Anomalous annealing behavior of the high resistivity CCD irradiated at cold temperature.

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1 Introduction

CCDs on board space missions usually operate at cold temperatures in order to mitigate radiation damage accumulated in the harsh space environment. It is common practice to warm up such devices once in a while to anneal at least some radiation defects and improve device performance. X-ray CCDs made on high resistivity substrates flown on board the Chandra X-ray Observatory demonstrated an anomalous behavior when the focal plane was warmed up early in the mission after it suffered exposure to low energy protons in the Earth's radiation belts.

The focal plane temperature was elevated to approximately $+30^0$ C for 8 hours and then the CCDs were cooled back down to the normal operating temperature of -100^0 C. After this bakeout the Charge Transfer Inefficiency (CTI) of the frontside illuminated CCD (measured using the on-board Fe^{55} calibration source) increased from 2.05×10^{-4} to 2.75×10^{-4}.

A vast body of literature has been devoted to studies of radiation damage in CCDs. Most of this research is based on data acquired on the ground, and in almost all the cases the devices under investigation were irradiated at room temperature. The reason is that it is extremely difficult to perform experiments involving irradiation of the devices in cryogenic conditions because an entire CCD camera with cooling equipment should be placed into the chamber where the irradiating beam is produced. Also, dose rate must be high in the experiments reproducing years of in-flight damage accumulation, so the activation of camera creates serious problems. Meanwhile, the detectors flown on-board space missions undergo irradiation at low temperatures and the mechanism of the defect creation and the dynamics of the defect interactions can be very different than that at room temperature. This makes the task of studying the radiation effects in the cold devices very important for space based instruments. This paper describes an attempt in this direction.

2 Experimental details

Recently we performed an experiment in the laboratory designed to reproduce and better understand the behavior of Chandra CCDs. A CCD from the same lot as the flight devices was cooled down to -100^0 C and then irradiated cold with 120 keV protons in the linear accelerator at NASA Goddard Space Flight Center. Such a low energy of the proton beam was chosen because the flight CCDs accumulated radiation damage mostly from the exposure to low energy protons in the beginning of the mission [1]. The protons of this energy are the most damaging in terms of CTI – they are stopped mainly in the buried channel of a CCD. The frame store of the CCD was shielded during the irradiations (the same was true for the flight devices – only unshielded image section suffered damage from low energy protons). This simplified data analysis because charge transfer through the damaged area involves only one type of transfer – fast transfer from image section to the frame store; slow readout of the frame store section is unaffected.

A CCD camera with a dewar was attached to the exit window of the accelerator, and a movable Fe^{55} source was placed in front of the CCD in order to allow an accurate $in-situ$ measurement of the CTI. The proton dose and energy was measured by a silicon diode detector (ORTEC model TU-013-025-300). We used the CCD itself to map the proton beam intensity and to calibrate the dose monitoring silicon detector during the test runs at very low proton beam currents. In this mode we were able to register every individual proton by the CCD. For the regular, larger dose irradiations the CCD power was turned off.

Several irradiation and warm-up/cool-down cycles to the room temperature and an intermediate (-60^0 C) temperature were introduced to simulate the scenario experienced by the flight detectors. CTI measeurements

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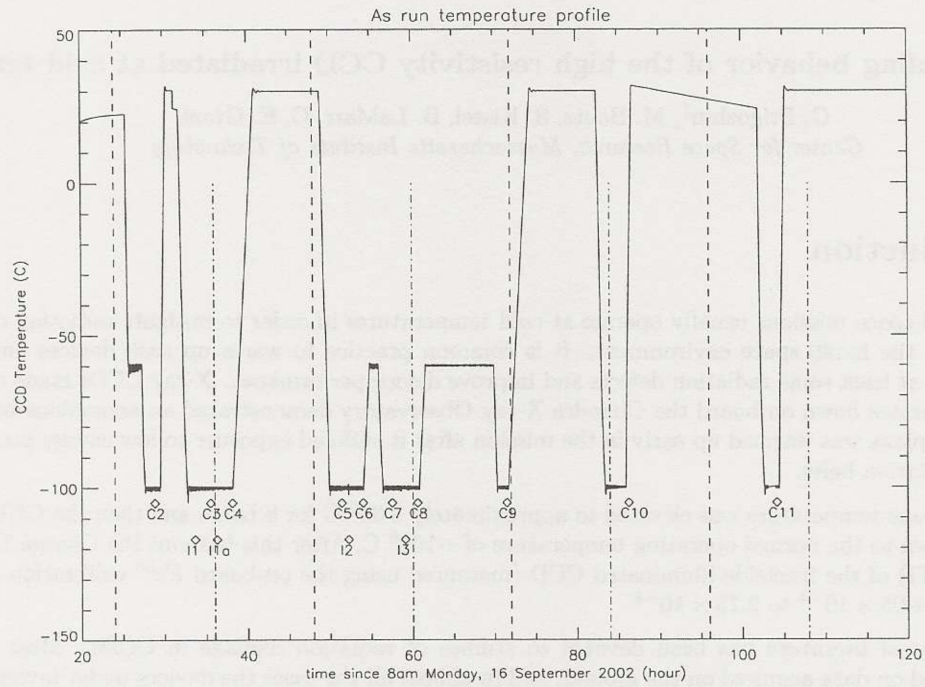

