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Influence of Displacement Damage Dose on Dark Current Distributions of irradiated CMOS Image Sensors

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Abstract**—Dark current increase distributions due to displacement damages are modeled using displacement damage dose concept. Several CMOS image sensors have been exposed to neutrons or protons and we have characterized their degradation in terms of dark current increase. We have been able to extract a set of two factors from the experimental dark current increase distributions. These factors are used to predict and build dark current increase distribution and leads to a better understanding of displacement damage effects on CMOS image sensors.**

Index Terms**— Active Pixel Sensor (APS), Monolithic Active Pixel Sensor (MAPS), CMOS Image Sensor (CIS), Dark Current Distribution Model, Displacement Damage Dose (DDD)**

I. INTRODUCTION

CMOS Image Sensors (CIS) dedicated for space or scientific applications should be able to operate in a radiative environment. For irradiated CIS, a key issue remains the dark current increase with the radiation doses [1]. Ionization and displacement damage effect contribute to the degradation of the CIS performances. The total ionizing dose (TID) lead to a uniform increase of the dark current in the whole pixel arrays [1], [2]. For the displacement damage dose (DDD), the number of interactions is less important and only some pixels are impacted by this non-uniform effect (in the range of DDD associated to space missions), leading to hot pixels and to the dark current distribution distortion [1]-[7]. Thanks to the last generation of CIS and to the CIS hardened against TID, ionizing effect impacts are clearly reduced [6] and now displacement damage becomes the main issue for CIS dedicated to space and scientific applications.

Displacement damage effect understanding is still an active research field in silicon devices [8]-[11]. For such study, CIS presents the advantages to provide the statistical distribution of the dark current increase thanks to the large amount of data from the whole pixel array. The dark current distribution studies appear to be interesting to bring new insights concerning the basic mechanisms of displacement damages.

Previous studies on CIS, also called Active Pixel Sensor (APS), [3] show that the mean dark current increase scales with DDD using the Universal Damage Factor (UDF) introduced by Srour [8]. This universality implies that independently of the particle type and energy, the final mean dark current increase remains proportional to DDD using the K_{dark} factor.

In addition to the average increase, several studies in CIS show large dark signal non-uniformity (DSNU) after displacement damage radiations [1]-[7]. All the observed dark current distributions have in common a hot pixel tail which features a quasi-exponential decrease. As we can see in Fig. 1, proton and neutron irradiations distort the dark current distribution in the same way. Moreover, in this figure, we observe that using similar DDD (iso-DDD), both irradiations lead to the superimposed tails. The hot pixel tails were attributed to inelastic nuclear interaction in [1], elastic and inelastic nuclear interactions in [3] whereas electric field enhancement (EFE) is also proposed in [4] and [7]. In these previous studies, EFE theory [12] correctly predicts the dark current distribution for CIS processed using technology nodes until 0.25µm generation and not dedicated for imaging, where a high electric field was evidenced in photodiode. But, beyond 0.25µm technology nodes and thanks to process dedicated to imaging, electric field becomes less important and does not seem to contribute significantly to DSNU [3].

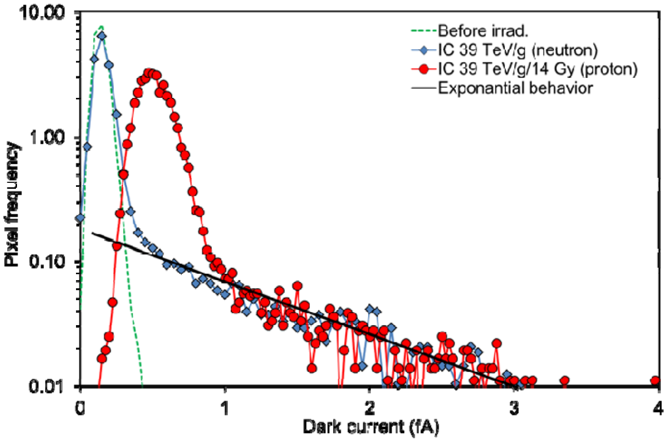

Fig. 1. Dark current distributions after neutron and proton irradiations. An exponential fit is drawn in the graph to fit the hot pixel tail. Displacement damage dose reaches 39 $TeV.g^{-1}$ for both irradiation cases. For proton irradiation, the shift of the Gaussian is attributed to TID [3]

