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Dark Current Spectroscopy in neutron, proton and ion irradiated CMOS Image Sensors: from Point Defects to Clusters

Jean-Marc Belloir, Vincent Goiffon, Cédric Virmontois, Philippe Païlet, Romain Molina, Olivier Gilard, Pierre Magnan

Abstract — Dark current spectroscopy is tested on twenty CMOS image sensors irradiated with protons, neutrons and various ions at different energies. The aim of this work is to differentiate the effect of coulomb and nuclear interactions on the radiation-induced dark current distribution and to identify the main radiation-induced defects responsible for the dark current increase for each type of interaction. For low-energy protons and low-energy light ions (which produce well-separated low energy coulomb interactions), we find that most of the pixels belong to a quantized dark current spectrum at low dark current. In these pixels, the dark current increase seems mainly dominated by specific point defects such as the divacancy and the vacancy-phosphorus complex. Thus, these simple defects seem to form when the displacement damage is rather low and sparse. On the contrary, for nuclear interactions (with neutrons or high-energy protons) producing high coulomb NIEL silicon PKAs or for low energy heavy ions (also having high coulomb NIEL), the DCS spectrum is not visible and all the pixels belong to an exponential hot pixel tail which extends to very high dark current. In these pixels, the dark current increase is mainly dominated by defects with close-to-midgap energy levels. These defects seem more complex than point defects because they can have many different generation rates (explaining the smooth hot pixel tail) and because they tend to form when the displacement damage is high and dense.

Index Terms — Dark Current Spectroscopy (DCS), dark current distribution, CMOS Image Sensor (CIS), Pinned PhotoDiode (PPD), coulomb interactions, Rutherford scattering, elastic and inelastic nuclear interactions, NIEL, irradiation, radiation-induced defects, traps, point defects, clusters, annealing, activation energy.

I. INTRODUCTION

Radiation can severely degrade the performance of silicon-based electronic devices such as CMOS Image Sensors (CIS), also called Active Pixel Sensors (APS). In state-of-the-art CIS such as Pinned PhotoDiode (PPD) CIS, one of the most problematic effects is the radiation-induced dark current [1-2] because it decreases the sensitivity and the dynamic range of the CIS. Two main radiation processes contribute to the dark current increase in CIS: the ionization in the silicon oxide and the displacement damage in the silicon bulk [1-2]. In both cases, the dark current increase is due to the formation of electrically active defects in the depleted silicon, either at the interface between the silicon and the silicon oxide (for the ionization) or within the silicon bulk (for the displacement damage). These defects, also called Shockley-Read-Hall Recombination-Generation (SRH R-G) centers, can introduce energy levels close to the middle of the silicon bandgap, allowing the thermal generation of electron-hole pairs [3]. On one hand, the ionization induces a progressive and uniform increase of the defect density at the oxide interface, leading to a similar dark current increase in all the pixels of the CIS [1]. On the other hand, the displacement damage corresponds to the displacement of a silicon atom (called Primary Knock-on Atom or PKA) in the silicon bulk by the incident particle [2]. The PKA can displace other atoms until coming to rest, forming a displacement damage cascade. The atomic disorder can rearrange in one or several electrically active defects, and the dark current increase will depend on the amount of displacement damage deposited by the particle in the pixel. For particles typical of space and nuclear experiment environments, nuclear interactions exist and can transmit very high energies to the PKA. In that case, the displacement damage can induce high dark current increases in some pixels and lead to a high dark current non uniformity in the CIS [2].

The displacement damage can be deposited by two main mechanisms depending on the particle and its energy: the coulomb (Rutherford) scattering and the nuclear scattering [4]. The coulomb scattering corresponds to the electrostatic repulsive interaction between the nucleus of the target silicon atom and the incident ion. This interaction transmits low energies to the PKA, typically tens to hundreds of eV for an average of roughly 200 eV [4,5]. Indeed, the Probability Density Function (PDF) of the energy transmitted to the PKA in a coulomb interaction decreases with the square of the PKA energy [5,6]. If we assume that the number of displaced atoms is proportional to the PKA initial energy and that the mean displacement energy per atom is 2.5 T_D [7,8] (where T_D is the displacement threshold energy and is about 21 eV in silicon [6]), then each interaction displaces only a few silicon atoms (five in average for a squared multiplicative inverse PDF, which corresponds to a mean PKA energy of 250 eV).
On the other hand, nuclear scattering corresponds to the direct collision between the ion and the target atom nuclei. This interaction can be elastic (the momentum is conserved and the nuclei are not modified) or inelastic (which corresponds to nuclear reactions such as fragmentation or spallation). Nuclear interactions can transmit a non-negligible fraction of the incident particle energy to the PKA, typically hundreds of keV to a few MeV [9,10]. Typically 10 to 20% of the PKA energy is converted into phonons and displacement damage (which is quantified by the Lindhard partition function [11]), the rest of the PKA energy being deposited into ionization. The mean damage energy deposited in nuclear interaction by high-energy neutrons or high-energy protons is typically 100 keV to a few MeV [4, 9], and the damage energy PDF remains non-negligible up to high energies (e.g. about 250 keV for 20 MeV neutrons [9]). Therefore, nuclear interactions often produce large damage cascades with thousands of displaced atoms.

