Electron-Induced Displacement Damage Effects in CCDs

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35-Word Abstract:

We compare differences in parametric degradation for CCDs irradiated to the same displacement damage dose with 10-MeV and 50-MeV electrons. Charge transfer efficiency degradation was observed to not scale with NIEL for small signals.

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I. Introduction

Charge-coupled devices (CCDs) are a frequently chosen focal plane array (FPA) technology for science imaging and star tracking applications. For many missions locations (e.g. Mars and Low Earth Orbit) the majority of the mission displacement damage dose (DDD) is caused by high energy protons from solar flares or trapped radiation belts, or neutrons from on-board radioisotope thermoelectric generators (RTGs). As a result, much CCD radiation testing has been performed using protons or neutrons to characterize CCD displacement damage effects: reduced charge transfer efficiency (CTE), increased bulk dark current and dark current non-uniformities, and the creation of "hot pixels." In general, few data exist for electron-induced displacement damage effects on focal plane arrays.

In this paper, we examine a subset of results from preliminary high-energy electron tests performed to assess the end-of-mission (EOM) performance of a CCD-based stellar reference unit (SRU) for the NASA New Frontiers Juno Mission [1]. Juno is a spinning spacecraft with a unique Jovian polar orbit. Although the highly elliptical orbit allows the spacecraft to avoid much of Jupiter's extreme radiation environment (dominated by high-energy electrons in the Jovian radiation belts), during the 32 science passes near perijove, a relatively high, electron-dominated DDD is imparted by EOM. Of interest to the concept study was how the qualitatively different recoil spectra of electrons, compared to the usual testing species, may influence CCD displacement damage effects for a given DDD. Other investigators have shown that displacement damage effects are qualitatively different depending on the energy and species imparting the damage; the distribution of displacement damage over the many tiny pixel volumes in an FPA strongly influences performance, in particular, dark current non-uniformities [2-4]. Our 10-MeV and 50-MeV electron results showed differences not only in dark current non-uniformities, but also in CTE for smaller signal levels.

II. Experimental Details

Three samples of the Atmel TH7890M CCD were irradiated to a DDD of 4.3E7 MeV/g. The TH7890M is a multiphase pinned (MPP), front-side illuminated, n-channel, frame transfer CCD. It has 512 x 512 pixel image and storage regions, and 17 x 17 micron pixels. Irradiations were performed at the Gaerttner LINAC, Rensselaer Polytechnic Institute (RPI), Troy, NY. Two samples were irradiated unbiased in air, with all pins shorted and grounded (one with 10-MeV electrons, and the other with 50-MeV electrons). A third sample was irradiated in vacuum at -74ºC while transferring and reading out frames; this sample was irradiated with 10-MeV electrons. The Gaerttner LINAC supplies a pulsed electron beam; 50 ns pulses with a 200 pps rep rate were used for our irradiations. Dosimetry was performed using lithium borate thermoluminescent dosimeters which register total ionizing dose (TID). Absorbed TID was converted into 10- or 50-MeV electron fluence using collisional stopping power values provided by NIST ESTAR.

Mean dark current, hot pixel distributions, and CTE were characterized before and after irradiation. CTE measurements were taken at -85ºC (the nominal flight temperature) using soft x-rays from an Fe-55 source, and were repeated with hard x-rays from a Cd-109 source. Some additional CTE measurements were taken at higher temperatures. 100 kHz transfer and readout rates were used.

III. Results & Analysis

A. Mean Dark Current

Mean dark current increases were found to scale reasonably well with non-ionizing energy loss (NIEL). Hopkinson and Mohammadzadeh have

also shown mean dark current increases in the TH7890M to scale approximately with NIEL, when samples were irradiated with 10-MeV and 60-MeV protons [5]. We followed their approach to analysis, which assumes that bulk dark current damage increases linearly with fluence (surface dark current is suppressed in the TH7890M, because the MPP mode keeps the surface inverted – filled with holes). All three of our samples were irradiated to a DDD of ~4.3E7 MeV/g, and the average increase in dark current was 48 pA/cm^2 (at 20ºC). Samples #2 and #6 were irradiated with 10-MeV electrons, and sample #4 was irradiated with 50-MeV electrons. Devices #2 and #6 were each compared to sample #4 to generate two 50-MeV/10-MeV electron damage ratios for mean dark current: 1±0.2 and 1.5±0.3, respectively. The NIEL ratio for 50-MeV/10-MeV electrons is 1.42 [6].

