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2.5 µm PACE-I HgCdTe 1024x1024 FPA

L.J. Kozlowski, K. Vural, S.C. Cabelli, C.Y. Chen, D.E. Cooper
G.L. Bostrup, D.M. Stephenson, W.L. McLevige and R. B. Bailey
Rockwell Science Center
Thousand Oaks, CA 91360

K. Hodapp and D. Hall
University of Hawaii
Institute for Astronomy
Honolulu, Hawaii 96822

W.E. Kleinhans
Valley Oak Semiconductor
Westlake Village, CA 91362

ABSTRACT

Rockwell Science Center and the University of Hawaii have developed a short wavelength infrared (SWIR) 1024x1024 focal plane array (FPA) for the U.S. Air Force Phillips Laboratory supporting their Advanced Electro Optical System (AEOS) 3.67 m telescope project on Haleakala, Maui. First light in the University of Hawaii's 2.2 m telescope was achieved two days ahead of schedule; performance highlights include read noise of 8.5 e-, FPA dark current <0.1 e-/sec, pixel yield >99%, quantum efficiency >50%, and BLIP-limited sensitivity at low-10^9 photons/cm^2-sec background and operating temperatures to 120K. Though specifically developed for infrared astronomy, the device is extremely useful for surveillance applications. Proprietary hybridization and mounting techniques are being used to insure hybrid reliability after many thermal cycles. The hybrid methodology has been modeled using finite element modeling to understand the limiting mechanisms; very good agreement has been achieved with the measured reliability.

1.0 INTRODUCTION

We report the development of the world's first high performance megapixel IR FPA, which is named the *H*gCdTe *A*stronomical *W*ide *A*rea *I*nfrared *I*mager (HAWAII). The University of Hawaii and Rockwell team succeeded in integrating the first photons two days ahead of schedule in time to observe the comet Shoemaker-Levy 9 collisions with Jupiter. Figure 1 shows photographs of Jupiter generated during the first-light effort.

Figure 1. Images of Jupiter showing Shoemaker-Levy 9 comet collision sites using HAWAII 1024x1024 FPA.

The HAWAII FPA is a hybrid consisting of a HgCdTe detector array fabricated on an alternative Al_20_3 substrate that is flip-chip bonded to a CMOS silicon multiplexer via indium interconnects. Figure 2 shows the hybrid in its 84-pin leadless chip carrier package. Its 18.5 µm pixel pitch accommodates both SWIR to MWIR optics and fabrication of the large readout ($\approx$20 x 20 mm^2) using world-class submicron photolithography. Defect-free multiplexer yield >12% was achieved in the first lot made by Rockwell's commercial production line in 0.8 µm CMOS; the yield exceeded our conservative estimate for the low defect density process. Growing the HgCdTe detectors on sapphire substrates is unique to Rockwell; the sapphire-based (PACE-I) photovoltaic detector arrays are fabricated on 3″ wafers and have mean detector R_oA product $>10^6$ Ω-cm^2 at 150K with dark current much less than 0.1 e-/sec at 78K.

Figure 2. Photograph of SWIR 1024x1024 HAWAII FPA

Though specifically developed for infrared astronomy, the FPA's features and performance make it useful for surveillance applications. Table 1 lists its key attributes including 8.5 e- read noise, FPA dark current <0.1 e-/sec, pixel yield >99% and >50% quantum efficiency. The specifications translate to BLIP-limited sensitivity at low-10^9 photons/cm^2-sec background to operating temperatures approaching 120K.

Table 1. HAWAII FPA Characteristics

Parameter	Value	Units
Array Format	1024^2	
Pixel Pitch	18.5	µm
Pixel Yield	>99	%
Detector Type	HgCdTe/Al_2O_3	
Quantum Efficiency	>50	%
Cutoff Wavelength	2.5	µm
Detector Dark Current	<0.01	e-/sec @ 78K
Detector R_oA	10^5	Ω-cm^2 @ 150K
Optical Fill Factor	>95	%
FPA Dark Current	<0.1	e-/sec @ 78K
Mean D* at T<120K	$\geq 10^{14}$	cm-$Hz^{1/2}$/W
Maximum Frame Rate	3.8	Hz
Minimum Read Noise	$\leq$8.6	carriers
Charge-Handling Capacity	$\geq 10^4$	carriers
Maximum Usable Dynamic Range	0.91	10^4
Responsivity Nonuniformity	<10	%
Output Channels	4	
Power Dissipation	<3	mW
Maximum Data Rate per Output	1	MHz

2.0 INFRARED DETECTOR ARRAY

Large area, high performance FPA development is a multidisciplinary challenge encompassing detector physics, IR substrate growth, detector material growth and array fabrication, readout integrated circuit design, silicon multiplexer wafer fabrication, and hybrid assembly. Highest detector performance is normally accomplished by processing bulk material or growing the photosensitive layer on a lattice-matched substrate to minimize the potential for intrusion of yield- and performance-limiting defects into the photosensitive layer. This is normally accomplished in the HgCdTe material system via epitaxial growth on Cd(Zn)Te substrates using liquid phase (LPE) or molecular beam epitaxy (MBE).[1] Large substrates are, however, not readily available and expensive; substrate availability is a key issue shared by many high performance detector materials including InSb. Since the problem is pervasive, fortunate ultimate detector performance is not necessary for SWIR astronomy ($\lambda_c \leq 2.5$ µm) since cryogenics for cooling to ~80K are readily available at most observatories. SWIR FPA operation at 80K is compatible with extremely long exposure times due to very low dark current.