In this work, twenty CIS are irradiated with various particles (protons, neutrons, deuterium, helium, carbon, oxygen and aluminum) and at different particle energies to study the effect of coulomb and nuclear interactions on the radiation-induced dark current. The Dark Current Spectroscopy (DCS) technique [12,13] is used to detect the main radiation-induced defects for each irradiation and try to identify them. First of all, neutrons are tested to study the effect of nuclear interactions alone on the radiation-induced dark current distribution. In particular, two orders of magnitude of Displacement Damage Doses (DDD) are covered by high-energy neutrons to study the effect of the number of nuclear interactions per pixel. Then, the effect of coulomb interactions is studied with high-energy protons (for which they are mixed with nuclear interactions) and with low-energy ions (coulomb interactions only). A very broad range of coulomb NIEL (six orders of magnitude) is covered from 60 MeV protons (very low NIEL) to EOR (End-Of-Range) aluminum (very high NIEL), which allows testing the effect of the coulomb displacement damage density on the dark current distribution. The aim of this work is to discriminate the contributions of coulomb and nuclear interactions to the radiation-induced dark current distribution, identify which kind of defects are generated by each type of interaction using the DCS and finally determine if the nature of the defects is linked to the displacement damage density rather than to the interaction type. A better knowledge of the defects generated by displacement damage for various particles is of great interest in order to improve the dark current distribution prediction for various radiation environments.

II. EXPERIMENTAL DETAILS

Two different CIS are tested in this study; their main characteristics are detailed in Table I. Both are four-transistor (4T) Pinned PhotoDiode (PPD) custom CIS fabricated in a commercially available 0.18 μm process designed for imaging; a schematic cross-section of this type of pixel is presented in Fig. 1. PPD CIS were chosen in order to have a very low intrinsic (pre-irradiation) dark current (6 e/s for CIS 1-15 and 3 e/s for CIS A-E at T = 22°C), permitted by the isolation of the photodiode depleted volume from the oxide interfaces [14]. Hence, PPD CIS provide a good dark current increase sensitivity which allows detecting the main radiation-

| Table I: Main characteristics of the tested PPD CIS |
|-----------------|-------------|-------------|
| **PPD CIS**    | 1-15        | A-E         |
| Array size     | 512 x 512   | 256 x 256   |
| Pixel pitch    | 7 μm        | 4.5 μm      |
| Photodiode area| 26 μm²      | 2.2 μm²     |
| Depleted volume| 30 μm³      | 0.7 μm³     |

![Fig. 1: Schematic cross section of a 4T-PPD pixel. The three transistors used in the readout circuit are not depicted here.](image)

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induced defects using the DCS. Moreover, the isolation of the depleted volume from the oxide limits the ionization induced dark current because the oxide interface states are passivated by holes [14]. Hence, PPD CIS allows measuring and studying only the displacement damage induced dark current in ion irradiated CIS.

Table II summarizes the irradiation conditions for the twenty 4T-PPD CIS tested in this work. The high-energy proton (60 MeV) and neutron (spectrum centered on 22 MeV) irradiations were performed at Université Catholique de Louvain (UCL) in Louvain, Belgium. The low-energy neutron irradiation (220 keV) was performed with CEA DAM (Bruyères-Le-Châtel, France) and the helium irradiations were conducted using a 30 kBq activity $^{241}$Am source emitting 5.5 MeV alpha particles. Lastly, all the remaining irradiations (low-energy protons, deuterium, carbon, oxygen and aluminum) were performed at Centro Nacional Aceleradores in Sevilla, Spain. All the particle beams can be considered monoenergetic in this study, except the UCL neutron beam which is a spectrum centered on 22 MeV but spreading from 10 to 40 MeV. The particle energy given in Table II is the energy within the photodiode depleted volume; it can be lower than the initial particle energy due to the electronic and nuclear stopping power in the top layers (5.5 µm) of the CIS.

