PERFORMANCE AND EVALUATION OF LARGE FORMAT 2KX2K MBE GROWN MCT HAWAII-2RG ARRAYS OPERATING IN 32-CHANNEL MODE

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Abstract:

Large format 2Kx2K HgCdTe Hawaii-2RG arrays grown on CdZnTe substrates when used in state-of-the-art infrared instruments are powerful detectors, especially as high spatial and spectral resolution require low dark current and readout noise and high QE. We have evaluated several λ_c=2.5 µm Hawaii-2RG arrays and developed a special 32 channel package which allows reading out all 32 output channels of the detector in parallel using cryogenic CMOS preamplifiers. Dark currents of <0.01 e/s/pixel at operating temperatures of 80K have been measured. With multiple sampling techniques using the reference pixels the readout noise can be reduced to 2.3 electrons rms. The persistence of the MBE/CdZnTe arrays still exhibits a threshold effect. The simultaneous readout of a guide window does not disturb the full science frame.

Key words: Hawaii-2RG, persistence, reference pixel, guide mode, ASIC, cryogenic preamplifier

1.   INTRODUCTION

Instruments for 100 m class telescopes such as OWL require not only high sensitivity but also extremely large formats of several Gigapixels [1].

Adaptive optics combined with multiple integral field units feeding high resolution spectrographs drive the pixel performance and require the large detector formats offered by the Hawaii-2RG array. The first Hawaii-2RG is already generating scientific results in one of the VLT instruments, the integral field spectrograph SINFONI [2]. Three more instruments, the wide field imager Hawk-I which will house a 2x2 mosaic, the multi-integral field spectrograph KMOS, and the infrared arm of the X-Shooter spectrometer, which observes simultaneously all wavelengths from UV to K-band, will all be equipped with λ_c=2.5 µm HgCdTe Hawaii-2RG arrays.

The Hawaii-2RG array combines the most advanced silicon multiplexer with a new growth technology for infrared diode arrays. Instead of using liquid phase epitaxy (PACE material) the Hawaii-2RG arrays are grown by molecular beam epitaxy on CdZnTe substrates. The infrared arrays are double layer planar heterostructures with a narrow bandgap capping layer. In comparison to PACE material the new growth technology has lower defect densities. As a consequence, the detector dark current is reduced substantially. The arrays have high quantum efficiency over their entire sensitive spectral range. The MBE growth process on a lattice matched CdZnTe substrate was also expected to reduce the persistence effect. Unfortunately, this expectation is not fully met for λ_c=2.5 µm arrays.

2.   SETUP

A 34-channel detector package was developed for the Hawaii-2RG multiplexer interfacing all 32 video channels plus one extra channel for the guide mode and one for the reference pixel [3]. Symmetric cryogenic CMOS operational amplifiers are placed next to the focal plane instead of using ASIC's which are not yet available. The internal bus of the detector is accessed directly, bypassing the on-chip buffer amplifier. The detector set-up for a single detector is shown in figure 1.

For the Hawk-I focal plane which will be equipped with a 2x2 mosaic of Hawaii-2RG arrays a modified GL-scientific mosaic module originally developed for JWST will be used [4]. The area required for the miniaturized pcb detector board with the 34-channel preamplifier is 31 mm x 86 mm which is larger than the area provided for the SIDECAR ASIC in the JWST module. However, since the width of the detector board is smaller than the size of the detector, it can be used for the mosaic if the four preamplifier modules are attached to the GL-Scientific mosaic module in separate light tight housings.
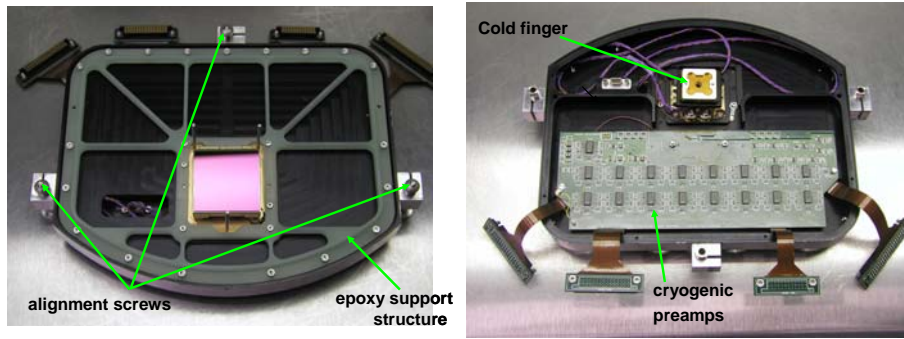
Figure 1. Hawaii-2RG detector mount for single detector with cold finger, focus and tip tilt alignment screws and cryogenic preamplifiers for 32 video channels plus one reference channel and one channel for guiding window.

