Influence of Terrestrial Cosmic Rays on the Reliability of CCD Image Sensors

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Abstract

An aging effect in solid-state image sensors is studied : the generation of hard errors resulting in hot spots or white pixels. These effects even occur in sensors that are stored on the shelf. This paper describes experiments that are conducted to prove that the main origin can be found with neutrons that are part of terrestrial cosmic rays.

Introduction

It is well known in the imaging community that image sensors are subject to a degradation effect due to radiation. These effects manifest themselves as an increase in dark current, a loss in transfer efficiency (in the case of CCDs) and in extra “hot spots” [1][2]. Devices intended for space application are fabricated in special processes so that the sensors can withstand radiation or to make them radiation-hard. The question is whether similar effects are also responsible for the creation of hot pixels during normal on-the-shelf storage of image sensors. Simply storing imaging devices on the shelf does indeed result in a few extra hot spots in the picture taken at a later time. The problem is illustrated in Figure 1 : shown is a dark image generated by a particular imager at two time points separated by 1.5 years. Notice the creation of a few extra hot spots over time.
It is important to point out that these hot spots are permanent. They are not a soft error, in the sense that a high-energy particle is absorbed in the silicon, generates a cloud of charge carriers and after the next image all effects are gone. The effect investigated in this study are hard errors : once they are created, they remain present in the imagers.

Evaluation Method

To study the hot spot generation in image sensors, an extensive measurement program has been established. In its simplest form, devices were stored on the shelf and were measured at time intervals of several weeks. By comparing dark images obtained during various measurement cycles, research can be done to study the generation of hot spots over time. All measurements reported are done on CCD frame-transfer imagers with an active area of 8.8 x 6.6 mm^2, integration of 20 ms, pixelclock of 18 MHz and at 60°C. The images were captured by a camera (internal gain 256, internal black level 0), 12 bit ADC, a frame grabber and a PC.
After having two measurements available images are compared on a pixel-by-pixel basis. The result of this analysis is not just the amount of extra hot spots generated in the sensor between the two measurements, but also the amplitudes of the newly-generated hot spots are recorded.

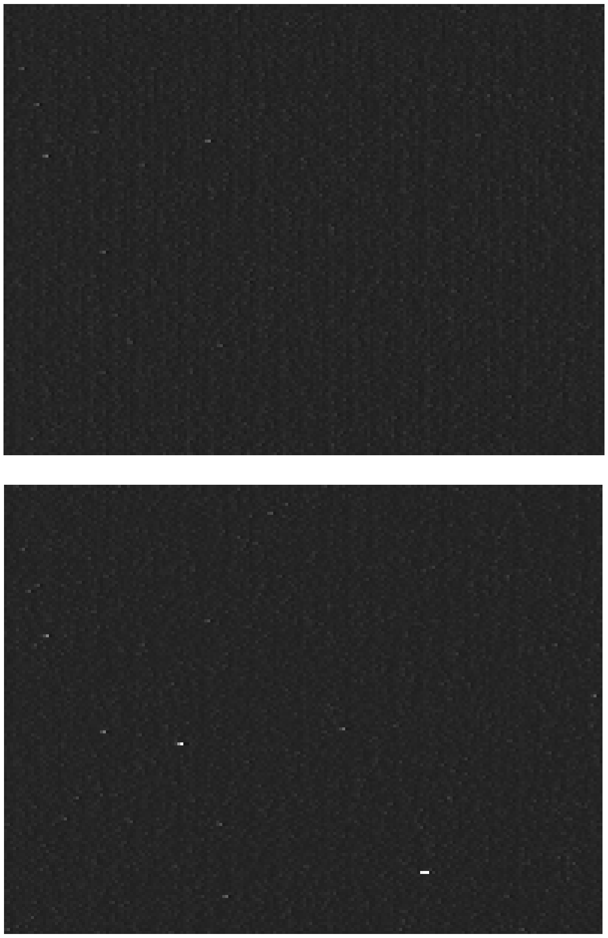

Figure 1 : Problem definition, two dark images (200 x 150 pixels) taken by the same image sensor, time elapsed between the two pictures is 1.5 years (the horizontal line shape of the hot spots is due to the stretching of the image).

