Experimental Determination of the Impact Ionization Coefficients in Irradiated Silicon

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***Abstract*—We present new results on the influence of radiation-induced damage on the electron Impact Ionization (I.I.) coefficient α, suggesting a small but distinct reduction of α at high fluence with respect to unirradiated silicon. Experiments on thick (1.5 μm) and thin (1 μm) epitaxial silicon samples confirm that such a reduction of α is expected even in cases where impact ionization is not simply a field driven process because of strongly non local transport conditions.**

A consistent increase on the breakdown voltage of a 3D radiation detector has been evaluated by means of TCAD simulations using the experimentally extracted I.I. coefficient for irradiated silicon.

These results clarify the impact of radiation damage on some of the key model parameters for TCAD simulations and allow for improved accuracy toward predictive breakdown simulations of silicon particle detectors, e.g., for the ATLAS experiment.

***Index Terms*—Breakdown voltage, impact ionization, radiation induced damage, 3D detectors.**

I. Introduction

SILICON particle detectors are the solution of choice in high energy physics experiments thanks to: 1) the good tracking performance, useful for studying long-lived particles; 2) the ability to sustain the very large number of particles per collision produced in modern high energy experiments; 3) the limited amount of material to which particles interact, thus avoiding energy losses in the determination of the particle momentum. On the other hand, the very high values of luminosity required lead to intense fluxes of heavy particles to which silicon detectors are exposed. For instance, in *Large Hadron Collider* (LHC) experiments at CERN the luminosity has a nominal value of 10^{34} cm^{-2}s^{-1}, and it will be nearly doubled at the startup of LHC Phase I in 2016 [1]; this means that the *Insertable B-layer* (IBL), which will be added to the present ATLAS Pixel detector in 2016, will accumulate a fluence of $\sim 5 \times 10^{15}$ $n_{eq}\cdot$ cm^{-2} during its life time considering also the design safety factor [1]. Such a particle fluence heavily deteriorates the detector performance. The sensor radiation tolerance is therefore of fundamental interest and has been widely investigated by a large number of research groups worldwide [2]–[8].

The main macroscopic changes in the detector performance consist of an increase in the leakage current proportional to the fluence, a damage-related decrease of the charge collection efficiency and a dramatic increase of the depletion voltage needed to maintain a full sensitivity of the whole detector [2]–[4], [6], [9]. It thus becomes very important to understand and predict the conditions for sensor breakdown in order to determine if the condition of full depletion holds [10]. Since the breakdown voltage is determined by the regenerative feedback inherent with simultaneous electron and hole Impact Ionization (I.I.) it becomes clear that a detailed study of the I.I. phenomenon, responsible of the avalanche multiplication, and its relation to the radiation damage is strongly needed.

In addition to that, I.I. has an important role also in the recently reported charge multiplication effect [11]–[13]: it has been observed that avalanche multiplication keeps the charge collection efficiency at satisfactory values also in silicon detectors irradiated at fluences in the order of 10^{16} $n_{eq}\cdot$ cm^{-2}. Possible changes in I.I. due to radiation exposure are thus important in view of simulating the detector at high fluences where charge multiplication enhances the detected signal.

Note that direct measurements of the I.I. coefficients on the silicon detector would be difficult and inaccurate because of the low sensitivity of the detector to the multiplication current in the pre-breakdown regime.

The sensitivity of I.I. and breakdown to radiation has been extensively investigated [14]–[16] in a large set of devices (MOSFETs, bipolar transistors, SiGe Heterojunction Bipolar Transistors,...) in view of space, medical or high energy physics applications. However, to the best of the author's knowledge, in all these studies I.I. monitors (such as for instance the MOSFET substrate current) have been measured with the aim of understanding how the radiation induced interface traps or charges in the oxide layers were changing the internal electric field profile [17] rather than to identify possible effects of radiation damage on the I.I. rate itself.

The aim of this work instead is to shed light on this latter aspect by analysing the inherent sensitivity of the I.I. rates to radiation damage. At this regard we start observing that in a uniform electric field I.I. is fully and univocally described by the I.I. coefficients which represent the number of electron-hole pairs generated per unit distance by the carriers and depends on the electric field strength.

