Challenges in Improving the Performances of Radiation Hard CMOS Image Sensors for Gigarad (Grad) Total Ionizing Dose

Vincent Goiffon¹, Serena Rizzolo¹, Franck Corbière¹, SÉbastien Rolando¹, Azouz Chabane¹, Marius Sergent¹, Philippe Paillet², Sylvain Girard³, Magali Estrébeau¹, Pierre Magnan¹, Marco Van Uffelen⁴, Laura Mont Casellas⁴, Marc Gaillardin², Robin Scott⁵ and Wouter De Cock⁶

¹ISAE-SUPAERO, 10 avenue Edouard Belin, 31055 Toulouse, France
²CEA, DAM, DIF, Arpajon, France
³Université de Saint-Etienne, Laboratoire Hubert Curien, UMR-CNRS 5516, France
⁴Fusion for Energy (F4E), c/Josep Pla, nº 2, Torres Diagonal Litoral, Ed. B3, 08019 Barcelona, Spain
⁵Oxford Technologies Ltd.(OTL), 7 Nuffield Way, Abingdon OX14 1RL, UK.
⁶SCK-CEN, Boeretang 200, 2400 Mol, Belgium

Email: vincent.goiffon@isae.fr, Phone: +33 5 6133 8093

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I. INTRODUCTION

Solid-state high definition and color imagers with radiation hardness well above than a Total Ionizing Dose (TID) of 100 Mrad(SiO₂) are required for the development of critical remote handling systems in ITER fusion reactor (Fig. 1). The availability of such rad-hard imager would also completely transform the way remote handling and monitoring are performed in highly radioactive environments, by increasing operational efficiency, but also by reducing risks, costs and the frequency at which cameras are replaced. It would enable the inspection of radioactive areas that cannot be observed today. Typical applications that would greatly benefit from this solution are remote handled maintenance, monitoring and inspection operations in many nuclear facilities—such as nuclear power plant, nuclear storage waste repository, particles physics and irradiation facilities (e.g. CERN)—as well as mobile rescue robots.

This IISW proceeding paper discusses the main challenges to meet in order to develop a Gigarad-rad-hard-CMOS Image Sensors (CIS) with acceptable performances. The discussion is based on the most recent results obtained on the currently developed demonstrator for ITER remote handling (this development is described more in details in [1]) compared with previous work on different design and process variations [2], [3]. All the results reported here have been obtained on a standard 180 nm CIS technology.

Only conventional photodiode architectures (i.e. 3T pixels [4]) are considered here since ionizing radiation renders Pinned Photodiodes (PPD) [5], [6] unusable after several Mrad [2]. As regards irradiation conditions, ⁶⁰Co gamma ray and 10 keV X-ray sources have been used with different biasing conditions (ON or OFF) and for the main discussion developed here, these different irradiation conditions lead to comparable degradation at a given TID. Therefore, for the sake of clarity, irradiation conditions are not stated for each results discussed here.

II. MAIN CHALLENGES

Deep submicrometer CMOS transistors are often supposed to be intrinsically radiation tolerant and the use of enclosed geometries is not always relevant for low or moderate TID applications (such as space or medical applications). Especially the use of enclosed geometries is often not considered for P-channel transistors or for core (i.e. low voltage) MOSFETs.

For a targeted end-of-life TID between 100 Mrad and 1 Grad, the use of Enclosed Layout Transistors (ELT) [7] appears necessary on both N-channel and P-channel “low” (1.8 V) and “high” (3.3 V) voltage MOSFETs to mitigate the radiation induced narrow channel effect (RINCE [8]). Fig. 2 illustrates this first conclusion as it shows that after a few Megarad the tested standard P-MOSFET is not functional anymore whereas the ELT P-MOSFET after 300 Mrad can still be used.

Hence, by using appropriate radiation hardening by design techniques [9], basic analog and digital CMOS functions (combinatorial and sequential logic, amplifiers, multiplexers, I/O pads, ADCs...) can tolerate up to 1 Grad of TID without suffering critical failure (see Fig. 3 and 4 for illustrations).

Fig. 4 shows the remaining degradation measured on a CIS current source ELTs for different device type. As expected [9], when thinner gate oxide is used (1.8 V transistor compared to 3.3 V one), the radiation induced voltage shift is significantly reduced (about a factor of 4 reduction). However, 3.3 V N-channel transistors are less degraded than 1.8 V P-channel ones for higher TID than 300 Mrad.

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As a consequence, for analog circuits, avoiding P-channel transistors and using N-channel 3.3 V MOSFETs as much as possible is an efficient solution (in this technology) to keep the radiation induced voltage shift acceptable and a wide linearity range between 100 Mrad and 1 Grad.

Thanks to their limited thickness, the optical properties of dielectric material typically used on top of CIS are not significantly degraded (see Fig. 5 and Fig. 6 for an illustration of color filter array transmittance evolution with TID).

As a first conclusion, the main issues to solve are related to the pixel design and more precisely to the influence of photodiode design on the radiation induced Dark Current (DC) increase.

III. REDUCING DARK CURRENT

To identify the levers that can influence this DC increase, several technological options are explored (see Tab. I for a quick summary) alongside a few variants of the promising gate overlap design (discussed in [2]) as illustrated in Fig. 7.

In this particular design with a protective gate, the lowest dark current should be reached for a negative or low gate voltage (as in PPD pixels) when the gate channel in placed under accumulation. Such behavior is observed in Fig. 8, as expected, on the gate overlap design terminated by a P+ ring. If the gate voltage is increased beyond this optimum gate voltage, the dark current rise again in the P+ isolated pixel because of high electric field effects. On the contrary, in the pixel with only a gate isolation (Fig. 7b), increasing further the gate voltage reduces the measured dark current. The fact that the dark current shot noise (secondary Y axis in Fig. 8) also decreases with the dark current confirms that this phenomenon is a real reduction of dark current (not a simple subthreshold reset compensation current).