For CIS 1-6, the NIEL and the fluence are well known (less than 10% uncertainty) hence the DDD can be calculated and is given in Table I. For some CIS (7, 11, 12, A and E), the NIEL is known but the uncertainty on the fluence is important (up to a factor of two) due to the uncertainty on the flux, for example because of the small distance between the CIS and the isotropic source of radiation; the DDD can only be estimated in that case. Lastly, for the remaining CIS (8-10, 13-15, B-D), the NIEL is unknown and the DDD cannot be estimated. For some of these CIS (9, 13 and C), the reason is that the NIEL cannot be found in the literature. For the remaining CIS (those irradiated with EOR ions), the initial ion energy (in parenthesis in Table II) has been chosen so that the ions stop in the depleted volume of the photodiodes (in order to study the damage generated at the End-Of-Range (EOR) of the ions). In that case, the DDD cannot be simply calculated from the NIEL because the NIEL varies a lot at the end of the ion trajectory. This is also the case for 10 keV protons (CIS B), for which the energy and NIEL vary too much in the depleted volume to estimate the DDD.

The dark current is measured after four weeks of annealing. The dark current distributions are presented at $T = 22^\circ$C in the paper but the dark current is also measured at $-8^\circ$C in order to calculate the dark current activation energy. The mean dark current increase (delta dark current before/after irradiation) at $T = 22^\circ$C is given for each CIS in Table I.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. High-energy neutrons

Fig. 2 presents the dark current increase distributions measured at $T = 22^\circ$C for CIS 1, 2 and 3 irradiated with high-energy neutrons (only nuclear interactions) at different DDD.
that case, the exponential mean (the inverse of the exponential slope) corresponds to the mean dark current increase $\Delta I_{\text{dark}}$ per nuclear interaction. It is known from previous work [4,9,20] that the mean damage energy per nuclear interaction $E_{\text{disp}}$ is about 100 keV for 10 to 40 MeV neutrons. Moreover, the Universal Damage Factor (UDF) [21] applies for neutrons which means that the mean dark current increase is proportional to the DDD, the depleted volume and to the UDF $K_{\text{dark}}$ (which is $1.0 \times 10^5$ e/s /cm³/(MeV/g) at $T = 22^\circ C$ and after four weeks of annealing [22]). Hence, the mean dark current increase per nuclear interaction should be:

$$\Delta I_{\text{dark}} \approx \frac{K_{\text{dark}} E_{\text{disp}}}{\rho} \approx \frac{1.0 \times 10^5 \times 10^{0.1}}{2.33} \approx 4.3 \times 10^3 \text{e}^-/\text{s}$$

Fig. 2 shows that the agreement between the experimental distributions and the model is quite good with an exponential mean of $4.3 \times 10^3$ e/s and with the values of $\mu$ previously calculated. This value is also in agreement with previous work [9] (if calculated for the same annealing conditions), which corresponds to 3T-pixel CIS irradiated at the same neutron energy. It is also close to the value found in [2] for similar neutrons and for high-energy protons (60 to 500 MeV), yet slightly smaller due to the longer annealing time, the lower temperature measurement. Moreover, it is possible that 500 MeV protons have a larger mean damage energy per nuclear interaction than lower energy protons or neutrons, increasing the average value of the exponential mean determined in [2]. Consequently, the present results support the idea that the exponential hot pixel tail observed at low DDD corresponds well to the dark current PDF of a nuclear interaction and that the Gaussian shape observed for high DDD is due to the superimposition of nuclear interactions in the pixels.

While the overall agreement between the experimental data and the model is good, a slight discrepancy can be seen at the end of the hot pixel tail where the model underestimates the experimental distribution. It is likely that the dark current PDF generated by a nuclear interaction slightly differs from the exponential function, generating this discrepancy at high dark current. This hypothesis is supported by the fact that the dark current distribution has a slightly different shape than predicted the model at high dose (CIS 3, $10^{13}$ n/cm²), even at low dark current otherwise. Otherwise, dark current enhancement effects such as electric field enhancement [23] or intercentre charge transfer [24] could be held responsible for the slightly higher dark current increases than predicted by the model. However, no significant dark current enhancement is detected in this work because the activation energy of the dark current remains centered on about 0.63 eV for all the hot pixels (even for those with the highest dark current increases as can be seen in Fig. 3 and Fig. 5b), as predicted by the universal damage factor [21]. Overall, the most part of the experimental distribution is well reproduced by the model (which does not take dark current enhancement effects into account) except the few hottest pixels, which suggests that these effects are indeed negligible in these CIS. Eventually, border effects cannot be incriminated for the difference observed at high dark current because they should induce a reduction of the pixel count at high dark current instead of the augmentation observed [4,7,25].

