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How to cite:

Dunford, A.; Stefanov, K. and Holland, A. (2018). Ageing and proton irradiation damage of a low voltage EMCCD in a CMOS process. *Journal of Instrumentation*, 13, article no. C02059.

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Version: Accepted Manuscript

Link(s) to article on publisher's website:

<http://dx.doi.org/doi:10.1088/1748-0221/13/02/C02059>

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2017

THE OPEN UNIVERSITY, MILTON KEYNES

Ageing and Proton Irradiation Damage of a Low Voltage EMCCD in a CMOS Process

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ABSTRACT: Electron Multiplying Charge Coupled Devices (EMCCDs) have revolutionised low light level imaging, providing highly sensitive detection capabilities. Implementing Electron Multiplication (EM) in Charge Coupled Devices (CCDs) can increase the Signal to Noise Ratio (SNR) and lead to further developments in low light level applications such as improvements in image contrast and single photon imaging. Demand has grown for EMCCD devices with properties traditionally restricted to Complementary Metal-Oxide-Semiconductor (CMOS) image sensors, such as lower power consumption and higher radiation tolerance. However, EMCCDs are known to experience an ageing effect, such that the gain gradually decreases with time. This paper presents results detailing EM ageing in an Electron Multiplying Complementary Metal-Oxide-Semiconductor (EMCMOS) device and its effect on several device characteristics such as Charge Transfer Inefficiency (CTI) and thermal dark signal. When operated at room temperature an average decrease in gain of over 20% after an operational period of 175 hours was detected.

With many image sensors deployed in harsh radiation environments, the radiation hardness of the device following proton irradiation was also tested. This paper presents the results of a proton irradiation completed at the Paul Scherrer Institut (PSI) at a 10 MeV equivalent fluence of 4.15×10^{10} protons/cm². The pre-irradiation characterisation, irradiation methodology and post-irradiation results are detailed, demonstrating an increase in dark current and a decrease in its activation energy. Finally, this paper presents a comparison of the damage caused by EM gain ageing and proton irradiation.

Keywords: EMCCD, CMOS image sensors, proton irradiation.

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1. Introduction

In many space-based applications, Charge Coupled Devices (CCDs) are inevitably exposed to hostile radiation environments, such as proton radiation and gamma rays from solar flares, producing notable deterioration in device performance. CCDs have undergone extensive testing to understand the sources of this damage and the possibility of mitigating it. In comparison, Complementary Metal-Oxide-Semiconductor (CMOS) image sensors, which have been tested and implemented in large space imaging missions, such as the JANUS camera on the JUICE mission to the Jovian system [1], are known to have a higher radiation tolerance, with a reduced power consumption and faster readout [2].

The Electron Multiplying CCD (EMCCD) has experienced a rapid growth in popularity, in part, due to its ability to achieve high signal-to-noise (S/N) performance, enabling photon counting. EMCCDs have yet to be fully utilised in space imaging. However, this will shortly change with the first flight missions planned in the coming years [3, 4]. Due to these developments, interest has grown in the range of potential applications of EMCCDs in radiation environments, with recent research demonstrating a similar deterioration in performance as seen in traditional CCDs, such as increases in the Charge Transfer Inefficiency (CTI) and dark current [5].

EMCCDs can experience a unique additional reduction in performance, due to what is described as an ageing process, resulting in a decrease in the EM gain over the period of operation. However, demand has grown for an EMCCD with the ability to identify single photons with the qualities previously limited to CMOS image sensors. Electron Multiplying Complementary-Metal-Oxide-Semiconductor (EMCMOS) devices aim to bridge the gap [6]. However, to date, there has been limited testing regarding the effects of radiation and continued operation leading to ageing. The results presented here are for an EMCCD in a low voltage CMOS process which has demonstrated that it can achieve a gain exceeding 3% per stage at an operating voltage of 13.0 V [7]. This paper describes results from testing pertaining to the ageing and proton irradiation of the device.

2. The Electron Multiplying Test Chip 1

Developed at The Open University, the Electron Multiplying Test Chip 1 (EMTC1), aims to provide a high EM gain with relatively low power consumption and operating voltages. The EMTC1 is a 4-phase buried channel, back-illuminated CCD with $10\text{ }\mu\text{m}$ square pixels. The image sensor was built using the $0.15\text{ }\mu\text{m}$, 6 level metal $1.8/5\text{ V}$ CMOS process by ESPROS Photonic Corporation (EPC) [8]. The image area has an array of 100×256 pixels subdivided into 8 blocks of 32 columns within a total chip size of approximately 3.7 mm square. The device has a column parallel architecture, with readout organised in 8 blocks of 32 columns and differential output with Correlated Double Sampling (CDS) per block.