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Numerous authors have extracted the I.I. coefficients in silicon [18]–[23]. Among these studies the one by Van Overstraeten is probably the most widely accepted and models for I.I. implemented in commercial TCAD device simulators are often calibrated on it. All these experiments however, refer to virgin semiconductor devices that were never exposed to a harsh radiation environment; the validity of these results for irradiated devices is thus not obvious. In fact, radiation induced defects in the bulk of the semiconductor act as scattering centers for the energetic carriers responsible of the I.I. phenomenon. Since the carrier mean free path is reduced by scattering, the ionization coefficients may be reduced as well. However simple this reasoning may appear, to the best of the author's knowledge no data is available from well designed experiments addressing the radiation dependence of I.I. coefficients in silicon.

The main goal of the present work is therefore to determine if and how the I.I. coefficients are affected by the radiation damage. To this purpose, we extract the I.I. coefficients on devices irradiated at different fluences. Finally as an application of the new results, the radiation dependence of the I.I. parameters in a state-of-the-art 3D silicon particle detector has been studied by means of TCAD simulations.

II. Measurement and Extraction Procedure

We characterized carrier multiplication by means of Bipolar Junction Transistors (BJT). Compared with other experimental techniques these devices allow to inject only one type of carrier inside the high field region where multiplication occurs (i.e., the base-collector (BC) junction) by forward biasing either the emitter/base or the collector/substrate junction. In this way it is possible to isolate the multiplication effect of only one carrier at a time (i.e., either electrons or holes), thus simplifying the ionization coefficients extraction procedure [19], [20].

The BJTs used in this work are the same npn devices used in [23], [24] and were fabricated in an industrial production quality Si planar technology. They are characterized by two different thicknesses of the epitaxial layer (1 and 1.5 μm), that consequently affects the width of the multiplication region ($\simeq 0.2\ \mu$m and $\simeq 0.7\ \mu$m, respectively). The procedure to extract the ionization coefficients α and β for electrons and holes respectively, from the measured multiplication factors $M_n(V_{\rm CB})$ and $M_p(V_{\rm CB})$ is the same adopted in [23], [24], and it is briefly summarized below.

Assuming a pure electron injection inside the depletion region of the BC junction, the electron multiplication coefficient M_n is the ratio between the current emerging from one side of the junction and the current injected on the other side and it is given by [23], [24]:

$$1-\frac{1}{M_n}=\int_0^W \alpha\cdot\exp\left[-\int_0^x(\alpha-\beta)dx'\right]dx \qquad (1)$$

where we assume a large area device with negligible edge effects and with the depletion region extending between $x=0$ and $x=W$ along the emitter/base/collector/substrate direction. A similar expression can be derived for holes assuming a pure hole injection in the depletion region.

α and β depend on the carrier energy distribution function in the multiplication region and thus they are a function of the coordinate x. In general it is possible to extract α (or β) as a function of x by measuring the respective multiplication coefficient at different BC voltages ($V_{\rm CB}$) and then relating α (or β) to another x-dependent quantity characterized separately, such as the electric field E [19], [20] or the average carrier energy [22], accurately determined by means of calibrated TCAD simulations. For each $V_{\rm CB}$ a suitable discretization of the electric field in the BC junction is used, allowing to invert (1) (and the similar expression for holes) and thus yielding α and β [23], [24].

Irradiation of the samples bonded to alumina packages has been performed with neutrons at the TRIGA nuclear reactor of the Jožef Stefan Institute in Ljubljana [25]. The fluences are 10^{14} n$\cdot$ cm^{-2} and 10^{15} n$\cdot$ cm^{-2}, obtained with a flux of 1.9×10^{12} n$\cdot$ cm^{-2}s^{-1}; accuracy of 1 MeV neutron Non-Ionizing Energy Loss (NIEL) equivalent fluences is better than 10%. Due to activation of the packages a further exploration at higher irradiation levels has not been possible.

III. Experimental Results Before Irradiation

As a first step we have measured the multiplication coefficients $M_n(V_{\rm CB})$ and $M_p(V_{\rm CB})$ of the unirradiated devices and tested our extraction procedure with respect to data found in literature. Measurements have been carried out at room temperature (between 20°C and 25°C approximately) forcing the emitter current (I_E) and the BC voltage ($V_{\rm CB}$) and sensing the base and collector currents (I_B, I_C). Due to the small value chosen for $I_E=10\ \mu$A self-heating is not a concern, thus the experiments have been performed in DC without any junction temperature control. Repeatability of the measurements against possible variation of room conditions (e.g., humidity) was assured by complete passivation and packaging of the test devices and by the adoption of a RF shielded box. The impact on the extracted I.I. coefficients of the 5°C uncertainty in the room temperature is definitely negligible as it can be proved by considering the reported temperature dependence of the I.I. coefficients [26], [27].