The power dissipation of the preamplifiers consisting of 68 CMOS operational amplifiers (2/channel) is ~ 1 W. In comparison, the power dissipation of the detector using the unbuffered outputs is negligible (~ 10 mW, 300µW/channel). Thus, in the vicinity of the detector the main heat source are the preamplifiers. They put a heat load of 230 mW on the detector, which is only 23 % of the total power dissipated by the preamplifiers. The main portion of the preamplifier power dissipation is heat-sinked to the instrument and the first stage of the closed cycle cooler by a thermal clamp of the detector cables located close to the preamplifier board. The measured temperature of a sensor glued onto one of the operational amplifiers was 150 K. At this temperature the photon flux seen by a λ_c=2.6 µm cut-off detector is 0.1 photons/s/pixel assuming a solid angle of 2π steradian. Moderate baffling corresponding to f/10 reduces the flux generated by thermal emission of the CMOS opamps to negligible levels of $2 \cdot 10^{-4}$ e/s/pixel.

3.   DARK CURRENT

The darkcurrent of the λ_c=2.5 µm Hawaii-2RG MBE/CdZnTe array was measured in a test facility equipped with a two stage pulse tube for cooling the detector. The dark current measurements were carried out with the detector being completely enclosed in a black anodized aluminum box. As can be seen in figure 2, the dark current is < 0.01 e/sec at temperatures below 80 K (filled triangles). For comparison the darkcurrent measured with a λ_c=2.5 µm Hawaii2 LPE/Al_2O_3 science grade array (filled squares in figure

2), a Hawaii1 LPE/Al_2O_3 science grade array (empty squares in figure 2), and a λ_c=1.7 μm PICNIC MBE/CdZnTe array (triangles) are also shown. Note the darkcurrent of the PICNIC array was scaled to the pixel size of 18 μm. At an operating temperature of 100K, the darkcurrent of MBE/CdZnTe arrays with λ_c=2.5 μm is a factor of 1660 times lower than that of LPE/Al_2O_3 arrays. This improvement is of particular importance for instruments which do not have closed cycle coolers but have to manage with liquid nitrogen bath cryostats. Even for low flux spectroscopic applications science grade arrays of good cosmetic quality can be operated at a temperature of 80 K.
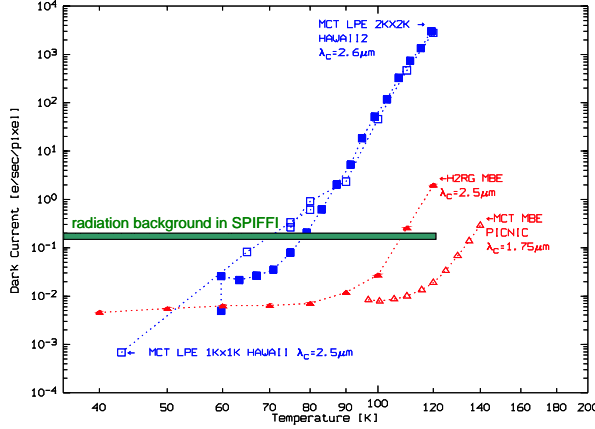

Figure 2. Dark of HgCdTe arrays current versus temperature. Squares: LPE material. (empty squares is Hawaii1 1Xx1K and filled squares is Hawaii2 2Kx2K). Triangles: MBE on CdZnTe substrate. (filled triangles is λ_c=2.5 µm Hawaii-2RG array and empty triangles is λ_c=1.7 μm PICNIC array).