Figure 1. (a) Photograph of EMTC1. (b) Block diagram of EMTC1: The pixel variants are indicated by the number. Pixel variants 1 and 2 are non-EM, while 3-8 are EM-based.

The EMTC1 was devised not only to provide proof of concept of an EMCMOS device but to test the functionality of two newly developed EM gate structures. Shown in Figure 1 (b) the EMCCD section of the image sensor is subdivided into 6 columns of EMCCD pixel variants (3-8). Four of these columns have a traditional rectangular structure which vary in width and length, while the final two columns (pixel variants 7 and 8) contain two novel pixel types aiming to increase EM gain. More information pertaining to the structure of these pixels will be presented in a future paper.

The initial EM gain differed for each pixel variant. To ensure that the maximum gain was achieved for each pixel structure, a voltage range of 12.8 to 14.5 V was utilised achieving a gain of 2 to 3% per stage.

Table 1. The devices that have been used through the experimental process and the mounting technique for each device

Device	Experiment	Device mounting
EMTC1_B1	Control during proton irradiation	Soldered to a PCB
EMTC1_B2	Proton irradiated to a 10 MeV equivalent fluence of 4.15×10^{10} protons/cm ²	Soldered to a PCB
EMTC1_C5	Aged with a input signal of 10k electrons per frame for 175 hours	In a socket
EMTC1_B3	Aged in 3 stages with 3 different input signals for a total of 558 hours	Soldered to a PCB

3. Proton Irradiation

3.1 Proton Irradiation and Methodology

Investigations into the effect of proton irradiation on device characteristics have been completed on a number of EMCCDs [9] including testing for several missions such as the WFIRST mission [10]. Previous studies [5] have demonstrated that while these devices were still operational post proton irradiation, increases in dark current, hot pixel density and CTI were observed. These results were found to be comparable to those seen in traditional CCDs after irradiations of similar fluences.

Prior to the irradiation, complete characterisations of EMTC1_B1 and EMTC1_B2 devices were completed in a vacuum chamber with a temperature range -30 to +30 °C cooled by a Peltier cooler.

EMTC1_B2 was irradiated using the Proton Irradiation Facility (PIF) at the Paul Scherrer Institut (PSI) [11]. The beam was configured with a diameter of approximately 45 mm and flux of 2×10^7 protons/s/cm². The beam homogeneity was better than 5% in the device area. The device pins were shorted and the EMTC1_B2 was mounted centrally in the proton beam. The device was irradiated at room temperature to a 10 MeV equivalent proton fluence of 4.15×10^{10} protons/cm² with a main beam energy of 72.80 MeV.

3.2 Proton Irradiation Damage Results

Post-irradiation the device was characterised using the same equipment and processes as those employed prior. The device was found to be fully operational, however, an increase in the dark current and the number of hot pixels was detected. This is clearly demonstrated in Figure 2, with not only an increase in the average dark current across the sensor from 3.12 nA/cm² to 10.52 nA/cm² but also in the spread of the dark current, demonstrating an increase in the number of hot pixels.

Figure 2. (a) Dark current pre and post-irradiation at room temperature (20.4 ± 0.6 °C) for pixel variant 5 for EMTC1_B2; (b) Activation energy of the dark current pre and post-irradiation for pixel variant 5.

For the context of this paper, a hot pixel is defined as a pixel with dark current which exceeds the average by more than 5 times the standard deviation. Studies of the number of hot pixels have shown that there was an increase in the number of the hot pixels post-irradiation and the average magnitude of the hot pixels. Pre-irradiation, the hot pixel population was 1.2 ± 0.05 % of the total pixel population, which rose to 2.1 ± 0.05 % after irradiation. A study of the magnitude of individual hot pixels provided insight into the hot pixel growth mechanisms post-irradiation. While all pixels experienced an average increase in the dark current of approximately 230 % at room temperature, the dark current of hot pixels defined post-irradiation experienced an average growth of over 430 % when compared to the average dark current before irradiation. This increase can be attributed to new traps forming, demonstrated by the decrease in activation energy seen in Figure 2 (b), creating additional hot pixels. However pre-existing hot pixels also experienced an increase in the dark current due to additional damage to those hot pixels.

