Infrared Detectors for WFC3 on the Hubble Space Telescope

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ABSTRACT

Rockwell Scientific Company is developing a new type of HgCdTe 1K×1K detector, called WFC3-1R, with cutoff wavelength at 1.7\,\mu m and 150K operating temperature. The detector will be installed on the Wide Field Camera 3, the fourth generation panchromatic instrument for the Hubble Space Telescope (HST) to be installed during HST Servicing Mission 4, currently scheduled for 2004. The detector uses HgCdTe MBE grown on a CdZnTe substrate and a new type of multiplexer, the Hawaii-1R MUX. Six lots of detectors have been produced so far, and have demonstrated the capability to meet or exceed the project requirements. In particular, detectors show quantum efficiency as high as \sim 90\% at $\lambda = 1.4$-1.6\,\mu m and greater than 50\% at $\lambda > 1.0$\,\mu m, readout noise of 30 \,e-\textsuperscript{rms} with double correlated sampling, and dark current <0.2 \,e/s/pix at 150K. We illustrate the behavior of the reference pixels, showing that they allow the compensation of drifts in the dc output level. A number of detectors show a peculiar instability related to the variations of diode polarization, still under investigation. We also report on the environmental testing needed to qualify the WFC3-1R detectors as suitable for flight on the HST. We finally provide an update of the project status.

1. INTRODUCTION

The relatively high temperature of the Hubble Space Telescope optical assembly (~300K, Robberto et al. 2000) creates an absolute minimum of background emission at about 1.7\,\mu m. An IR instrument optimized for this window, like the Wide Field Camera 3 (WFC3, Cheng et al. 2002; MacKenty et al 2002), can reach background-limited sensitivity without requiring the low temperatures provided by cryogenic fluids like LN\textsubscript{2}. The thermal design of WFC3 is based on thermoelectric coolers. They provide long lifetime and, on the IR channel, a focal plane temperature of approximately 150K. Conventional near-IR detectors with cut-off wavelength at 2.5\,\mu m, like the Rockwell Hawaii-1 and Hawaii-2 arrays, cannot be operated at this temperature due to the exceedingly high dark current. This motivated the new type of near-IR detectors presented in this paper.

In July 2000, Rockwell Scientific Company, LLC (RSC) was contracted to fabricate the WFC3-1R FPA, a 1024x1024 hybrid HgCdTe device MBE grown on a CdZnTe substrate, with alloy composition selected to provide a long-wavelength cutoff at \sim 1.7\,\mu m. The detector array is indium bumped to the new Hawaii-1R multiplexer (MUX), a device largely based on the Hawaii-2 design and on the recent advances for the NGST project. Excellent performances is required of the WFC3-1R detector, e.g. dark current <0.2e/s at 150K, quantum efficiency >45\% over the broad range 1.0-1.63\,\mu m, and readout noise <30 \,e-\textsuperscript{rms} with correlated double sampling.

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In the last two years RSC has produced six lots of detectors that have demonstrated the capability to meet these requirements. In this paper we give a general description of these devices (Section 2) and discuss their performance (Section 3), as measured on engineering and science grade parts tested at the Detector Characterization Laboratory (DCL) of the NASA Goddard Space Flight Center (Greenbelt, MD). In Section 4 we summarize the results of the environmental tests. In Section 5 we describe the next steps of the development program and list the main conclusions.

2. DETECTOR ARCHITECTURE

2.1 Hawaii-1R multiplexer
The Hawaii-1R MUX is a CMOS array structured with four independent quadrants, each quadrant supporting 1 or 8 output channels. WFC3 uses 1 output channel per quadrant. The optically active area is 1014x1014 pixels; the outer 5 rows and columns of the MUX contain reference pixels, providing a constant voltage. There are therefore 507x507 photoactive pixels per quadrant. The four quadrants are mirror images of each other; otherwise they are electrically identical. On each quadrant, the readout starts from the outermost corner with the fast axis (X axis) reading in toward the central columns of the MUX. The slow clock (Y axis) is read toward the central rows (Figure 1). Therefore, at the beginning of the readout, the 5 horizontal lines of reference pixels are sequentially read, whereas the last pixel to be read is the innermost pixel of the quadrant, one of the 4 central pixels of the MUX. The Hawaii-1R MUX fully exploits an advanced 0.5 $\mu$m photolithographic technique allowing 18 $\mu$m pixel size (like the Hawaii-2 and unlike the Hawaii-1 having 18.5 $\mu$m pitch). Reference pixels are a new feature; they may be used to reduce the effects of thermal or electrical drifts in the detector, in the off-chip electronics, or both. They are discussed in Section 2.3.

