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Spec Title: RADIATION HARDENING OF CYPRESS STAR SENSORS - AN5011

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Radiation Hardening of Cypress STAR Sensors - AN5011

Introduction

Several types of radiation can cause degradation effects in solid-state imagers. Two basic mechanisms can be distinguished: generation of electron-hole pairs (ionization) and the displacement of atoms from their lattice positions (displacement damage). Particles passing through a silicon device will, in general, lose their energy by ionization of the silicon and the oxides and deposit the remainder of the energy into displacement. The deposition of energy by means of ionization can lead to transient or permanent degradation due to an accumulation of a certain total ionizing dose. Typically, the latter type of degradation is studied by means of gamma rays from a Co-60 source. On the other hand, single heavy ions can generate enough electron-hole pairs to cause single event effects (SEE). Displacement damage effect studies are mostly performed by use of energetic protons.

Radiation Hardening of STAR Sensors

Total Ionizing Dose (TID) Damage

Ionizing radiation gives rise to the production of positive charges in the gate and field oxides of MOS structures. As a consequence of this positive charge build-up, the flatband and threshold voltages of the particular MOS structure will decrease (the amount depends on the oxide thickness and biasing voltage). This charge build-up leads also to a significant leakage current increase in normal transistors and to the loss of isolation between adjacent devices. The generation and trapping of radiation-induced holes that takes place in the surface oxide layers results in an increase of the leakage current in the photodiode and thus a larger dark current figure of the imager. Ionizing radiation can also degrade the photoresponsivity of the pixels.

Cypress has studied total ionizing dose damage in detail and has developed proprietary design techniques to enhance the TID tolerance drastically. Both STAR250 and STAR1000 are processed in the standard 0.5 μm AMIs CMOS technology and the radiation-tolerant layout rules have been applied consequently throughout both designs. All nMOS transistors and photodiodes in these sensors are designed with special gate geometries and additional guarding structures to avoid or reduce above-mentioned degradation effects.

Single Event Effects (SEE)

Apart from the long-lived effects that are usually caused by a particular total ionizing dose, a energetic heavy ion (cosmic ray) or proton may generate enough electron-hole pairs along its track that is can affect the functionality of circuits.

A transient effect is called single event upset (SEU). For a CMOS APS, an SEU can occur in different forms. A flux of ionizing particles impinging in the pixel array will cause a random arrangement of white speckles, because charges generated by the radiation are collected in the same way as charges from absorbed visible light. The sensor cannot discern different types of radiation. An SEU in the peripheral logic circuits can result in false read or reset pointers, etc. However, an SEU causes no permanent damage and the problem can in most cases most easily be solved by appropriate system design (increased frame rate, majority logic, etc.).

The p-n-p and n-p-n parasitic bipolar transistors that are inherent in CMOS structures may cause radiation-induced latch-up. Latch-up will lead to permanent damage if the power supply of the circuits is not immediately switched off. In the STAR sensors, the guarding of the transistors, which results immediately from the radiation-tolerant design techniques described above, gives rise to a reduction of the distributed resistance across any base-emitter junction. This results in a highly improved latch-up immunity.

Displacement Damage

Energetic photons and charged particles incident on silicon can also lose their kinetic energy by an energy transfer to the silicon nuclei and can in that way cause displacement of the atoms. Various types of defects are then created in the silicon. These defects disturb the lattice periodicity and can have a major impact on the electrical behavior of the semiconductor device.

Cypress has studied and modeled the proton-induced dark current increase and dark current non-uniformity in detail. The increase depends on the fluence, type and energy of the particles through their non-ionizing energy loss (NIEL) value. The displacement damage reflects the fundamental outcome of the way protons interact with the silicon and, as a consequence, the defect production cannot be avoided. However, the induced dark current increase scales proportionally with the depleted volume in which the defects are created. The STAR sensors are designed using the proprietary technique of Cypress to collect photo-charges in the pixel with a small photodiode and high quantum efficiency.