In order to identify the defects responsible for the dark current increase, the dark current is also measured at -8°C to calculate the dark current activation energy. Indeed, according to the SRH formalism [3], the generation rate of a defect has an exponential dependence on temperature. Hence, if the dark current in a pixel is dominated by a given defect, then the dark current can be written as:

$$I_{\text{dark}} \approx \text{Aexp}(-\frac{qE_a}{kT}) \text{ (eq. 4)}$$

Where $E_a$, the dark current activation energy, depends directly on the defect energy level. If the electron and hole emission cross sections $\sigma_n$ and $\sigma_p$ the defect are similar (and assuming that effects such as bandgap narrowing, electric field enhancement or intercentre charge transfer are not present), then $E_a$ is linked to the defect energy level $E_d$ by the equation:

$$|E_d - E_i| \approx E_a \approx -0.65 \text{ eV (eq. 5)}$$

Where $E_i$ is the middle of the bandgap. Hence, the lowest measurable activation energy is 0.65 eV and corresponds to a defect with an energy level at $E_i$. Fig. 3 presents the dark current activation energy as a function of the dark current at $T = 22^\circ C$ for all the pixels of CIS 2 ($10^{12}$ cm² 22 MeV neutrons). The activation energy is calculated using eq. 4 at two different temperatures of -8°C and 22°C. Above 22°C, the diffusion current becomes non-negligible which is why the activation energy is only calculated below room temperature. Below -8°C, the generation current is so low that the dark current cannot be accurately measured with reasonable integration times. Eventually, it is not necessary to test intermediate temperatures between -8°C and 22°C thanks to the 0.1°C accuracy of the stove. The activation energy of the mean dark current increase activation energy in the CIS is 0.61 eV, which is close to previous work: 0.63 eV for the mean dark current increase in [2] and also 0.63 eV for the UDF [21]. The similar value confirms that our activation energy measurement is quite accurate. The obtained value is slightly lower than the minimum activation energy of 0.65 eV, which
could be explained by $\sigma_n \neq \sigma_p$ (for example, 0.61 eV is measured if $\sigma_n$ and $\sigma_p$ differ by a factor of five) [3]. Overall, some of the defects generated by nuclear interactions seem to have energy levels very close to $E_t$, which explains the very high dark current increases observed (the generation rate decreases exponentially with $[E_t - E_i]$ [3]) and the mean activation energy of 0.61 eV (these defects dominate the dark current). Moreover, the smoothness of the hot pixel tail (Fig. 2) suggests that these defects can have various generation rates and thus many different structures, on the contrary to point defects which have simple structures and defined generation rates, producing a quantized dark current distribution [13]. It is possible that the defects generated by nuclear interactions are more complex than point defects (clusters of interstitials, clusters of vacancies or amorphous inclusions) and can introduce various energy levels in the bandgap, some of them being very close to $E_i$. Therefore, the defects responsible for the hot pixel tail are referred to as “clusters” in the rest of the paper to highlight the idea that they correspond to defects with more complex structures than point defects.

At low dark current (few 1,000 of e/s and less), the dark current activation energy is higher (Fig. 3) suggesting that the dark current is dominated by different defects with non-midgap energy levels (which explains the lower dark current). In the following section, we will see that these defects could correspond to point defects rather than clusters and could be similar to the main point defects detected in the previous work on alpha irradiated PPD CIS [13], which were attributed to the divacancy V$_2$ and the vacancy-phosphorus complex VP.

Overall, most of the pixels have a dark current activation energy around 0.63 eV which means that the dark current is mainly dominated by clusters in neutron irradiated CIS. While an activation energy distribution similar to Fig. 3 is observed at low dose in CIS 1 (not shown here), all the pixels have activation energies around 0.63 eV at high dose CIS 3 (because the dark current is dominated by clusters in all the pixels of the CIS due to the large number of nuclear interactions per pixel).

B. 60 MeV protons

Fig. 4 presents the dark current distributions for CIS 4, 5 and 6 irradiated with 60 MeV protons at different DDD. According to literature, the mean damage energy per nuclear interaction is similar for 60 MeV protons and for 10 to 40 MeV neutrons (for example, 115 keV for 20 MeV neutrons in [20] and 120 keV for 60 MeV protons in [4]). Hence, the empirical model should be able to reproduce the hot pixel tail generated by 60 MeV protons with a similar exponential mean ($4.3 \times 10^3$ e/s). However, for 60 MeV protons, the NIEL has both nuclear (2.7 keVcm$^2$/g) and coulomb (1.3 keVcm$^2$/g) contributions [6] as reported in Table II, on the contrary to 10 to 40 MeV neutrons for which it is only nuclear (4.0 keVcm$^2$/g) [19]. Because the nuclear NIEL for protons is only about two thirds the nuclear NIEL for neutrons (and assuming that the mean damage energy per nuclear interaction is similar for both particles), then the nuclear interaction cross section for protons is likely two thirds the cross section for neutrons (about 1.3 barns instead of 1.9 barns). In [4], the inelastic nuclear cross section (0.54 barns at 60 MeV) is given separately from the elastic (coulomb + nuclear elastic) cross section (about 340 barns at 60 MeV). However, it is not possible to determine the total nuclear cross section (nuclear elastic + inelastic) from these values. In [18], similar inelastic cross sections than in [4] are given but the total nuclear cross section are not presented either. Therefore, the total nuclear cross section can only be estimated from the nuclear NIEL [19, 6] and from the mean damage energy per nuclear interaction [4]. By doing this, we find that the mean number of nuclear interactions per pixel $\mu$ should be about 0.2, 0.6 and 2 in CIS 4, 5 and 6 (eq. 3). The model calculated with these values (and with an exponential mean of $4.3 \times 10^3$ e/s) shows good agreement with the experimental distributions (Fig. 4).

