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The Use of High Energy X-Ray Generators for TID Testing of Electronic Devices

Vincent Girones, Jérôme Boch, Alain Carapelle, Arnaud Chapon, Tadec Maraine, Timothee Labau, Frédéric Saigné, Rubén García Alía

***Abstract* — A high energy X-ray generator is studied in order to perform dose tests on electronic components. The main idea is to reduce the photoelectric effect in order to get closer to the Compton scattering. For this, the spectrum of the X-ray generator is filtered in order to cut out the low energy photons. Experimental results and simulations show that it is possible to filter the spectrum. From this result, the filtered X-ray generator is used to study the dose response of the electronic components and the obtained data are compared to the Cobalt 60 irradiation. The obtained results are analyzed and discussed. This work provides a first demonstration of the use of a filtered high-energy X-Ray generator for TID testing.**

***Index Terms*—Total Ionizing Dose, X-ray, Cobalt-60, Dose testing, MOS, BJT.**

I. Introduction

Electronic devices used in many space, military, accelerator and nuclear power plants systems may be exposed to Total Ionizing Dose (TID). For the use of these devices, it is essential to have test methods to determine the hardness in a radiative environment. A number of different standards and guidelines exist for testing TID effects. The most common are: MIL-STD-883 test method (TM) 1019 for TID qualification and Radiation Lot Acceptance Testing (RLAT) [1], ESA ESCC Basic Specification No. 22900 [2], and ASTM F 1892 Standard Guide for Ionizing Radiation (Total Dose) Effects Testing of Semiconductor Devices [3]. These standards specify device testing using irradiation from photons sources (such as cobalt-60 γ irradiators or Cesium-137 γ irradiators), electrons beams, and low energy (approximately 10 keV) X-ray generators.

Cobalt-60 (60-Co) is the most common radiation source used for total ionizing dose testing of electronic components. 60-Co is usually considered as the reference ionizing radiation source to perform TID tests on electronic devices and systems. MIL-STD-883 TM 1019 and ESA ESCC No. 22900 specify 60-Co, although ESA ESCC No. 22900 still allows the use of electron beams and ASTM F 1892 allows the use of Cesium-137 irradiators or low energy photons from X-ray generator. In this latter case, when X-rays is used for RLAT, it is recommended to correlate to 60-Co testing. It should be recognized that none of these test facilities will provide an accurate simulation of the actual radiative environment that will be encountered by the component. The use of either test facility will require extrapolation to the effects to be expected from the specified radiation environment.

An X-ray generator is generally considered much more convenient for TID testing. The main advantage is that radiation safety issues are more easily managed with an X-ray generator than with radioactive sources (there are no concerns for handling radioactive materials) or particles beams (which are generally heavy installations with a high maintenance requirement). This is due to both the relatively low energy of the photons which can be easily stopped by a protective enclosure, and the fact that the X-ray generator can easily be turned off. Another advantage of the X-ray generator is that the photon energies are low enough that it can be easily collimated. As a result, it is possible to irradiate with ARACOR-like 10 keV generator a single device on a wafer. X-ray generator also offers a relatively high dose rate, in comparison to 60-Co or Cesium-137 sources, thus offering reduced testing time. During the design of a system, this allows a fast (within a day) TID sensitivity characterizations of several components of the same type (screening), in order to obtain a first estimate of the TID hardness. Finally, X-ray generators are less expensive to purchase and maintain than radioactive sources or particle beams. The main disadvantage of low energy X-ray generators is that photons penetration depth is low and irradiation must be performed at wafer level or with delidded devices, while higher energy radiation sources remain mandatory for radiation tests on packaged devices or at system-level (electronic board). Other disadvantages are related to charge yield, and dose enhancement [4-7]. As a result, it is often difficult to compare ionizing radiation hardness results obtained with an X-ray generator with those obtained with 60-Co. Although it is not entirely clear that the differences between the effects of X-ray and gamma radiation from 60-Co are well understood at this time, quantitative estimates of the magnitude of these differences in effects can be found in [8].

We can see that none of these installations are ideal and that there is always a compromise to be made. New solutions must be proposed to meet emerging needs in many application areas such as New Space and civil nuclear applications where COTS components and system-level testing are issues of interest. An example of a new facility to perform test at system-level, the ORIATRON facility, can be found in [9-11].

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In this paper, we propose a new facility to perform TID testing at system-level or for screening with low radiation safety issues, low purchase and maintenance costs, the possibility to test packaged devices, and the presence of a collimator to irradiate only a small area (a component or a subsystem). This installation is based on a high-energy X-ray generator which allows to obtain a spectrum of photons whose maximum energy can vary from 60 to 320 keV, and on the use of filters in order to cut low energies and to obtain high penetration depths. The use of filters will allow us to limit the photoelectric effect by cutting the low energies where this effect is dominant. We will thus get closer to compton scattering processes, at least for low-Z material.

The high-energy generator used in this study is presented in part II. The role of the filtration used is presented through the analysis of the photon spectra. In part III, two different electronic components (MOS and bipolar transistors) are irradiated with this high energy X-ray generator and results are compared to 60-Co irradiation. In part IV, a study is conducted to better understand the effect of a given spectrum (whose maximum energy varies) on the degradation of components. Dicussion of the obtained results and conclusions are given in part V.

II. High-Energy X-ray Generator

A. Objective

In order to perform TID testing at system-level or for screening, we propose to study in this paper the use of a high-energy X-ray generator with voltage up to 320 kV allowing to obtain photons up to 320 keV. A photograph of the X-ray generator used in this study is given in Fig. 1.

