PIN diodes to calibrate the CERN-EP/ESE irradiation systems

F.Faccio, G.Borghello, H.Koch

October 5, 2018

The CERN-EP/ESE group has 2 X-ray irradiation facilities dedicated to the study of radiation effects in microelectronics technologies. The characteristics of these sources are very similar to those described in [1] for a commercial irradiation system originally proposed by ARACOR. The tube uses a tungsten (W) target material, a beryllium window in the the tube-housing and then a 150um Al filter to eliminate the low-energy portion of the spectrum. These X-rays below 8-10 keV do not deposit the dose uniformly even in the first tens of microns of silicon, making the dosimetry very impractical and dependent on the depth of the sensitive zone in the irradiated material.
The approach proposed by ARACOR in [1] is to eliminate this low-energy X-rays by the addition of an Al filter, and to use a pre-calibrated PIN diode to measure the dose rate. To do so correctly, the PIN diode has to have a very thin sensitive volume, so that the dose deposited by the X-rays is uniform across the whole sensitive volume. The original PIN diode used by ARACOR has the following characteristics:

- sensitive depth: 25 um
- sensitive area: 10 mm^2
- entrance window: 0.75 um

These diodes were manufactured by Quantrad Sensor in California, and CERN procured 2 samples at the time of purchasing the first irradiation system, in 1996. These 2 samples have been calibrated under contract by a French company, Corad, situated in Montpellier. These diodes have been used since for the measurement of the dose rate in the CERN-EP/ESE X-ray irradiation system.

In 2013, a verification of the calibration of the X-ray source has been carried on. New radio chromic films were available with a sensitive thickness of just 40 um, and calibration curves for these films were available from the supplier and from other irradiation sources. This exercise yielded an agreement better than 20% between the dose measured in the same conditions by the films and by the diodes.

In 2017, during the study of the radiation effects in the 65 nm CMOS technology, a series of irradiations were performed on individual transistors in two different ^{60}Co facilities at two very different dose rates. Other than revealing a dose-rate effect in this technology, the data gathered in that occasion have been used to compare the radiation effects at the different facilities. To this purpose, identical experiments were performed at the ^{60}Co sources and at our X-ray machine. Each of the three sources used a different calibration methodology:

- Pagure irradiator at LABRA/CEA Saclay (1.9 Mrad/hour): ionisation chamber and radio chromic films
- CC60 irradiator of the EN department at CERN Prévessin (35 krad/hour): RPLs and RadFETs, plus simulation
- EP/ESE X-ray irradiator (36 krad/hour, 1.9 Mrad/hour and 8.9 Mrad/hour): calibrated PIN diode and radio chromic films.

The comparison of the damage induced by this large set of exposures is summarised in Figs. 1 and 2, that report the percentage degradation of the maximum drive current I_{on} of both NMOS and PMOS transistors in 65 nm.

The degradation of the NMOS transistors is very small, in particular in the range of TID where data for all the sources is available, up to about 22 Mrad (please note that all doses in this document are referred to SiO_2). As a consequence, the clearest result is visible from the PMOS results in Fig. 2. There is a relatively large variability between different devices, however it clearly appears that the damage induced at the different facilities is very comparable - when the dose rate is the same. The conclusion is that the calibration of the EP/ESE X-ray irradiator is adequate to reproduce the damage induced by the gamma-rays of any 60Co source, which is the universal reference for TID studies in electronics devices.

