eliminating cryogen lifetime limitations. NEO Surveyor will utilize four 2k x 2k mid-wave infrared (MWIR, 5.7μm-cutoff) HgCdTe and four 2k x 2k LWIR (~11μm-cutoff) HgCdTe focal plane arrays produced by Teledyne Imaging Sensors (TIS). Since NEOs attain temperatures near 300K, peak sensitivity demands this LWIR response. The WISE and NEOWISE missions have already demonstrated the utility of space-based MWIR HgCdTe and LWIR Si:As FPAs for NEO detection. However, the Si:As FPAs required life-limiting cryogens to maintain their 8K operating temperature. For NEO Surveyor to utilize LWIR

FPAs with a bandpass near the 300K blackbody peak for NEOs while taking advantage of a wholly passively-cooled thermal design, NEO Surveyor project partners at TIS, University of Rochester, JPL, and University of Arizona have worked since 2005 to improve the performance of the LWIR FPAs. The result is LWIR FPAs with excellent quantum efficiency, low dark currents while maintaining adequate well depth, and >90% operability at 40K focal plane temperature. This paper covers the past development of this technology and recent results from the testing of NEO Surveyor FPAs.

INTRODUCTION:

The Near Earth Object Surveyor is an upcoming NASA mission designed to survey for Near Earth Objects - NEOs – which assume a temperature of ~300K with peak emission near 10 μm wavelength. Consequently, LWIR (long wavelength infrared- 10+ μm) arrays are required for the survey. These arrays, termed NC2, are complemented by 5+ μm arrays, termed NC1. The WISE (Wright et al. 2010) and NEOWISE (Mainzer et al. 2011) missions employed Si:As Impurity Band Conduction LWIR arrays for earlier NEO surveys, but those arrays require cryogenic cooling to 6-8K, so when the cryogen ran out, the long wavelength capability was lost. NEO Surveyor plans to use passive cooling in order to contain mission costs and to ensure the possibility of a long-lived survey. University of Rochester astronomers had worked on mid-wave 5 μm detector arrays for *Spitzer Space Telescope* (Gallagher, Irace and Werner 2003), which operated at 13K during the prime mission from 2003 to 2009, but which warmed up to an operating focal plane temperature of ~27K once the cryogen was depleted. It was clear that longer wavelength arrays which could be passively cooled were desirable for survey missions. *Spitzer* continued operating from 2009 until it was turned off in January 2020, obtaining amazing data with only the mid-wave arrays. In the late 1990s, in order to address the need for long wave IR arrays to operate at passively cooled temperatures, the University of Rochester and Teledyne Imaging Sensors (formerly Rockwell Scientific) began developing long wavelength HgCdTe single pixel detectors which, with appropriate physical parameters, can attain sufficiently low dark currents at focal plane temperatures of ~40K. The Rochester team then began development of small LWIR HgCdTe arrays. In 2005, Amy Mainzer, then at JPL, conceived employing LWIR HgCdTe arrays for a mission she called NEOCam, the precursor mission which became NEO Surveyor in 2020. The team overcame many challenges to the development of low dark current, low noise, high quantum efficiency, high operability and large format LWIR detector arrays that would also survive space's charged particle environment. Today, NEO Surveyor, now directed by Mainzer's team at University of Arizona, has achieved development of monolithic 2k x 2k 10+ μm arrays with the desired basic characteristics (Quantum Efficiency QE in band > 55%; Dark Current < 200 e-/s), CDS (Correlated Double Sampling) Noise < 36 e-, Well depth >44 ke-, Operability > 92%). Current efforts are directed to longer wavelength cutoff arrays, and determination of the secondary aspects defining detector array performance which are critical to mission success. NEO Surveyor also will employ NC1 (4-5.2 μm) arrays which are already well-developed for the James Webb Space Telescope (JWST) and other missions. The use of both wavebands not only assists in identifying NEOs and their orbits, but also improves the accuracy of NEO diameter determination, a fundamental scientific goal of NEO Surveyor.