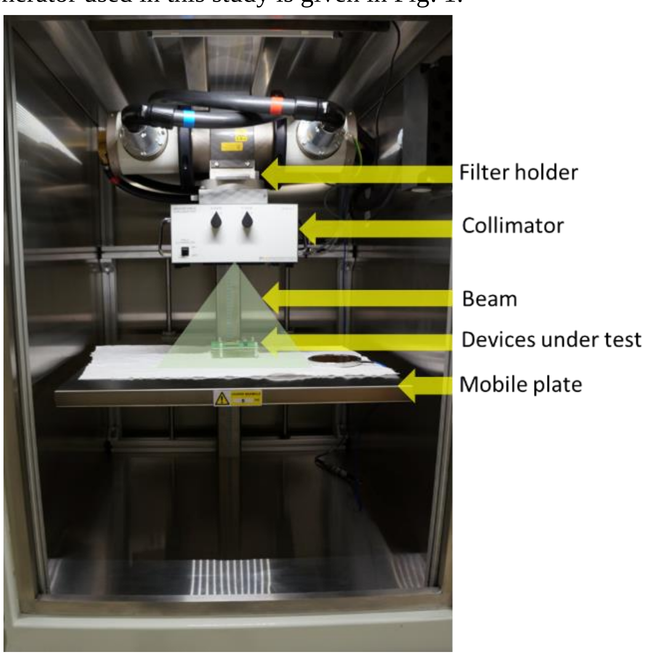

Fig. 1. Photograph of the used high-energy X-ray generator with voltage up to 320 kV. The filter holder is used to filter low energy photons. The collimator allows to irradiate a single area (a component or a subsystem) of an electronic board.

A representation of both the photon spectrum of the used X-ray generator and 60-Co source is depicted in Fig. 2, with the relative importance of the three main interaction processes: photoelectric effect, compton scattering and pair production. For 60-Co, usually considered as the reference for TID testing, two emission rays at 1.17 and 1.33 MeV are observed, and the interaction process is Compton scattering. For X-ray generator, the low energy photons will interact with photoelectric effect while the high energy photons will follow Compton scattering.

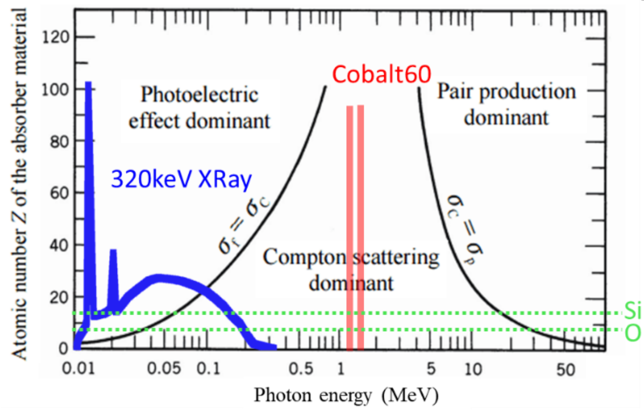

Fig. 2. Comparison of the photon spectrum of the used X-ray generator and 60-Co source with the relative importance of the photoelectric effect, Compton scattering, and pair production from [12].

For the photoelectric effect, low energy photons have a low penetration depth but have a significant impact on the absorbed dose; and this effect is dependent on the atomic number Z of the materials due to the variability of the mass energy-absorption coefficients [13]. These conditions are far from optimal for component testing where the goal is to achieve a high penetration depth and an energy deposition that does not depend on the Z of the material. This is the reason why we have decided to cut the low energy photons (below 100 keV). This cut is realized with a lead (Pb) filter. This filter is studied in the next sections thanks to the experimental measurement of the spectrum of the studied generator that we correlate with simulation results.

B. Experimental X-ray spectra

To verify our hypothesis that a filter can be used with a high energy X-ray generator to cut low energies, we first tested it experimentally in the three following conditions: (1) no filter, (2) a 2 mm aluminum (Al) filter, and (3) a 2 mm aluminum plus 1 mm lead (Pb) filter. For this purpose, the spectrum of the X-ray generator used in this work, an X-RAD320 from PRECISION, has been experimentally measured in the three conditions. The experimental acquisitions of the spectrum are carried out with a counting chain from Amptek: a XR-100CdTe detector (CdTe detector diode and an integrated preamplifier) with PX5 acquisition system (Digital Pulse Processor, power supply). Its ideal measurement range is 15 to 100 keV. This measurement range suits us because we are mainly interested in the effect of filtering on the low energies. In order not to saturate the information (in both the detector and the MCA), we limit the acquisition to 100 keV and we use a shutter with a diaphragm of 200 µm diameter. The obtained results for an X-ray irradiation with a 100 keV maximum energy (the applied voltage is 100 kV) are shown in Fig. 3. Experimentaly, with the used acquisition chain, it was not possible to measure photons with energy lower than 15 keV. So data below 15 keV in Fig. 3 are not usable. Data above 100 keV correspond to noise.

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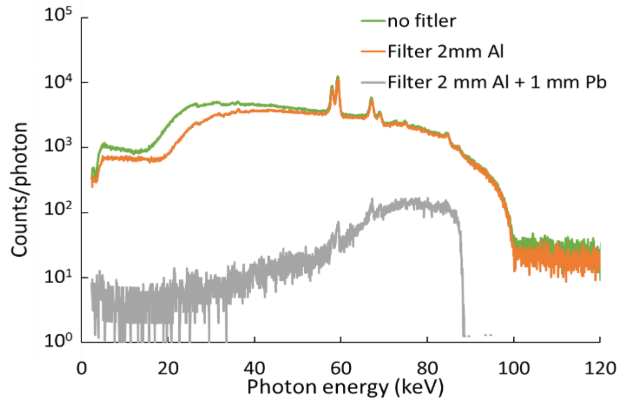

Fig. 3. Experimental X-ray spectra of X-RAD320 at 100 keV 1mA for 100s for three conditions: (1) no filter, (2) 2 mm Al filter and (3) 2 mm Al + 1 mm Pb filter, carried out with XR-100CdTe and PX5 from AMPTEK.

In Fig. 3, it can be observed that the Al filter (condition 2) has only a small impact on the spectrum obtained with no filter (condition 1) with only a small reduction of photons with energy below 40 keV. On the other hand, the Pb filter (condition 3) has a large impact on the spectrum. Indeed, this last filter allows to strongly reduce the number of low energy photons with a factor higher than 100 for photons with energies lower than 60 keV and a factor of 10 for photons with energy around 80 keV. The strong decrease observed at 88 keV corresponds to K-absorption edge of lead [13].

C. Simulated X-ray spectra

In order to validate the obtained experimental spectra, simulation have been performed. The TASMICS spectra model [14] has been used to simulate the X-ray generator spectra in the three previous mentioned conditions. We used this tool to see what is the effect of a filter on the spectrum of the X-ray generator with a quantitative approach (the use of code such as GEANT4 [15] should be preferred for a qualitative approach). The three obtained spectra are presented in Fig. 4 for an X-ray irradiation with a 100 keV maximum energy (the applied voltage is 100 kV). As obtained experimentally, the Al filter induces a reduction of photons for energy below 40 keV. We can note that this reduction becomes very important below 15 keV. This point is important because performing dosimetry for photons of energy below 15 kev is very delicate. This is the reason why this type of filter is recommended when an irradiation is performed with a low energy X-ray generator [3].