The radiation induced positive trapped charge leads to the creation of weak inversion channels at the interfaces of Shallow Trench Isolations (STI) that are all connected to in-pixel ELT outer drains (biased to VDD or a voltage close to VDD). In this configuration (illustrated by the drawing presented in Fig. 9), dark electrons generated at the STI interface as well as dark electrons generated at the gate oxide interfaces are more likely to be collected by the high voltage N+ drains than by the photodiode itself, then cancelling the dark current coming from these interfaces.

This DC cancellation mechanism [3] has limited unwanted effects on the CIS performances as far as the gate voltage stays low enough to prevent the reduction of the full well capacity.

Fig. 10 shows that the studied technological variations (Tab. I) also allow reducing the dark current by an additional order of magnitude compared to the results presented at 2015 IISW [2]. Best results in terms of absolute dark current level in the 100 Mrad – 1 Grad range on the studied radiation hardened photodiode designs are low enough to enable acceptable imaging performances with sufficient illumination conditions (which is the case of this particular development). However, in applications where light power is limited, further dark current increase would be beneficial. Future research will focus on mitigating further this limiting radiation induced dark current increase.

REFERENCES

Fig. 1: Illustration of ITER fusion reactor and magnification of one of the in vessel remote handling systems for which rad-hard cameras are required.

Fig. 2: Minimum size 3.3V P-MOSFET current-voltage characteristics evolution with TID (from 0 to 30 or 0 to 300 Mrad(SiO$_2$)) presented for a standard (open layout) and an radiation hardened (enclosed layout) transistor. The standard P-MOSFET layout suffers from a gate oxide positive trapped charge induced flatband voltage shift in addition to a RINCE induced voltage shift. This transistor is too degraded after 30 Mrad to enable the design of a Grad radiation tolerant CIS. On the other hand, the ELT design mitigates the RINCE effect in this PMOSFET and the remaining degradation after 300 Mrad is a 1 V threshold voltage shift due to the gate oxide positive trapped charge.

Fig. 3: Transfer function of 10 bit radiation hardened column Single-Slope ADCs manufactured with a 180 nm CIS process before and after exposure to $^{60}$Co gamma-rays for a TID of 0.6 Grad(SiO$_2$). Differential and Integral Non Linearities (DNL and INL) degradations are below 2 LSB after 0.6 Grad.

Fig. 4: Readout chain current source voltage shift as a function of TID for three MOSFET technology: 1.8V P channel MOSFET (thin gate oxide), 3.3V P channel MOSFET (with double gate oxide thickness) and 3.3 N channel MOSFET (with double gate oxide thickness). Using the thin gate oxide (1.8 PMOST) delays the degradation without reaching saturation whereas 3.3V NMOSFET degrades faster but saturates at 0.1-0.2 Grad leading to better performance beyond 0.3 Grad.

Fig. 5: Color Filter Array (CFA) transmittance before and after irradiation (TID = 1 Grad) showing that CFA degradation is negligible.

Fig. 6: Color image captured by a 256x128-pixel-rad-hard-CIS (RH CIS 2 with 3.3V N-MOSFETs for the analog functions) before (a) and after (b) the absorption of 1 Grad(SiO$_2$) of TID. This figure illustrates the good functionality of the rad-hard CIS and its ability to discriminate contrast and colors (with acceptable degradations) after 1 Grad.
Table I: Summary of the main technological differences between the studied radiation hardened CISs. Pixel array size varies between 128x128 and 256x256 pixels. All the studied imagers have been manufactured using a commercial 180 nm CIS process.

<table>
<thead>
<tr>
<th>Photodiode type</th>
<th>Pixel voltage</th>
<th>Analog readout chain MOSFETS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH CIS 1</td>
<td>Deep</td>
<td>3.3V</td>
</tr>
<tr>
<td>RH CIS 2</td>
<td>Deep</td>
<td>3.3V</td>
</tr>
<tr>
<td>RH CIS 3</td>
<td>Shallow</td>
<td>3.3V</td>
</tr>
<tr>
<td>RH CIS 4</td>
<td>Shallow</td>
<td>1.8V</td>
</tr>
</tbody>
</table>

Fig. 7: Gate overlap pixel design top view illustrations with (a) a P+ isolation between photodiodes and (b) a gate isolation between photodiodes. Undulating arrows represent dark current cancelation paths.

Figure 8: Dark Current (DC) as a function of surrounding gate voltage at 40 Mrad on a 3.3V pixel with a deep diode (CIS 2) for the two isolation cases depicted in Fig. 7. Total output noise (readout + dark current shot noise) is also presented for the gate isolation pixel on the second Y axis to demonstrate that the dark current is effectively cancelled (not just compensated) for gate voltage >0.6V.

Figure 9: Illustration of the Dark Current (DC) cancelation mechanism in irradiated pixel with a gate isolation. After irradiation, dark electrons generated in the gate depleted region are collected by the nearest N+ VDD contacts (in-pixel MOSFET drains) through the STI interface (weakly inverted because of radiation induced positive trapped charge) with no influence on the photocurrent.

Figure 10: Dark current evolution with TID for the different technologies and designs studied. Best results in the Grad range are obtained with the shallow diode with 1.8V operating voltage and a gate isolation between photodiode to enable the dark current cancellation mechanism highlighted in Fig. 8 and 9.