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Ageing Effects on Image Sensors: Neutron Irradiation Studies on Wafer and Packaged devices

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Abstract
We analyze the "ageing" effects on image sensors introduced by neutrons present in terrestrial cosmic environment. In a previous work we compared post-flight measurements at aviation altitudes to that of sea level. We extend our studies by corroborating results obtained at sea level with accelerated neutron beam tests on wafer and packaged devices.

Introduction

Gray hair and balding are considered to be the signs of ageing in humans! Imagers too exhibit a tendency to age which manifests as the generation of hard errors such as increase in hot pixels, increase in dark current, etc, even during on-the-shelf storage[1, 2]. These hot pixels are hard errors and are permanent unlike soft errors limiting the imaging performance. The increasing use of commercial and scientific on-the-shelf devices, with stringent hot pixel specification makes this study more important than ever before. It is known that ceramic package, cover glass, adhesives, etc have little effect on the creation of hot pixels, even though they have effect on the generation of soft errors due to α-rays[3]. It is hypothesized that the ageing phenomenon is due to the influence of terrestrial cosmic rays[4], which are the result of very high energy particles created in space or by the sun. The energy of the cosmic ray is high enough to displace a silicon atom from its lattice position forming an interstitial vacancy pair. Most pairs recombine before they form a stable defect. The defects, in turn, interact with impurities to form defect-impurity complexes. These defects introduce additional energy levels in the forbidden band gap. Only around 2% of the initially generated vacancies remain[5]. Single event effects due to cosmic rays and the comparison between accelerated testing and high altitude measurements have been reported by[6]. In a previous work we have compared post-flight measurements at aviation altitudes to that of sea level and presented activation energy analysis of the sensors[7]. We extend our studies by corroborating results obtained at sea level with accelerated neutron beam tests on wafer and packaged devices and for various image sensor operation conditions.

Experimental set up and evaluation method

Measurement setup consists of signal-processing and sensor board, frame grabber, laptop and LabVIEW programs capable of measuring 16 CCD's simultaneously. The device used is a frame-transfer CCD with an active area of 8.8 x 6.6 mm^2. Image sensors were irradiated in the ANITA[8] (Atmospheric-like Neutrons from Thick Target) beam at The Svedberg Laboratory (TSL), Sweden. Two different neutron flux settings were used: 200 $ncm^{-2}\ s^{-1}$ and $1x10^4\ ncm^{-2}\ s^{-1}$ at the user position; energies above 10 MeV. Measurements were also done on reference sensors at Delft, the Netherlands. Pixels with values eight times higher than the standard deviation over the pixel array are marked out as hot pixels and their amplitudes recorded. This is repeated for all sensors at Delft and at TSL.

Results and Discussion

Figure 1 depicts a 3D hot pixel map (pre-and post-neutron irradiation). To compare hot pixel development at terrestrial environment with accelerated neutron beam tests, non dependency of hot pixel generation on neutron flux is important. To verify this, two groups of sensors received same fluence (10^6 ncm^{-2}) but with different flux (200 $ncm^{-2}s^{-1}$ and 10^4 $ncm^{-2}s^{-1}$). From figure 2 we can deduce that both curves lie within the measurement error and hence the use of accelerated testing for comparison with the reference sensors is justified. Figure 3 depicts the effect of biasing on hot pixel generation. It is seen that biasing the sensor during irradiation increases the prospects of "lower amplitude" hot pixel generation by a factor of 2, and the effect drops for "higher amplitude" hot pixels, finally converging on the highest amplitudes. It is known that ceramic package, cover glass, adhesives etc have little effect on the creation of hot pixels, even tough they may have effect on the generation of soft errors. To analyze this, wafers were irradiated along with packaged sensors and results are depicted in figures 4 and 5. Details of the dose received by each wafer are given in table 1. With respect to dose, the hot pixel count is seen to increase monotonically and the total number of hot pixels generated with particular fluence is in agreement for both packaged device and wafer. Figure 6 depicts the FPN at 60^0 C for all devices in the four wafers. Figure 7 compares neutron spectra at Delft, the Netherlands, and ANITA beam at TSL, Sweden. Spectrum at Delft was calculated using the *QinetiQ Atmospheric Radiation Model* (QARM)[9]. ANITA spectrum was provided by the facility[10]. Figure 8 gives the comparison between reference sensors at the natural cosmic ray environment to sensors irradiated with neutrons at TSL. The curves reveal a similar hot pixel distribution pattern which provides further proof that neutrons in the cosmic rays are the major factor in the development of hot pixels.