Several approaches attempted to understand and to model the dark current distributions [2], [3], [5], [7], [13], [14] in

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order to predict the phenomenon. Previous studies [2], [5], based on the work of Marshall *et al.* [13], aimed at estimating the dark current increase distribution. In those cases, the prediction is firstly based on the construction of the damage energy distribution by a particle interaction in silicon microvolume. Such construction requires to perform a Monte Carlo simulation or to use the GEANT4 calculation code for each considered particle type or energy. The number of elastic and inelastic interactions is taken into account to obtain the final damage energy distribution. Then, the energy distribution is compared with experimental dark current results to obtain a conversion factor between the dark current and the deposited damage energy. This approach correctly predicts the distributions in irradiated CCD [2], [13] and in neutron irradiated CIS [3]. However, the calculation is strongly time consuming.

Other approaches are based on the fit of the cumulative dark current distribution [7], [14], to extract fitted parameters proportional to the number or the activity of the defects and the density of the spike. It is important to note that in these approaches, the considered distribution is not the dark current increase distribution but the cumulative dark current distribution. Therefore, in these cases, the dark current before and after irradiation is cumulated.

In this paper, many CIS dark current increase distributions have been characterized and examined in order to understand the dark current spikes. Based on these results, we proposed an alternative approach to analyze the hot pixel tails. Under the hypothesis of the UDF validity [8], we assumed that a universal distribution of dark current per interaction leading to electro-active defects per pixel, i.e. defects located inside the space charge region (SCR) of the in-pixel photodiode, should exist. Such electro-active defects generate carriers leading to the dark current. By looking at the exponential behavior of the dark current increase distribution after DDD, we suggest a formulation based on an exponential law for the estimated distribution. The mean of the exponential law, called υ_{dark}, corresponds to the mean current caused by one interaction per pixel leading to electro-active defects. Thanks to this exponential distribution we can properly model the dark current increase distribution for the whole range of studied DDD using a Poisson statistic. In this case, the mean value of the Poisson statistic, μ, corresponds to the average number of interactions leading to electro-active defects in the photodiode depleted volume. The mean value, μ, seems to be proportional to the DDD leading to a second unique factor, γ_{dark}.

The method developed in this paper is more direct than the one in [13] and shows for the first time that the dark current increase distribution only depends on DDD. Moreover, only two factors are needed to model all dark current increase distributions, no matter particle type or energy. This model is a useful tool to estimate dark current increase distribution and could also have an important impact on the design of CIS. Finally, the concept of estimated dark current increase distribution using υ_{dark} and γ_{dark} will allows a better understanding of displacement damage effect and of the physics of the electro-active defects created after irradiations.

TABLE I
IRRADIATION CHARACTERISTICS

Imagers	Particles	Energy (MeV)	Fluence (cm^{-2})	DDD (TeV/g)	TID (Gy)
IC 1	Neutron	22	1×10^{9}	4	<1
IC 2	Neutron	22	1×10^{10}	39	<1
IC 3	Neutron	14	5×10^{10}	182	<1
IC 4	Neutron	14	1×10^{11}	365	<1
IC 5	Neutron	14	5×10^{11}	1825	<1
IC 6	Proton	100	1.5×10^{10}	39	14
IC 7	Proton	100	1×10^{11}	259	93
IC 8	Proton	500	2.5×10^{10}	40	9
IC 9	Proton	500	1×10^{11}	159	36
DO	Neutron	14	1.1×10^{10}	40	<1
PI	Neutron	14	5×10^{10}	182	<1
UL 1	Neutron	14	5×10^{10}	182	<1
UL 2	Proton	120	5×10^{9}	12	4
UL 3	Proton	120	2×10^{10}	48	16

II. EXPERIMENTAL DETAILS

The studied CMOS image sensors are 7 & 10µm-pitch 128×128 pixel arrays with 3T-pixels and 7µm-pitch 256×256 pixel arrays with 4T-pixels including pinned photodiode. These circuits were manufactured in a 0.18µm commercial CIS process. Tab. I lists the 14 tested devices. Identical 3T-pixel arrays are called IC, two other devices, called DO and PI, are also 3T-pixel arrays and component UL is 4T-pixel arrays with pinned photodiode.