4.   QUANTUM EFFICIENCY

The QE of MBE material does not depend on temperature whereas the QE of LPE material drops when cooled from 80K to 40K [3]. Hence, the cosmetic quality of MBE engineering grade arrays, which improves rapidly at lower temperatures, can be enhanced by reducing the operating temperature without loss of quantum efficiency. Figure 3 shows the QE as function of wavelength measured with broad band filters and with a monochromator. The wavelength dependence of the monochromator efficiency was calibrated with a pyroelectric detector. The conversion gain was determined with the capacitance comparison method, since the standard

shot noise method yielded quantum efficiencies larger than 100 % [5]. For the science grade detector the quantum efficiency is 84% in K, 78% in H, 71% in J and 66% in Z. The Hawaii-2RG arrays outperform CCD's in Z band.
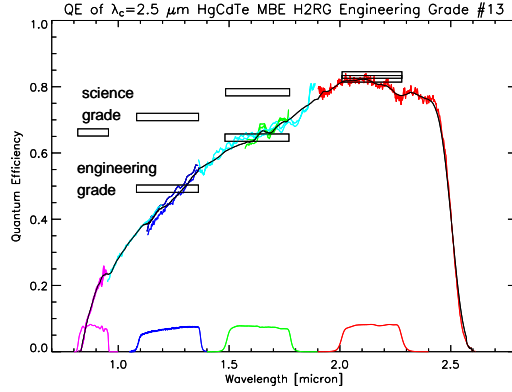

Figure 3. Quantum efficiency of λc=2.5 μm Hawaii-2RG engineering grade and science grade arrays. Transmission of band-pass filters is indicated at the bottom.

5.   READOUT NOISE

The readout noise with simple double correlated sampling is 17 electrons rms for infrared active pixels. The infrared active pixels of the Hawaii-2RG array are surrounded by 4 rows and columns of reference pixels at the edges of the array. The signals of these pixels are embedded in the regular video signal of 2048 x 2048 pixels. The reference pixels can be used to track low frequency noise pick-up [6]. Unlike standard infrared-active pixels, the reference pixels are not connected to detector photodiodes. Instead, they contain a simple capacitor C_{pix} whose capacitance is similar to the detector capacitance. The readout noise measured on these reference pixels at the edges of the array is only 8 electrons rms. This proves that the contribution of the readout multiplexer and the rest of the data acquisition chain including the preamplifiers and the IRACE electronics to the overall readout noise is small. The readout noise is dominated by the noise of the infrared pixel.

Although the cryo-opamps on the ESO detector board have all provisions necessary for testing the separate reference output, so far only embedded reference pixels have been tested. Since all 32 channels are used and the

array is organized in stripes of 2048 rows, the rows of a single stripe contain only 64 pixels. If the array is read out at a frame rate of 1.2 Hz the reference pixels are read every 400 μs, which is the time needed to read a single row. The squared transfer function of a double correlated clamp is $2\text{-}2\cos(2\pi f t_s)$. For a pickup frequency of 50Hz and a sampling interval t_s of 400 μs between reading the pixel and reading the reference, in the worst case the transfer function will be 0.125, which is the suppression factor for 50Hz pickup [6]. Four embedded reference pixels read at the beginning and four reference pixels read at the end of each row are averaged and routinely subtracted from the video signal for all readout modes. Depending on low frequency pickup this improves the readout noise by up to a factor of two.
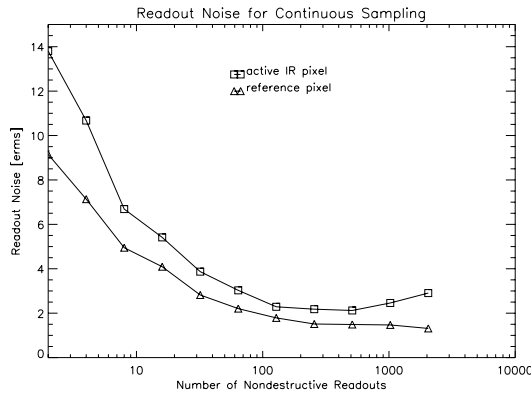