Another key issue is the mismatch in coefficient of thermal expansion between the detector substrate and the readout integrated circuit; mitigation often requires that the active detector material be grown on alternative substrates. Such substrates can have properties better matched to silicon, which is by far the best material for the readout multiplexer. Alternative substrates also provide dramatically larger processing area, enable batch processing for increased throughput, and can reduce fabrication cost. Most significantly, the ability to place several die on each wafer greatly reduces the impact of random variables affecting each lot's success.

Rockwell has successfully developed large MWIR and SWIR HgCdTe FPAs by fabricating photovoltaic detector arrays grown epitaxially on sapphire (Al_2O_3) substrates. Figure 3 compares the chronology of HgCdTe/Al_2O_3 FPA development to that of the rest of the IR industry including HgCdTe/Cd(Zn)Te, InSb and PtSi. InSb is often believed to be the most mature second generation FPA material since it is a III-V compound semiconductor. The sapphire-based HgCdTe technology has nevertheless yielded the first 256x256, 640x480 and 1024x1024 FPAs. The HgCdTe/Al_2O_3 detectors are referred to as PACE-I detectors; PACE is an acronym describing the fact that the devices present a *P*roducible *A*lternative to *C*dTe for *E*pitaxy. InSb FPAs use bulk material which does not directly benefit from the burgeoning commercial photonics market using III-V materials.

Figure 3. Chronology of mosaic IR FPA development (SC.3699CS.071594)

The PACE wafers are prepared by first growing CdTe on the sapphire substrate by metal organic chemical vapor deposition (MOCVD). The photosensitive HgCdTe is then grown via liquid phase epitaxy (LPE) from a Te–rich melt on to the buffered substrates to produce 2″ or 3″ HgCdTe wafers. Epitaxial layer thickness, as measured by the

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[1] J.M. Arias, J.G. Pasko, M. Zandian, L.J. Kozlowski, R.E.DeWames, "Molecular beam epitaxy HgCdTe infrared photovoltaic detectors," Optical Engineering 33 (5), May 1994, 1422-1428.

nondestructive beta–backscatter technique, typically varies <±2 µm across a 3″ wafer. Both thickness and uniformity are controlled by optimizing melt temperature control to make arrays having high and uniform photoresponse. Figure 4 shows a 3″ wafer populated with five 1024x1024 and four 256x256 NICMOS3 detector arrays. Each wafer hence provides both five chances for 1024x1024 success and also enables material characterization using the fully characterized NICMOS3 vehicle. This capability for making large, high performance detector arrays is unique to Rockwell.

Figure 4. Processed 3″ HgCdTe/Al_2O_3 (PACE-I) wafer.

The photovoltaic detectors are formed by boron ion implantation at room temperature followed by annealing. The detector architecture is *n*–on–*p*. The typical goal is to demonstrate pixels with >90% fill factor and <2% crosstalk. The junctions are passivated by ZnS or CdTe. CdTe passivation has been demonstrated to be more radiation hard. After metal pad deposition for contact to the junction and ground, indium columns are evaporated to provide interconnects for subsequent hybrid mating. Recent development has focused on the 18.5 µm pitch of the 1024x1024 detector arrays.

Detector illumination is through the sapphire, which is transparent for visible and infrared radiation to beyond 5.5 µm. Transmission can be extended to 6–7 µm by thinning the sapphire to <7 µm. Sapphire is commercially available in large wafers, its intermediate value (1.73) of refractive index acts to reduce reflection to a few percent over the broad spectral range of the detectors.

3.0 CMOS READOUT

The HAWAII FPA is structured in four independent quadrants having four outputs. Six CMOS-level clocks, two 5 V power supplies (one analog and one digital), and two fixed dc biases are required for basic operation. The multiplexer architecture has been optimized to minimize glow; lowest glow can be achieved by lowering the voltages below 5 V. The simple architecture also maximizes the fabrication yield.

The multiplexer is an array of cascaded source follower stages separated by MOSFET switches. Each pixel's signal voltage is first read through the first stage source follower consisting of a pixel-based driver MOSFET and a current source FET shared among the elements in a column. The column bus output then drives the output source follower or can be read directly to eliminate output amplifier glow in trade for reduced pixel data rate. The various MOSFET switches are appropriately enabled and disabled to perform the functions of sequential pixel access and row-based pixel reset. A maximum of six externally-supplied clocks is required. The CMOS-level clocks do not require precise adjustment for optimum performance.

Direct Detector Integration. Direct detector integration (Figure 5), also known as source follower per detector (SFD), is used for interfacing the detector in the HAWAII readout. This simple scheme works very well at low backgrounds and long frame times. The frame rate used for testing HAWAII FPAs is typically about 1 Hz.

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