Sensors were exposed to neutron beam at Université Catholique de Louvain (UCL) facility and CEA DAM Valduc. Proton irradiations were realized at TRIUMF (Vancouver), at Kernfysisch Versneller Instituut (KVI) and at UCL. The total DDD ranged from 4 to 1825 TeV/g and irradiations were performed at room temperature. Tab. I provides all irradiation characteristics.

Dark current distribution measurements were carried out three weeks after irradiations and inside an air oven at 23°C. Other temperatures ranging from 0°C to 60°C were also performed to deduce activation energy of the dark current.

III. DARK CURRENT INCREASE DISTRIBUTION

A. *Mean Dark Current Increase Due to DDD*

The great number of pixels in the whole array of each device allows obtaining a statistical distribution of the dark current increase. First, the average value of the distribution is investigated. As we know the depleted volume of the in-pixel photodiode thanks to TCAD physical simulations, we deduce the mean generation rate increase per pixel. Therefore, this value can be compared to those obtained for other devices as

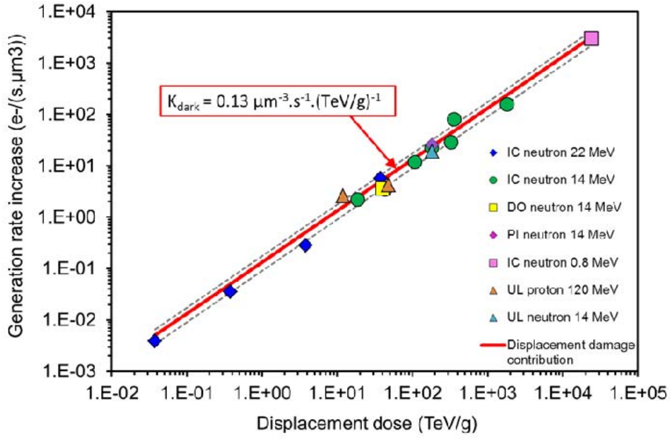

Fig. 2. Mean dark current increase measured on the studied pixel arrays. Estimation of dark current due to displacement damage is calculated thanks to the universal damage factor [8]. Independently of the particle energy and the fluence, the results agree with estimated displacement contribution.

large photodiodes with depleted volume one thousand times higher than the in-pixel photodiode. Moreover, we can compare our results to the one used to determine the UDF [8]. Fig. 2 presents the mean generation rate increase for the studied devices following the DDD. Most of the irradiations were performed with neutron. It is important to remind that neutron irradiations bring only DDD and, then, are useful tools to solely study displacement damage in CIS [3]. The generation rate increase contribution estimated thanks to the UDF [8] is also plotted in the figure for comparison. Our results agree with the UDF for the large explored ranges of energy and fluence.

The IC devices irradiated by protons are not included in the graph because, as explained in [15], the main part of the dark current increase for these standard 3T-pixel devices irradiated with protons is due to TID. Indeed, the ionizing effect brings another source of dark current from the field oxide interfaces in CIS [3] which disturbs displacement damage studies. Therefore, the generation rate increase of these proton irradiated devices is one order of magnitude higher than the UDF contribution (which is only related to displacement damage contribution) [15]. On the contrary, the results for the protons irradiated UL devices are plotted in the figure. Indeed, this last generation of 4T-pixel CIS using a pinned photodiode [16], [17], is processed using particular photodiode implants which reduce the contact between the photodiode depleted volume and the trench isolation oxide. This contact is related to the dark current increase due to TID [18]. As observed in the figure, the generation rate increase of proton irradiated UL devices agrees with the displacement damage contribution. Few studies have been reported concerning displacement damage effect on 4T-pixel CIS. However, the results in Fig. 2 emphasize the role of displacement damage for proton irradiations which could probably be the main effect leading to dark current increase in 4T-pixel CIS.