Figure 4. Readout noise versus number of nondestructive readouts. Squares are the active infrared pixels. Triangles are the reference pixels. Readout time for single readout is 825 ms. Lowest readout noise on active IR pixel is 2.3 e rms with 256 Fowler pairs. Lowest readout noise on reference pixels is 1.3 e rms.

Multiple sampling techniques substantially reduce the readout noise as can be seen in figure 4 which shows the readout noise versus the number of nondestructive readouts. Active infrared pixels are represented by squares; the reference pixels by triangles. The readout time for a single non-destructive readout is 825 ms. The detector is continuously read out in the nondestructive mode. The detector integration time for 1024 Fowler pairs is 845 seconds. The lowest readout noise on the active IR pixels is 2.3 e rms with 256 Fowler pairs, the lowest readout noise on reference pixels is 1.3 e rms.

This outstanding noise performance impressively demonstrates two accomplishments of the Hawaii-2RG multiplexer design. First, the shielding of the multiplexer glow, which because of glow-induced photon shot noise had limited the number of Fowler pairs to < 32 with previous multiplexers,

has been implemented very efficiently in the Hawaii-2RG device. Second, the implementation of 32 parallel video channels not only reduces the readout time, but also improves the noise performance, since more non-destructive readouts can be made within a given integration time. This results in a further reduction of the readout noise.

The shielding of the multiplexer glow is not perfect. For larger numbers of nondestructive readouts a few localized glow centers appear at random locations across the array. The glow centers have a ring-like structure. The intensity of the glow centers linearly depends on the number of nondestructive readouts. Good science grade arrays are devoid of these glow centers. The absence of glow centers is an important selection criterion for science grade arrays.

6.   PERSISTENCE

Latent charge, or "persistence," is the remaining signal apparent in a series of dark exposures, after the array has been exposed to a bright radiation source. Any process which, after some delay, releases charge into the conduction band can contribute to latent charge. Latent charge is a function of fluence during a previous exposure and the time elapsed since the previous exposure as shown in figure 5.
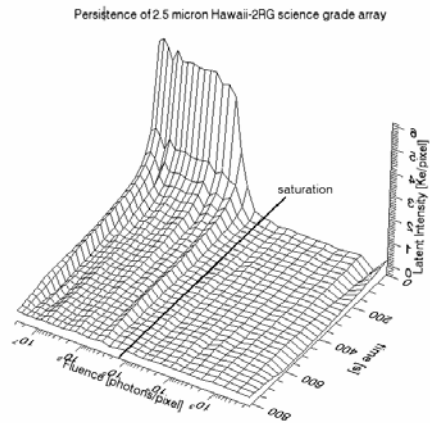

Figure 5. Decay of persistent image intensity as function of time and fluence. Note the threshold effect at saturation level of $1.2 \ 10^5$ electrons.

For fluence levels below the saturation ($\sim 10^5$ e/pixel) persistence is negligible. As soon as the fluence exceeds the saturation level, persistence can be observed. This threshold effect may indicate that traps in the surface passivation layer are filled when the p-n junction moves from reverse bias toward forward bias. If the Hawaii-2RG array is used in a high resolution spectrometer, latent images can be observed in subsequent dark exposures for several hours. It was expected that MBE material would not exhibit any persistence. This cannot be confirmed for the λ_c=2.5 µm MBE arrays grown on CdZnTe substrates, which have been evaluated so far.