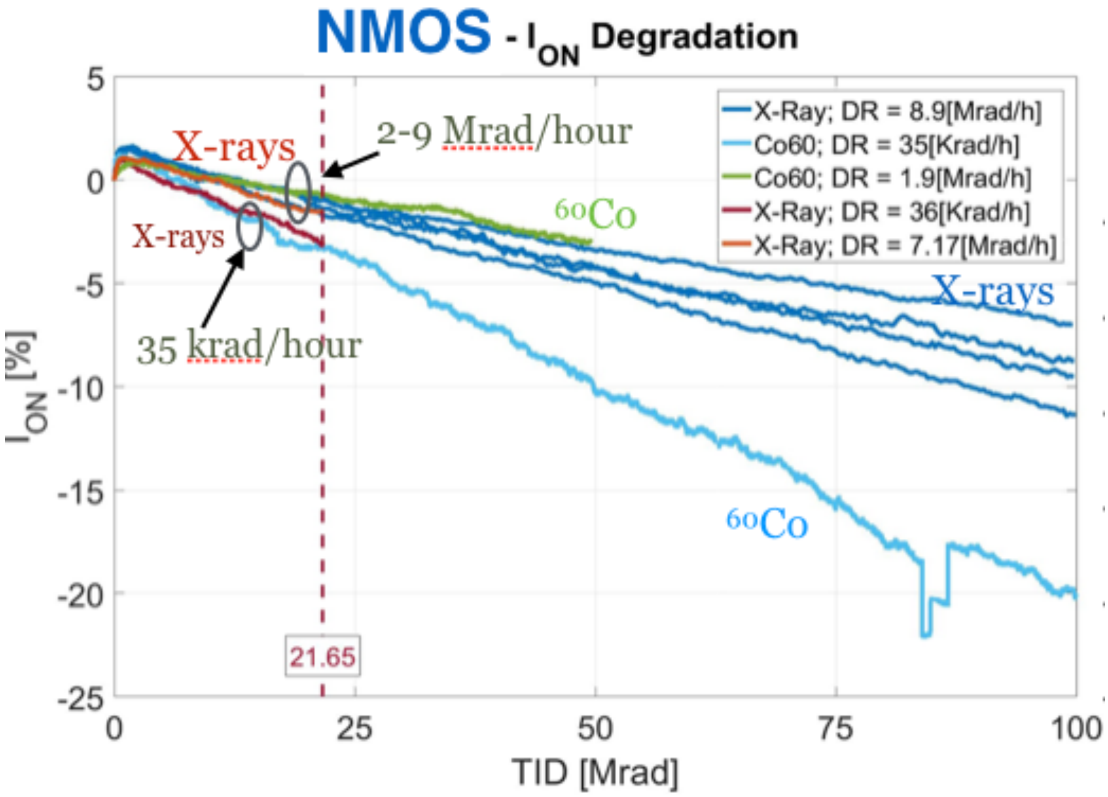


Figure 1: Comparison of the degradation induced on NMOS transistors in the 65nm process by the dose delivered by 2 different ^{60}Co sources and the CERN X-ray irradiation source. TID is always expressed in SiO_2.

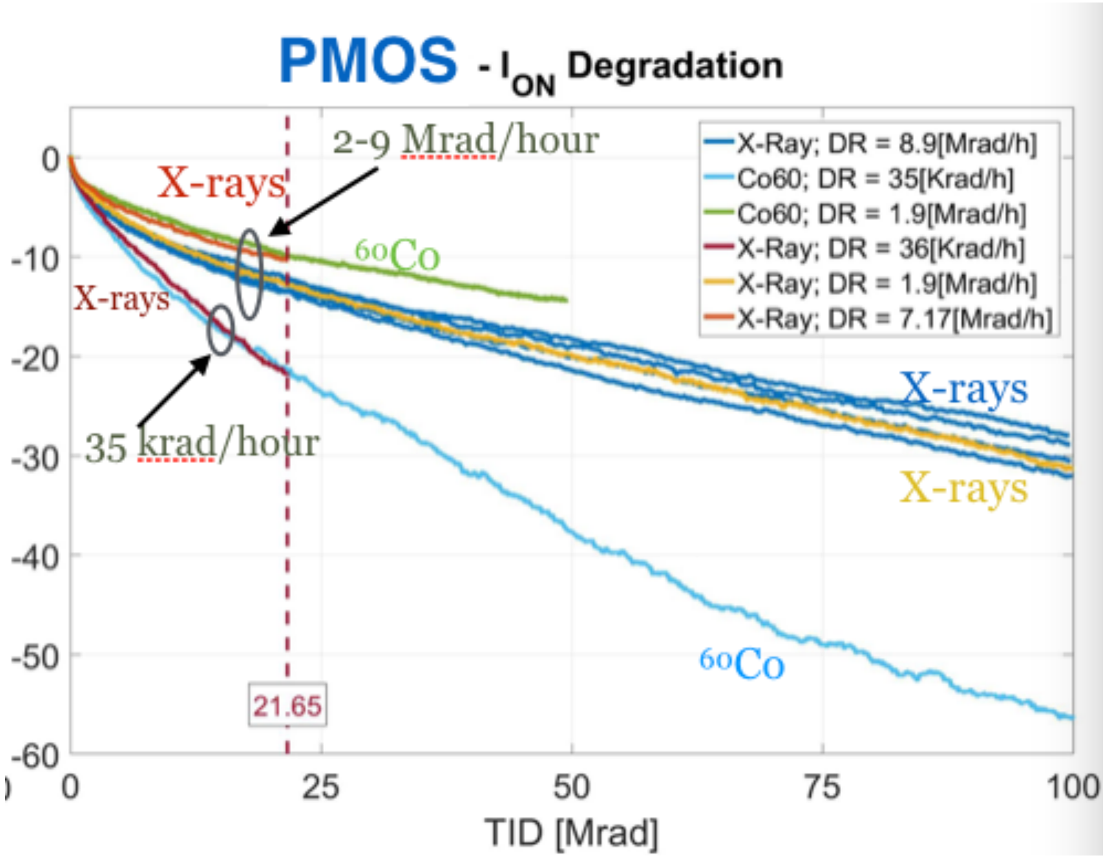


Figure 2: Comparison of the degradation induced on PMOS transistors in the 65nm process by the dose delivered by 2 different ^{60}Co sources and the CERN X-ray irradiation source. TID is always expressed in SiO_2.