Fig. 1 shows the I.I. coefficients extracted on virgin samples for both electrons and holes compared with previously reported data. We see that α is in perfect agreement with the literature. A slightly different situation is visible for β: while at high electric field the data lies on top of the literature data, at low electric field measured β values lie a little bit below the curve reported by [19]. This could be explained by considering that the extraction procedure for β is based on the M_p measured on the parasitic pnp transistor formed between the p substrate, the n$^+$ collector region and the p base (see inset in Fig. 2). In this case the depletion region where I.I. occurs forms across the substrate-collector junction that is not optimized to work under pnp conditions. In fact, the current gain of the parasitic substrate pnp device is very low ($h_{\rm fe}\sim10^{-3}$) and when extracting M_p it is thus quite hard to determine which variation of the collector current is due to I.I. or to other phenomena.

Note that our test structure enforces unipolar injection in the high field multiplication region. This condition is at the basis of the extraction procedure and it is well satisfied for electrons

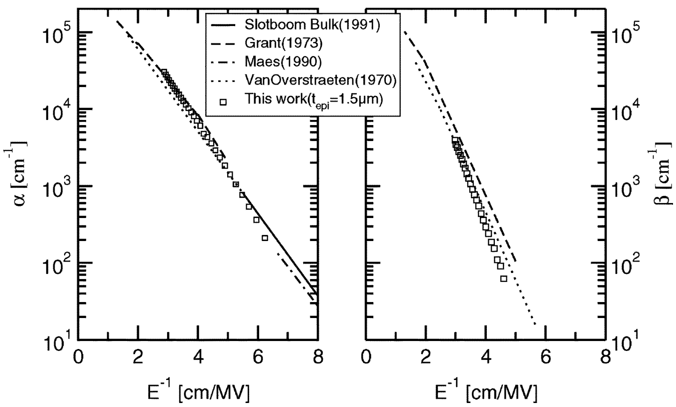

Fig. 1. Electron and hole ionization coefficient as a function of the electric field: experimental data extracted from unirradiated devices are compared with literature data.

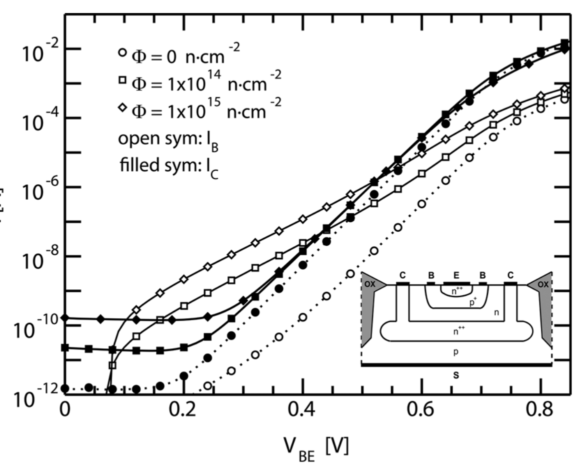

Fig. 2. Measured Gummel plots of the base and collector currents of a npn device with $t_{\rm epi} = 1.5\ \mu$m. Data taken before neutron irradiation are compared with those taken after exposition to fluences of 10^{14} and 10^{15} n· cm^{-2}. The inset reports a sketch of the cross section of the test devices.

in [20] and holes in [19] but not for the other cases. The most reliable reference data for unirradiated silicon is thus expected to be that from [19] for holes and that from [20] for electrons, respectively. The agreement of our data with these results thus strongly supports the validity of our extraction procedure.

IV. Experimental Results After Irradiation

Neutron irradiations have been performed on two samples with $t_{\rm epi} = 1.5\ \mu$m at fluences $\Phi = 10^{14}$ n· cm^{-2} and $\Phi = 10^{15}$ n· cm^{-2}, and on one sample with $t_{\rm epi} = 1\ \mu$m at $\Phi = 10^{15}$ n· cm^{-2}. The Total Ionizing Dose approximately corresponds to 100 kRad(Si) and 1 MRad(Si) for the 10^{14} n· cm^{-2} and 10^{15} n· cm^{-2} fluence, respectively.

