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On the use of Po^{210} and Am^{241} collimated alpha sources for the characterization of the onset of carrier multiplication in power devices

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Abstract—The design of robust power devices and the definition of their safe operating area require the quantitative characterization of charge multiplication in reverse biased junctions. This is mandatory especially for those mechanisms like single event burnout, where the failure is triggered by the massive impact ionization arising in the reverse-biased device from the charge generated by the impinging ionizing radiation, transported and eventually multiplied. Traditional DC characterization techniques exhibit usually limited sensitivity, such that they are not capable to detect the reverse current and the related charge multiplication before the occurrence of the junction breakdown. In the past, alternative methods aimed to improve the sensitivity at lower electric fields have been proposed that exploit either optical, or particle beams. However, these solutions cannot be simply applied to real commercial devices and in addition they just deliver averaged values of the multiplication factor. In this paper, single ionization events generated at the close vicinity of the reverse-biased junction of a commercial power PiN diode are acquired to measure the distribution of the multiplication factor at different reverse bias conditions. Here, the fast reverse current pulse produced by the initial ionization charge burst is collected by a dedicated spectrometry chain and processed to obtain the probability distribution of the current pulses and the related multiplication factor. This analysis accounts for the stochastic nature of the initial charge generation, as well as of the impact ionization process. The measurements results are compared with the multiplication values and distributions as obtained by *TCAD*, analytical models and by *Monte Carlo* simulation. The performance of two different exempt quantity alpha sources is investigated, namely Polonium (Po^{210}) and Americium (Am^{241}) that are used in conjunction with dedicated collimators. The technique is demonstrated based on a commercial 1.2 kV-70 A power PiN diode in the reverse bias range from 700 V to 1250 V. Detailed information is provided about the proposed hardware solutions, which can easily be implemented under usual laboratory conditions.

Keywords—Impact ionization; Carrier multiplication; Impact ionization coefficient extraction; Collimated alpha source; Polonium-210; Americium-241; Detection circuitry.

I. INTRODUCTION

The characterization of impact ionization in semiconductors is fundamental to the design and the robustness of power devices. As an example, is the measurement of the onset of carrier multiplication that is often used to define the maximum reverse/blocking voltage for the survivability of high-voltage devices to single event burnout phenomena produced by cosmic rays [1].

In this work, the use of free carrier bursts generated by ionization from a single alpha particle is proposed to characterize quantitatively the carrier multiplication occurring along the intrinsic layer of a (commercial) reverse-biased silicon PiN power diode.

The range and the angular spread of the alpha particles emitted by exempt quantity radioactive Po^{210} and Am^{241} sources are

calibrated in such a way that electron-hole pairs are generated in the close vicinity of the reverse-biased P^+N junction. In the particular case of a PiN diode, free electrons drift along the depleted region (punch-through diode) and are collected at the cathode. During the transport the carriers experience several inelastic scattering events, mainly with electrons and phonons. At high values of the local electric field, electrons (holes are neglected here) may acquire sufficient energy along their mean free path (inverse of the impact ionization coefficient) to ionize a semiconductor atom, resulting into an additional charge, i.e. in a charge multiplication. Hence, impact ionization (and charge multiplication) can be seen as a non-homogeneous stochastic process, where the number of scattering events experienced by every single drifting carrier is a random variable, whose variance increases as the reverse bias applied to the diode approaches the breakdown voltage. Theoretical models are available to predict the impact ionization coefficients of electrons and holes as function of the local electric field and of the temperature. Such models mainly provide an averaged value of the multiplication factor [2]–[6]. The probability distribution of the multiplication factor can only be obtained by *Monte Carlo* simulation [7], that nonetheless needs independent experimental data for calibration. In addition, *Monte Carlo* simulators are usually very demanding in terms of computation time and make use of quite complex and semi-empirical physical models. Experimentally, the multiplication factor is often inferred from the reverse current at a voltage quite close to the junction breakdown. However, this approach is not very accurate, because, in real devices, the breakdown first occurs at small isolated spots or lines (e.g. because of three-dimensional effects), where the local current density may achieve very high levels without reaching the current threshold, which can be detected by the usual instrumentation. To overcome this limitation, techniques have been proposed that exploit early generation of electron-hole pairs in the depletion layer of reverse-biased junctions by continuous or pulsed ionizing radiation beams (laser, particle beams), followed by the measurement of the resulting reverse current [5], [6], [8]. Unfortunately, such approaches also deliver just an average value of the impact ionization coefficients, without providing any direct information about the probability distribution of the multiplication factor. The proposed solution combines the use of alpha emitters for the generation of the initial charge burst with a dedicated spectrometry chain for the acquisition of the resulting charge pulses with a duration in the nanosecond range. The acquired data is processed offline by a dedicated software to obtain the distribution of the charge pulses at a given reverse bias of the PiN diode. The average carrier multiplication is extracted from the experimental distribution by different criteria and compared to the outcome of the main theoretical models for impact ionization, as well as to the results of *TCAD* and *Monte Carlo* simulations. The investigated device is a silicon 1.2 kV-75 A PiN diode [9] with 1385 V breakdown voltage (measured at 1 μA). The onset of