B. Dark Current Non-Uniformities

The peak of Juno's differential electron fluence spectrum is close to 10-MeV. For this electron energy, 73% of the recoils in silicon have an energy less than 1keV [7], therefore the defect inventory is dominated by diffuse, isolated point defects. Juno's SRU will experience a wide spectrum of electron energies, so an additional CCD sample was tested with 50-MeV electrons (a higher, achievable energy at RPI) to examine qualitative differences in damage caused by different electron energies. The fraction of the NIEL coming from recoils with energies greater than 2keV is considerably higher for 50-MeV electrons. It has been noted previously that 50-MeV electrons actually have a very similar recoil spectum to 10-MeV protons [7,8], so the presence of larger, if more sparse, cluster defects is to be expected for 50-MeV electrons. Hotter pixels have been attributed to the presence of higher energy recoils [4]. We were especially interested in how differences in dark signal non-uniformities (DSNU) and CTE, for these two electron energies, might affect SRU functionality.

Figure 1 shows dark current distributions for 10-MeV and 50-MeV irradiations to ~4.3E7 MeV/g. As expected, a larger number of "hotter" pixels are observed for 50-MeV electrons.

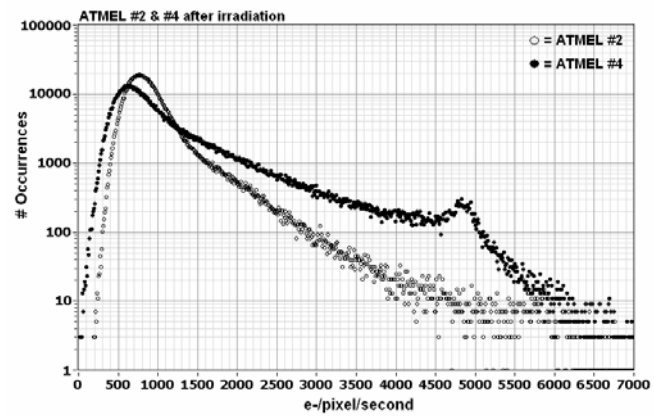

Fig. 1 Dark current distributions at 20ºC for Atmel #2 (10-MeV) and Atmel #4 (50-MeV). Both samples were irradiated to ~4.3E7 MeV/g.

Dark current non-uniformity values were calculated over a hypothetical 10 x 10 pixel tracking window, assuming 900 line/second time delayed integration (TDI). The number of electrons rms (per sec) is very low at -85ºC, however the value was approximately three times higher for 10-MeV electrons than for 50-MeV electrons.

The sample irradiated with 10-MeV electrons at -74ºC was examined for dark current annealing effects following a temperature cycle to room temperature. Marshall et al. recently observed significant annealing of hot pixels and mean dark current following a 4 hour anneal at +30ºC, for a Hubble E2V CCD43 irradiated with protons at -84ºC [9]. We were not able to discern any significant annealing related to mean dark current or hot pixels. However, our SRU-appropriate integration times were *considerably* shorter (30 seconds, vs 1.5 hours in the Marshall study) and at -74ºC dark current is very suppressed; charge injection from an ESD protection diode may also be masking annealing effects. In the final paper, we will present results from a 2-MeV electron irradiation of a TH7890M (again to ~4.3E7 MeV/g) performed at -85ºC, with longer integration times to characterize dark current distributions. Annealing behavior following cycling to room temperature and hot pixel activation energies will be discussed.

C. Charge Transfer Efficiency

CTE measurements taken with Fe-55 did not scale very well with NIEL. Table 1 lists horizontal and

vertical CTE values taken with Fe-55 for all three samples. At -85ºC, vertical CTE was worse for 10-MeV electrons, but at -10ºC the trend was reversed. The sample irradiated to ~4.3E7 MeV/g with 50-MeV electrons had worse VCTE at -10ºC. At -40ºC, similar VCTE was observed for both electron energies.