Figure 1: Readout addressing scheme of the Hawaii-1R MUX. Top-left is a schematic of the four quadrants, with the long and short arrows respectively indicating the fast and slow clock directions, from the corners to the center. The corner of Quadrant 3 is shown enlarged to the right. The outermost rows and columns contain the outboard reference pixels, with a 4x periodicity in the value of their capacitances. The four adjacent rows and columns contain the onboard reference pixels (See Section 2.3).
Like its Hawaii-1 and Hawaii-2 predecessors, the Hawaii-1R unit cell (Figure 2a) contains 3 FETs, one controlling the reset pulse and the others on the output line. The readout circuit is based on a cascade of source followers. The first stage is on each individual pixel, the second stage is at each output of the array. This final amplification stage can be bypassed; WFC3 uses external amplifiers to avoid amplifier glow entirely. A network of MOSFET switches performs the basic address, reset and read operations. The 3 FET design implies that reset is applied to the entire row. The multiplexer is designed to operate up to a nominal data rate of 200KHz; in the case of WFC3, the nominal readout rate is 91 KHz, corresponding to a minimum readout time of approximately 2.5 seconds.

One of the major concerns during the design phase has been the mitigation of the amplifier glow, present on previous RSC detector including NICMOS and more recent Hawaii-2 devices. The glow, produced mostly by the on-chip output amplifiers, has been often seen in dark current frames both at the edges of the detector or even inside the detector, since the detector substrate can act as a wave-guide. RSC employed various techniques for glow suppression to the Hawaii-1R multiplexer design. These techniques were very successful in reducing the multiplexer glow to a minimum.

2.2 Hawaii-1R detector layer
Each pixel is a PN junction of the type P-over-N, where an As-doped HgCdTe material (P type) is implanted over an Indoped (N type) HgCdTe common layer during the detector processing phase. To obtain reverse bias conditions, the voltage across the junction must be negative, i.e. the reset voltage must be lower than the substrate voltage. Typically, WFC3 operates the detector at $V_{bias} = V_{RST} - V_{SUB} = -250mV$, setting $V_{RST} = 500mV$ and $V_{SUB} = 750mV$. The junction is biased at the beginning of the exposure by closing the reset switch. This creates a depletion region of $\sim 100,000$ electrons in the N type material. Photon flux discharges the equivalent capacitance of the junction, producing a voltage change monitored by the source follower chain. The change of capacitance also alters the characteristics of the P-N junction, causing the intrinsic non-linearity of this type of devices, a well understood feature that can be calibrated out. Total node capacitance for WFC3-1R arrays has been measured (on FPA#43) approximately 43 fF, implying a detector capacitance of $\sim 23 fF$. The typical detector gain is $\sim 2.9 \mu V/e^-$. 

![Figure 2: Schematic layout of the unit cells for the active pixels (left) and the reference pixels (right). The on-board and off-board reference pixels differ for the location of the capacitance.](image)

2.3 Reference pixels
Reference pixels have been implemented on the WFC3-1R detector in order to mitigate the effects of thermal drift and low frequency noise encountered with previous generations of space flown detectors, NICMOS in particular. The detector interface circuit (figure 2b) is in general the same for the photactive pixels and for the reference pixels. Reference pixels are built by inserting a capacitor between the input transistor gate and the substrate bias DSUB, to approximately mimic the detector capacitance. The HgCdTe diodes are deactivated in the corresponding reference pixels, so there is no photo-generated current. The indium bumps are still present to preserve the optimal mechanical coupling between the two parts of the hybrid device. The WFC3-1R detector has two types of reference pixels:
- Inboard reference pixels;
- Outboard reference pixels.