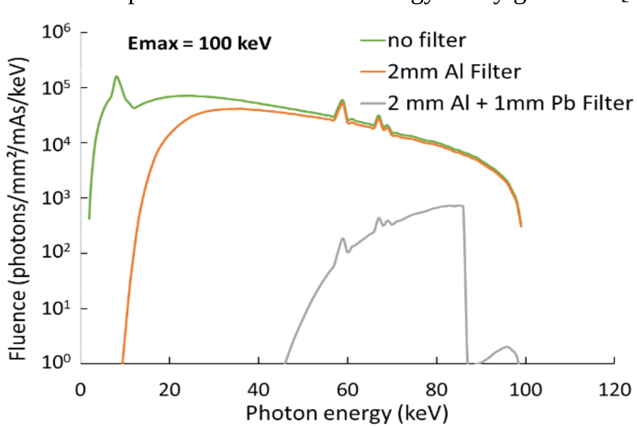

Fig. 4. TASMICS fluence (photons/mm²/mAs/keV at 100 cm from the source) simulation of an X-ray irradiation with a 100 keV maximum energy (the applied voltage is 100 kV) for three conditions: no filter, Al filter and Pb filter.

We can also observed in Fig. 4, that a large reduction of photons is obtained with the Pb filter which corresponds to experimental results presented in Fig. 3. The K-absorption edge of lead (88keV) is also observed.

In order to investigate the impact of such a Pb filter on the photons with higher energy available on the used X-ray generator, simulation have been also performed for an X-ray irradiation with a 320 keV maximum energy (the applied voltage is 320 kV) as shown in Fig. 5.

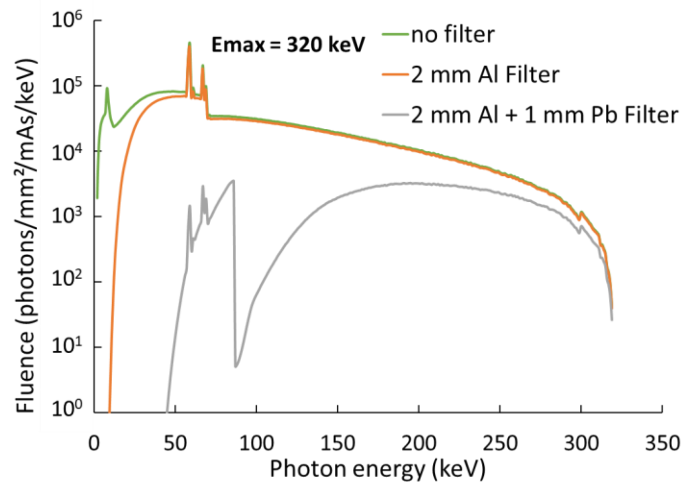

Fig. 5. TASMICS fluence (photons/mm²/mAs/keV at 100 cm from the source) simulation of an X-ray irradiation with a 320 keV maximum energy (the applied voltage is 320 kV) for three conditions: no filter, Al filter and Pb filter.

In Fig. 5, the same results as the ones obtained in Fig. 3 and 4 can be observed. Moreover, we can observe that when the energies increase from 88 keV (after the K-absorption edge of lead) to 320 keV, the Pb filter has less impact when the photons energy increases.

Experimental and simulation results presented in this part show that an X-ray generator spectrum can be filtered with a Pb filter. Such a filter induces mainly a large decrease of the photons with low energy.

III. Irradiation of Electronics Devices

After validating our hypothesis that a filter can be used to reduce the number of low energy photons and thus reduce the amount of dose deposited due to the photoelectric effect, it is necessary to study the impact of this type of filter on the dose response of electronic components. In this part, two different electronic components are investigated: MOS and bipolar transistors. The experimental protocol is described and transistors are irradiated with X-ray with filters. The obtained results are compared to 60-Co irradiation.

A. Experimental protocol

In this ~~ge~~work, two different electronic components are investigated: MOS and bipolar transistors. For MOS transistors, DMN601K NMOS and DMP2004 PMOS have been studied. For bipolar transistors, the LM3086 BJT NPN has been chosen.

For each condition, at least 5 MOS transistors and 3 bipolar transistors have been irradiated (in some cases up to 10 and 5 for MOS and bipolar, respectively). In all the curves presented in the rest of this paper, the data correspond to the average of these components.

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Due to the high TID sensitivity of the selected MOSFET references, it was chosen to irradiate the components un-biased, even if this is not the worst case. So, all the components have been irradiated at room temperature with all pins grounded. We can note that the irradiation area of the X-ray generator is 20 cm x 20 cm, which allows us to irradiate several components at the same time or an entire board for system-level testing. Electrical characterizations were performed with a B1500 semiconductor device parameter analyser from Keysight: Id(Vgs) for MOS transistors and Forwad-Gummel (Ib,Ic(Vbe)) for bipolar transistors were measured. Measurements are made within 40 minutes after irradiation. The threshold voltage extraction are performed with a Vds=+10 V and Id=1 mA for NMOS and Vds=-10 V and Id=-1 mA for PMOS [16]. The Forwad-Gummel are made with Vbe=Vce varying from 0 to 10V from which we extract the maximum current gain.

Two irradiation facilities are used in this work: a 60 curies 60-Co source and an 320 keV X-RAD320 X-ray generator. These two facilities are part of the PRESERVE Platform located in Montpellier (France). The 60-Co is a panoramic irradiator with a 60 curies Cobalt source in a 9x4 m² room. The X-RAD320 is a high energy X-ray generator from PRECISION (USA) with a maximum voltage of 320 kV. For dosimetry, two cross-calibrated (in Air) ionization chambers from PTW are used to mesure dose rates: the TM30013 (with a 30 keV to 50 MeV energy range) connected to the Unidos E dosimeter for 60-Co, and the TM7862 (with a 7.5 keV to 420 KeV energy range) connected to the same Unidos E dosimeter for the X-ray.