Let us consider first the effects of radiation on the samples with thick $t_{\rm epi}$. Fig. 2 reports typical npn transistor Gummel plots. The detrimental effect of radiation damage is clearly visible: the base current increases, especially at low bias. For instance, at $V_{\rm BE}$ between 0.4 and 0.5 V the base current for the lower fluence is from 30 to more than 100 times larger with respect to the unirradiated condition. For the highest fluence the base current has a further increase, even if not as large as in the previous case. The base current (I_B) curves of the irradiated devices have a slope of $V_{\rm th}/2$, confirming the dominant effect of SRH recombination on the overall base current [28]. The collector current I_C shows an increment as well, but quite smaller than for I_B.

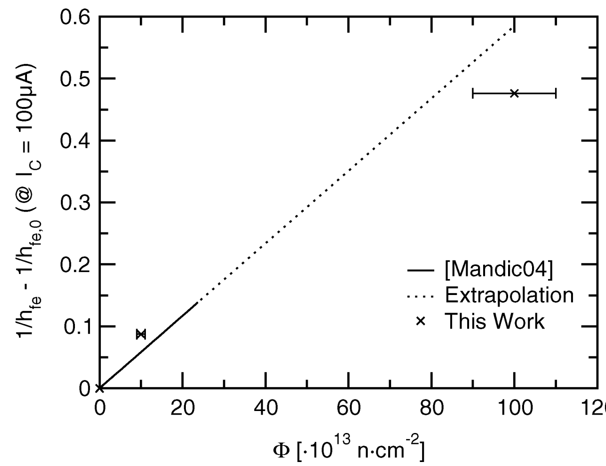

Fig. 3. Current gain degradation $(1/h_{\rm fe})$ observed in our devices as a function of fluence Φ compared with data reported in [29]. Current gains have been calculated at $I_C = 100\ \mu$A.

By plotting $1/h_{\rm fe}$ as a function of fluence Φ it is possible to compare the current gain degradation with the data reported in [29]. Fig. 3 plots the variation of $1/h_{\rm fe}$ with respect to the before irradiation $1/h_{\rm fe,0}$ in our devices and compares it with the data in [29] for silicon npn BJTs irradiated at very similar conditions. A good agreement between the two can be seen. The horizontal error bars take into account the 10% uncertainty in the determination of the fluence.

The comparison between the unirradiated and irradiated samples was carried out also for the parasitic pnp transistors. The $h_{\rm fe}$ parameter of the virgin pnp BJTs was very small $(h_{\rm fe} \sim 10^{-3})$ due to their parasitic nature. For this reason we found that after irradiations it became difficult, if not impossible, to measure a hole multiplication due to neutron damage degradation. The curves were heavily deteriorated at the point that it was no longer possible to decouple the base width modulation (*Early* effect) from the base current variation due to carrier multiplication. For this reason we have decided to consider only electron multiplication in the following.

The electron impact ionization coefficient α has been extracted from the electron multiplication factor M_n measured in thin and thick $t_{\rm epi}$ irradiated devices; to simplify the extraction procedure we have assumed negligible hole multiplication $(\beta = 0)$, that is a low multiplication factor. In this case (1) becomes:

$$M_n = \exp\left(\int_0^W \alpha dx\right) \tag{2}$$

allowing the direct extraction of α from the single measurements of M_n. Although the assumption of $\beta = 0$ could appear unrealistic, we have verified in virgin samples that the value of β doesn't affect the extraction of α, at least for the values of

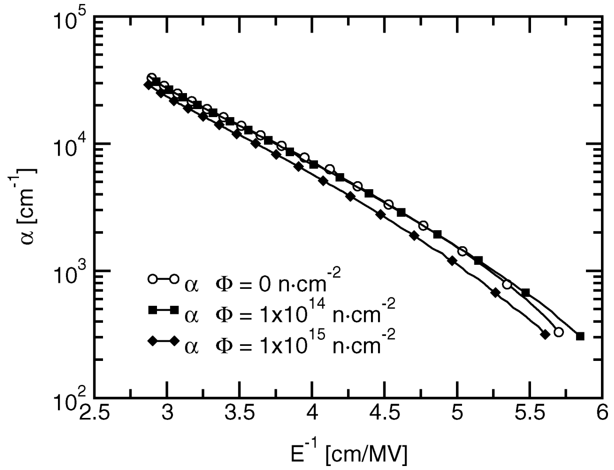

Fig. 4. Electron ionization coefficient α as a function of the inverse electric field extracted from the BJT with $t_{\rm epi} = 1.5\ \mu$m operated in npn mode for various fluences.