B. Origins of Dark Current

Displacement damage effect occurs during proton and neutron irradiations. When such particles impinge the silicon lattice, they can create stable electro-active defects acting as generation center in the depleted volume of the photodiode. To obtain information about the generation mechanism of the dark current after irradiation, activation energy is measured for all irradiated components. Fig. 3 presents the dark current activation energy distribution for device IC 2 irradiated with 22 MeV neutrons. Equation (1) is used to calculate activation energy, Ea :

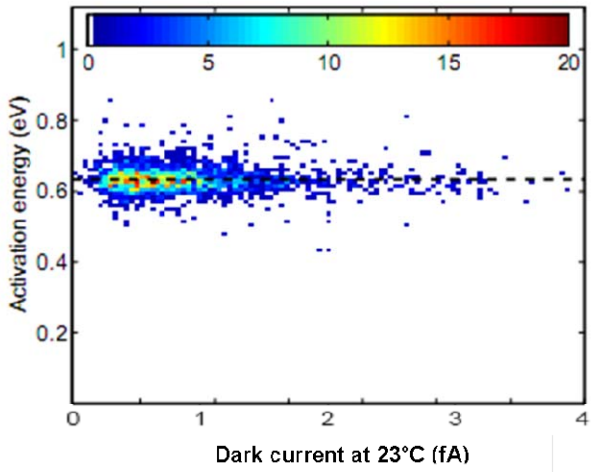

Fig. 3. Device IC 2 irradiated with 22 MeV neutrons presents activation energy centered around the silicon mid-gap value (0.6 eV) for all pixels even those at the highest dark current. Classical SRH generation mechanism occurs in each pixel after irradiation.

$$I_{dark} \propto \exp\left(-\frac{Ea}{kT}\right) \qquad (1)$$

where I_{dark} is the dark current, k is the Boltzmann constant and T is the temperature varying from 0°C to 60°C.

The value is found to be around 0.6 eV for each pixel in all components, even those with the highest dark current, leading to a Shockley-Read-Hall (SRH) generation mechanism and a defect energy level around silicon mid-gap value. These measurements also demonstrate that no EFE [12] is observed in our CIS.

C. Concept of the Estimated Exponential Distribution

As regards the previous studies about displacement damage effect on imagers [1]-[7], an exponential behavior of the dark current increase distribution is generally observed. Moreover, under the assumption of the UDF, the dark current increase is proportional to DDD using K_{dark}, independently of the particle types and energies. Therefore, we assumed that a generic distribution of dark current increase should exist. We normalized all our dark current increase distributions by the number of pixels, the photodiode depleted volume and the DDD. Thus, this frequency is proportional to the electro-active defects created per pixel in the photodiode depleted volume and per TeV/g. The results are shown in Fig. 4 for our irradiated CIS which DDD under 200 TeV/g. We clearly observe that all normalized distributions seem to be superimposed which lead to a generic exponential distribution related to all irradiated CIS under study. Independently of the particle types (proton and neutron) and energies (in the range

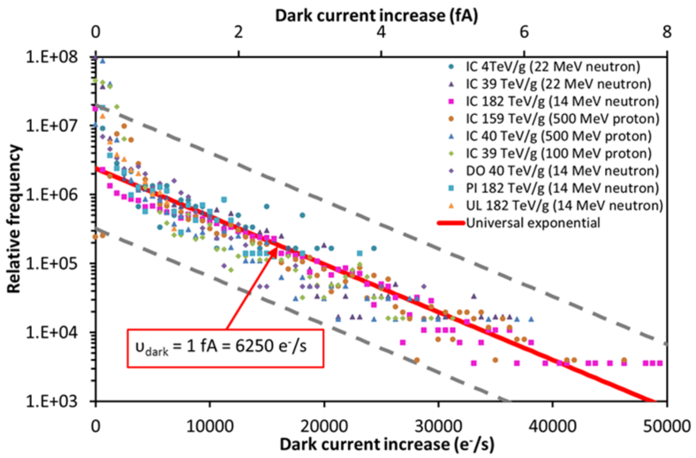

Fig. 4. Displacement damage induced exponential distribution of the dark current increase. The relative frequency is normalized by the number of pixels, the photodiode depleted volume and the displacement damage dose. All studied distributions present the same exponential behavior. The mean of the exponential law, υ_{dark}, is extracted. The value is 1 fA (6250e$^-$/s).

of space missions), the displacement damage (under 200 TeV/g) induces the same exponential slope of dark current increase.