B. Co-60 irradiation results

In this section, we focus on Co-60 irradiation to obtain the dose response of the studied components. These results will be used as a comparison point in the rest of this work.

It is important to note that an advantage of X-ray generator will be to reduce the testing time. So, they offer a relatively high dose rate, in comparison to 60-Co. This difference in dose rate is therefore a parameter to be taken into account and it is important to know if the studied components are sensitive to a dose rate effect. In order to bring some elements for discussion, three dose rates have been investigated for the Co-60 irradiation. The dose rates values are given in Table I.

TABLE I
Co-60 dose rate testing

Type #	Filter #	Dose Rate Gy(Air)/h	length Source-target (mm)
Cobalt-60	No filter	5,57	300
Cobalt-60	No filter	0,62	1000
Cobalt-60	No filter	0,15	2000

An exemple of the obtained data is presented in Fig. 6. In this Fig. the Id(Vgs) curves of the DMN601K NMOS transistors are given for 60-Co irradiation performed with a 0.62 Gy(Air)/h dose rate. The current is limited to 100 mA that corresponds to the Keysight B1500 current limitation. As the dose accumulates, the curves shift to the left which corresponds to a decrease in threshold voltage. This can be explained by an accumulation of trapped charges in the oxides. The curves remain parallel to each other, i.e. there is no change in the sub-threshold slope, which suggests that the interface states play little role in the degradation. From such curves, the threshold voltage of MOS transistorants can be extracted.

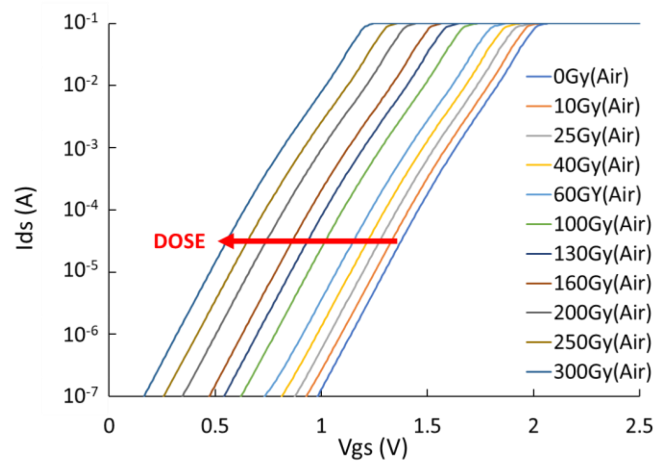

Fig. 6. Ids(Vgs) curves of DMN601K NMOS transistors for different dose for 60-Co irradiation with a 0.62Gy(Air)/h dose rate.

In Fig. 7 and 8, the threshold voltage degradation of the NMOS and PMOS transistors are given for Co-60 irradiation for the three investigated dose rates. On these Fig., the degradation corresponds to pre-irradiation value minus post-irradiation value, i.e. a positive degradation corresponds to a decrease of the threshold voltage. In both cases a no significant dependence on dose rate is observed.

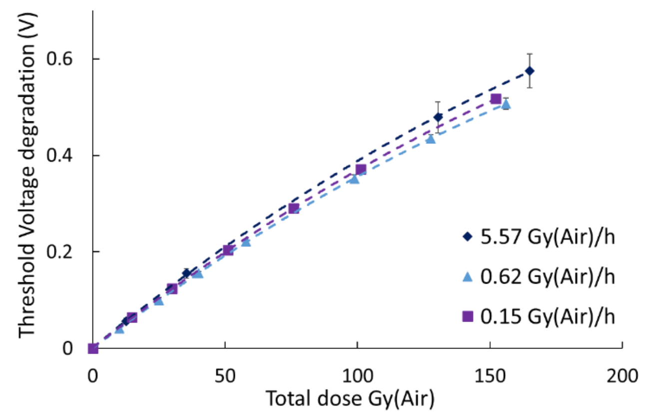

Fig. 7. Threshold voltage degradation of DMN601K NMOS transistors as a function of the dose for three dose rates under 60-Co irradiation. Error bars corresponds to 3 standard deviations.

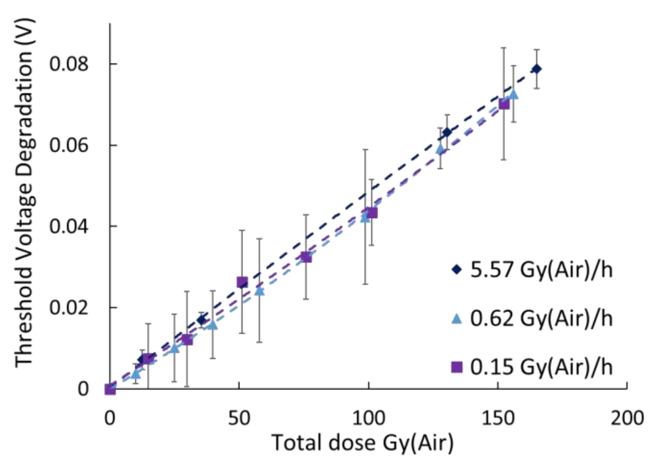

Fig. 8. Threshold voltage degradation of DMP2004 PMOS transistors as a function of the dose for three dose rates under 60-Co irradiation. Error bars corresponds to 3 standard deviations.

In Fig. 9, the gain degradation of the bipolar transistors is plotted as a function of the dose for the three investigated dose rates. The gain degradation corresponds to pre-irradiation value minus post-irradiation value, i.e. a positive degradation corresponds to a decrease of the gain. Contrary to what we had obtained previously for MOS transistors, a dependence on the dose rate appears for bipolar transistors. More degradation is observed for the lower dose rate. This result is however moderated by the fact that the error bars (corresponding to three standard deviation) are important, i.e. a large variability is observed between transistors. This point should be taken into account during the comparisons that we will make in the rest of this paper.