The inboard reference pixels are located on the four innermost rows and columns (Figure 1). They are “inboard” in the sense that their reference capacitors are contained within each unit cell. The DSUB bias is routed to the capacitance through the detector layer and the indium bumps. The outboard reference pixels are located on the outermost rows and columns. The capacitors in this case are located outside the unit cell, at the edge of the MUX. The DSUB bias is taken in
this case directly from the MUX routing metal lines. The inboard reference pixels have the same capacitance of \( \sim 40\text{fF} \). The outboard reference pixels have 4 different values distributed sequentially increasing along the row and column directions. The capacitance values are 8fF, 16fF, 32fF, and 64fF to span the signal range. Our tests show that the onboard vertical reference pixels provide the most reliable reference signal. Also, best performance have been obtained by inserting during the readout a \( \sim 3\) ms delay at the beginning of each row. This delay, multiplied by 512 rows, increases by about 1.5 s the minimum readout (and therefore integration) time for the whole array.

### 3. DETECTOR PERFORMANCE

On the basis of the experience gained with NICMOS, WFC3 will only implement a single readout mode: after an initial reset scan, up to 16 reads are done at time intervals selected by the user. This is the basic “sample-up-the-ramp” mode, known to provide the best monitoring and mitigation of cosmic ray events. Therefore, neither double correlated sampling nor Fowler sampling will be supported for scientific use. Whereas for engineering purposes the detectors are routinely operated in a variety of modes, the most relevant tests are those performed in sample-up-the-ramp mode, or “multiaccum” in the HST jargon. The results presented hereafter have been mostly obtained in this way.

#### 3.1 Quantum Efficiency (QE)

The requirement is a QE higher than 45% in the range 1.0-1.6\(\mu\text{m}\), with greater than 55% goal. The improvement in QE has been constant during the development process, with a major step forward reached with the so-called “process A” in lot 6. Figure 3 compares the absolute quantum efficiency (QE) of four detectors:

- FPA#18, one of the early engineering devices produced in lot 3, shows peak QE at 1.7\(\mu\text{m}\) at a 50% level, with a monotonic decrease at shorter wavelengths;
- FPA#32 (lot 4) shows improved peak QE at \( \sim 70\)% level, but the decrease at short wavelengths is still present;
- FPA#43 (lot 6, process “B”) shows peak QE comparable to lot 4 devices, but the decrease of QE at short wavelengths is significantly reduced;
- FPA#45 is another lot 6 device with different processing (“A” type). This shows a further increase of the peak QE almost to 90% level, i.e. close to the theoretical limit. At shorter wavelengths the improvement of QE is less pronounced; the QE curve is not as flat as for process B.

In general, improvements in the growth of the detector material and processing done with lot 6 have significantly improved the QE over the entire wavelength range. Note that lot 6 parts were processed in two different ways, but detectors with the same process show very little relative QE variations. It is worth noting that between 0.8\(\mu\text{m}\) and 1.1\(\mu\text{m}\), the absolute QE of lot 6 devices largely exceeds the QE of the WFC3 CCD detectors.

![Figure 3](image.png)

Figure 3. Left: comparison of the absolute quantum efficiency of four WFC3-1R detectors, as measured at the NASA/GSFC DCL. Right: histogram of the absolute QE for FPA#45 at 1.6\(\mu\text{m}\), quadrant nr.3.
Small gradients in the relative concentration of Hg vs. Cd within the detector material are reflected in a spatial dependency of the cutoff wavelength. This is shown in Figure 4, where the flat-field responses of FPA#31 to a monochromatic flux at 1.72\(\mu\)m and at 1.40\(\mu\)m are compared. In this case, the wavelength of 50% relative QE, averaged across the quadrants, ranges between 1.70\(\mu\)m and 1.71\(\mu\)m. The most recent parts consistently show very good uniformity, with cutoff wavelength close to 1.73\(\mu\)m and spatial variation smaller than 0.01\(\mu\)m. To guarantee the uniformity of the photometric system across the field of view, the WFC3 Science Oversight Committee has selected a broad “H-band” filter with red cutoff (5% relative transmission) at 1.70\(\mu\)m.