impact ionization is characterized at a reverse bias starting from 700 V up to 1250 V.

II. EXPERIMENTAL

A. Modeling the impact ionization

The impact-ionization rate after the *Chynoweth's law* [4] is an exponential function of the inverse electric field. The *Van Overstraeten and Moll* [10] model is a local impact ionization representation, which accounts for both types of carriers in narrow reverse biased junctions. This model has been extended by *Van Overstraeten and De Man* [6] to account for the threshold energy of the ionization process and the electric field dependent ionization ratio between different carriers. It was validated by measuring the multiplication factor in both narrow and wide *PN*-junctions in the electric-field range from 1.75×10^5 to 6×10^5 V/cm at room temperature. To account for higher temperatures and fields, the latter model has been extended to a pseudo-local model based on energy conservation observations by *Okuto and Crowell* [11]. Here, the local pair production rate is assumed not to be proportional to the local carrier density, with only a fraction of carriers having enough energy to enter ionization. The model has been validated for electric fields in the range 10^5 to 10^6 V/cm and up to 423 K. *Lackner* [2] has proposed a similar pseudo-local model in the same electric field range that is based on the derivation of the ionization rates from a modified *Chynoweth's law* to account for temperature dependencies. Additional investigations in the same electric-field range have been carried by using *BJT* in common-base configuration, where the generation current is extracted from the change of the base current. Similarly, with the measurement of the gate current in more sensitive static-induction transistors [8], [12], the multiplication factor could be characterized down to 5×10^4 V/cm. Based on latter data, an analytical model for the impact ionization coefficients of electron and holes ($\alpha_e(E)$, $\alpha_h(E)$) has been validated over ten orders of magnitude [8] and then extended to the *New Bologna Model* (in-depth reviews are given in [8], [13]–[15]).

The expression assumed by this model for $\alpha_e(E)$ is:

$$\alpha_e(E, T) = \frac{E}{a + b \cdot \exp\left(\frac{a}{c + E}\right)} \quad [1/\text{cm}] \quad (1)$$

where the model parameters are listed in *Table I*.

For single charge bursts, the multiplication factor M is defined [8] based on the impact ionization coefficients (e and h for electrons and holes, respectively), as

$$1 - \frac{1}{M} = \int_0^W \alpha_e(E(x)) \exp\left[-\int_0^x (\alpha_e(E(x')) - \alpha_h(E(x')) dx'\right] dx \quad (2)$$

where E is the instantaneous field and W is the width of the depletion layer [16]. Since the impact ionization coefficient for the holes $\alpha_h(E)$ in the considered range of the electric field is at least a factor of 10 lower than for electrons, it will be neglected for following considerations.