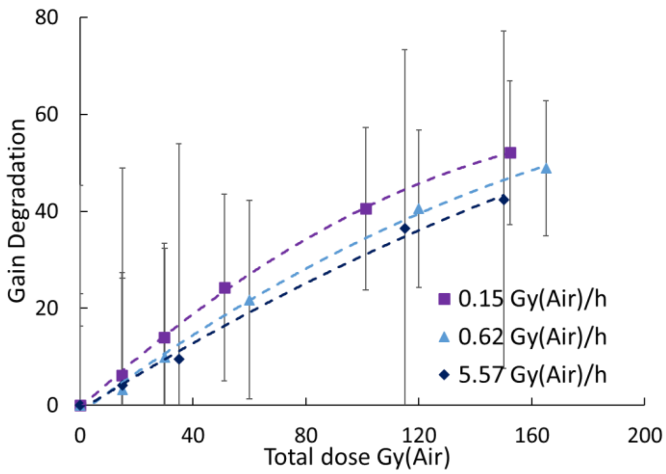

Fig. 9. Gain degradation of LM3086 NPN transistors as a function of the dose for three dose rates under 60-Co irradiation. Error bars corresponds to 3 standard deviations.

C. X-ray irradiation results and comparison to Co-60

In order to perfom X-ray irradiation and to compare to Co-60, three irradiation conditions are considered: 60-Co irradiation, X-ray irradiation with 2 mm Al filter, and X-ray irradiation with 2 mm Al plus 1 mm Pb filter.

For X-ray irradiation, the choice of filters was justified by the three following points. First, the Al filter was chosen to attenuate low energy photons (< 15 keV) as it is done in several standards (in [8] for example). This point is very important because the experimental measurement of the dose rate for low energy photons is delicate. Indeed, ionization chambers can only measure photons with energies higher than about ten keV (which is the case of our PTW TM7862 chamber whose limit is 7.5 keV). So if we want to measure the dose rate with an ionization chamber, it is important to attenuate the low energy photons. Second, since our objective is to attenuate the photons inducing a photoelectric effect (at least less than 120 keV) in order to get closer to the results we obtain with 60-Co irradiation, we chose to use lead. Lead is the most common, and cheapest, material to fulfil this mission. Third, one of the main advantages of using an X-ray generator is its high dose rate. The use of filters has an impact on the dose rate. The thicker the filter, the lower the dose rate we will get after the filter. It is therefore necessary to find a compromise between the attenuation of photons and the dose rate that we wish to obtain.

We chose 2 mm Al because this filter allows an attenuation of at least 3 decades of photons below 10 keV (as shown in fig. 4). We chose 1 mm Al because this filter allows sufficient attenuation (at least 2 decades except around 80 keV as shown in fig. 5) of photons below 120 keV while not reducing the dose rate too much.

For a cobalt irradiation, the spectrum has two significant peaks: one at 1173 keV and another at 1332 keV. In our case, with a panoramic irradiator in a large room, filters is not useful.

The irradiation conditions are given in Table II.

TABLE II
Irradiation conditions

Type #	Filter #	Dose Rate Gy(Air)/h	length Source-target (mm)
Cobalt-60	Nothing	0,62	1000
X-ray	2 mm Al	30	400
X-ray	2 mm Al + 1 mm Pb	30	400

For 60-Co, a dose rate of 0.62 Gy(Air)/h has been chosen. There is no significant difference between Gy(Air) and Gy(SiO_2) for high photon energies, which is the case for 60-Co source.

As defined in the objectives we want an X-ray spectrum with highest energies; i.e. a majority of photons that interact with Comptom scattering instead of photoelectric effect. The X-ray generator voltage is therefore set to 320 kV to obtain photons with a maximum energy of 320 keV. For the two X-ray irradiation, we have chosen to have, after the Al or Al + Pb filter, the same dose rate (i.e. 30 Gy(Air)/h). This dose rate is measured with the PTW ionization chamber. To obtain such a result, the X-ray current with the Al filter is 1.6 mA and 10.6 mA with the Al + Pb filter.

Using the ionization chamber values as a reference, each investigated transistor is irradiated with intermediate steps. In the following Fig., the TID is indicated in Gy(SiO_2) because it is the charges trapped in the oxide that are involved in the degradation mechanisms. Since each filter will modify the X-ray spectrum, a conversion factor has to be estimated for the used X-ray in the two conditions: Al filter and Al + Pb filter. This factor can be calculated using the energy-mass absorption coefficients (Air/SiO_2 ratio from[13]) summed over the entire used energy spectrum. In our case, for the X-ray irradiation with 2 mm Al this factor equals 2.25 and it equals 1.15 for the X-ray irradiation with 2 mm Al + 1 mm Pb. In all the curves presented in the rest of this paper, the “Air” dose has been corrected by the calculated conversion factor and we name it “Effective TID Gy(SiO_2)”.

In Fig. 10 and 11 the voltage thresholds of the two investigated MOS transistors are shown for the three considered irradiation conditions (Table II). For these two devices, more degradation is obtained for X-ray irradiation with Al filter. Moreover, the degradation is greater for X-ray irradiation with the Al filter than for X-ray irradiation with the Al + Pb filter. These two degradations being themselves more important than the 60-Co degradation. As obtained in [10,11], these results show that higher degradations are observed when photons with low energy are involved.

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From a electronic device testing point of view, the main result is that the degradation obtained with X-ray irradiation with the Al + Pb filter is closer to the one obtained with the 60-Co than when a simple Al filter is used, but a difference, which depends on the component studied, remains.

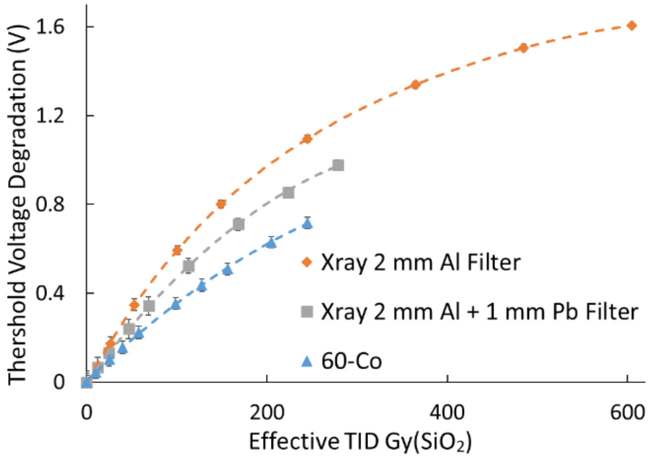

Fig. 10. Threshold voltage degradation versus effective TID for DMN601K NMOS transistors for the three investigated irradiation conditions.