Figure 4: Flat-field uniformity of FPA#31 at the 1.72\(\mu\)m cutoff wavelength (left) and at 1.4\(\mu\)m (right)

3.2 Readout Noise
Early lots of detectors (Lot 2 and 3) consistently exhibit readout noise of approximately 40-45 e\(^{-}\) rms. This is higher than the 30 e\(^{-}\) rms for a single correlated double sampling specified in the procurement contract. Improvements in the detector processing have been made with lot 4, and readout noise ~30 e\(^{-}\) rms has been reached. Figure 5 shows the readout noise for the lot 4 part FPA#32. A sample-up-the-ramp sequence of 16 reads has been taken, with almost zero delay (exactly, 62ms) between each frame. The data have been reduced by taking adjacent differences, i.e. the first point represents the average counts of the difference of frame 2 minus frame 1, the second point the difference of frame 3 minus frame 2, and so on. In this way, pixel-to-pixel variations cancel out, and the spatial standard deviation of the differences consistently provide a readout noise of ~30 e\(^{-}\). Figure 5 also shows that the readout noise estimated for the onboard vertical reference pixels is ~9.5 e\(^{-}\). This provides an upper limit to the noise performance of the electronics and constrains the nature of the noise. Since the 30e\(^{-}\) rms readout noise appears only in the active pixels, it appears to originate within the detector material rather than within the multiplexer or in the electronic chain. Other tests indicate that the noise shows a 1/f component and decreases roughly with the square root of the temperature, typical of Johnson noise from a resistive element. The high operating temperature of these detectors may make them more sensitive to this type of effects. At 37 K, the operating temperature for NGST, the readout noise is in fact reduced to <15 e\(^{-}\) rms.

The multiple readout scheme adopted for WFC3 will allow the reduction of the final readout noise. Garnett & Forrest (1993) and Fixsen et al. (2000) have discussed the theoretical ground for this improvement.
3.3 Dark Current
The WFC3-1R detector dark current is specified to be less than 0.2 e/s/pix at 150K. The development process demonstrated that dark current as low as 0.02e/s/pix can be reached. The majority of the detectors delivered to NASA are within specs once they reach steady state conditions (see next Section). Figure 6 shows the dark current map and histogram for FPA#32 (lot 4). The image, resulting from a 2hr long exposure, shows no evidence of amplifier glow.

It is instructive to follow how a typical dark current measurement is performed. Figure 7 shows a sequence of dark current ramps, each composed of 16 reads. Short exposures (~64s total) are interspaced between exposures of increasing duration, namely, 0.5 hr, 1hr, 1.5 hr, 2 hr, 2.5 hr, and 3.0 hr. The average counts of each read are shown in Fig.7a. Ramps are nicely linear, but a drift of the zero level is clearly visible especially in the 64s ramps. Figure 7b shows the corresponding behavior of the reference pixels. The drift, shown amplified by the plot scaling, is also present. Figure 7c shows the averages of Figure 7a after the reference pixels are subtracted: the drift has been removed. Finally, Figure 7d shows the dark current rate as estimated from the differences of adjacent frames divided by the corresponding integration time. With the exception of the first read immediately after the reset, showing the so-called “reset anomaly”, all the other

Figure 5. Left: readout noise measured on a quadrant of FPA32. Left: readout noise estimated by taking the standard deviation of adjacent differences in a 16 read ramp with the shortest integration time ~4.2 s. Right: histogram of the standard deviation estimated by stacking 8 independent differences (2-1, 4-3,…) of the same ramp.

Figure 6: Dark current for FPA#32. Left: dark image of the whole array. Right: histogram of the dark current as measured from the image on the left. The histogram contains 96.4% of the pixels.
points indicate a dark current below 0.2 e/s/pix. The plot also shows that a residual drift is still present at a level of 0.05e/s in ~10hr.

Figure 7. A typical dark current measure for FPA#32. Figure 7a-7d are from the top to the bottom. In the first three plots the charge integration goes in the negative direction (lower numbers have higher signal).
3.4 Dark Current Instability

Devices from lot 3 and lot 6, but not from lot 4, show an unexpected type of dark current instability. After an exposure to bright light, power cycling, or just a change of the detector bias, the dark current does not return immediately to its nominal level. The settling times for the instability can be as long as several hours. Although some settling time should be expected from these types of disturbances, long time scales are not compatible with WFC3 operations. In Figure 8 we show the behavior of the dark current of FPA#50 (Lot 6) before illumination (first ramp) and after a quick illumination producing a number of charges comparable to the saturation level (next three ramps). The sensitivity of the dark current to previous light exposure(s) would certainly complicate the on-orbit calibration of the instrument. Also, powering down the detector several times per day at the passage of the South Atlantic Anomaly, as is the case for NICMOS at present, would have an efficiency impact since extra-time should be allocated to allow the dark current to recover. This detector shut-down is not planned for WFC3, however.