In particular, the exponential hot pixel tail is well reproduced suggesting that the mean damage energy per nuclear interaction is indeed similar for 60 MeV protons and 10 to 40 MeV neutrons [4, 20]. In CIS 4 and 5, the part of the distribution at low dark current is underestimated by the model which suggests that it corresponds to dark current generated by coulomb interactions (which are not taken into account by the model). This part of the distribution may correspond to pixels which did not encounter a nuclear interaction but which already contain defects generated by coulomb interactions (which are much more probable than nuclear interactions).

In CIS 6, the experimental distribution is shifted to higher dark current compared to the model (by about 2,500 e/s), which could also be explained by a similar dark current increase in all the pixels of the CIS due to coulomb interactions.

Fig. 5a presents the activation energy in CIS 5 ($3 \times 10^{11}$ cm$^{-2}$ 60 MeV protons). Many pixels have low dark current increases and dark current activation energies between 0.70 and 0.75 eV, which should correspond to defects with energy levels distant by about 0.1 eV from $E_i$. However, the activation energy of the mean dark current increase is 0.63 eV in this CIS because the mean dark current increase is dominated by pixels with very large dark current increases and with dark current activation energies of 0.63 eV. This value is similar to the one obtained with neutrons in Fig. 3 (0.61 eV) which suggests that the mean dark current is also dominated by midgap defects for 60 MeV protons. According to previous
work [13], the defects leading to activation energies between 0.70 and 0.75 eV for low dark current pixels are likely to be V_2 and VP, because these defects have energy levels located respectively about 0.14 eV and 0.09 eV above E_1 [26,27,28]. Fig. 5.b presents the activation energy at higher dose in CIS 6 (10^{12} cm^{-2} 60 MeV protons). The activation energy remains between 0.70 and 0.75 eV at low dark current like in CIS 5 but falls around 0.63 eV at high dark current, similarly to neutron irradiated CIS in Fig. 3. Indeed, it is likely that more pixels have encountered a nuclear interaction at higher dose; hence more pixels belong to the hot pixel tail in CIS 6 than in CIS 5. The mean activation energy in CIS 6 is 0.60 eV, similarly to neutrons (0.61 eV).

Fig. 6 presents a direct comparison of the dark current distributions of 22 MeV neutrons and 60 MeV protons at similar fluence of either 10^{11} cm^{-2} or 10^{12} cm^{-2}. Because the total NIEL is similar for both particles, the DDD and mean dark current increase are also similar (see Table II) in agreement with the UDF [21]. The hot pixel tail has a similar shape and slope for protons and neutrons at both fluences, suggesting again that they have similar mean damage energy per nuclear interaction. The hot pixel tail is slightly higher for neutrons, which can be explained by the higher nuclear NIEL. On the contrary, the distribution is higher for protons at low dark current, which is likely to correspond to the contribution of coulomb interactions as observed in Fig. 4. Hence, it seems that coulomb interactions produce smaller dark current increases than nuclear interactions (which are responsible for the exponential hot pixel tail) which correspond rather to point defects (as observed in Fig. 5 at low dark current) than to clusters.

A closer look at the low dark current part of the distributions is presented in Fig. 7 for CIS 1 and 4 (low fluence). For neutrons, a unique sharp peak is located at 30 e/s and should correspond to the pixels which did not encounter nuclear interactions (about 70% of the pixels since μ ~ 0.3). In that case, the dark current increase is mainly due to ionization which could come from nuclear reaction recoils or from background radiation in the irradiation room. For neutrons, this peak is directly followed by the exponential hot pixel tail, i.e. by pixels impacted by nuclear interactions. On the contrary, a DCS spectrum comprising several equally spaced peaks separated by 50 e/s is observed for protons, suggesting the presence of specific point defects generated by coulomb interactions. While the first peak (located at 50 e/s) corresponds to the ionization induced dark current, the second peak (located at 100 e/s) is likely to correspond to pixels containing a specific defect with a generation rate of 50 e/s (hence the total dark current increase is 100 e/s). The third

Fig. 5: Dark current activation energy in (a) CIS 5 (3.0 \times 10^{11} cm^{-2} 60 MeV protons) and (b) CIS 6 (10^{12} cm^{-2} of 60 MeV protons).