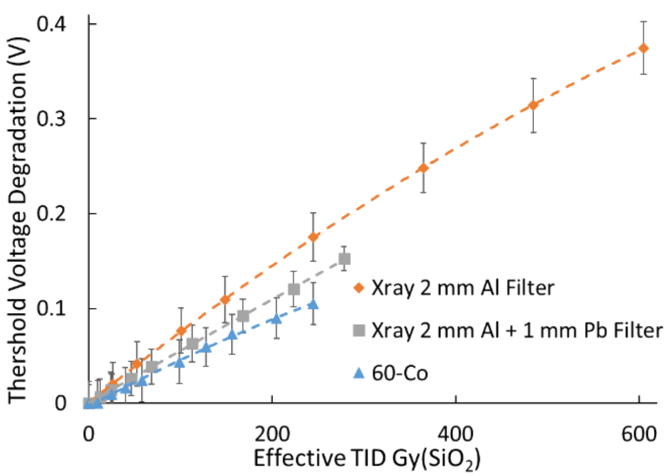

Fig. 11. Threshold voltage degradation versus effective TID for DMP2004 PMOS transistors for the three investigated irradiation conditions.

In Fig. 12, the gain degradation of the bipolar transistors are shown for the three considered irradiation conditions. For this device, the higher degradation is obtained for Co-60 irradiation. Contrary to the previous result, the higher degradations is not obtained when photons with low energy are involved (i.e. with X-ray).

This may be explained by the sensitivity of this transistor to dose rate as shown in Fig. 9. However, we still observe that the degradation obtained with X-ray irradiation with the Al + Pb filter is closer to the one obtained with the 60-Co (with a difference of 15% on average on the curve) than when a simple Al filter is used (the difference equals 45% in this case).

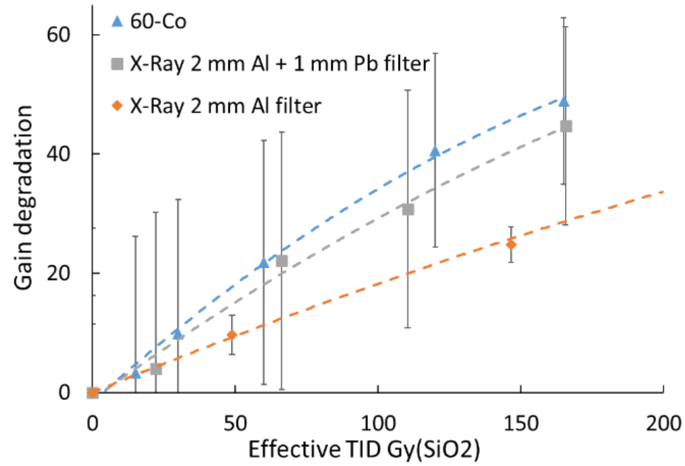

Fig. 12. Gain degradation versus effective TID for LM3086 NPN for the three investigated irradiation conditions.

D.Annealing

Since the X-ray irradiations are shorter than the cobalt irradiations, annealing effects have been investigated for some components. In Fig. 13, a comparison of the threshold voltage after X-ray irradiation and after 1 week of annealing at room temperature is shown for 8 NMOS and 8 PMOS transistors.

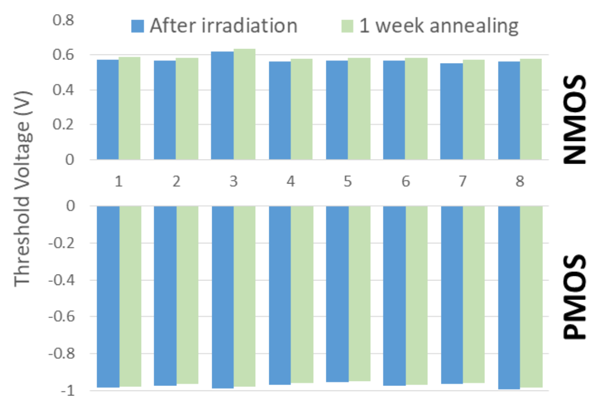

Fig. 13. Threshold voltage of 8 DMN601K NMOS and 8 DMP2004 PMOS transistors, after 320 kV X-ray irradiation (300 Gy(Air) at 30Gy(Air)/h with a 2 mm Al + 1 mm Pb filter) and after 1 week annealing at room temperature.

For NMOS transistors, a small increase in threshold voltage is observed after annealing, while for PMOS transistors, a small decrease (in absolute value) is observed. In both cases, the difference after annealing is small (less than 3%) and corresponds to a recovery of the degradation. This result allows us to conclude that the annealing effect is negligible for the MOS transistors studied in this work.

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IV. Study as a Function of the Maximum Energy of the Spectrum

In the previous part we have shown that the degradation obtained with X-ray irradiation with the Al + Pb filter is closer to the one obtained with the 60-Co than when a simple Al filter is used. Such a result has been obtain with a 320 keV maximum energy (the applied voltage is 320 kV). In this part, in order to understand the role of the applied voltage on the dose response of electronic components, we propose to investigate this parameter from 60 kV to 320 kV, i.e. the maximum energy of the spectrum will be from 60 keV to 320 keV.

The different investigated irradiation conditions are given in Table III. The dose rate has been fixed to 15 Gy(Air)/h since higher dose rates can not be reach for low X-ray voltages.

TABLE III
Irradiation conditions

Type #	Filter #	Dose Rate Gy(Air)/h	length Source-target (mm)
Cobalt-60	Nothing	0,62	1000
X-ray 320 kV	2 mm Al	15	400
X-ray 320 kV	2 mm Al + 1 mm Pb	15	400
X-ray 280 kV	2 mm Al	15	400
X-ray 280 kV	2 mm Al + 1 mm Pb	15	400
X-ray 250 kV	2 mm Al	15	400
X-ray 250 kV	2 mm Al + 1 mm Pb	15	400
X-ray 160 kV	2 mm Al	15	400
X-ray 100 kV	2 mm Al	15	400
X-ray 60 kV	2 mm Al	15	400

By changing the X-ray voltage, we change the spectrum. It is therefore necessary to calculate the conversion factors to correct the "Air" dose to "Effective TID Gy(SiO_2)" as explained in part III-C. The calculated factors are given in Fig. 14. The factor values decrease when the X-ray generator voltages increase since more high energy photons are present in the spectrum. Moreover, as we have already seen, the use of an Al + Pb filter allows a large reduction of low energy photons which explains why the factors are lower when an Al + Pb filter is used compared to a simple Al filter.