It has to be pointed out that similar results have been obtained for samples in a 130nm technology. These samples contained basic digital blocks, ring oscillators with differently sized and laid out inverters, and their TID-induced degradation was compared in a more limited range of dose rates. However, the degradation was well comparable at the ^{60}Co and X-ray facilities when the same dose rate was used.

In 2017 EP/ESE purchased a second X-ray irradiation system with similar characteristics - only the tube and tube-housing differed to produce a larger beam area. At the same time, a growing number of X-ray systems were starting to be used by the HEP community to qualify circuits for the ultra-high TID levels required for HL-LHC electronics. Since the same diodes procured in 1997 from Quantrad were not available anymore, new diodes had to be procured and calibrated to allow for a uniform and safe dosimetry at all facilities. A new diode model was therefore chosen and procured in a large number of samples. This diode, the AXUVHS5 from OptoDiode, has the following characteristics:

- sensitive depth: 50 um
- sensitive area: 1 mm^2
- entrance window: 3 to 7 nm

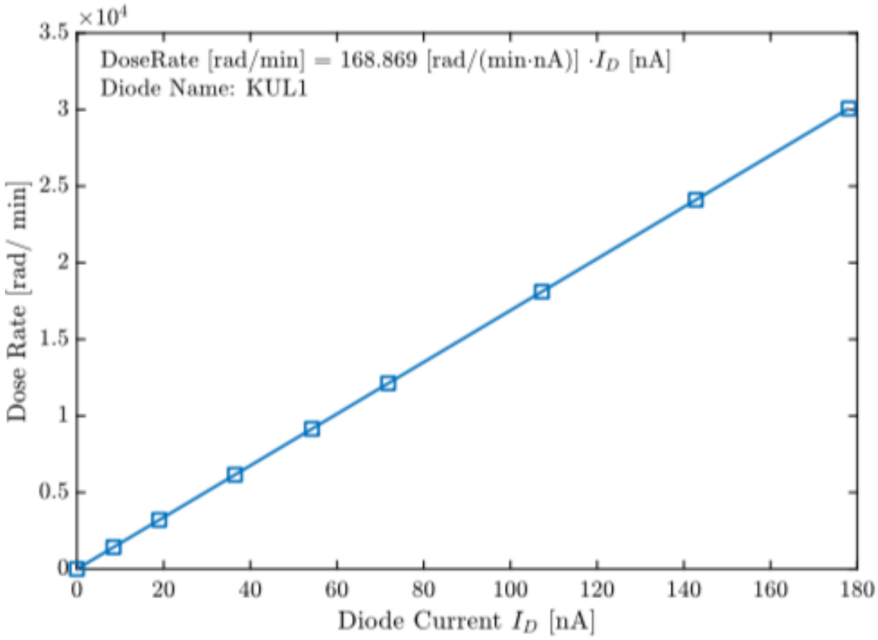
Some 21 diodes have been purchased by different institutes in the HEP community, and a global calibration campaign for all these devices has been organised at the EP/ESE irradiation facilities. Both X-ray irradiation systems were first characterised using the old Quantrad diodes to produce a known curve of the dose rate as a function of the tube parameters (voltage, current) in a given geometrical configuration. At that point, and to gain additional confidence in the calibration performed with the diodes, radio chromic films were used again. Table 1 summarises the results of the measurements performed with FWT60 films compared to the dose obtained with a Quantrad diode (diode n.18). The dose obtained with the diode is always larger than for the films, but the percentage difference (last column) is limited to about 25-27% in the last two measurements, where the background signal of each film has been measured before exposure and correctly subtracted. It should be highlighted that the radio chromic films used in this study are quite old, and that there are different approximations that are used to convert the dose in the FWT60 (3rd column) in SiO_2 (4th column).