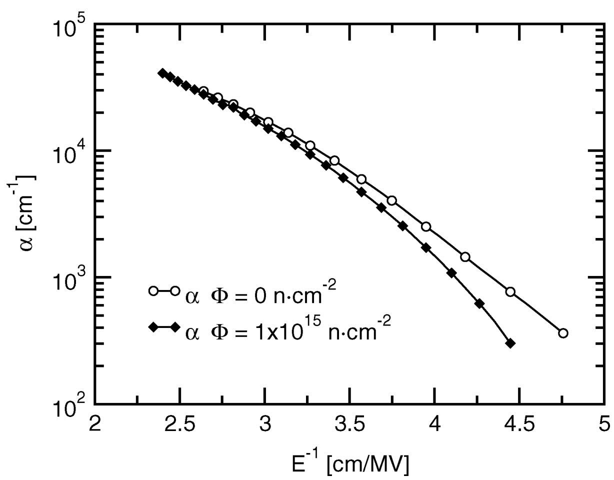

Fig. 5. Electron ionization coefficient α as a function of the inverse electric field extracted from the BJT with $t_{\rm epi} = 1\ \mu$m operated in npn mode for various fluences.

E considered here. In addition to that we have verified that the extraction of α is only marginally affected by the value of β. In particular, since in the irradiated conditions α and β cannot be extracted simultaneously (since M_p is not reliable), we have extracted α assuming either $\beta = 0$ or the same β as measured before irradiation finding an almost negligible difference of 3.5% @ $\mathrm{E} = 3.1 \cdot 10^5$ V/cm and a maximum difference of 11% @ $\mathrm{E} = 3.4 \cdot 10^5$ V/cm. For this reason, the results reported here have been obtained assuming $\beta = 0$ when extracting α from the M_n data.

Figs. 4 and 5 report the experimental results. The effect of radiation damage is clearly visible. At the lowest fluence the radiation has hardly affected the I.I. coefficient, while at the highest fluence we observe a decrease of the α coefficient between 30% and 40%.

The α extracted from the thin epitaxial device (Fig. 5, $t_{\rm epi} = 1\ \mu$m) is lower than that extracted from thick epitaxial samples (Fig. 4, $t_{\rm epi} = 1.5\ \mu$m). This is because the epitaxial layer thickness affects the width of the depletion region ($W \simeq 0.2\ \mu$m vs. $W \simeq 0.7\ \mu$m for $t_{\rm epi} = 1\ \mu$m and 1.5 μm respectively) and the steepness of the electric field profile. This causes the electron energy to strongly deviate from the equilibrium condition in the thin-epi devices, so we cannot assume a local relation between α and the electric field [22], [23].

The most rigorous way to overcome this difficulty and to account for non local effects would be to evaluate the full energy distribution of the carriers. However, at first order and following quite standard procedures and terminology, it is possible to relate the αs to a unique parameter of the distribution, namely its equivalent average temperature $T(x)$ or corresponding average energy $w(x) = (3/2)KT(x)$. According to simple energy balance equations [22] $T(x)$ can be expressed as a *non-local* function of the electric field as:

$$T(x) = T_0 + \frac{2}{5}\frac{q}{k}\int_0^x E(x')e^{\frac{x'-x}{\lambda_e}}dx' \tag{3}$$

where λ_e is the *energy relaxation length*. It is then possible to define an *effective* electric field:

$$E_{\rm EFF}(x) = \frac{5}{2}\frac{k}{q}\frac{T(x) - T_0}{\lambda_e}, \tag{4}$$

as the field providing the electron temperature T in uniform conditions. Given $E(x)$ and λ_e we can thus derive $E_{\rm EFF}(x)$ and then extract α as a function of the effective field instead of the electric field profile [23], [24]. Clearly $E_{\rm EFF}(x)$ tends to E when non local effects become negligible. Note that the parameter λ_e refers to the intensity of the scattering process in the bulk silicon. Therefore it should be independent of $t_{\rm epi}$ but not necessarily of Φ.

