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Performance evaluation and calibration issues of large format infrared hybrid active pixel sensors used for ground- and space-based astronomy

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Abstract

Instruments for large 10-m class telescopes increasingly require high sensitivity large format focal planes. The high spatial resolution achieved with adaptive optics combined with multiple integral field units feeding high resolution spectrographs are driving the pixel performance and require large detector formats. In the infrared spectral range, the array formats have arrived at 2K × 2K pixels with both LPE and MBE grown HgCdTe on CdZnTe substrates. In the optical, fully depleted Si-PIN diodes of the same format are used. The light-sensitive diode arrays are hybridized to CMOS FET switched multiplexers such as the Hawaii-2RG array, which has recently been installed in one of the infrared instruments of the Very Large Telescope (VLT). Basic performance characteristics of the Hawaii-2RG arrays will be discussed such as the noise performance when a special technique of using reference pixels is employed. Larger focal planes are realized as mosaics of 2K × 2K arrays. In order to increase the format of single arrays to 4K × 4K and larger, the limited substrate sizes make it necessary to reduce the pixel size. However, with smaller pixels the coupling between pixels becomes a limiting factor for the detector point spread function. Fundamental calibration issues relevant to photon transfer techniques of modern CMOS active pixel sensors with special regard to the influence of interpixel coupling capacitances will be analyzed in detail. A novel technique will be presented to directly measure the point spread function generated by the capacitive coupling between adjacent pixels.

Keywords: Conversion gain; Interpixel capacitance; Hawaii-2RG; HgCdTe; Point spread function; Quantum efficiency; Readout noise

1. Introduction

An infrared hybrid active pixel sensor is composed of two components, a diode array fabricated with narrow-band gap semiconductor material sensitive at infrared wavelengths and a silicon CMOS readout multiplexer with a buffer source follower, a reset switch and addressing switches placed in the unit cell of each pixel. The two components, the infrared diode array and the Si CMOS multiplexer are hybridized with In bumps making the electrical interconnections for each pixel between the infrared diode and the unit cell of the Si multiplexer [1].

Currently, three semiconductor materials achieve the highest performance for detectors used in infrared astronomy. For most scientific applications the wavelength range below 1 μm is still dominated by silicon CCD's, yet the performance of silicon PIN diode arrays hybridized to Si readout multiplexers is rapidly improving and has some advantages with respect to versatility, quantum efficiency (QE) at the cutoff wavelength and readout speed. In the near-infrared spectral range from 1 to 5 μm, two semiconductor materials are competing, namely InSb and HgCdTe grown by liquid phase epitaxy (LPE) or molecular beam epitaxy (MBE) on Al_2O_3, Si or CdZnTe substrates. Extrinsic blocked impurity band Si:As arrays cover the mid-infrared spectral range from 8 to 28 μm [1]. This paper will focus on HgCdTe arrays grown on CdZnTe substrates.

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The European Southern Observatory (ESO) has established a long-lasting collaboration with the two main manufacturers of scientific infrared sensors, namely Rockwell Scientific and Raytheon Vision Systems. ESO is well-equipped for assessing all aspects of the sensor performance relevant to ground and space-based astronomy. The results of the detector evaluation is taken into account by the manufacturers to improve and optimize the arrays for astronomical applications.

In order to achieve the highest sensitivity with infrared instruments, the detector dark current must be negligible in comparison to the photon generated current ($<10\,e/h$). The readout noise should be small in comparison to the photon shot noise ($<3\,e\,rms$). The interpixel crosstalk and the effect of latent image effect should be as small as possible, whereas the QE should be close to 100%. Recent inconsistencies [2] encountered with modern CMOS arrays having pixels as small as 18 microns triggered a more thorough investigation of the applicability of standard calibration methods which will be described in Section 4 below.

2. Limitations of array format

The high spatial resolution provided by adaptive optics on large telescopes having diameters in the range of 10–100 m requires extremely large focal planes of up to more than 10^9 pixels in order to Nyquist sample [3] diffraction limited images. At present, the focal plane technology has arrived at formats of $2K \times 2K$.