EARLY WORK – FROM SINGLE PIXELS TO 1K X 1K ARRAYS

$Hg_{1-x}Cd_xTe$ photovoltaic detectors can be tailored to different cutoff wavelengths λ_{co} at a specific focal plane temperature by modifying the Cd molar fraction x. The empirically derived bandgap energy E_g in eV as a function of x and temperature T is given by Hansen , Schmit and Casselman (1982):

$$E_g = -0.302 + 1.93x - 0.81x^2 + 0.832x^3 + 5.35(1-2x)10^{-4}\,T \quad (1)$$

and

$$hc/\lambda_{co} = E_g \quad (2)$$

SWIR (short wave IR, $x \sim 0.73$ at T=40K) and MWIR (Mid-wave IR, x~0.3 at T= 40K) HgCdTe arrays are extremely mature and have been demonstrated on a variety of telescopes, both in space and on the ground (e.g. Rauscher et al. 2014). LWIR arrays (x~0.225) were at a far different point when the University of Rochester and Teledyne Imaging Sensors (TIS) began their array development efforts, basing their work on single pixel experiments described by Bailey et al. (1998). Rochester graduate student Jian Wu was responsible for the 10.6 μm detector data in Figure 8 in the paper by Bailey et al., fitting the dark current vs. 1/T data to thermal generation-recombination (GR) and diffusion dark currents as well as tunneling currents. This demonstrated the need for low doped HgCdTe to attain sufficiently low dark currents for astronomical uses at focal plane temperatures of ~40K.

In 2003, under the auspices of a NASA grant, TIS delivered to the University of Rochester 512 x 512 format LWIR arrays in an attempt to meet low dark current goals at a focal plane temperature of 40K (Bacon et al. 2003, 2004, 2005, 2010). Those LWIR arrays did not support adequate reverse bias, thus the well depth of low dark current, high QE pixels was small, although a modestly high percentage of the pixels exhibited low dark current. The softness of LWIR arrays (because of the larger Hg concentration than in SWIR or MWIR arrays) led to an increased number of high dark current pixels, affecting the overall array operability. Consequently, TIS effected changes in the LWIR array processing steps to overcome this problem. McMurtry et al. (2013) tabulated the results for these 512 x 512 arrays, as well as the primary results of the paper, the successful 1k x 1k format arrays discussed below. The early 512 x 512 format results were sufficiently promising to encourage the nascent NEOCam program.

NASA Discovery funding (2010) to NEOCam PI Mainzer (then at JPL) to address those detector array aspects requiring technical development, combined with NASA APRA funding of the Rochester test and optimization work, provided the means to take LWIR HgCdTe array development at TIS to the next level. McMurtry et al. (2013) outlined the success of these efforts in their description of the characteristics of 1k x 1k format LWIR arrays: low noise, low dark current, high quantum efficiency, adequate well depth, and high operability, all at focal plane temperatures of 40K. This focal plane temperature was selected because it was feasible to passively cool the LWIR arrays to that temperature on NEOCam/NEO Surveyor, while still attaining low dark current. McMurtry et al. also evaluated the effect of backfilling with epoxy the space between the IR sensitive HgCdTe array and the silicon ROIC (read out integrated circuit). Backfilling would prove essential for the next phase, namely removing the CdZnTe substrate on which the HgCdTe was grown after the array was indium bump-bonded to the ROIC. The CdZnTe substrate has been shown to produce luminescence in shorter wavelength HgCdTe arrays when irradiated with high energy protons (Waczynski et al.

2005). For LWIR arrays, the impact of substrate removal on proton irradiation was evaluated as expanded upon below.

Dorn et al. (2016) described a series of proton irradiation experiments on LWIR 1k x 1k HgCdTe arrays. These experiments took place at the Crocker Nuclear Laboratory, University of California Davis. To evaluate the effect of the substrate on LWIR arrays under proton irradiation, three arrays were tested at beam energies ranging from 12-63 MeV—one with 800 μm CdZnTe substrate intact, one with all but 30-μm substrate removed, and one completely substrate-removed. At the dark level of the radiation test dewar (supplied by colleagues at NASA Ames), we detected no luminescence in non-hit pixels during proton testing for both the substrate-removed detector array and the array with 30-μm substrate. The detector array with full CdZnTe substrate exhibited substantial photocurrent for a flux of 103 protons⁄cm^2 s at a beam energy of 18.1 MeV (~750 e⁻⁄s) and at 34.4 MeV (~65 e⁻⁄s). All subsequent arrays developed for NEOCam/NEO Surveyor are designed to be radiation hard.