CTI measurements were made using the Extended Pixel Edge Response (EPER) technique utilising a LED light source that provided an input signal of approximately 950 electrons. The CTI of the device was found to be high prior to the proton irradiation, with an average CTI value of $9.9 \pm 0.5 \times 10^{-3}$ at -20.4 ± 0.6 °C across the device. Averaging across the columns gave an increase in CTI post-irradiation of 68.1 ± 0.3 % demonstrated in Figure 3 for pixel variant 5. A significant increase in the CTI is noted post-irradiation at temperatures below 0.0 ± 0.6 °C. A series of investigations completed by Hopkins et al. [12, 13] on the effect of proton irradiation on CCDs determined that displacement damage was the dominant factor affecting the CTI. This could also account for the increase in hot pixels described previously.

Figure 3. The average CTI pre and post proton irradiation for EMTC_B2 pixel variant 5. Measurements were made using EPER with an input signal of ~950 electrons.

4. EMCCD Ageing

EMCCD ageing is a known factor that affects several device characteristics and manifests as a decrease in gain during the operational period. It has been hypothesised that this decrease in gain is due to holes becoming trapped beneath the DC gate electrode in the gain register [14] or attributed to damage to the gate dielectric by hot electrons during device operation [15]. Previous research has been primarily restricted to traditional EMCCDs and has demonstrated an approximately logarithmic decrease of gain with time [16].

Figure 4. (a) Dark current pre and post ageing for EMTC1_C5 pixel variant 5 at room temperature, demonstrating an increase in dark current post ageing. (b) Activation energy of the dark current of EM pixel 3 pre and post ageing.

Investigations recently completed by Stevens et al. [15] into an EMCCD device measured no detectable ageing. This research is highly relevant as both the device described by [15] and the EMTC1 utilise an oxide-only dielectric structure beneath the high voltage gate. To test the potential decrease in EM gain, several devices were operated at a P2HV voltage of 15.0 V for extended periods of time. Two devices were aged separately at different temperatures to compare the impact of temperature on the ageing process.

EMTC1_C5 was aged at a temperature of 10.0 ± 0.6 °C over a period of 175 hours. The percentage decrease in gain for rectangular pixel variant 5 is shown in Figure 5. The pixel variant experienced a decrease in gain of nearly 20% after an initial gain of 16.2 ± 0.5 , exhibiting power-law behaviour over time. Across the other pixel variants, an average decrease in gain of 28% was noted with the maximum reduction found to exceed 30%. While further testing is required to understand this disparity, it can be hypothesised that it is due to the large spread in the initial gain as the ageing decay was largely uniform across the pixel variants. After ageing, the dark current was found to be considerably higher; however, there was a negligible increase in CTI.

Figure 5. The decrease in EM gain of EMTC1_C5 over a period of operation of 175 hours for pixel variant 5 at P2HV voltages of 12.5 V, 13.0 V and 14.0 V. The initial gain at each voltage was 6.5 ± 0.5 , 9.1 ± 0.5 and 16.2 ± 0.5 respectively.

A second device (EMTC1_B3), was aged in 3 stages at -30.0 ± 0.6 °C. EMTC1_B3 was initially operated without an external input signal at a P2HV voltage of 15.0 V. When retested after an operational period of 107 hours, no decrease in gain was detected and there were negligible changes in the CTI and dark current. With no decrease in the gain after the initial ageing period, it was apparent that the ageing process was signal dependent. During the second ageing period, EMTC1_B3 was operated with a charge input of 1000 electrons over 377 hours. A linear decrease in the gain and a small increase in the dark current was detected; however, no change was noted in the CTI. Finally, the device was aged with an input signal of 10k electrons for a period of ~75 hours. An ageing decay exhibiting power-law behaviour similar to that demonstrated in Figure 5 was seen and a notable increase in the dark current was detected however once again no change in the CTI was noted.

Both aged devices demonstrated an increase in the dark current, but it was most significant in EMTC1_C5, which had been aged exclusively with a high input signal (approximately 10k electrons), increasing from 3.06 to 5.28 nA/cm². This increase, when compared to that caused by the proton irradiation, was not as significant, with an increase of 72% compared to 230% demonstrated post-irradiation when measured at room temperature. However, there were similar reductions in the activation energy of the dark current.