Conclusions

1. Influence of neutron flux (dose rate) and biasing on hot pixel generation is studied. Our experiments revealed no influence of dose rate as expected. Hence the use of accelerated testing for hot pixel development analysis and comparison is justified. Biasing the sensor during irradiation increases the prospects of "lower amplitude hot pixels" and hence may have a negative influence on hot pixel generation.
2. Wafer level irradiation experiments are successfully compared with measurements on packaged devices, confirming the non dependence of hot pixel development (hard errors) to storage and packaging materials.
3. Hot pixel developments at sea level (terrestrial cosmic radiation environment) are corroborated successfully with accelerated neutron beam tests which further validates the hypothesis that the prominent cause of hot pixels is displacement damage in the silicon bulk due to neutron radiation, introduced by secondary cosmic rays.

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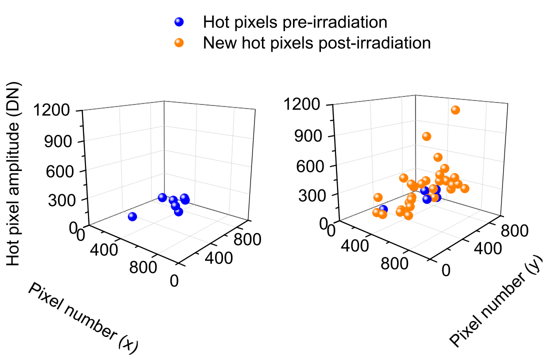

Figure 1: 3D hot pixel map from one sensor: (left) pre-irradiation and (right) post-neutron irradiation. Newly generated hot pixels are indicated.

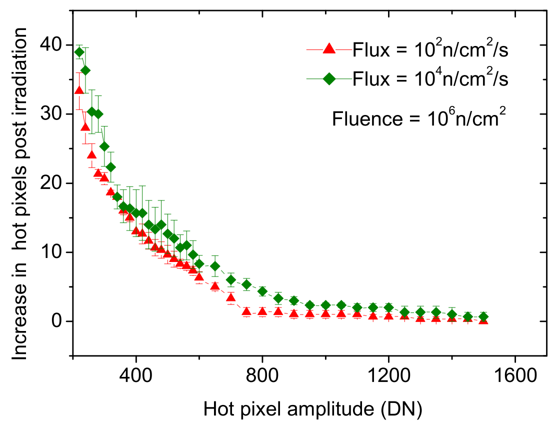

Figure 2: A comparison of the effect of neutron flux on hot pixel generation (average from measurement of 6 sensors). Both curves lie within measurement error justifying the use of accelerated neutron beam test for hot pixel analysis.

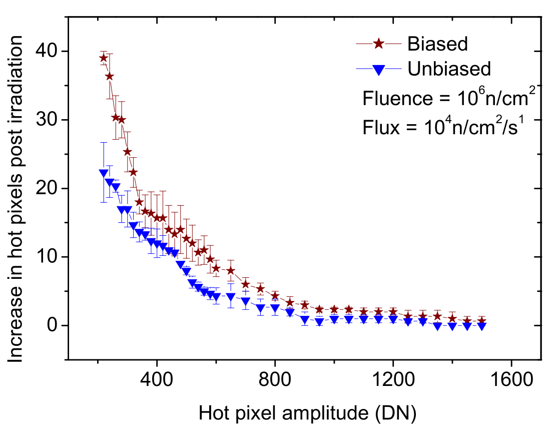

Figure 3: Effect of biasing on hot pixel generation (average from 6 sensors). Biasing increases the prospects of “lower amplitude” hot pixel generation by a factor of two. Effect is seen to drop for “higher amplitude” hot pixels.