Based on the exponential law for the estimated dark current increase distribution (2):

$$f\left(\Delta I_{dark}\right) = \lambda \cdot \exp\left(-\lambda \cdot \Delta I_{dark}\right) \qquad (2)$$

where the mean of the exponential law, 1/λ, corresponds to the mean current, we suggest a factor ,called υ_{dark}, equal to 1/λ. The factor, υ_{dark}, extracted from the slope is equal to 1 fA, that is to say 6250 e$^-$/s in our devices.

Experimental data, at low dark current increase value, are not considered because they are due to reproducibility error between measurements done before and after irradiation. Moreover, the dark current increase under 1 fA is not taken into account for 3T-pixel CIS irradiated with protons due to the effect of the TID on the dark current increase.

Thanks to υ_{dark} we can build a generic dark current increase distribution presented in Fig. 5. This distribution corresponds to the dark current increase due to one interaction per pixel leading to electro-active defects. In other words, the distribution corresponds to the Probability Density Function (PDF) representing the dark current increase due to one interaction per pixel leading to electro-active defect.

As the number of interaction per pixel leading to electro-active defects could be interpreted as an independent random variable during irradiation, this estimated distribution cannot be obtained experimentally. The solution to deduce the mean of the exponential distribution from the experimental results is to observe the lower irradiation doses. Indeed, at low DDD (under 200TeV/g for our devices), the number of interaction per pixel is limited and we assumed that the maximum number of interaction per pixel leading to electro-active defect is 1. In this case the slope of the experimental exponential distribution is the same than the PDF presented in Fig. 5. However, for DDD over 200 TeV/g, the exponential behavior of the experimental data is distorted. As we can see in Fig. 6, where the dark current increase distributions for a large range of DDD is plotted. In the figure, we observe a clear exponential behavior of the hot pixel tail for the lowest DDD. However, at higher DDD the exponential behavior is distorted. As regards to the results, we assume that under 200 TeV/g, a small number of statistical events have occurred in the IC devices and the exponential slope tends towards the fundamental exponential slope (Fig. 5). Therefore, under 200 TeV/g, the maximum number of interaction leading to electro-active defects is equal to one per pixel. Above this dose, more than 1 interaction per pixel leading to electro-active defects occur and the exponential behavior seems to be distorted. Therefore, a complementary method to estimate the dark current increase distribution for the whole DDD range should be used.

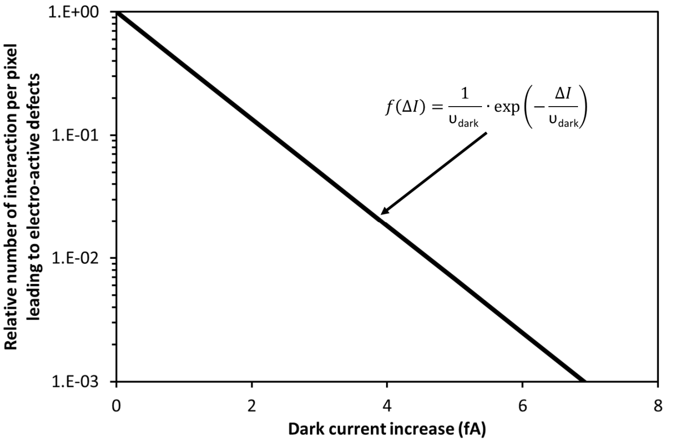

Fig. 5. Probability density function of the dark current increase related to one interaction per pixel leading to electro-active defects.