Comparison with CCDs

Co-60 irradiation of standard CMOS APSs shows that the dark current signal and dark current non-uniformity increases rapidly with increasing total ionizing dose. The total ionizing dose tolerance is usually limited to a few hundreds of Gys (1 Gy = 100 rad). This is the same order of magnitude for the total ionizing dose at which failure of most commercial CCDs is observed. However, voltage shifts are smaller in CMOS APSs. Since the progress of CMOS technologies is accompanied by a reduction of the gate oxide thickness, radiation-induced shifts of the flatband and threshold voltages will further decrease. Gate oxides in CCD technologies are typically thicker and their biasing voltages are larger. As a consequence, the shifts in CMOS APSs are much less problematic.

CCD-like charge transfer losses are absent. Since CMOS APSs require only one charge transfer for signal readout, they

are insensitive to CTE problems induced by either ionizing radiation or displacement damage.

In the STAR sensors, the dark current increase after proton irradiation appears to be significantly lower than in CCDs. The reason for this can be found in the smaller pixel-depletion volume that determines the number of elastic and inelastic recoils in each pixel. In comparison to the depletion volumes in CCDs and CIDs, the depletion volumes in CMOS APSs can be considerably smaller using FillFactory's high fill factor technology (US Patent nr. **6,225,670)**.

Presently Performed Radiation Tests and Results

Cypress has presently tested STAR250 extensively for total ionizing dose damage with Co-60 source and for displacement damage with protons. Latch-up tests on STAR250 have not been done by Cypress, but by customers in the framework of an ESA contract. No latch-up has been observed up to 68 MeV.cm^2/mg (highest tested LET). A more limited number of total ionizing dose tests were performed on STAR1000. The results are in line with the results from STAR250 devices as could be expected since for both sensors the same design techniques are used (radiation-tolerance by design). It is expected that the results for proton damage will also be comparable although one should take into account that STAR1000 has only one photodiode per pixel instead of four in STAR250. This should result in smaller dark current spikes for STAR1000.

Results of TID

Dark Current

Figure 1 shows the dark current density increase measured on two sensors as a function of the total ionizing dose. The measurements of the dark current density increase are plotted on a logarithmic total ionizing dose axis.

Contrarily to the large dark current increase seen in standard CMOS APSs, the dark current in STAR250 devices shows a much smaller and logarithmic increase. The dark current increase DC_{TID} due to total ionizing dose damage can be fitted with the empirical formula

$$\Delta DC_{TID}(TID) = max(0,(K\log 10)\frac{TID}{TID_{thres}})$$

with TID the total ionizing dose, TID_{thres} a total ionizing dose threshold and K a proportionality factor that gives the dark current density increase per decade (nA/cm^2/dec). The fitted curve is shown in *Figure 1* as well with TID_{thres} = 350 Gy and K = 0.54 nA/cm^2/dec.

Fixed Pattern Noise (FPN)

The on-chip FPN correction scheme in the STAR sensors has been designed to cope with radiation-induced voltage variations. *Figure 2* shows the FPN as a function of the total ionizing dose for three different STAR250 sensors. These values are measured on the whole pixel array. These measurements show that there is no increase in FPN with ionizing radiation. The remaining FPN is measured to be well below 0.4 % of full well for the whole array. If the FPN is measured locally on 10 x 10 windows, its value is 0.07 % (1.2 mV).

Photo-response and Photo-response Non-uniformity (PRNU)

The influence of ionizing radiation on the photo-response and PRNU in STAR250 is shown in *Figure 3*.

A decrease of up to 20 % can be observed. The local PRNU increases from 0.5 % up to 1 %.