Two major problems are to be solved when the format of hybrid active pixel sensors is increased. Firstly, the mating force that has to be applied to the hybrid components to produce a robust indium interconnect bond scales with the detector format. Secondly, when hybrids employing intrinsic narrow-bandgap materials are cooled to cryogenic temperatures, they have to withstand the thermal mismatch between the infrared active material, the detector substrate and the Si readout multiplexer, all of which have different coefficients of thermal expansion (CTE).

The size of available detector substrates will eventually impose a limit on the format of detectors. Presently, CdZnTe substrates with 60 mm diameter limit the format of HgCdTe arrays to $2K \times 2K$. Alternative substrates for HgCdTe such as Si and Al_2O_3 constitute a viable approach to larger formats, but limit the pixel performance because of higher dislocation densities due to the imperfect lattice match of the detector material and the substrate.

Hence, the detector manufacturers tend to shrink the pixel size from 20 to 10 μm to accommodate larger array formats on the limited space of the biggest detector substrates. The advances in In bump technology permit pixel sizes of 10 μm. However, if the pixel size is shrinking, other effects limiting the detector performance such as the interpixel capacitance are becoming more important. The effect will be discussed in detail in Section 4.

An alternative to increasing the number of pixels in focal planes is the installation of closely packed mosaics. An example for an array mosaic currently under development is the VISTA focal plane, which is being built for the Infra-Red Survey Telescope VISTA by the UKATC and RAL for ESO [4,5].

VISTA is a wide-field survey telescope which has a diameter of 4 m. It will initially be dedicated to IR imaging surveys. The focal plane is located in the Cassegrain focus and is populated with 16 $2K \times 2K$ science detectors packed at 90% spacing in one direction and 42.5% in the other. The VIRGO detector produced by Raytheon has been selected for VISTA. It is a LPE HgCdTe array grown on a CdZnTe substrate. The CdZnTe substrate provides an excellent lattice match for the IR active HgCdTe layer resulting in low defect densities and stacking faults. The pixel size is 20 μm. Each detector has 16 parallel outputs organized in parallel stripes, which can be read at a pixel rate of 400 KHz. The total channel count adds up to 256 channels. The scaleable ESO controller IRACE is used to read out the complete VISTA focal plane at a frame rate of up to 1.6 Hz. All 16 science grade arrays have been delivered and tested at UKATC. The QE of the best arrays is 85% at 1.2 μm and above 95% between 1.75 and 2.5 μm. The detector dark current is 0.03 e/s/pixel at an operating temperature of 77 K. Fig. 1 shows the VISTA focal plane at Rutherford Appleton Laboratory which is partially populated with four bare Si multiplexers having no IR active layers and two hybridized engineering grade $2K \times 2K$ HgCdTe VIRGO arrays [6]. The aluminum plate shown in Fig. 1 has since been replaced by the real molybdenum plate.

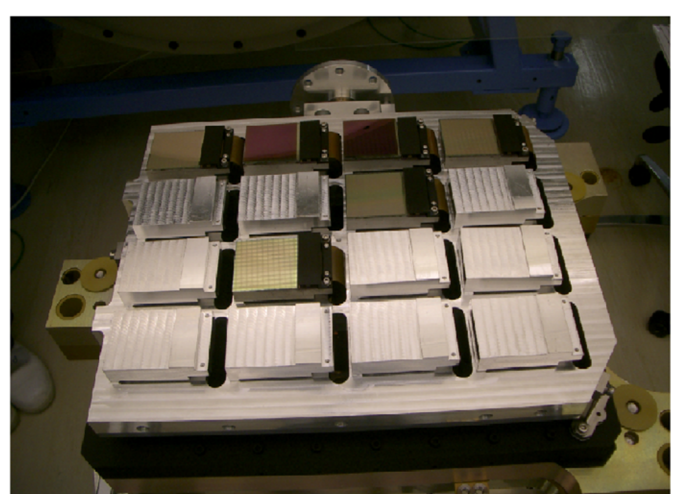

Fig. 1. VISTA mosaic of 16 $2K \times 2K$ arrays populated with four bare Si multiplexers having no IR active layers and two hybridized engineering grade $2K \times 2K$ HgCdTe VIRGO arrays.