![Figure 8: Dark current anomaly after illumination for FPA#50. Between the first and the second dark current ramp ~70,000 electrons have been photo-generated through a cold LED located inside the dewar. The dark current rate is estimated from the mean value of the differences of adjacent pairs.](image)

4. ENVIRONMENTAL TESTS

IR detectors designed to operate on space missions like the HST are subject to a variety of stress factors. An important part of the development process is therefore to verify that they meet their mission lifetime requirements, which in our case is 5 years on orbit. One of the major concerns is the reliability of the interconnection between the detector layer and the multiplexer (indium bumps). New FPAs typically have a small number (10s to 100s) of unbonded pixels near the device corners (Figure 9). However, the number of unbonded pixels may increase with time depending on:

1. Quality of hybridization during FPA assembly
2. Stresses induced in the indium columns

Stresses on the detector may be produced during the test phase (installation into the test dewars and repeated thermal cycling), during the assembly phase (again, installation and thermal cycling), during the final tests of the entire
instrument (vibration/shock tests and in thermal vacuum), and obviously during the launch and on orbit. In general, they can be divided into thermal and mechanical stresses. We have tested a number of detectors against these two factors, and the results are summarised in the following subsections.

4.1 Thermal cycling

The purpose of the thermal cycling tests was to measure the number of pixels that became electrically disconnected from their detectors due to thermally induced stresses in the indium columns. Three FPAs, chosen among those exhibiting low radiometric performances but with good interconnect yield, were subjected to 1000 thermal cycles between 293 K and 77 K. RSC used an automated test that cycles the FPA between liquid nitrogen and room temperature with heating from a quartz lamp. With a duty cycle of 3 minutes, the cool-down rate is ~10.8º per second and warm-up rate is ~1.35º per second. Each FPA was warm tested after 10, 100, 500, and 1,000 cycles, looking only for thermo-mechanically induced indium column failures.

The results indicate that 2 out of 3 FPAs showed no change in the number of unbonded pixels; the third device showed less than 1.2% increase in the number of unbonded pixels. This demonstrates the reliability of the WFC3-1R hybridization process and of the packaging, employing a balanced composite structure matching the HgCdTe detector, the Si multiplexer, the Molybdenum mount, and the thermoelectric cooling stack, all optimized to keep the indium strains low. Since these test conditions are much more severe than the typical on-orbit thermal environment, there is a high degree of confidence that WFC3-1R FPAs will maintain full operability over the mission lifetime.

4.1 Vibration tests

Two non-flight FPAs were epoxy bonded onto a molybdenum plate similar to the flight wedge. During each step of this preparatory operation the number of unbonded pixels was monitored to make sure that the process itself was not causing unbonding. At NASA/Goddard, both parts went under two sets of vibration tests, a light shake and a strong shake. In each case a small increase of unbonded pixels was noticed. Overall, however, the devices were fully operational and still meet flight requirements. The vibration modes were similar to that planned for the detector enclosure.

With lot 5/6, Rockwell has modified their hybridization procedure. A new vibration test is now schedule for September 2002 with two new flight-like FPAs. The vibration plan, upon further analysis, has also been refined to reflect more accurately the vibration modes expected during the early flight phases.

Figure 9: Unbonded pixels for FPA #31. Monitoring of the population of unbonded pixels at the DCL shows a very small rate of growth with thermal cycling.
5. CONCLUSION
Rockwell Scientific Company has demonstrated that the requirements for the detectors to be installed on WFC3 can be met. At present, the best performances on readout noise and dark stability have been obtained on lot 4 parts, whereas lot 6 parts show extremely high QE. The physical processes limiting the readout noise and dark current stability are fairly understood, and the next lot of devices is expected to deliver the final WFC3 flight detectors in late Fall 2002.

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REFERENCES