THE PATH TO 2K X 2K SPACE QUALIFIED ARRAYS FOR NEO SURVEYOR

In 2015, NEOCam was awarded Phase A funding by NASA's Discovery program, and in early 2017, Extended Phase A funding under the then newly formed Planetary Defense Coordination Office. It was after 2015 that TIS began development of 2k x 2k LWIR arrays in earnest. Although NEOCam was originally proposed to utilize eight 1k x 1k LWIR HgCdTe arrays, it was clear that four 2k x 2k arrays mounted in a row would be superior for the NC2 channel in order to increase the fill factor and simplify the electronics and thermal design. The MWIR arrays planned for the NC1 channel were already well developed in a 2k x 2k format for JWST, among other missions. Because of the afore-mentioned softness of the LWIR detector material, which made it harder to work with, and because of the existing processing machines at TIS, the project took small steps toward the 2k x 2k goal. The first step was to produce 2k x 1k "duplex" arrays and to mount them to the 2k x 2k H2RG ROIC, butted as closely as possible. Following successful implementation of that step, full scale monolithic 2k x 2k devices were produced. For all of the detector and hybrid configurations, TIS manufactured the detector layers with their standard p-on-n structure which they have been tuning specifically to meet the requirements of NEO Surveyor. Doping of the sensitive HgCdTe material has been carefully designed to yield excellent dark current and well depth, and recent innovations at TIS have assured uniform *x* values across the HgCdTe material, so that the cutoff wavelength is constant across the array.

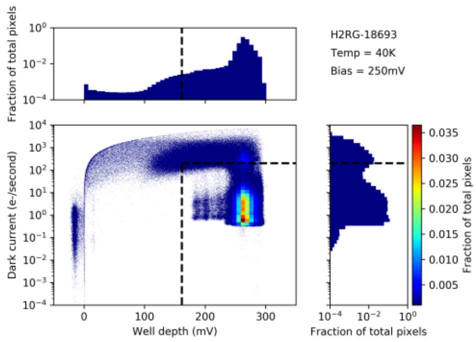

Fig.1 Dark current vs. well depth for H2RG-18693. Most pixels have high well depth and low dark current.

The first monolithic 2k x 2k arrays were delivered to Rochester in late 2016. Dorn et al. (2018) reported on one of those arrays, H2RG-18694 with a 9.6 μm cutoff wavelength. It sustained applied biases of 250 and 350 mV, and operabilities > 90% at 35, 40, and 42K. In that paper as well as in McMurtry et al. (2013), the methods employed to obtain and analyze these data are discussed. Here we illustrate results for a 9.9 μm cutoff array, H2RG-18693. At an applied bias of 250 mV, and a focal plane temperature of 40K, Fig.1 illustrates with dashed lines the required well depth (in mV, as determined from an electrons to mV conversion for our system) as well as the maximum dark current (200 e-/s). The pixels meeting both requirements reside in the rectangle defined by the dashed lines, and define the primary input to the operability. As shown in Fig. 2, the operability exceeds 90%. Quantum efficiency for this array is measured to be ~65% at 8 μm (Dorn, PhD Thesis, University of Rochester, 2019).

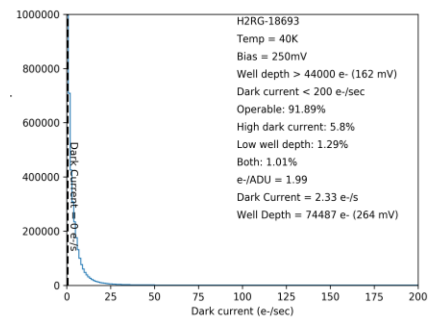

Fig. 2 Dark Current Histogram for H2RG-18693

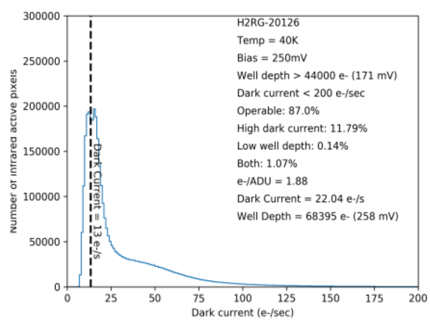

Fig. 3 Dark current histogram for H2RG 20126

Longer cutoff wavelength arrays have been manufactured at TIS. The first three pathfinder arrays (longer cutoff wavelength than 10 μm) were delivered to University of Rochester for evaluation using engineering grade ROICs. H2RG-20071 and H2RG-20126 were the better pathfinder arrays of the three that University of Rochester tested. Shown in Fig. 3 is the dark current histogram for H2RG-20126, an 11 μm cutoff array. The dark current and well depth operability measured by the Rochester group is ~87% at 250 mV applied reverse bias and 40K focal plane temperature, slightly below the NEO Surveyor requirement. TIS measured the QE of a process evaluation chip from the wafer utilized for the array: the QE was > 80% from 2 – 9.8 μm. TIS tests showed that the Quantum Efficiency spatial uniformity was high.