Fig. 6: Dark current distributions in CIS 1 and 2 (22 MeV neutrons) and CIS 4 and 6 (60 MeV protons).

Fig. 7: Dark current distributions in CIS 1 (22 MeV neutrons) and CIS 4 (60 MeV protons) at a fluence of 10^{11} cm^{-2}.
peak (located at 150 e/s) could correspond to pixels which contain another type of defect with a generation rate of 100 e/s or, more likely, exactly two defects identical to the defect of the second peak. Two different defects with a generation rate of 50 e/s were previously detected in alpha irradiated CIS [13] and attributed to V$_2$ and VP by comparison to previous work [26,27,28]. In conclusion, it seems that coulomb interactions produce rather point defects such as V$_2$ and VP (explaining the rather small dark current increases) whereas nuclear interactions produce rather clusters with close-to-midgap levels (explaining the high dark currents in the hot pixel tail).

C. Effect of the proton energy

Fig. 8 presents the dark current distributions in CIS 4, 12, 7 and 8 irradiated with respectively 60 MeV, 16 MeV, 3 MeV and EOR (i.e. below 100 keV) protons. In these CIS, the DDD is not precisely known; hence the dark current distributions are only qualitatively compared to each other. A similar DCS spectrum (with peaks separated by 50 e/s) is observed at low dark current (Fig. 8.a) for all proton energies, which suggests that the corresponding point defects remain similar regardless of the proton energy. For 16 MeV, 3 MeV and EOR protons, the mean dark current increase is similar (Table I) but the mean dark current of the DCS spectrum increases with decreasing proton energy. Hence, it seems that the fraction of point defects increases with decreasing ion energy. This suggests that point defects are mainly generated by coulomb interactions, which interaction cross section $\sigma(E,T)$ is inversely proportional to the ion energy $E$ [5]:

$$\sigma(E,T) = \frac{4\pi Z_1^2 Z_2^2 e^4}{M_1 M_2} \frac{1}{ET^2} \quad (eq. 6)$$

Where $Z_1$ and $Z_2$ are the ion and target atom charge, $M_1$ and $M_2$ are the ion and target atom mass, $E$ is the ion energy and $T$ is the energy transmitted to the PKA. For 3 MeV and 60 MeV protons, the dark current distributions are superimposed at low dark current (Fig. 8.a) in the DCS spectrum (which suggests a similar number of point defects) but the hot pixel tail has a much lower probability at 3 MeV at high dark current (Fig. 8.b). This suggests that the hot pixel tail is mainly generated by nuclear interactions, which cross section is much smaller at 3 MeV than at 60 MeV [6]. For 16 MeV protons, the hot pixel tail has a higher probability than at 3 MeV but the DCS spectrum has a lower mean dark current, hence the fraction of clusters seems to increase at higher ion energy. For EOR protons, the DCS spectrum contains more point defects than at 3 MeV but, on the contrary, the hot pixel tail has a very low probability and seems to deviate from the exponential shape observed at higher energies. Indeed, for EOR protons (which have energies below 100 keV), there are probably no nuclear interactions (elastic or inelastic) because the threshold is at a few MeV [29,30]. Therefore, the DCS spectrum and the exponential hot pixel tail seem to be generated respectively by the coulomb and the nuclear interactions, which explains why the DCS spectrum is very populated compared to the hot pixel tail for EOR protons.

D. Light ions

Fig. 9 presents the dark current distributions for the light ions (up to helium) in CIS 7-11. For EOR protons and deuterium, the hot pixel tail has a similar shape (non-exponential) and a very low probability, suggesting the absence of nuclear interactions. The distributions are almost superimposed for these particles for a similar mean dark current; hence the damage produced by these particles is likely to be similar. In previous work [13], a similar hot pixel tail was observed in EOR helium irradiated CIS, also suggesting...
similar damage. For 3 MeV ions, the hot pixel tail has a similar shape regardless of the ion (proton, deuterium or helium) suggesting similar damage. They are almost superimposed for 3 MeV deuterium and helium for a similar mean dark current, also suggesting a similar damage for these ions. The hot pixel tail probability is lower for 3 MeV protons than for 3 MeV deuterium (despite the similar fluence), which could be explained by the lower coulomb NIEL for protons (which is proportional to the ion mass according to eq. 6). Overall, the hot pixel tail has a lower probability for EOR ions than for 3 MeV ions despite the higher coulomb NIEL at the EOR. This suggests that some nuclear interactions exist for 3 MeV light ions and are responsible for the higher probability at high dark current.