On-the-shelf storage of imagers at sea level

Devices were stored on-the-shelf in Bree (Belgium, N 51°08’29”, E 05°35’19”), and measured at regular time intervals. Figure 2 shows a typical result obtained from such a series of measure-ments : on the horizontal axis the amplitude of a newly-grown hot spot is shown, the vertical axis shows the probability that such a hot spot will be created per sensor and per day. The devices were stored on-the-shelf for periods of 6 weeks or longer between two measurements. The curve shown is the average of all measurements done over a period of 4 years. From these results it is clear that the generation of new hot spots can be relatively high, but strongly depends on the amplitude of the hot spot itself.

What can be the origin of the extra generated hot spots ? Tests were done extensively to exclude the effect of the cover glass, ceramic package, adhesives, storage foam, shipping box, etc. These materials had no effect at all on the creation of hot spots or hard errors, although it is known that they can have an effect on the generation of soft errors [3]. Shielding the imagers with lead (3 mm thickness) did not help either.

Overseas shipping of devices

After an extensive literature search, it is believed that the effect illustrated in Figures 1 and 2 is due to high-energy cosmic rays, present even at sea level. Terrestrial cosmic rays are the result of very-high energy particles created in space and/or by the sun, which hit the earth's atmosphere [4]. These GeV-particles create an avalanche effect on their way to the earth's surface. The energy, density and nature of the cosmic rays is very dependent on global altitude and latitude. To prove the fact that terrestrial cosmic rays are the cause of the hot spot generation, and to check the dependency on altitude and latitude, sensors were shipped by aircraft and by boat to Japan. During all experiments, reference sensors were stored on the shelf in Bree and were used for comparison tests.

The results from a shipment by aircraft to Tokyo are illustrated in Figure 3 (similar experiments were done with sending imagers to San Francisco). This experiment was based on two trips back and forth. Every flight from Amsterdam to Tokyo or vice versa takes about 12 hours. So, a complete trip corresponds to about 1 day. The reference curve shown in Figure 3 is the one already discussed in Figure 2. With respect to the results in Figure 3, a few interesting remarks can be made :

- notice the increase in probability to create extra hot spots. On the average, sending imagers back and forth to Tokyo corresponds to an increase in hot spot density that is equivalent to a storage of 100 days at sea level. This is fully in line with research done by IBM and Boeing on soft error creation in memories [5][6],
- hot spots with a large amplitude seem to suffer more from this effect,
- the repeatability of the experiments is remarkable, the two trips in were several months separated from each other,
- flying the devices to Tokyo brings them to an higher altitude (33,000 feet) and to a higher latitude as well, Both effects can not be separated from the experimental results, but their effect on the hot spot creation is obvious.

Image sensors were shipped to Tokyo by boat as well : they left the harbor of Rotterdam fro a trip of 40 days to Tokyo. After arrival in Japan they were immediately returned by boat (40 days extra). After a total trip of 80 days the sensors were analyzed again. The results are shown in Figure 4. When the devices travel by a boat, they stay at sea level. If the terrestrial cosmic rays are the cause of the hot spot generation, then shipping the sensors by boat should incur a less pronounced effect than sending them by airplane. Figure 4 proves this statement. Even a slight improvement can been seen : for hot spots with a larger amplitude, the generation probability is even less than the one for the reference material. The explanation for this effect can be found in the route the boat took : after leaving Rotterdam, it rounded South Africa before continuing to Tokyo. During this route, the boat moves away from the earth's magnetic north pole and actually the sensors travel on a more favorable latitude [4].