In the analytical approach, the (averaged) multiplication factor M is derived by evaluating the integral in (2) along the depletion layer of the *PiN* diode, where the local strength of the one-dimensional electric field is calculated after (5) and (6) and different models for the impact ionization coefficients are assumed. Present calculations are focusing on the *Van Overstraeten and De Man*, *Okuto and Crowell*, *Lackner* and the *New Bologna* models (*Eq. 1*). Similarly, the integral in (2)

TABLE I. Model parameters of electron impact ionization coefficient after the *New Bologna model* in Eq. 1 [8], [12], [14]. Following units apply: $[\alpha_e(E)] = 1/\text{cm}$; $[E] = \text{V/cm}$, $[T] = \text{K}$, $[a_i] = [b_i] = \text{V}$, $[c_i] = [d_i] = \text{V/cm}$

Parameters					
$a(T) = \sum a_k(T)^k$			$k = 0-3$		
$b(T) = \sum b_k(T)^k$			$k = 0-10$		
$c(T) = \sum c_k(T)^k$			$k = 0-3$		
$d(T) = \sum d_k(T)^k$			$k = 0-2$		
a_0	4.65403				
a_1	-8.76031e-3	b_4	-1.82482e-12	c_0	7.76221e3
a_2	1.34037 e-5	b_5	-4.82689e-15	c_1	25.18888
a_3	-2.75108e-9	b_6	1.09402e-17	c_2	-1.37417e-3
b_0	-0.128302	b_7	-1.24961e-20	c_3	1.59525e-4
b_1	4.45552e-3	b_8	7.55584e-24	d_0	7.10481e5
b_2	-1.0866e-5	b_9	-2.28615e-27	d_1	3.98594e3
b_3	9.23119e-9	b_{10}	2.73344e-31	d_2	-7.19956

has been evaluated under the assumption of a power law approximation of the impact ionization coefficients, as proposed by *Fulop* [17] and *Baliga* [18]. The multiplication factors obtained from the different models for the *PiN* diode under investigation are shown in Fig. 1b, summarized in *Table II*, and compared in Fig. 1c.

For the sake of comparison, the multiplication factors for the same reverse bias values have been calculated also by the *Simple Monte Carlo v1.11 (SMC)*, [19]) code originally developed to simulate single photon avalanche diodes and that uses a simplified band structure to reduce computational requirements. The parameters assumed by the simulator to solve the Poisson equation are specified in *Section II.E*. The distribution of the multiplication factors as function of the reverse bias is reported in Fig. 1a and the extracted values are compared to those obtained by the analytical models in *Table II* and Fig. 1c.

B. Extraction of the probability density function of the charge multiplication factor

The charge generated in the depletion region of the *PiN* diode and finally collected at the preamplifier is a random variable, which is the result of two distinct stochastic processes: the carrier generation by a single alpha particle and the charge multiplication by impact ionization. The probability distribution p_{CC0} associated to the first stochastic process can be easily measured at a sufficiently low reverse bias, where the depletion region is completely formed, all charges generated by the single alpha particle are collected, but no multiplication occurs (in present measurement p_{CC0} is acquired at 700 V). The probability distribution p_{MULT} associated to the second stochastic process refers to the variability of the charge multiplication during the transport of the charge across the depletion region, which is correlated among others to the random number of scattering events experienced by the carriers during the transport.

TABLE II. Multiplication factors as calculated by following models. A. *Van Overstraten De Mann* [6], B. *New Bologna* [8], C. *Lackner* [2], D. *Okuto Crowell* [11], E. *Monte Carlo SMC* [19], F. *Fulop Approximation* [17], and G. *Baliga Approximation* [18].

Vbias / Vrated	A	B	C	D	E	F	G
0.6	1.25	1.07	1.08	1.00	1.02	1.04	1.09
0.8	4.30	1.69	1.92	1.09	1.45	1.25	1.54
0.9	10.85	2.21	3.15	1.26	2.14	1.44	2.02
1	45.05	4.12	6.71	1.68	4.24	1.77	3.04

Fig. 1. (a) Distribution of the electron multiplication factor as calculated in the depletion layer of the *PiN* by the *Monte Carlo* simulation code *SMC* [19] for different reverse bias levels. (b) Multiplication factors as function of the reverse bias as calculated in the *PiN* by different analytical models. (c) Comparison of the multiplication factors as obtained from the different models.