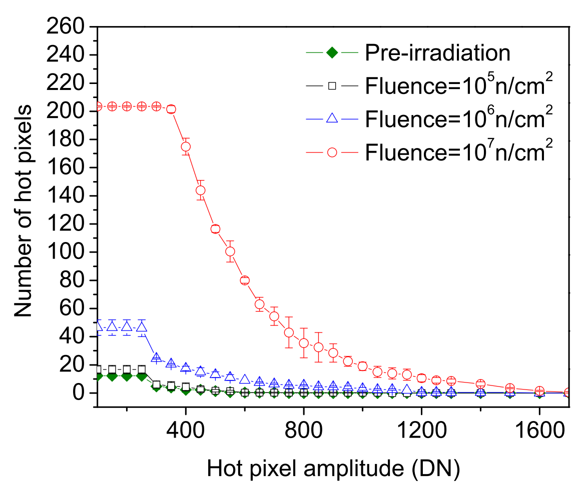

Figure 4: Hot pixel generation as a function of neutron fluence (average from 3 sensors together with standard error) in packaged devices.

Wafer	Number of devices	Received neutron fluence
A	36	10^5 n/cm^2
B	42	10^6 n/cm^2
C	46	10^7 n/cm^2
D	41	None, control group

Table 1: Wafer code and the received neutron fluence

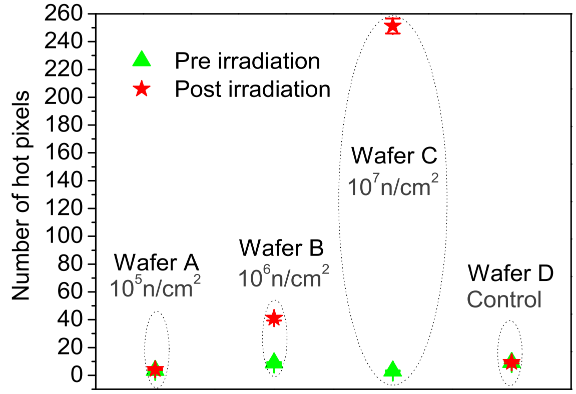

Figure 5: Hot pixel generation as a function of neutron fluence in wafers. Pre- and post irradiation measurement for different wafers that received fluence of 10^5 n/cm^2 (A), 10^6 n/cm^2 (B) and 10^7 (C) n/cm^2 respectively. One wafer is kept as a control group (D).

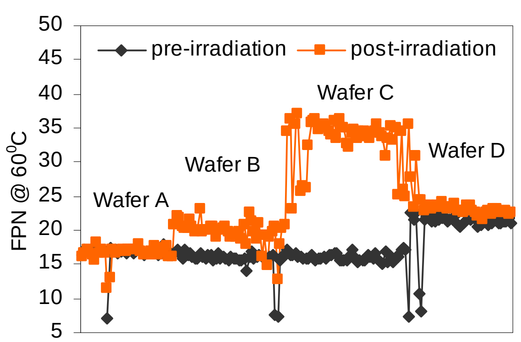

Figure 6: Pre- and post irradiation FPN

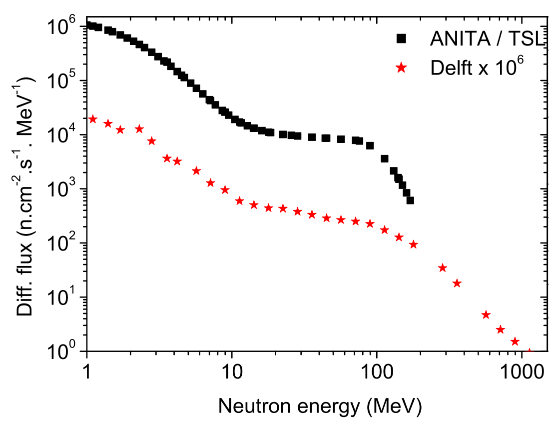

Figure 7: Neutron spectra at Delft and ANITA beam of TSL. ANITA neutron spectra provided by the facility. Delft spectra multiplied by a factor of 10^6 for comparison with ANITA/TSL and calculated using QARM.

Figure 8: Comparison of reference sensors (natural cosmic ray environment) with neutron irradiated sensors (average data from 10 sensors). Graphs are put on scale by normalizing the reference sensors (/day) and neutron irradiated sensors (/second). The similar pattern establishes terrestrial cosmic ray neutron as a major contributing factor in hot pixel development.