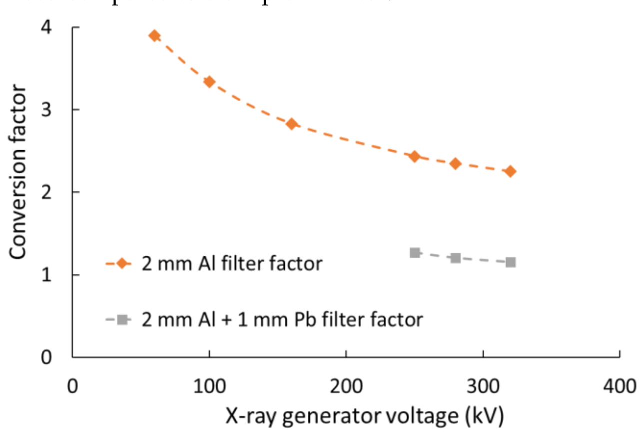

Fig. 14. Calculated conversion factor as a function of the X-ray generator voltage for the irradiation conditions presented in Table III.

In Fig. 15, the threshold voltage degradation is plotted as a function of the effective dose for X-ray generator voltage from 60 keV to 320 keV with a 2 mm Al filter. It can be observed that X-ray irradiation with a low voltage (60 kV) induces a large overestimation of the degradation (an increase of 205%). We can see that as the generator voltage increases (320 kV), we get closer to the response obtained with Co-60 (the increase is only equals to 160%). In this case, with a 2 mm Al filter the best result is obtained at 320 kV. As already mentioned, these results show that higher degradations are observed when photons with low energy are involved [10,11], i.e. for low voltages. The main conclusion is that the use of an x-ray with the highest possible voltage is recommended for the dose testing.

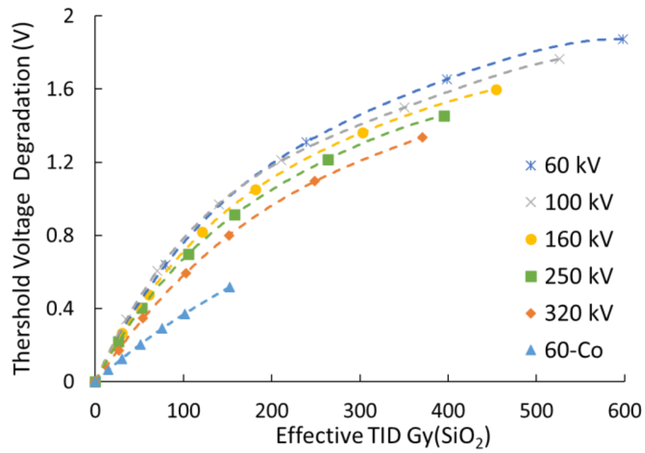

Fig. 15. Threshold voltage degradation versus effective TID for DMN601K NMOS transistors for different X-ray generator voltages and with a 2 mm Al filter.

In Fig. 16, the effect of the 2 mm Al + 1 mm Pb filter is investigated when the X-ray voltage varies from 320 kV to 250 kV. In the Fig. 15, the best result (the closer to the Co-60) was obtain with the 2 mm Al filter with a 320 kV X-ray voltage. In Fig. 15, we can observe that a 2 mm Al + 1 mm Pb filter always give a best result whatever the X-ray voltage from 320 kV to 250 kV. We finally observe that the use of an Al + Pb filter with a voltage of 320 kV gives a result close to an irradiation performed with Co-60 (within 10% for the 15 Gy/h dose rate).

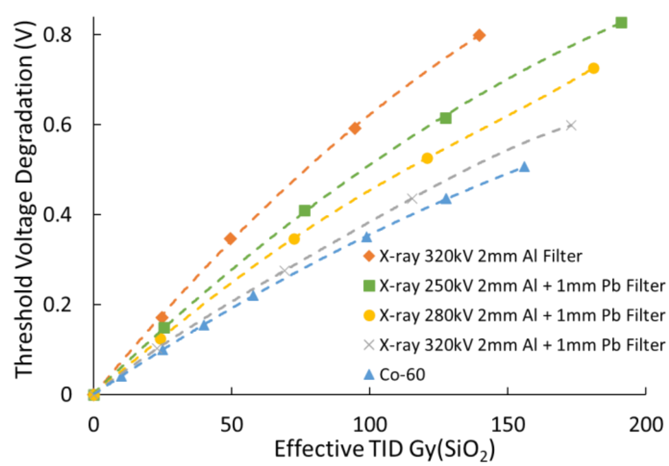

Fig. 16. Threshold voltage degradation versus effective TID for DMN601K NMOS transistors for different X-ray generator voltages and with 2 mm Al + 1 mm Pb filter.

The results obtained in this part are essential for the proper use of a high-energy X-ray generator, especially since such equipment is relatively common. Indeed, some X-rays generators using 160 or 250 kV voltage are often used, especially for the study of optical fiber dosimetry [17].

V. Discussion and Conclusions

In this work we have provided a first demonstration of the use of a filtered high-energy X-Ray generator for TID testing. Such a generator has many advantages: low radiation safety issues, low purchase and maintenance costs, the possibility to test packaged devices due to high penetration depths. It is particularly suitable for system level testing due to its large irradiation area and the presence of a collimator.

Thanks to simulation, we have shown that a lead filter can be used to cut low energy photons. This result has been validated experimentally with a 320 keV X-ray generator. The use of filters allow to limit the photoelectric effect by cutting the low energies and to get closer to Compton scattering processes. If the interaction mechanisms are similar to those involved in the use of 60-Co as an irradiation source, we can expect to have an identical dose response of electronic components. In order to provide some answers, electronic components have been irradiated within 3 conditions: 60-Co irradiation, X-ray irradiation with Al filter, and X-ray irradiation with Al + Pb filter. Degradation closer to 60-Co has been obtained with X-ray irradiation when low energy photons were cut (i.e. when a lead filter is used). But a difference of degradation remains. The degradation difference can be attributed to several factors: the contributions of packaging or backscattered photons in Back End Of Line (BEOL) stack (contacts, metal layers, insulating layers) that can induce a significant TID contribution in the sensitive oxide [10]. Dose enhancement due to secondary electrons emitted by metal layers can also be an important factor [4-7,18-22]. Such an effect will have to be studied. Another explanation can be Time Dependent Effect (TDE) or True Dose Rate Effect (TDRE) due to the use of different dose rates for 60-Co and X-ray irradiations.