Fig. 10 presents the dark current distributions in CIS A-E irradiated with low energy protons, low energy carbon ions or low energy neutrons. A similar DCS spectrum with peaks separated by 50 e/s is visible in all CIS and is similar to the spectrum observed in CIS 4, 7 and 8 in Fig. 8.a. At high dark current (not shown here), the hot pixel tail for 110 keV and 730 keV protons has a similar shape than for EOR protons in Fig. 9 and the hot pixel tail for 2.8 MeV carbon has a similar shape than for 3 MeV ions in Fig. 9. For 220 keV neutrons, the hot pixel tail is quite exponential (see Fig. 7 in [9]) but has a lower exponential mean than for high-energy neutrons or protons (1.2 × 10^7 e/s instead of 4.3 × 10^8 e/s as determined in [9]). As suggested in [9], this could be due to a lower mean damage energy per nuclear interaction for low-energy neutrons, leading to a lower mean dark current increase per interaction (which corresponds to the exponential mean of the hot pixel tail as explained in section A of this paper).

E. Low-energy heavy ions (carbon, oxygen and aluminum)

Fig. 11 presents the dark current distributions for EOR protons, 3 MeV protons, EOR carbon, and for low-energy heavy ions (1 MeV oxygen, EOR oxygen and EOR aluminum). For low energy ions (1 MeV or below), the nuclear interactions are likely to be impossible. Indeed, the threshold for protons is a few MeV [6] and the threshold is supposed to increase with increasing ion size [29,30]. For EOR carbon, the hot pixel tail is similar to 3 MeV protons rather than EOR protons. Hence, it seems that the damage produced by EOR carbon is different from the damage produced by EOR lighter ions (Fig. 9) and is closer to the damage generated by nuclear interactions (which exist for 3 MeV protons). For the low-energy heavy ions, the mean of the hot pixel tail (the inverse of the slope) seems to increase with increasing ion size. For EOR oxygen and aluminum, a hot pixel tail similar to high-energy protons and neutrons (high mean and exponential shape) is observed. The empirical model can be tested on these dark current distributions by normalizing the experimental and calculated mean dark current increase. As shown in Fig. 11, a good agreement is obtained (with an exponential mean of 4.3 × 10^8 e/s for aluminum and 2.5 × 10^8 e/s for oxygen). For aluminum, the exponential mean is similar to the one generated by nuclear interactions for high-energy neutrons and protons. Consequently, it seems that low energy heavy ions produce a similar damage than nuclear interactions despite the idea that they interact exclusively by coulomb scattering. This effect starts to appear for end-of-range carbon, it is more pronounced for oxygen and even more for aluminum (similar exponential mean than nuclear interactions). Moreover, since the mean PKA energy is independent on the ion mass and charge according to eq. 6, this effect cannot be explained by a higher mean PKA energy for heavier ions.

A possible explanation of this behavior is that the coulomb interaction probability becomes so high for low energy heavy ions that the displacement damage density becomes similar to the one produced by a silicon PKA generated in a nuclear interaction. Indeed, the maximum non-ionizing stopping power of ions (which is reached at a few keV and thus corresponds only to coulomb scattering) is respectively 11 eV/Å (480 MeV cm²/g) for carbon, 17 eV/Å (750 MeV cm²/g) for oxygen and 36 eV/Å (1.6 GeV cm²/g) for aluminum [31]. This is very similar (especially for aluminum) to the maximum non-ionizing stopping power for silicon in silicon (i.e. for silicon PKAs) which is 40 eV/Å (1.7 GeV cm²/g). On the other hand, for protons, deuterium and helium, the non-ionizing stopping power remains below 1 eV/Å, which is much lower than for heavy ions and could explain the non-
exponential hot pixel tail observed. Indeed, in silicon, the energy needed to displace a silicon atom is about 21 eV [31] and the mean interatomic spacing in crystalline silicon is 2.4 Å. Hence, it can be roughly assumed that an atom is displaced on each crystal plane crossed by the ion if its coulomb NIEL exceeds about 9 eV/Å (this neglects the fact that some coulomb interactions transmit lower energies than the displacement threshold and thus do not lead to displacement). Hence, above 9 eV/Å (i.e. for carbon, oxygen, aluminum and silicon (nuclear interaction PKA) ions), the displacement damage cascades (few atoms) from different coulomb interactions are likely to overlap. In that case, the displacement damage could be clustered (like in nuclear interaction damage cascades) and lead to the formation of larger defects (such as clusters) than point defects. On the other hand, below 1 eV/Å (for protons, deuterium and helium), the displaced atoms from different coulomb interactions are likely to be well separated from one another and the few displaced atoms of each interaction are likely to form rather small defects such as point defects.