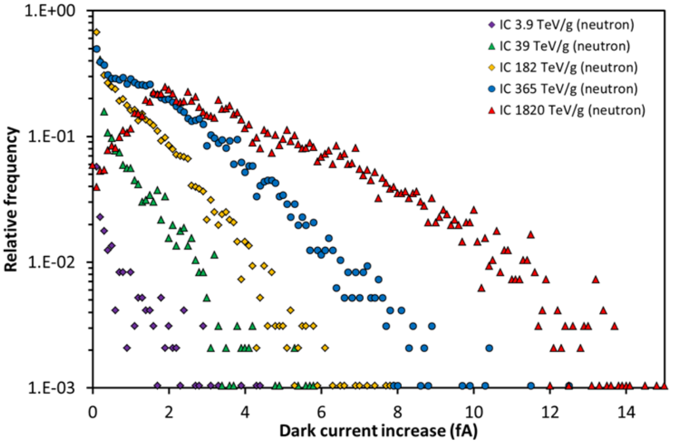

Fig. 6. Dark current increase distributions after neutron irradiations at several Displacement Damage Doses. Exponential behavior is observed for the lowest doses.

IV. CONSTRUCTION OF THE DARK CURRENT INCREASE DISTRIBUTIONS

The model of the dark current increase distributions developed in the paper is based on the exponential distribution obtained above. As explained previously, the distribution shown in Fig. 5 represents the dark current increase related to one interaction per pixel leading to electro-active defects. During irradiation process, interactions leading to electro-active defects are proportional to elastic and inelastic nuclear interaction. (elastic and inelastic nuclear interactions are known to be responsible of DDD induced dark current increase distribution [3]). These interactions do not impinge the totality of the pixels of the whole CIS array (for the space range doses). They follow a random process, that is to say, for a particular irradiation, pixels can receive several interactions whereas another pixels cannot be impinged. Therefore, if we consider that dark current increase due to one interaction per pixel leading to electro-active defects corresponds to a discrete random variable X associated to the exponential PDF (Fig. 5), we assume that X is an independent discrete random variable. Thus, if we introduce a second random variable Y, which corresponds to the dark current increase due to two interactions per pixel leading to electro-active defects, this second variable corresponds to:

$$Y = X + X \tag{3}$$

and the PDF associated to Y, $f_Y(x)$, is defined as the convolution of the PDF associated to X, $f_X(x)$, by itself:

$$f_Y(x) = f_X(x) * f_X(x) \tag{4}$$

Thus, we can build the PDF corresponding to the number of interaction per pixel leading to electro-active defects. However, this number of interaction should follow a specific statistic. As the number of elastic and inelastic interactions per pixel, including the number of interaction per pixel leading to electro-active defects, is related to a large number of events with few successes, we suggest a Poisson statistic to describe the number of interaction per pixel leading to electro-active defects, N_{int} . The Poisson statistic is defined as:

$$f(N_{\text{int}}, \mu) = \frac{\mu^{N_{\text{int}}} \cdot \exp(-\mu)}{N_{\text{int}}!} \tag{5}$$

where μ is the mean number of interaction per pixel leading to electro-active defects.

Fig. 7 illustrates the PDFs of the dark current increase due to 1, 2, 3,… N_{int} . υ_{dark} is used for the exponential distribution. The construction of the dark current increase distribution PDF which N_{int} is weighted by the Poisson statistic is also presented. In this case the mean value of interactions, μ, is 5. The final PDF related to the dark current increase distribution is defined as:

$$\begin{aligned} f_{N_{\text{int}}}(\Delta I_{dark}) = {} & Poisson\{1,\mu\} \times f(\Delta I_{dark}) \\ & + Poisson\ \{2,\mu\} \times (f * f)(\Delta I_{dark}) \\ & + Poisson\ \{3,\mu\} \times (f * f * f)(\Delta I_{dark}) + \ldots \end{aligned} \tag{6}$$

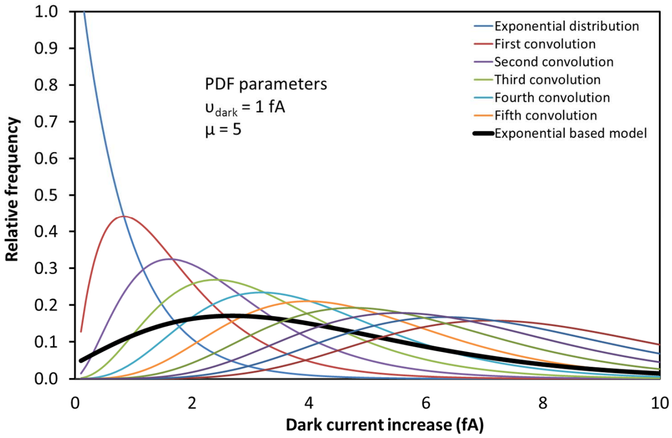

Fig. 7. PDF exponential distribution with υ_{dark} = 1 fA and its convolution by itself are used to build the exponential based model. μ = 5 is used in this example.