The results obtained in this work also allow us to draw some recommendations for the use of a high energy X-ray generator for the dose testing of electronic components. Indeed, we have shown that the use of a filter (lead) allowing the cutting of low energy photons is essential to get closer to the dose response obtained with cobalt. This is the most important recommendation for using a high energy X-ray generator for dose testing of electronic components. A second recommendation is to use an X-ray generator with the highest possible voltage to obtain the highest proportion of high-energy photons.

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References

[1] MIL-STD-883 Test Method Standard, “Microcircuits”, Department of Defense, Defense Supply Center, Feb. 22, 2017.

[2] ESA, ESCC, ESCC Basic Specification No. 22900 Issue 5, “Total Dose Steady-State Irradiation Test Method”.

[3] ASTM F1892, “Standard Guide for Ionizing Radiation (Total Dose) Effects Testing of Semiconductor Devices”, ASTM International, 2018.

[4] D. M. Fleetwood, P. S. Winokur, and J. R. Schwank, “Using laboratory X-ray and cobalt-60 irradiations to predict CMOS device response in strategic and space environments”, IEEE Trans. Nucl. Sci., vol. 35, no. 6, pp. 1497–1505, Dec. 1988, doi: 10.1109/23.25487.

[5] T. R. Oldham and J. M. McGarrity, “Comparison of 60Co response and 10 KeV X-ray response in MOS capacitors”, IEEE Trans. Nucl. Sci., vol. NS-30, no. 6, pp. 4377–4381, Dec. 1983 , doi: 10.1109/TNS.1983.4333141.

[6] M. R. Shaneyfelt, D. M. Fleetwood, J. R. Schwank, and K. L. Hughes, “Charge yield for cobalt-60 and 10-keV X-ray irradiations of MOS devices”, IEEE Trans. Nucl. Sci., vol. 38, no. 6, pp. 1187– 1194, 1991, doi: 10.1109/23.124092.

[7] D. M. Fleetwood, P. S. Winokur, R. W. Beegle, P. V. Dressendorfer, and B. L. Draper, “Accounting for dose-enhancement effects with CMOS transistors”, IEEE Trans. Nucl. Sci., vol. NS-32, no. 6, pp. 4369–4375, Dec. 1985 , doi: 10.1109/TNS.1985.4334126.

[8] ASTM F1467-99(2005)e1, “Standard Guide for Use of an X-ray Tester (≈10 keV Photons) in Ionizing Radiation Effects Testing of Semiconductor Devices and Microcircuits,” ASTM International, 2005.

[9] D. Aubert et al., "A 6 MeV electron linac facility for multipurpose radiation testing," 2016 16th European Conference on Radiation and Its Effects on Components and Systems (RADECS), Bremen, Germany, 2016, pp. 287-289, doi: 10.1109/RADECS.2016.8093158.

[10] D. Lambert et al., “TID effects evaluation induced by photon sources in MOS devices: Impact of geometry and materials”, IEEE Trans. Nucl. Sci., to be published, doi: 10.1109/TNS.2021.3074711.

[11] M. Gaillardin et al. “Investigations on spectral photon radiation sources to perform TID experiments in micro-and nanoelectronic devices”, in IEEE Transactions on Nuclear Science, vol. 68, no. 5, pp. 928-936, May 2021, doi: 10.1109/TNS.2021.3072583.

[12] R.D. Evans, The Atomic Nucleus, McGraw-Hill, p. 712, 1955.

[13] X-Ray Mass Attenuation Coefficients - NIST Standard Reference Database 126,. DOI: https://dx.doi.org/10.18434/T4D01F.

[14] A.M. Hernandez, J.M. Boone, “Tungsten Anode Spectral Model using Interpolating Cubic Splines; Unfiltered x-ray spectra from 20 kV to 640 kV”, Med Phys. 41, 042101, 2014, doi: 10.1118/1.4866216.

[15] S. Agostinelli et al., “Geant4—a simulation toolkit” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 506, no. 3,pp. 250-303, July 2003, doi: 10.1016/S0168-9002(03)01368-8.

[16] https://www.diodes.com/assets/Datasheets/DMN601K.pdf

[17] A. Morana et al.,–“Performances of Radiation-Hardened Single-Ended Raman Distributed Temperature Sensors Using Commercially Available Fibers”, in IEEE Transactions on Nuclear Science, vol. 67, no. 1, pp. 305-311, Jan. 2020, doi: 10.1109/TNS.2019.2954586.

[18] A. Dasgupta, D. M. Fleetwood, R. A. Reed, R. A. Weller, M. H. Mendenhall, B. D. Sierawski, “Dose enhancement and reduction in SiO_2 and high-κ MOS insulators” in IEEE Transactions on Nuclear Science, vol. 57, no. 6, pp. 3463-3469, Dec. 2010, doi: 10.1109/TNS.2010.2079950.

[19] D. M. Fleetwood et al.,“Comparison of enhanced device response and predicted x-ray dose-enhancement effects on MOS oxides” –in IEEE Transactions on Nuclear Science, vol. 35, no. 6, pp. 1265-1271, Dec. 1988, doi: 10.1109/23.25450.

[20] A. Griffoni et al. "Dose enhancement due to interconnects in deep-submicron MOSFETs exposed to X-rays" 2008 European Conference on Radiation and Its Effects on Components and Systems, Jyvaskyla, Finland, 2008, pp. 432-437, doi: 10.1109/RADECS.2008.5782758.

[21] K. Huang, K. Yan and Y. Yu, "Study of dose enhancement effects in the vicinity of high Z atoms with Geant4 Monte Carlo simulation" 2010 3rd International Conference on Biomedical Engineering and Informatics, Yantai, China, 2010, pp. 1260-1264, doi: 10.1109/BMEI.2010.5639270.

[22] D. M. Long, D. G. Millward, R. L. Fitzwilson, W. L. Chadsey, “Handbook for dose enhancement effects in electronic devices”, final technical report, March 1983, https://apps.dtic.mil/sti/pdfs/ADA128490.pdf.