Table 1 CTE results using Fe-55 x-rays (~1620 e- signal)

CCD #	ATMEL #2		ATMEL #4		ATMEL #6	
	before	after	before	after	before	after
HCTE -85ºC	>.99999	.99991	>.99999	.99986	.99994	.99979
VCTE -10ºC	.99993	**.99967**	.99994	**.99948**	*	*
-40ºC	>.99999	.99940	>.99999	.99944	*	*
-85ºC	.99991	**.99957**	.99993	**.99974**	.99992	**.99953**
Radiation Level	4.3E7 MeV/g 4.2E11 e/cm^2 **@ 10-MeV**		4.3E7 MeV/g 2.9E11 e/cm^2 **@50-MeV**		4.3E7 MeV/g 4.1E11 e/cm^2 **@10-MeV**	

Differences in the spatial distribution of displacement damage created by 10-MeV and 50-MeV electrons may be causing this effect. At -85ºC, and with short integration times, there is very little trap filling benefit to CTE from fat zero. The presence of a larger number of smaller, and more uniformly distributed, point defects in the 10-MeV samples may give signal electrons a higher likelihood of encountering a free trap during transfer. At -10ºC, dark current rates are higher, and at that temperature devices irradiated with 10-MeV electrons may be experiencing higher CTE because a more uniform and more effective fat zero is influencing the measurements by filling a large number of traps. At -40ºC, dark current rates are less than at -10ºC, and trap emission times are not favorable to SRU transfer rates; this is often a poor operational temperature for CCDs. Hopkinson and Mohammedzadeh also observed a dip in CTE at -40ºC following proton irradiation of the TH7890M. However, NEIL scaling for 10-MeV and 60-MeV protons was observed to hold for several signal and background levels, when evaluated at temperatures from -60ºC to -40ºC (4 µs line transfer times were used in their study). The final paper will include CTE results taken with 250 kHz transfer and readout rates.

CTE data taken with Cd-109 did not appear to be influenced by electron energy. The effect observed with Fe-55 may be a subtle one that is very sensitive to signal level. CTE is known to be simultaneously highly influenced by temperature, signal size, and background levels (fat zero). The K_α line for Cd-109 produces roughly 4 times more signal electrons per x-ray than the K_α line of Fe-55, and this may be high enough to overcome the impact of differing defect distributions. Table 2 shows CTE data taken at -85ºC with Cd-109.

Table 2 CTE results using Cd-109 x-rays (~6300 e- signal)

CCD #	ATMEL #2		ATMEL #4		ATMEL #6	
	before	after	before	after	before	after
HCTE -85ºC	*	*	>.99999	.99990	.99994	.99987
VCTE -85ºC	.99991	**.99978**	.99993	**.99976**	.99997	**.99981**
Radiation Level	4.3E7 MeV/g 4.2E11 e/cm^2 **@ 10-MeV**		4.3E7 MeV/g 2.9E11 e/cm^2 **@50-MeV**		4.3E7 MeV/g 4.1E11 e/cm^2 **@10-MeV**	

The CTE effect we observed has an impact on SRU CCD performance analysis. When Fe-55 and Cd-109 CTE data are both used to calculate worst-case global charge transfer efficiency for a single pixel signal (such as a star imaged in the furthest corner from the output amplifier), the differences are noticeable. Fig. 2 shows global CTE at -85ºC vs. the electron energy used to irradiate the sample to 4.3E7 MeV/g. Fe-55 and Cd-109 data are presented for samples #2 (10-MeV) and #4 (50-MeV). The lack of NIEL scaling for the smaller signal size can be seen.

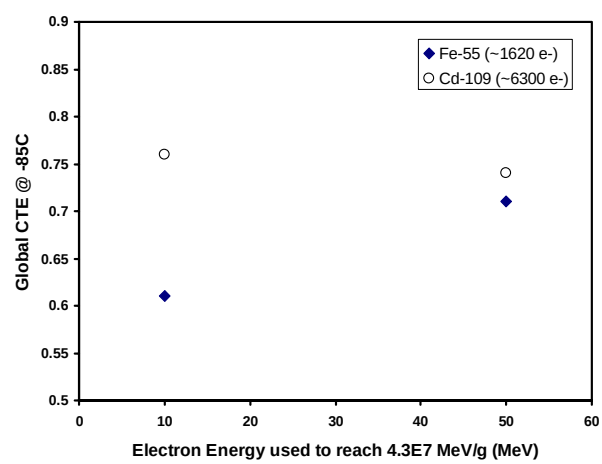

Fig. 2 Global CTE for samples irradiated to 4.3E7 MeV/g with 10-MeV or 50-MeV electrons. Fe-55 and Cd-109 based measurements are compared.