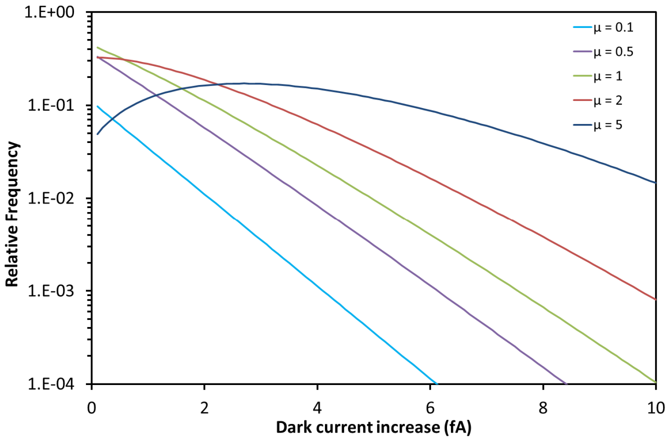

Fig. 8. Construction of dark current increase PDF for several μ parameters

Using this equation (6), we can build PDF dark current increase distribution per pixel for several mean values of the number of interactions per pixel leading to electro-active defects (μ). Such distributions are presented in Fig. 8 where the μ parameter ranges from 0.1 to 5. For the lowest value of μ, we observed an exponential behavior related to the universal exponential PDF. Then, at the highest value, the exponential behavior disappeared and a quasi-exponential tail is observed. These modeled results agree with the experimental data show in Fig. 5.

In order to investigate the physical aspect of μ, we extract the μ parameter from all studied CIS to explore it behavior with DDD. To compare the results from all the studied CIS, the μ parameter is normalized by the photodiode depleted volume. Fig. 9 illustrates this analyze by reporting neutron and proton data. Proportionality appears between both parameters for a wide range of DDD leading to a new factor, γ_{dark}, which can be defined as:

$$\mu = \gamma_{dark} \cdot V_{dep} \cdot DDD \tag{7}$$

where V_{dep} is the photodiode depleted volume. γ_{dark}

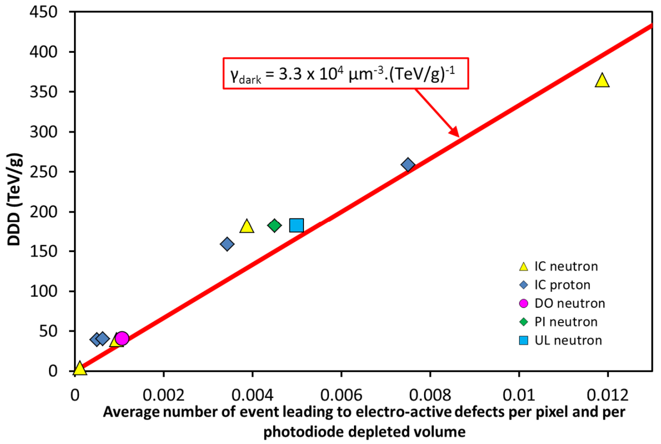

Fig. 9. Relation between µ parameter normalized by photodiode depleted volume and the displacement damage dose. Proportionality between both parameters seems to appear leading to another universal parameter γ_{dark}. The value of γ_{dark} is around 3.3×10^4 µm^{-3}.(TeV/g)$^{-1}$

corresponds to the average number of interaction leading to electro-active defects per each pixel photodiode depleted volume and per displacement damage dose. The value of γ_{dark} is around 3.3×10^4µm^{-3}.(TeV/g)$^{-1}$.

Finally, by using solely two factors, υ_{dark} and γ_{dark}, we can build the DDD induced dark current increase distribution.