The α versus $E_{\rm EFF}(x)$ curves extracted with this approach for the $t_{\rm epi} = 1\ \mu$m device are reported in Fig. 6. In each case the energy relaxation length has been determined by forcing the αs extracted as a function of $E_{\rm EFF}(x)$ with those extracted from the long device ($t_{\rm epi} = 1.5\ \mu$m): this procedure is justified by the observation that the thick-epi device has a smooth enough field profile to consider the carrier distribution in local equilibrium with the electric field. In non irradiated conditions $\lambda_e = 53$ nm is obtained, in reasonable agreement with [22], which reports $\lambda_e = 65$ nm. A slightly lower value (50 nm) was identified for $\Phi = 10^{15}$ n$\cdot$ cm^{-2} consistently with the expected deterioration of the carrier mean free path in irradiated samples.

V. Implications for Particle Detectors

The previous results show that radiation damage has a weak but definite effect on electron I.I.

It is thus interesting to evaluate the impact of the variation of α on the breakdown behaviour of a realistic silicon detector. For this purpose we have performed TCAD simulations [27] and we have chosen as a test device a 3D detector of the same type of those under development for IBL replacement at FBK-Trento [30]. The simulated detector has the electrodes etched through the entire substrate and arranged in a 4-E configuration: in the case of an ATLAS pixel of $50 \times 400\ \mu$m^2 the charge is thus collected from 4 columnar electrodes. The pitch between ohmic

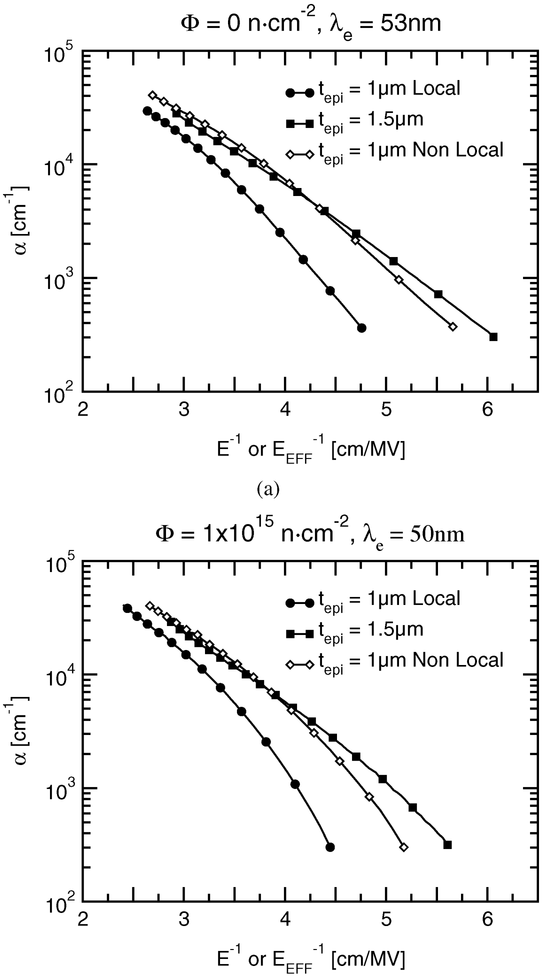

Fig. 6. Ionization coefficient α extracted using the non-local model (in the $t_{\rm epi} = 1\ \mu$m device) compared with values extracted in $t_{\rm epi} = 1\ \mu$m and $t_{\rm epi} = 1.5\ \mu$m devices considering the local electric field model: (a) unirradiated device, (b) $\Phi = 10^{15}$ n$\cdot$ cm^{-2}.

and junction electrodes is thus approximately 56 μm. The substrate considered in the simulations is 250 μm thick. Superficial n^{+} and p^{+} implants around the electrodes have been considered, both extending into the silicon bulk for approximately 1 μm below the Si/SiO_2 interface. A uniform shallow p-*spray* implant on both surfaces of the wafer guarantees the electric isolation between the electrodes and counteracts the effect of a positive trapped charge at the Si/SiO_2 interface with an areal density of about 10^{11} elementary charges per cm^2.

Consistently with the analysis in Section III we have adopted in the device simulator the ionization coefficients from [20] for electrons and from [19] for holes. Table I reports the simulated breakdown voltages. As can be seen, our choice causes the lowering of $V_{\rm BR}$ by about 8.5 V (i.e., ≈5%) with respect to the default calibration (both α and β from [19]).