Figure 1: Temperature of the device during the experiment as a function of time recorded by the temperature controller. Diamonds marked with letter C and a number indicate CTI measurement. Events marked with letter I and a number indicate an irradiation.

Irradiation number	Monitor counts, 10^7 counts	Exposure time min	CCD fluence, 10^7 p/cm^2
I1	6.4	35	5.0
I1a	6.6	27	5.2
I2	2.0	15	1.6
I3	1.8	12	1.4

Table 1: Accumulated beam monitor counts and estimated 120 keV proton fluence for each irradiation.

were performed before and after every irradiation and every temperature cycle, allowing us to closely watch CTI behavior. The measurements were always done at temperature of -100^0 C. All the irraditaion and measurement events as well as the temperature of the CCD during the entire experiment are shown in the time diagram on Fig. 1. The doses for each of the 4 irradiations are shown in Table 1. After the measurement C10 was finished, the device was warmed up and the CCD camera was disconnected from the accelerator vacuum chamber. Device was kept warm after that, except for a few control measurements (C11 one day later and C12 two weeks later).

3 Results and discussion

Before and after each irradiation and anneal, the Fe^{55} source was moved into the field of view of the CCD and a CTI measurement was made. Measurement results as a function of time are shown in Fig. 2. As expected, each irradiation increased transfer inefficiency. Very importantly, both warm-ups to -60^0 C did not measurably change device characteristics. On the other hand, the first warm-up to room temperature with subsequent cool-down significantly increased CTI from 1.2×10^{-4} to 2.9×10^{-4} (points C4 and C5 in Fig. 1 and 2). This change in CTI is in agreement with the flight experience, where similar behaviour was observed, although the magnitude of the change in flight was slightly smaller. This is not surprising since the proton spectrum in orbit is certainly different from the one in the laboratory.

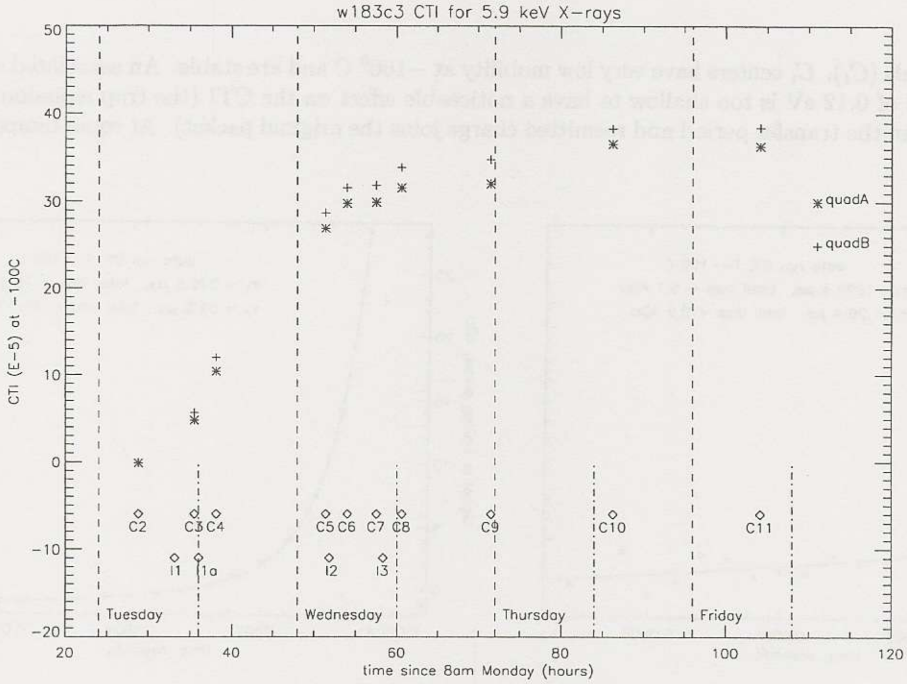

Figure 2: CTI measured at different times during the experiment. Data for 2 irradiated quadrants of the device are shown.