V. COMPARISON WITH EXPERIMENTAL DATA

A. Neutron experimental data

Model described in the previous section is used to obtain estimated dark current increase distributions which are compared to the experimental measurements. The results of neutron irradiated CIS are plotted in Fig. 10 with the model. As neutrons only provide displacement damage [3] the model agrees with experimental data for the whole dark current increase and for the whole range of DDD explored.

B. Proton experimental data

Fig. 11 compares the proton induced dark current increase data and the model. As explained previously, protons provide TID which induced dark current increase in 3T-pixel CIS. This effect is observed in Fig. 11: at low dark current increase, a peak appears related to TID. However, the second part of the proton distributions (the hot pixel tail) is mainly impacted by DDD. We remind that the model suggested in the paper is based on DDD without consideration of TID. Therefore, as we can see in Fig. 11, solely the dark current increase tail agrees with the model.

VI. CONCLUSION

An alternative approach to study displacement damage induced dark current increase in CIS is presented in this paper. The model is based on exponential law deduced from the analysis of numerous experimental data. It consists of two factors, υ_{dark} and γ_{dark}, which allow the construction of the dark current increase distributions. This model could be used for a large range of displacement damage dose, independently of the

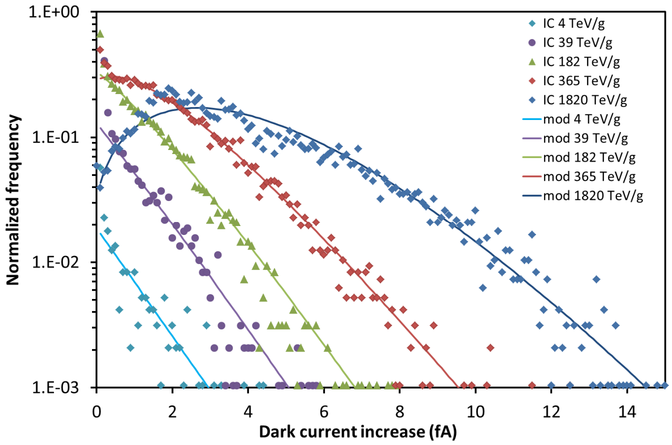

Fig. 10. Experimental dark current increase after neutron irradiations and modeling calculation. The model agree with experimental data.

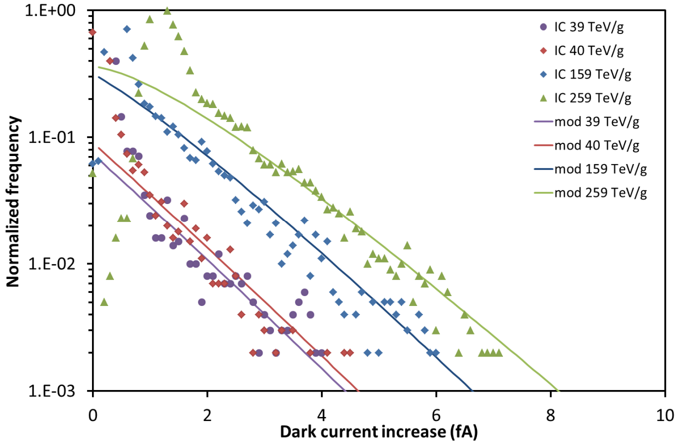

Fig. 11. Experimental dark current increase after proton irradiations and modeling calculation. As explained previously,in case of proton irradiations, the peak of dark current increase under 2 fA is attributed to TID. Displacement damage induced dark current increase is observed above this value. Therefore, the model which is related to solely DDD, agrees with dark current increase above 2 fA (the hot pixel tail).

energies and types of the particle (neutron or proton). It could be a useful tool to predict dark current increase in other CIS dedicated for scientific or space applications. However, due to our CIS technology, this model solely considered the displacement damage induced dark current increase related to electro-active defects acting through the classical SRH generation-recombination process. In case of CIS presenting EFE, the model wills under estimate the dark current increase because it does not considered any enhancement factor. Finally, the model is based on a generic exponential distribution which is related to displacement damage induced electro-active defects in silicon. This distribution provides new insights about the understanding of displacement damage in solid-state devices.

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