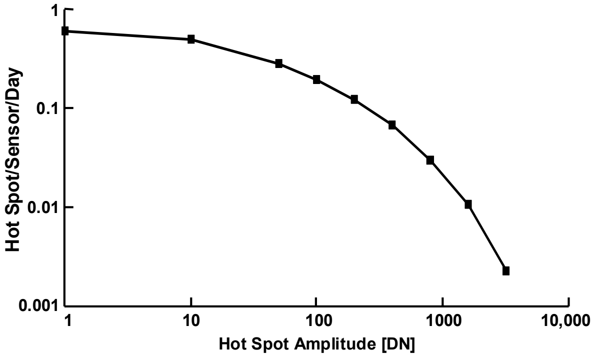

Figure 2 : Cumulative probability of hot spot creation : the number of hot spots created per sensor and per day as a function of the amplitude of the hot spots.

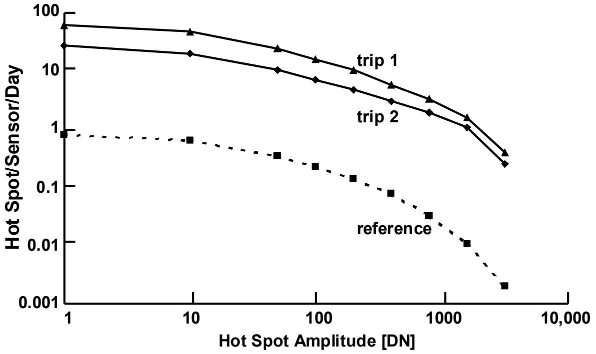

Figure 3. Results obtained after sending the imagers back and forth to Tokyo by airplane, two experiments are shown. Solid curves represent the measurements, dotted curve illustrates the reference material.

On-the-shelf storage at non-sea levels

Another interesting experiment is the storage of the sensor at elevated altitude for a longer period of time. The imagers were put on the shelf of the Jungfraujoch lab. (Switzerland, 3450 m above sea level) for a period of 3 months. After their return, they were immediately measured. The experimental results are shown in Figure 5. What could be predicted came through : an increase in the hot spots, due to an increase of cosmic ray density at higher altitudes. The ratio between the reference material is almost a factor 10 for the large-amplitude hot spots, for the small-amplitude hot spots, the ratio is about a factor 5.

Storing the sensor underground was the subject of a last storage experiment. To completely protect the imagers from incoming cosmic rays, a concrete wall of 20 m is needed. The SCK-lab in Mol, Belgium, is located underground at a depth of 250 m under sea level. Measurements performed by the SCK engineers proved that 250 m of clay ground is more than enough to absorb all incoming cosmic rays. When the devices came back out of the laboratory, they were immediately analyzed. The results are sown in Figure 6. They did not really conform to the expectations :

- a factor of 10 to 1000 improvement could be seen for large-amplitude hot spots. Due to the fact that the lab underground is completely free of cosmic rays, even a larger improvement was expected,
- almost no improvement could be recognized for small-amplitude hot spots. This result might indicate that more effects than just cosmic rays are present. One possible explanation is the increase of dark current over time. A slight increase of the average value gives rise to the increase of dark fixed-pattern noise as well, and this can be seen as an increase in the lower-amplitude hot spot density.

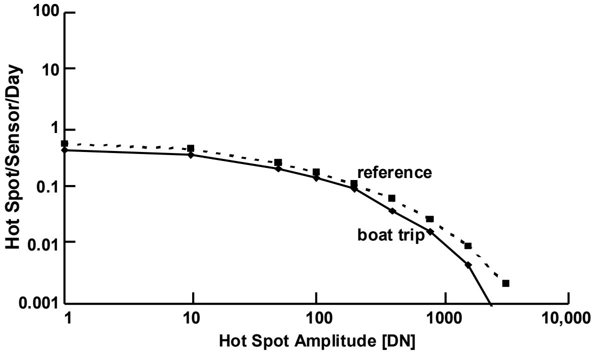

Figure 4. Results obtained after sending the imagers back and forth to Tokyo by boat. Solid curves represent the measurements, dotted curve illustrates the reference material.