Sample Number	Ref Value	Dose FWT60 (kGy)	Dose FWT60 (SiO2) (kGy)	Diode D18 kGy (SiO2) (kGy)	Diff [%]
1	0.064	8.3	62.47911104	75	-16.69
2	0.064	8.5	64.03661761	75	-14.62
7	0.064	9.8	73.62873913	120	-38.64
8	0.064	23.9	179.0184501	262.5	-31.80
9	0.064	21.2	159.0709211	200	-20.46
10	0.064	18.0	134.9693071	171.7	-21.39
11	0.064	11.6	87.07712003	120	-27.44
13	0.07	9.9	74.44720204	100	-25.55

Table 1: Comparison of the dose measured in the EP/ESE X-ray systems with the FWT60 radio chromic films and with one of the calibrated Quantrad diodes (n. 18 in this case). Samples 1 and 2 were used in the newly acquired X-ray system, while samples 7 to 13 in the system purchased in 1996. Only for samples 11 and 13 the pre-irradiation background signal was directly measured and subtracted, for all other samples a "nominal typical" background was used - therefore these are less precise.

In summary, all comparisons presented above with either radio chromic films or with CMOS transistors irradiated in ^{60}Co facilities indicate that the dosimetry at the EP/ESE X-ray systems is adequate for the studies that are typically carried in the framework of the qualification of technologies and circuits for HEP applications. Dosimetry at an X-ray facility is very complex because of the limited penetration of the photons: the dose deposition is non uniform in depth, so bulk dosimeters such as ionisation chambers are not adequate. As an example of the nonuniformity of the dose even in thin materials, we can quote that a silicon thickness of only 300 um is sufficient to drop the dose rate by a factor of 2.2.

Given the very reasonable calibration results above, the radiation field inside the X-ray systems can be characterised using the Quantrad diodes. In this known field, it is then possible to calibrate the newly procured OptoDiode diodes. This is the procedure that has been followed to produce a curve for each of the new diodes expressing the dose rate (in SiO_2) as a function of the current in the diode. Two example curves are shown in Fig. 3, where it is possible to see that the slope of the curve is very different for the 2 samples. In fact the new diodes appeared to belong to 2 different groups in terms of current response, both groups being very uniform in their response. A first group (for which the device KUL1 in Fig. 3 is representative) had a much smaller current response than the second group (for which the device D2 in Fig. 3 is representative). As a result the equation to obtain the dose rate from the current has a very different slope (168 for the first group versus 52 for the second).



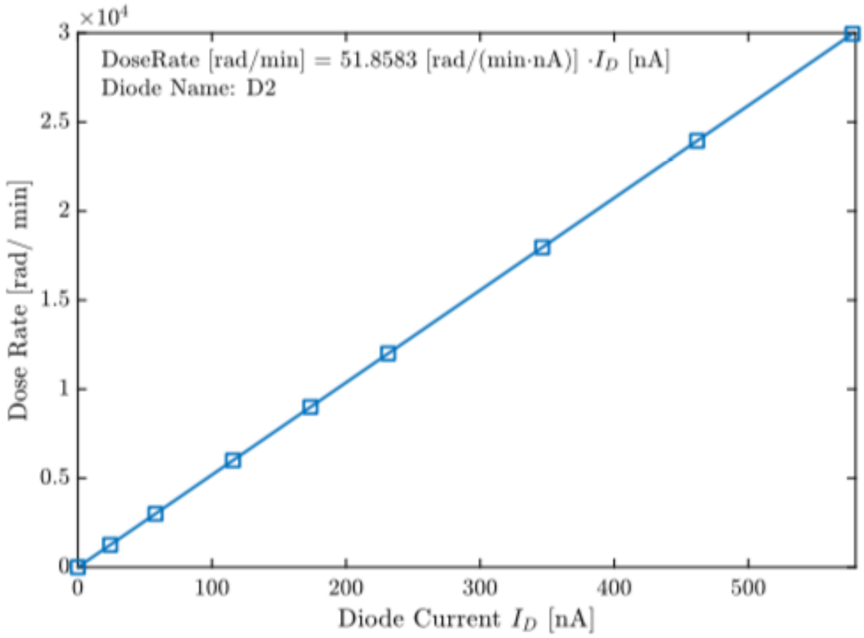


Figure 3: Calibration curve for representative samples from the 2 groups of response found for the newly purchased AXUVHS5 diodes from OptoDiode. The group of diode KUL1 (top) yielded a considerably smaller current at the same dose rate. For all diodes the linearity of the current with the dose rate is excellent.

All the newly procured diodes have been individually calibrated following this same procedure, and they have then been distributed to several HEP institutes where they will be used to ensure the dosimetry at local X-ray irradiation facilities. It is however important to point out that the calibration curve provided with the diodes are based on data taken at the CERN-EP/ESE facilities, where the tubes use a W target and there is a 150 um Al filter along the X-rays path. So these curves can be used as good reference only for the characterisation of sources with identical characteristics.

References

[1] L.J.Palkuti, J.J.LePage, “X-Ray Wafer Probe for Total Dose Testing”, IEEE Trans. Nucl. Science, Vol.29, n.6, Dec.1982, pp.1832-1837