More recent TIS efforts have continued focusing on producing excellent longer cutoff wavelength arrays. From our experience with the 10.6 μm 1k x 1k array H1RG-16885 discussed by McMurtry et al., as well as Rochester's experience with TIS' production of excellent 13 and 15+ μm arrays (Cabrera et al. 2019, 2020), we are confident we can meet the flight needs of NEO Surveyor. A critical evaluation of the longer wavelength cutoff arrays will be to determine whether the basic array properties will remain constant if the focal plane temperature of 40K varies by ±2K.

The development of high quality LWIR arrays was difficult, and was made more complicated upon the death of the GL Scientific's director, Gerry Lupino. The team had initially planned on the detector mounts to be purchased from GL Scientific. TIS then launched a development effort in-house to produce the required space-qualified mounts, the FRSBE (FouR Side Buttable Edge) packages. All arrays developed for NEO Surveyor are mounted on FRSBE packages. The NEO Surveyor Project worked with TIS to space qualify the MWIR and LWIR Sensor Chip Assemblies on FRSBE packages to vibration levels of 23.7 G_rms and 30 thermal cycles between 25K and 300K.

DETAILED CHARACTERIZATION OF THE LWIR ARRAYS

In addition to the basic array properties of QE, Dark Current, Well Depth, Noise, there are a number of important features of the arrays relevant to NEO Surveyor performance. These include image quality (both Modulation Transfer Function and Brighter Fatter effects), temperature fluctuation stability, residual image performance, and additional calibration details such as reference pixel scale factor.

1. Image Quality: MTF-Modulation Transfer Function and Influence of Brighter Fatter Effects

Zengilowski et al. (2021a) describe in detail Rochester's measurements of the LWIR MTF, and the influence of the two brighter-fatter effects on image quality. A system's MTF can be obtained by taking the magnitude of the Fourier transform of the two-dimensional point spread function (PSF), which is the image produced when observing a perfect point source. With point sources unavailable, we utilized instead a knife edge in contact with the detector surface, at a slight angle to one detector pixel edge. From illumination of the knife edge in contact with the array, the Edge Spread Function ESF is formed and the MTF is the Fourier Transform of the derivative of the smoothed ESF. The resultant MTF at ~10 μm is the curve shown in Fig. 4, and the value is always quoted at the Nyquist Frequency. Noise Pixels -NP- is another way of specifying image quality , and is related to the area under the MTF curve (Wright 1985).

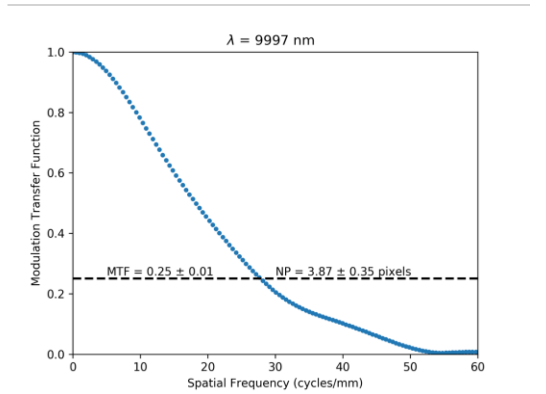

Fig. 4. MTF = Fourier Transform of derivative of smoothed ESF.

In addition to the MTF, there are two so called "Brighter Fatter" effects which broaden a point source response on a detector array. The first effect (which we call BF1) was noted by Plazas et al. (2018) for HgCdTe arrays, and is related to unequal lateral diffusion for a bright pixel (consequently having a smaller depletion region) than its dim neighbors. BF2 is another brighter fatter effect discovered at Rochester during the evaluation of the individual pixels' non-linearity in NEO Surveyor arrays. BF2 occurs when a pixel entering saturation shares current with its neighbors.