Then, we have compared the breakdown voltage obtained for a virgin detector with the breakdown voltage obtained from the simulation of the same detector in which the I.I. parameters are those extracted from measures at $\Phi = 1 \times 10^{15}$ n$\cdot$ cm^{-2} but the effect of radiation damage on the silicon substrate is neglected: doping concentrations and carrier lifetime are the same of those

TABLE I
RESULTS OBTAINED FROM SIMULATIONS OF A 3D PARTICLE DETECTOR

Φ [n $\cdot$ cm^{-2}]	MODEL ADOPTED	$V_{\rm BR}$ [V]
0	α, β from [19]	172
0	α, β this work (α from [20], β from [19])	163.5
1×10^{15}	α, β this work No Radiation Damage Effects	169
1×10^{15}	α from [20], β from [19] Substrate Radiation Damage Effects: Doping & Carrier Lifetimes	158.1
1×10^{15}	α, β this work Substrate Radiation Damage Effects: Doping & Carrier Lifetimes	163

in the virgin detector. The difference is only about 6 V (i.e., ≈ 4%), thus confirming the limited impact of the radiation induced variation of the I.I. parameters.

We have then included radiation-induced effects to the silicon bulk considering the so-called Hamburg damage model presented in [9], with the rate of introduction of defects g_c measured in [7]. The effective carrier trapping times have been calculated using experimental data from [7], [31], [32]. We have not considered here surface damage effects, i.e., the increment of positive oxide charge, since the resulting impact on the breakdown voltage of the detector is strictly bounded to the chosen peak concentration of the p-spray doping [33]. A detailed reproduction of the surface damage effects goes far beyond the aim of this work so in the simulations we have always considered a fixed positive oxide charge concentration of 10^{11} cm^{-2}. Under these conditions, as seen in Table I, the difference in the breakdown voltage between the I.I. models for unirradiated devices with α from [20] and β from [19] vs. that for α and β from Fig. 4 at $\Phi = 1 \times 10^{15}$ n$\cdot$ cm^{-2} is 4.9 V. The breakdown voltage changes by approximately 4% as a consequence of the reduced ionization coefficients after radiation exposure with respect to the unirradiated case.

It is important to note that the Impact Ionization coefficients are material properties, independent of the device, at least as far as the electric field is a smooth function of position and therefore α and β are simply functions of the local electric field. This is the case in both our thick epitaxial devices and in the simulated 3D detectors. Thus it is possible to extend our results on irradiated silicon BJTs to 3D silicon particle detectors. This conclusion is also supported by the similarity between doping profiles and electric field strengths in the two cases. Indeed we verified that the electric field strength in the breakdown region of 3D detectors falls in the range explored by our experiments with the BJTs. Furthermore in 3D detectors breakdown takes place at the junction formed between p-spray and $\rm n^{+}$ implantation regions, whose doping levels are close to the ones in the base-collector region of the bipolar structure employed here, and a few hundred nanometers below the Si/SiO_2 interface, thus in analogy with the position of the depletion region of our bipolar devices. The latter aspect allows us to expect, for the same fluence, the same damage level in both structures. Based on these considerations we believe that the results presented throughout this work are applicable also to the analysis of particle detectors.

VI. Conclusion

In summary our results on the influence of radiation-induced damage on the Impact Ionization coefficient α show a small but distinct reduction of α at high fluence with respect to virgin silicon. A consistent 4% increase is observed on the breakdown voltage of a 4-E 3D radiation detector as evaluated by means of TCAD simulations.

Experimental results on short devices confirm that the same small reduction of α is expected in a large family of silicon devices even in cases where non local transport is important. These results clarify the impact of radiation damage on silicon sensors TCAD simulation parameters and allow for improved accuracy in the predictive simulations of silicon particle detectors for the ATLAS experiment.

On the other hand it is important to note that the fluences explored here are about 5 times lower than the values of interest for operation at the LHC Phase I, and at least one order of magnitude lower than values foreseen at LHC Phase II, where fluences even higher than 10^{16} $n_{eq}\cdot$ cm^{-2} are expected. Projecting the experimental evidences reported here we expect that changes of the I.I. coefficients at these higher fluences may strongly impact the performances of the detector.

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