Summarizing, the combination of these relevant processes can be represented analytically by the convolution of the related probability distributions:

$$p_{CCM}(Q) = K_1 \int_C p_{CC0}(Q) * p_{MULT}(Q - \gamma) d\gamma \equiv \mathcal{C}(p_{CC0}, p_{MULT}) \quad (3)$$

where K_1 is a normalization factor and p_{CCM} is the probability density function of the charge pulses measured at a given reverse voltage. Therefore, as p_{CCM} and p_{CC0} are known from the measurements, p_{MULT} can be extracted numerically by following deconvolution integral:

$$p_{MULT} = K_2 \mathcal{C}^{-1}(p_{CCM}, p_{CC0}) \quad (4)$$

where K_2 is again a normalization factor.

It has to be noted that a third stochastic process related to the distribution of the generation site of the carriers (calculated by *Monte Carlo* simulation in Fig. 2) can be neglected here, since the size of generation volume ($< 3 \mu\text{m}$) is much smaller than the total width of the depletion region ($85 \mu\text{m}$). This is also the case of the stochastic contributions due to the variability of the charge collection and of the noise of the spectrometer chain, since they are negligible.

C. Monte Carlo simulation of the range and deposited charge in the depletion region

Range and charge deposition in the depletion region of alpha particles emitted by the Po^{210} and Am^{241} sources as calculated by the *Monte Carlo* simulation code *SRIM 2013* [20] are shown in Fig. 2a-c. Both isotopes have been assumed to emit monoenergetic alpha particles (5308 keV for Po^{210} and 5486 keV for Am^{241}) with an emission angle (defined by the collimators) ranging from -20° to 20° and -5° to 5° for Po^{210} and Am^{241} , respectively. The thickness of the dead layer (see Sect. II.E) has been varied to fit the peak of the charge distribution as measured at 700 V (p_{CC0} , no multiplication),

i.e. at a reverse bias, at which no multiplication occurs. The simulated distribution of the deposited charge is derived from the energy of every single alpha particle transmitted through the dead layer, divided by 3.62 eV , i.e. the energy required to the generation of a single electron-hole pair, and finally multiplied by the elementary charge. The calculated range of the alpha particles from the Po^{210} source in the depletion region is shown in Fig. 2a. The distribution of the collected charge pulses at 700 V for Po^{210} and Am^{241} are shown in Fig. 2b and 2c, respectively. The tail at the low end of the Po^{210} spectrum in Fig. 2b is due to alpha particles impinging on the chip surface at high angles. This results in a reduction of the range and energy deposition of the particles in the depletion layer, as well as an increase of the average energy straggling. In the measured spectrum, this tail is just partially visible, since it is suppressed below 10 fC because of the energy cut-off of the spectroscopy chain. On the contrary, this tail is less pronounced in the spectrum of Am^{241} in Fig. 2c, because of the better angular collimation of the source.

D. The measuring principle

After decapsulating the plastic packaged *PiN* diode by fuming nitric acid and removing two out of the three aluminum bond wires, the collimated alpha source is placed in contact with the chip. The scope of the collimator is to restrict the size of beam spot, in order to irradiate the active area of the device only, and avoid the irradiation of the terminations. In addition, the collimators reduce the energy straggling of the alpha particles absorbed in the depletion layer and also limit the particle flux by lowering the pile-up probability of two subsequent ionization events. Measurements are repeated at increasing reverse-bias voltage, starting at 60% (no multiplication occurs), up to 100% of the rated voltage of the device. Under such conditions, ionization events produced by single alpha particles can be detected, which generate charge

Fig. 2. (a) *Monte Carlo* simulation by *SRIM 2013* of the range of the alpha particles emitted by the Po^{210} source in the depletion region of the *PiN* diode after passing a $24.3 \mu\text{m}$ silicon-equivalent thick dead layer (impinging angle from -20° to $+20^\circ$). Probability function of the charge deposition in the depletion layer at 700 V (i.e. no multiplication) for (b) the Po^{210} and (c) the Am^{241} (impinging angle: -5° to $+5^\circ$), respectively. The calculation is based on the simulation by *SRIM 2013* of the probability function of the residual energy of the alpha particles transmitted through the dead layer. The equivalent experimental curve at 700 V is shown in Fig. 10(a) and 10(b).