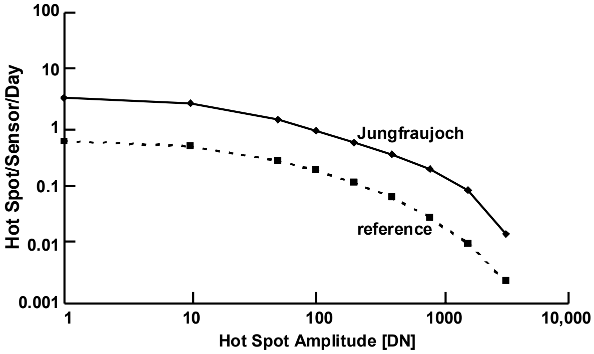

Figure 5. Results obtained after storing the imager for 3 months at Jungfraujoch (350 m above sea level). Solid curves represent the measurements, dotted curve illustrates the reference material.

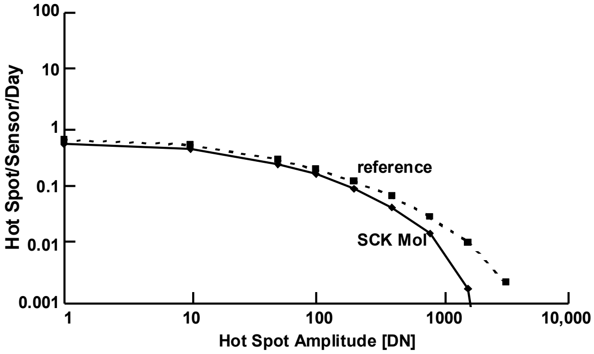

Figure 6. Results obtained after storing the imagers for 3 months 250 m under the ground. Solid curves represent the measurements, dotted curve illustrates the reference material.

Fitting the experimental data

Another way of presenting the results from the on-the-shelf-storage experiments is shown in Figure 6. A cumulative histogram is shown, with the hours of storage on the horizontal axis, and on the vertical axis the cumulative amount of sensor (in %) that show an extra hot spot. The dots shown in Figure 6 are measurements obtained for hot spots with a value of 2250 DN or larger. The solid curve is a fit through the measured points by means of an exponential curve :

$$y = 100\cdot[1-\exp(a_x\cdot t)]$$

in which y represents the cumulative amount of sensors with a newly-generated hot spot of amplitude 250 DN, 1250 DN, 2250 D and 3250 DN, t represents the storage time (in hours) and a_x is the fitting parameter (/hour) and x the hot-spot amplitude. For every spot amplitude x, a fitted curve can be generated and a fitting parameter a_x can be found. In this work hot spots with amplitudes between 250 DN and 3750 DN with a steps of 250 DN are investigated. In Figure 7 the exponent a_x is shown as a function of the amplitude x of the hot spots. The locus is the result of the aforementioned curve-fitting exercise. The two straight lines are two fits to the empirically obtained data points. It is noticeable from Figure 7 that two groups of results can be recognized :

- data points for hot spots with larger amplitudes correspond to relatively low values of the fitting exponent. These hot spots are most probably due to damage of cosmic rays created in the bulk of the silicon. The energy of the cosmic rays is high enough to displace a silicon atom from its original location in the mono-crystalline bulk. Typically and energy of about 150 keV is needed to displace a silicon atom in the bulk lattice [7]. In this way a vacancy as well as an interstitial is created. Vacancies created by incident radiation are unstable and migrate to energetically favorable positions in the lattice. Typically the vacancies become trapped near impurity atoms due to the stress imposed on the lattice by these impurities. Typically only 2 % of the initially generated vacancies remain [8],
- data points for hot spots with smaller amplitude correspond to relatively high values of the fitting exponent. These hot spots are most probably due to damage created at the Si-SiO_2 interface, due to the creation of extra interface states, and resulting as well in an overall increase of the dark current and dark-current fixed-pattern noise.