The most remarkable result of the warm-up, though, was not just the change in the CTI. The composition of traps responsible for the charge losses also changed dramatically. This conclusion can be drawn from the top 2 panels of Fig. 3 corresponding to measurements C4 and C5 that show plots of the average amplitude of the signal in the 18 pixels trailing Manganese K_α photon events as a function of row number (which is proportional to time) for the irradiated CCD before and after room temperature anneal. Only charge packets generated near the top of the image section (above row 700) and thus passing through a large portion of the damaged silicon were taken into account for this analysis. Signal amplitude distribution in the pixels trailing an X-ray event depends on how fast the traps in the buried channel reemit the electrons captured from the original charge packet, and hence can be used to characterize emission time constant of a trap. It is not possible to accurately measure trap time constants, especially the long ones, based on the data collected during the experiment, but the qualitative conclusions are quite clear.

A more than an order-of-magnitude increase after the bakeout of the signal amplitude in the first trailing pixel indicates that the density of fast traps (with emission time constant comparable to the transfer period of 40 μs) grew accordingly. Before the bakeout the majority of the trap population was comprised of traps with a much longer time constant. Another significant change in trap composition occured after the experiment was finished and the CCD was warmed up to room temperature. The trailing pixel distributions for the control measurements C10 and C11 reveal a striking difference in the amplitude of short time constant component. The density of fast traps, which stayed almost unchanged in all the measurements between C5 and C10 suddenly dropped dramatically after C10. Additional measurements two weeks later (device stayed warm during this time) show distributions similar to the one at C11. Since the CTI value did not change from C10 to C11, the only conclusion can be that the trap did not disappear, but rather was converted into a trap with a different time constant.

The usual suspects comprising the traps in proton-irradiated CCDs such as the P-V (phosphorus-vacancy), V-V (divacancy), and O-V (oxygen-vacancy) centers are known to be stable below 150^0 C and cannot be responsible for the observed phenomenon. The annealing behavior after the first room temperature bake-out is consistent with the mechanism suggested by Kono *et al.* [2]. It can be explained by the relatively high concentration of carbon in the float zone material used for high resistivity X-ray CCDs. Under irradiation, vacancies and silicon interstials (S_i) are created. Both are highly mobile even at very low temperatures. When S_i meets substitutional carbon atom (C_s) they can exchange positions and produce carbon interstitials (C_i). C_i centers have very low mobility at -100^0 C and are stable. An associated electron trap energy level of 0.12 eV is too shallow to have a noticeable effect on the CTI (the trap emission time is much smaller than the transfer period and reemitted charge joins the original packet). At room temperature,