7. GUIDE MODE

It is planned to upgrade the VLT telescope on which the Hawk-I imager will be mounted, with an AO secondary mirror and laser guide stars. Since a laser guide star AO system still requires a natural guide star for correcting image motion induced by atmospheric turbulence, a tip-tilt sensor operating on a natural guide star has to be included. This tip-tilt sensor can be implemented by using a separate detector system. An alternative solution is offered by the guide mode of the Hawaii-2RG science arrays in the HAWK-I mosaic focal plane.

The guide mode operation of the Hawaii-2RG detector allows simultaneous operation of the full field and the sub-window readout with independently controllable reset and readout timing. It generates an interleaved pixel pattern at the analog outputs which, depending on the chosen timing, contains a certain order of full field and window pixel data. The video output of the guide window is connected to a separate output stage on the multiplexer and needs a separate video channel of the data acquisition system.

The readout noise for simple double correlated sampling of the guide window is 17 erms. This noise can also be reduced by multiple sampling. However, since the readout time has to be shared between the full frame and the guide window, multiple sampling of the guide window will increase the readout time for the full frame.

If the guide window is read out nondestructively without resetting, only one frame has to be read to generate the double correlated image, since the previous frame can always be subtracted from the currently read frame. In effect, this increases the system bandwidth by a factor of 2. Furthermore, using the nondestructive readout for the guide window, the area of the guide window is not lost in the full science frame as can be seen in figure 6. Of course the guide window has to be reset before pixels saturate. Also on long

dark exposures with the low readout noise no degradation of the science frame by the guide window could be observed [7].

The modularity of the IRACE data acquisition system is well suited to include the guide window operation in the readout of the Hawaii-2RG array. A second gigabit optical fiber link is required in the detector front end electronics to send the digitized guide window data to the real time tip-tilt processor.
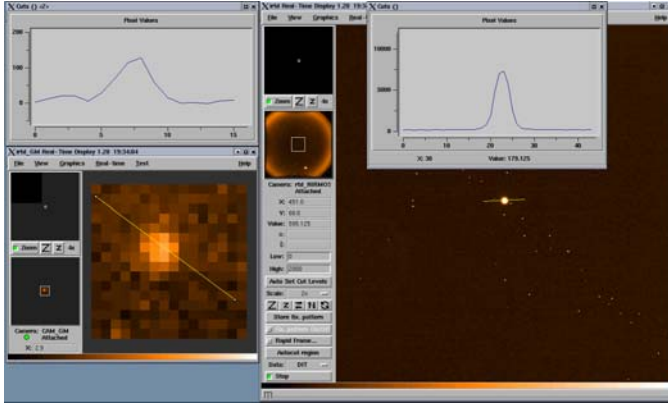

Figure 6. Screen shot of real time display showing simultaneous data acquisition of Hawaii-2RG guide window and full science frame. Left: top profile, bottom image of guide window. Right: top: profile, bottom: image of full science frame. Nondestructive readout of window preserves window in full science frame and increases bandwidth by a factor of 2.

8. CONCLUSIONS

Cryogenic CMOS preamplifiers at the focal plane do not limit the performance of the detector even if used in bath cryostats. MBE HgCdTe arrays grown on CdZnTe substrates have high QE (84% in K) and extremely low dark current (< 0.01 e/s/pixel at T=80K) but still have latent images if exposed beyond the saturation level. The readout noise of the Hawaii-2RG MBE arrays is higher (17 e rms) than the noise measured with LPE arrays (10 e rms). However, the shielding of the multiplexer glow is very efficient and allows using 256 Fowler pairs. This reduces the readout noise to 2.3

erms. Simultaneous operation of the guide window does not degrade the full science frame.

9.   REFERENCES

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