Nature of the cosmic rays

The cosmic rays that reach the earth's surface are the co-called secondary rays. The primary cosmic rays come from the Milky Way and from the sun. These are mainly composed out of protons with very high energies, ranging into the GeV. The primary cosmic rays collide with the various atoms and molecules of the atmosphere and an avalanche effect is generating secondary cosmic rays. These are composed out of protons, pions, electrons, neutrons, muons, etc. The energy of the secondary cosmic rays is much lower than the energy of the primary one, but still can range into the MeV [4].

The amount of particles and the nature of the species composing the secondary cosmic rays can be calculated by some simple formulae [4]. Knowing this data, is it possible to calculate the ratio in electron, proton, pion, neutron and muon concentration within the cosmic ray flux between Bree on one hand and Jungfraujoch and airplane altitudes on the other hand. These results are listed in Table 1.

The hot-spot generation data from the airplane trips and the storage experiment at Jungfraujoch showed an increase in number of hot spots by a factor of 100 and 10 respectively. Comparing these numbers with the data from Table1, the conclusion might be taken that the creation of hot spots is primarily due to neutrons. This statement is fully in line with research data obtained from experiments with neutron radiation on image sensors [9].

Conclusion

The generation of hard errors, resulting in hot spots or white pixels has been studied. These effects occur in sensors that are even stored on the shelf. This paper describes experiments that have been conducted to prove that in fact two mechanisms are responsible for the hot spot generation. The most severe one can be attributed to neutron radiation, introduced by secondary terrestrial cosmic rays. The creation of hot spots is due to displacement damage in the silicon bulk. It is a typical silicon issue, independent of technology, architecture, sensor type or sensor vendor, and it can be observed in CCDs as well as in CMOS image sensors.

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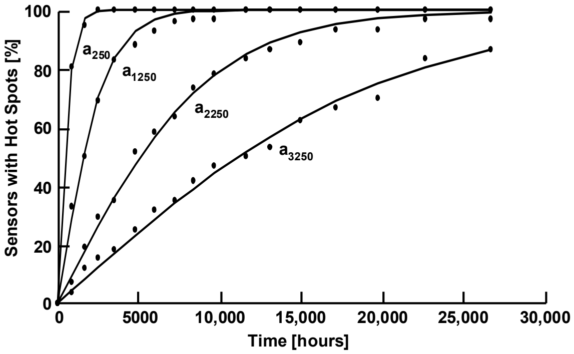

Figure 6. Cumulative number of sensors showing an extra hot spot (of 2250 DN) as a function of storage time. Dots represent the measured data, solid curve is an exponential fit.

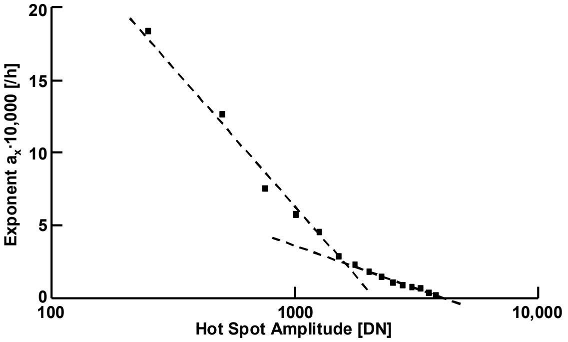

Figure 7. Fitting parameter a_x as a function of the hot spot amplitude.

Table 1. Ratio of the various cosmic ray species between Jungfraujoch and Bree and the airplane trips and Bree.

	Ratio Jungfraujoch/Bree	Ratio Airplane/Bree
Electrons	26	1171
Protons	20	616
Pions	20	616
Neutrons	9	118
Muons	2	4

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