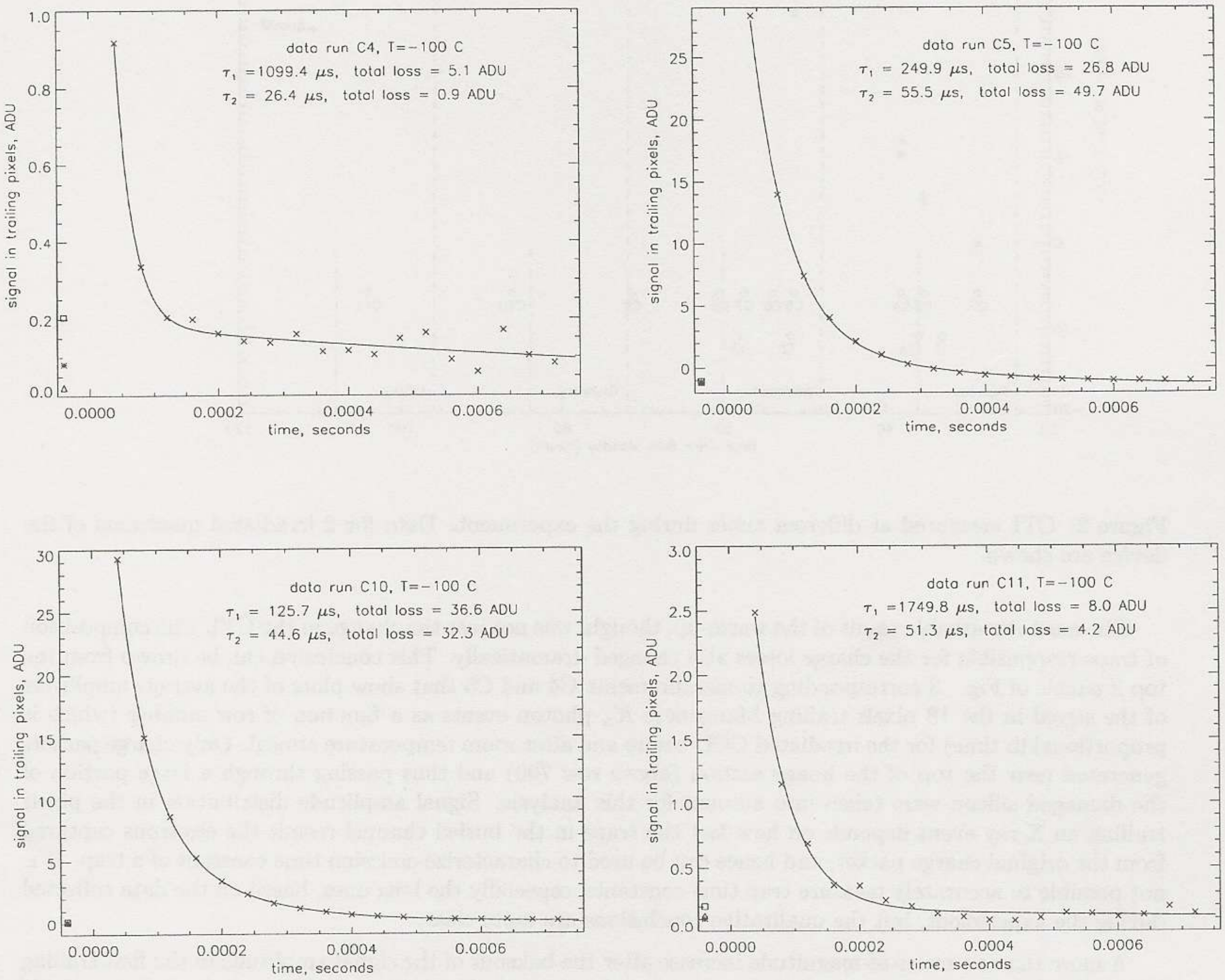

Figure 3: Average signal amplitude in the pixels trailing the detected Manganese K_α photons near the top of the array as a function of time. Solid line shows the best fit to the data points by the sum of the two exponential functions. C4: data taken after irradiation but before the first room temperature anneal. C5: data taken immediately after the first room temperature anneal. C10: data taken after the second room temperature anneal. C11: data taken one day after the final warmup upon the experiment completion. Note the difference in the vertical scale in all 4 plots.

though, C_i atoms become mobile. If they encounter phosphorous atoms (the buried channel dopant), they can form a defect ($P_s - C_i$) that is able to trap electrons with several possible energy levels (0.21, 0.23, 0.29, and 0.3 eV). Another known center that carbon atoms can form is $C_i - C_s$ (0.17 eV). These traps are harmful at our operating temperature and frequency. Both $P_s - C_i$ and $C_i - C_s$ are so-called metastable defects which can switch from one configuration to another with a different trap energy level (see, for instance, [3]). This switching can probably explain the change in the amplitude of the trailing pixel distributions between measurements C10 and C11. The exact reason for this change remains unclear and requires an additional more detailed investigation.

4 Conclusion

A cold CCD at -100^0 C irradiated by low energy protons showed a significant increase of CTI after warm-up to room temperature. Signal distribution in the event-trailing pixels suggests that the warm-up caused significant increase in the density of traps with time constant close to 40 μs. No significant change in either CTI or trap composition could be detected after -60^0 C anneals. Further room temperature annealing resulted in a conversion of the traps with short emission time constant into a different population with much longer time constants.

The described behavior is consistent with a previously proposed explanation in which the relatively high concentration of carbon in float zone high resistivity silicon, and instability of carbon-related defects (such as $P_s - C_i$ and $C_i - C_s$), leads to changes in the trap population after annealing.

An important practical result of the described experiment is that irradiating CCDs at low temperature can produce different trap population than the same irradiation at warm temperature. Keeping the CCD cold at all times may prevent formation of certain types of defects in the buried channel of the device and reduce the CTI.

References

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