2. Temperature Fluctuation Stability

Both NC1 MWIR and NC2 LWIR arrays were evaluated in this study. First, at a constant temperature (57K for NC1 array and 40K for NC2 array) 64 correlated double sampled (CDS) images were obtained. After the baseline images were gathered, a series of focal plane temperature modulated images were obtained. Reference pixel correction was executed using a Savitsky-Golay filtered list of the average values in each row of the array. Prior to reference pixel subtraction, a reference pixel scale factor of 0.75 was applied to account for the capacitance mismatch between reference and photo-active pixels. Once those results were signal non-linearity corrected, the values were converted to electrons from ADUs (analog to digital units). Subtracting two consecutive CDS images and dividing by √2 provides a measure of the noise used to track the consequence, if any, of temperature fluctuation. The NC2 array had a non-modulation noise of 16.8 e-.

The detector temperature for the NC2 array was varied by ±50 mK on both a fast and slow time scale (periods of 9 minutes, 79.2 minutes). Median noise for the NC2 array increased very slightly by 1 e- in the fast modulation case only.

The NC1 array was subjected to temperature fluctuations at 13.4, 78.6, and 200.0 minute periods. There was no change in the noise with temperature modulation.

3. Reference Pixel Scale Factor

As noted above, a scale factor of 0.75 approximately corrects reference pixels before subtraction from photon-sensitive pixels. However, the exact scale factor value depends on the specific array, and the signal level. The appropriate averaging method to be employed on each row's reference pixels as well as other factors, such as signal level and focal plane temperature will be discussed in an upcoming paper by Zengilowski et al. (2021b).

4. Residual Image Performance

When an array views a very bright source, it often leaves a residual image once the view has changed. Table 1 lists the 5 residual image tests performed on the LWIR NC2 pathfinder detector array, in order to allow appropriate NEO Surveyor calibration.

TEST	SOURCE FLUX (e/s)	SOURCE EXPOSURE (s)	DELAY SLEW TIME (s)	DARK EXPOSURE (s)	DESIRED RESIDUAL FLUENCE (e)	NUMBER OF REPEATS
1	430	28	8	0.55	<100	16
2	Saturated	28	3	0.55	<200	16
3	3900	3	6	0.55	<100	16
4	Saturated	3	3	0.55	<200	16
5	Saturated	3600	3	0.55	<200	8

The data acquisition strategy was to illuminate the array as specified for each test, then move the filter wheel to the cold dark shutter and take relatively fast dark images. In all cases, the acquired decay data were fit to

$$S = A\exp(-t/\tau 1) + B\exp(-t/\tau 2) \quad (3)$$

For the unsaturated cases 1 and 3, the coefficient *A* was 13 and 42 e-, certainly < 100 e-. For the saturated cases, the coefficient *A* was ~80 e- within the uncertainty, certainly < 200 e-. The coefficient *B* was < 0.19*A in all cases. The decay time constant $\tau 1$ ~0.2s while $\tau 2$ ≥1.6s. Two examples of the decay curves are shown below in Figs.5 and 6.

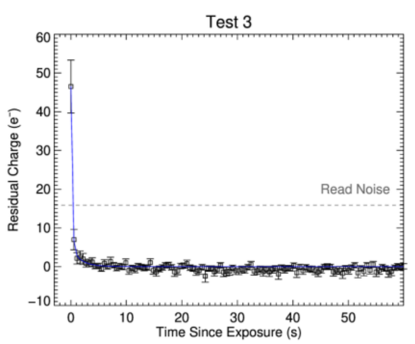

Fig. 5 Decay curve for Test 3

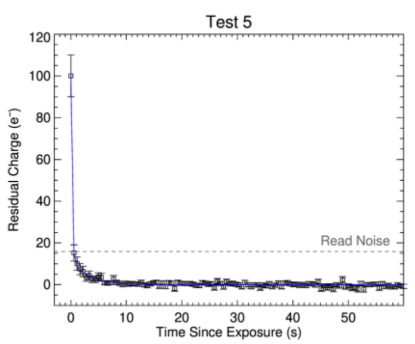

Fig. 6 Decay Curve for Test 5 to 40K

CONCLUSIONS

Excellent, flight quality 2k x 2k LWIR arrays that can be passively cooled to 40K, have been developed by TIS, University of Rochester, University of Arizona and JPL for the NEO Surveyor Mission. These arrays, in concert with 2k x 2k MWIR arrays (similar to those developed for JWST and other missions), enable a survey which will identify and characterize both low albedo NEOs (inaccessible to visible wavelength surveys) and higher albedo NEOs. The arrays meet all the basic QE, dark current, well depth, noise and operability requirements for NEO Surveyor. Further characterization of image quality, residual image performance, and other properties important for calibration, demonstrate that the LWIR arrays will perform well in flight.

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