These differences lead to corresponding differences in how EOM star brightness losses are

interpreted. Table 3 shows calculated EOM star brightness losses for single pixel and 2-pixel (single pixel star with a one pixel tail) stars, relative to the magnitude of the dimmer stars Juno's SRU will see in-flight.

Table 3 SRU CCD Performance following EOM DDD of 4.3E7 MeV/g

Electron Energy	Star Brightness Loss* Single pixel Fe-55/Cd-109 (Star Magnitude)	Star Brightness Loss* 2-pixel Fe-55/Cd-109 (Star Magnitude)
10-MeV	-.53/-.30	-.18 / -.06
50-MeV	-.37/-.32	-.09 / -.08

* after centroiding; assumes maximum number of line and column transfers – worst case

For Juno, the Cd-109 signal is actually more representative of the signal from stars the SRU will see in-flight.

IV. Conclusions

Electron-induced displacement damage effects in the Atmel TH7890M CCD have been studied. Samples were irradiated with 10-MeV or 50-MeV electrons to the same displacement damage dose. The final paper will incorporate additional results from 2-MeV electron testing to 4.3E7 MeV/g, including low temperature annealing effects. CTE values for 250 kHz transfer and readout rates will also be included. Although mean dark current increases obeyed NIEL scaling reasonably well, CTE was observed to not scale with NIEL for small signal levels, leading to an impact in the way EOM SRU performance is interpreted. We attribute this effect to the qualitative nature of the different recoil spectra for 10- and 50-MeV electrons. The effect is not present for signal levels as high as ~6300 electrons under our operational conditions. This effect may be more important for low temperature science applications where transfer rates can be slower and integration times are longer.

V. Acknowledgments

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VI. References

[1] H.N. Becker, J.W. Alexander, and T. Elliott, "High-energy electron testing of CCDs for a Jovian science mission," Proc. of SPIE, **5902**, Aug. 2005.

[2] C.J. Dale, et al., "A Comparison of Monte Carlo and Analytical Treatments of Displacement Damage in Si Microvolumes," *IEEE Trans. Nucl. Sci*., **41**, no. 6, pp. 1974-1983, Dec. 1994.

[3] P.W. Marshall, C.J. Dale, and E.A. Burke, "Proton-Induced Displacement Damage Distributions and Extremes in Silicon Microvolumes," *IEEE Trans. Nucl. Sci*., **37**, no. 6, pp. 1776-1783, Dec. 1990.

[4] C.J. Dale, P.W. Marshall, and E.A. Burke, "Particle-Induced Spatial Dark Current Fluctuations in Focal Plane Arrays," IEEE Trans. Nucl. Sci., **37**, no. 6, pp. 1784-1791, Dec. 1990.

[5] G.R. Hopkinson,and A. Mohammadzadeh, "Comparison of CCD Damage Due to 10- and 60-MeV Protons," *IEEE Trans. Nucl. Sci*., **50**, no. 6, pp. 1960-1967, Dec. 2003.

[6] G.P. Summers, et al., "Damage Correlations in Semiconductors Exposed to Gamma, Electron, and Proton Radiations," *IEEE Trans. Nucl. Sci*., **40**, no. 6, pp. 1372-1379, Dec. 1993.

[7] C.J. Dale, et al, "High Energy Electron Induced Displacement Damage in Silicon," *IEEE Trans. Nucl. Sci*., **35**, no. 6, pp. 1208-1214, Dec. 1988.

[8] J.R. Srour, C.J. Marshall, and P.W. Marshall, "Review of Displacement Damage Effects in Silicon Devices," *IEEE Trans. Nucl. Sci*., **50**, no. 3, pp. 653-670, June 2003.

[9] C.J. Marshall, et al., "Hot pixel annealing behavior in CCDs irradiated at -84ºC," *IEEE Trans. Nucl. Sci.*, to be published Dec. 2005.