Figure 6. (a) Cross section along column 14 of dark signal pre and post ageing at 19.9 ± 0.6 °C for EMTC1_B3 pixel variant 2 (non-EM). (b) Cross section of dark signal pre and post ageing at 19.9 ± 0.6 °C for EMTC1_B3 pixel variant 5.

Post ageing, the most significant increase in the dark signal is located closest to the output, where the greatest amount of signal passes through the device. Figure 6 (b) demonstrates that the larger the signal passing through this region, the greater the damage, inducing higher dark signal. It can be concluded that not only is the decrease in gain, signal dependent but also the increases in dark signal and subsequently dark current. In comparison, Figure 6 (a) demonstrates little increase in the dark signal as it represents the pixel variant 2, a non-EM pixel.

5. Comparison of Damage

A comparison of the device characteristics post proton irradiation and ageing aims to provide an increased understanding of the damage occurring during these processes. It is apparent that both induce damage within the device, detectable by the significant increases in dark current and the number and magnitude of the hot pixels. However, the notable disparities in the CTI post ageing and irradiation provide insight into the source of this damage. A significant increase in the CTI was noted post-irradiation, with an average increase across the pixel variants of 68.10 ± 0.3 % from $9.91 \pm 0.5 \times 10^{-3}$ to $1.67 \pm 0.5 \times 10^{-2}$ at -20.4 ± 0.6 °C. This increase was not mirrored in the aged devices, with minimal change detected across the pixel variants. The disparity in these results can be attributed to the difference in the nature of the damage and the location of the traps. It is known that CCDs can experience both surface and bulk damage due to radiation damage, however, when considering CTI increases within a buried channel CCD, it is the traps that form within the

bulk region that lead to charge transfer losses. The activation energies provided in Figure 2 provide insight into the nature of these traps. To confirm the nature of these traps, trap pumping would provide insight into the emission time constants and activation energies of the traps.

In comparison, the aged devices experienced no CTI and the EM gain ageing is clearly dependent on the size of the signal packet passing through the device, demonstrated by Figure 6(b) where an increase in the dark signal is noted toward the output (towards row 0) where the greatest quantity of signal passes. It can be concluded that the dominant source of damage in an aged device can largely be contributed to surface trapping.

Simulations completed by Bush et al. [17] have shown that traps in the gain register may contribute to a decrease in the CTI. Traps were found to form within two distinct regions: (a) between the DC and HV gates due to the proximity of the charge during transfer to the interface and (b) beneath the HV gate due to the proximity to the charge storage location. It can be proposed that these traps may release the trapped charge during the transfer and reduce the CTI. However, temperature is a known factor in this process [18] and the data presented here were collected at several temperatures with negligible difference in the results. It is of interest to note that the initial activation energy is lower than that of silicon band gap at 1.11 eV at 300 K [19], likely due to pre-existing traps formed during the manufacturing process.

Due to the unique nature of the device, some non-uniformity was detected across the device. The dark current, CTI and EM gain prior to any damaging processes differed depending on the pixel variants. It is of interest to note that post-irradiation increases in dark current and CTI were uniform across the pixel variants indicating that damage is independent of the gate pixel. In comparison, the aged devices experienced non-uniform increases in dark current. It can be assumed that this is in part due to the differing initial gain; however, the effect of the pixel gate structure on these factors is not fully understood and requires further investigation.

6. Conclusions

The work presented here demonstrates the damage caused to an EMCCD in a CMOS process by two different processes, EM ageing and proton irradiation. Post-irradiation and ageing, devices were found to be functional; however, there were noticeable increases in dark current. The increase in the CTI experienced post proton irradiation was not mirrored in the aged devices. This difference in the CTI results can be attributed to the different nature and location of the traps. It has been established that the EMTC1 experiences signal dependent ageing despite its oxide-only dielectric, with an increase in dark signal that is focused closest to the device output. Further testing should provide insight into the potential for annealing to reduce the effects of proton and ageing damage in EMCOS devices and enable a comparison with other CMOS device annealing studies [20].

Acknowledgment

The authors would like to thank the team at Teledyne e2v especially Doug Jordan and Dave Burt for their guidance and support and to ESPROS for their aid in developing the sensor.

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