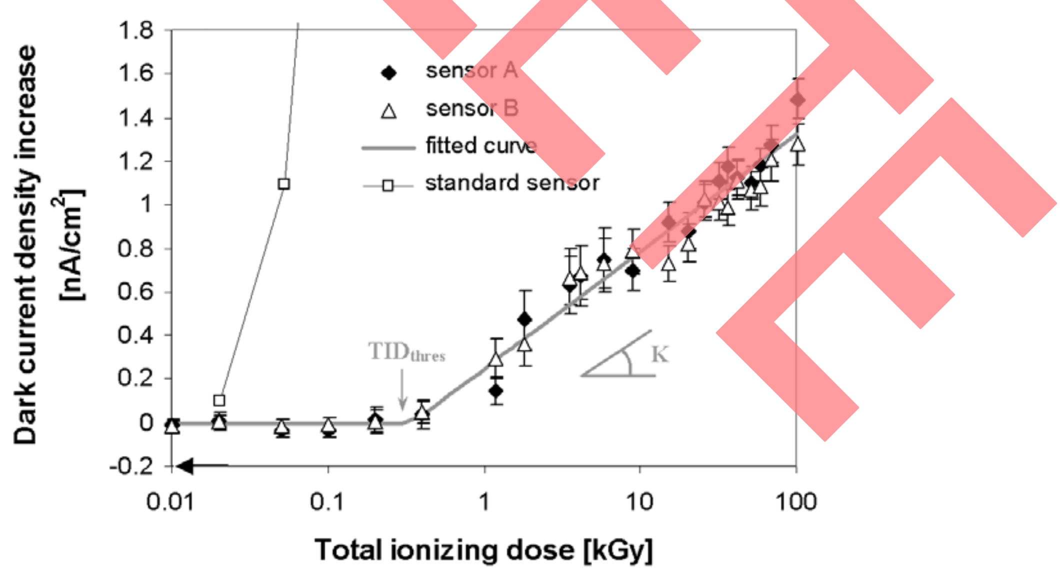


Figure 1. Measured dark current density increase versus the logarithm of the total ionizing dose (sensor A and B) (dose rate: 100 Gy(Si)/h). The TID_{thres} is the total ionizing dose threshold that is necessary to observe a dark current increase. K gives the dark current density increase per decade (nA/cm^2/dec). The dark current increase measured in a standard sensor is shown as

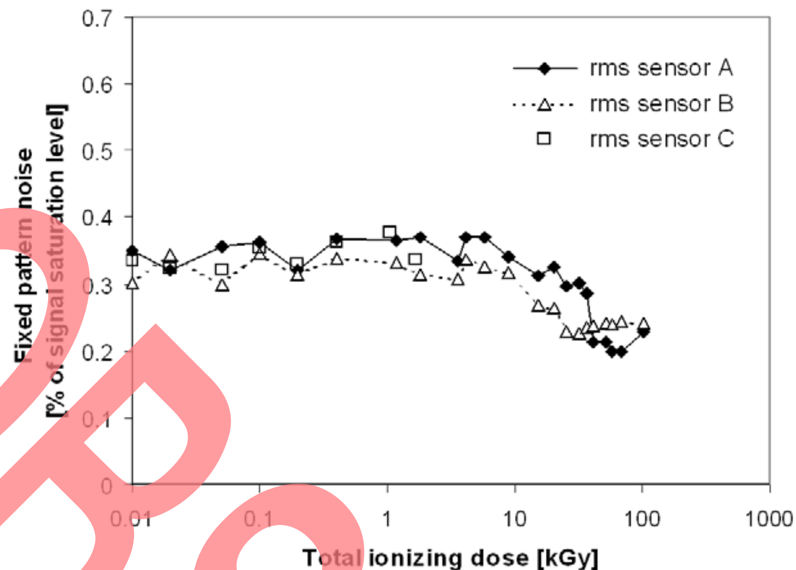


Figure 2. Fixed pattern noise (rms) as a function of the total ionizing dose for three different sensors. The fixed pattern noise was measured on the whole pixel array.