F. Effect of annealing on the point defect population

Fig. 12 presents the dark current distributions in CIS B (irradiated with 110 keV protons) before and after annealing at different temperatures. The hot pixel tail gets steeper with annealing, which means that the hot pixel tail probability reduces faster at high dark current than at low dark current. This suggests that the defects responsible for the highest dark current increases (with energy levels very close to $E_i$) are also the less stable, in agreement with the hypothesis that they are large structure defects such as clusters. On the other hand, the probability increases at low dark current (in the DCS spectrum). This effect can be explained by pixels switching from the hot pixel tail to the DCS spectrum when the high generation rate defects (clusters) anneal, leaving only the point defects which seem more stable.

Fig. 13 presents the activation energy in CIS 10 (irradiated with EOR deuterium) before annealing (13.a) and after 30 minutes of annealing at 200°C (13.b). Before annealing, two groups of pixels are visible at a dark current of 50 e/s and at activation energies of 0.70 and 0.75 eV. Therefore, the DCS spectrum with peaks separated by 50 e/s observed for light ions (Fig. 7, Fig. 8.a) is actually composed of two different defects which were also detected in helium irradiated CIS [13]. These defects were attributed to $V_2$ (at 0.75 eV) and VP (at 0.70 eV) because they have energy levels located respectively at about 0.14 eV and 0.09 eV above $E_i$ according to literature [26,27,28] (which corresponds well to the measured activation energies according to eq. 5). At 100 e/s, two other groups are visible at 0.75 eV and 0.72 eV and could correspond respectively to pixels with two $V_2$ and pixels with one $V_2$ and one VP (leading to an intermediate activation energy between 0.70 and 0.75 eV). After 200°C annealing, the pixel groups located at 0.70 eV have disappeared; hence VP seems to have completely annealed at 200°C in agreement with previous work on alpha irradiated CIS [13] and with literature [26,27,28]. After 200°C annealing, almost all the pixels have activation energies around 0.75 eV, suggesting that they contain mostly $V_2$. Five main pixel groups are visible every 50 e/s at 0.75 eV and are likely to correspond to pixels containing one to five $V_2$. Another defect (noted $D_1$) with a generation rate of 13 e/s is also detected, because pixels groups appear around 63 e/s (they contain one $V_2$ plus this new defect) and 113 e/s (they contain two $V_2$ and this new defect). This defect was also detected in [13].
Fig. 14: (a) DCS spectrum in CIS 8, 10, 11 and 13 after 200°C annealing. The helium and oxygen distributions are lowered by one order of magnitude for clarity. (b) Dark current distributions in CIS B, C and E after 260°C annealing.

Fig. 15: Scatter of the activation energy of the dark current CIS A (730 keV protons) after 300°C annealing.

The dark current spectroscopy was tested on twenty PPD CIS irradiated with protons, neutrons and ions at different energies to study the effect of coulomb and nuclear interactions (and the effect of the coulomb NIEL) on the dark current distribution. First of all, nuclear interactions produce mainly a high dark current exponential hot pixel tail which dark current is dominated by close to midgap defects. The smoothness of the hot pixel tail and the very high dark currents suggest that these defects can have large structures and many different generation rates; hence they could correspond to complex defects such as clusters of interstitials or vacancies, or amorphous inclusions. On the contrary, coulomb interactions with a low coulomb NIEL (light ions up to helium) produce rather low dark current increases, mostly concentrated into a quantized dark current spectrum corresponding to specific point defects. Their generation rates and calculated energy levels suggest that these point defects are mainly the vacancy phosphorus complex (VP) and the divacancy (V2) after irradiation. VP is observed to anneal between 150°C and 200°C whereas V2 anneals only above 260°C, in agreement with literature. Other point defects also appear during annealing between 200°C and 300°C; it is possible that they form from components of the defects which are annealing (clusters, VP, V2) or from impurities which start to be mobile at these temperatures (oxygen for example).
high NIEL coulomb interactions (low energy heavy ions such as EOR carbon, oxygen and aluminum), an exponential hot pixel tail is observed similarly to nuclear interactions. Hence, low energy heavy ions seem to produce a similar damage than nuclear interactions, which is not surprising since nuclear interactions produce low energy silicon PKAs which have very high coulomb NIEL. Consequently, it is likely that the main type of radiation-induced defects (either point defects or clusters) is linked to the coulomb NIEL. A low coulomb NIEL (light ions) will likely lead to well separated displacement damage cascades (which contain only a few atoms for coulomb interactions) and likely to the formation of small defects such as point defects. On the other hand, at high coulomb NIEL (heavy ions or silicon PKA generated by nuclear interactions), it is possible that most of the silicon atoms are displaced on the ion trajectory and that the cascades can overlap, which could lead to the formation of larger and more complex defects such as clusters. This hypothesis is supported by the idea that these defects (which form the hot pixel tail) anneal at lower temperature than the point defects (DCS spectrum), hence they are less stable and likely have larger or more complex structures than point defects.

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REFERENCES