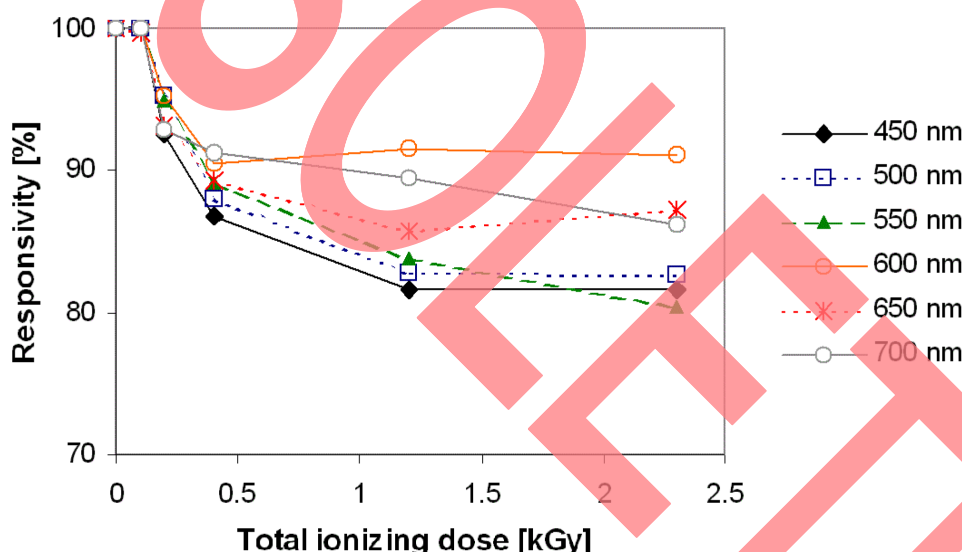
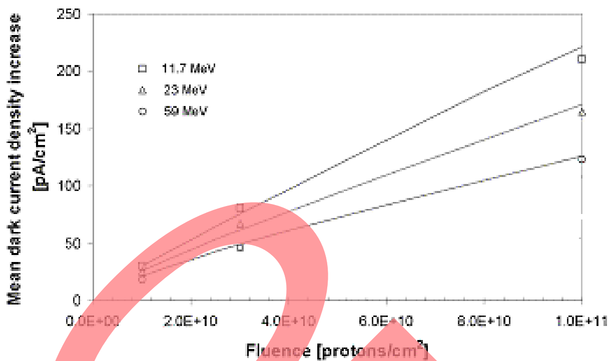


Figure 3. Average responsivity (% of pre-irradiation value) with total ionizing dose for different wavelengths (average of 5 different sensors).



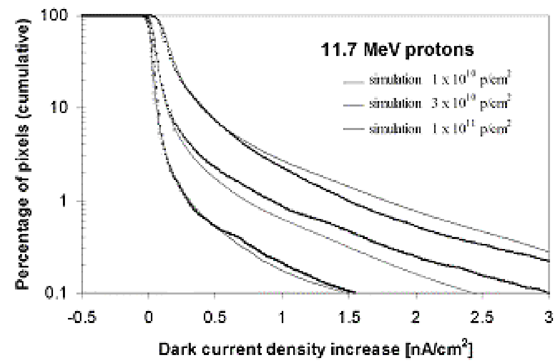


Figure 4. Mean dark current density increase measured on nine STAR250 devices and simulated curves (at 27 ºC) (left). Measured and simulated cumulative distributions of the dark current density increase for 11.7 MeV protons at different fluences (right).

Results of Proton Tests

The proton-induced displacement damage mainly affects the dark current distributions of the sensors. Cypress has not observed any measurable degradation of photo-response due to displacement damage. *Figure 4* (left) shows the mean dark current density increase measured on nine devices, together with the simulated curves, as function of the proton fluence at different proton energies.

Figure 4 (right) shows the cumulative distribution of the dark current increase in the case of 11.7 MeV protons. The figure gives the percentage of pixels that show a larger dark current density increase than the given dark current density increase. The illustrated curves can be used to predict proton-induced damage and lifetime of the sensor. For example, for a particular application it might be important that a certain percentage of pixels does not exceed a specified maximum dark current density increase. This criterion can easily be verified in the figure.

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