Fig. 3. (a) Basic cross-section of the irradiated power PiN diode showing the dead layer ($24.3 \mu\text{m}$ silicon equivalent), the depleted layer ($85 \mu\text{m}$), and the carrier generation/separation process. The impinging alpha particles generate a burst of electrons and holes in the depletion region, close to P^+N junction. The carriers are separated by the local electric field. In particular, electrons are accelerated towards the cathode and are forced to move through the depleted drift layer, where they experience impact ionization and eventually cause charge multiplication. This mainly happens in the top portion of the drift layer, where the electric field reaches its peak. (b) Top view of the power diode after decapsulation. The red dot evidences the location, where the collimated sources are pointing at. (c) Quartz capillary collimator of the Po^{210} rod source. (d) Energy spectrum of the Po^{210} planar alpha source, as measured with a Silicon detector. The peak shift $\Delta E = 700 \text{ keV}$ is due to the absorption in 2.5 mm air (250 keV at $dE/dx=92 \text{ keV/mm}$) and in the $3 \mu\text{m}$ thick dead layer of the Silicon detector (450 keV at $dE/dx=144 \text{ keV}/\mu\text{m}$). The $FWHM$ of the peak is 150 keV . The decay scheme of Po^{210} in the insert shows that the main reaction channel is alpha emission at 5305 keV .

pulses with sub-nanosecond duration and that range from 10 fC to 2 pC . The pulses are detected by a dedicated high-gain charge amplifier and converted by a fast ADC to a digital waveform, which is stored for further processing. The acquired waveforms are processed off-line by a dedicated software to obtain the probability density functions $pcc0$ and $pccm$.

E. PiN power diode

The device tested in this work is a commercial PiN power diode rated for 1.2 kV and 75 A [9] in a $DO-247$ package, whose cross-section and top view are shown in Fig. 3a and 3b, respectively. From the point of view of the signal generation, the passivation layer, the metal layer, as well as the anode diffusion all act as a dead layer, which reduces the energy and increases the energy straggling and the entrance angle in the depletion layer of the transmitted alpha particles. Since the thickness of the dead layer cannot be measured directly, it is extracted by reverse *Monte Carlo* simulation using the code *SRIM 2013* [20], where the simulated spectrum is fitted to the experimental curve acquired at 700 V (no multiplication). As shown in Fig. 2b and Fig. 2c the resulting thickness is $55.8 \mu\text{g}/\text{cm}^2$ (or $24.3 \mu\text{m}$ silicon equivalent). With a silicon-equivalent stopping power of $144 \text{ keV}/\mu\text{m}$ [21], the dead layer produces an average energy loss of the alpha particles by 500 keV . The thickness and the doping concentration of the intrinsic layer of the PiN diode have been extracted from the capacitance-to-voltage characteristics in Fig. 4 to be $85 \mu\text{m}$ and $1.11 \times 10^{14} \text{ cm}^{-3}$, respectively.

These parameters have been exploited for the *TCAD* model [22], as well as (by assuming a trapezoidal shape) to calculate the maximum and the minimum values of the electric field

E_{max} and E_{min} , which are reached at the $P-N^-$ and at the N^-N^+ junctions, respectively, as shown in Fig. 11a. E_{max} and E_{min} can be calculated from the applied reverse bias V_{rev} from:

$$E_{Max} = 142.85 * V_{rev} + 5.41 * 10^4 \text{ [V/cm]} \quad (5)$$

$$E_{Min} = E_{Max} - 1.08 * 10^5 \text{ [V/cm]} \quad (6)$$

Starting from $V_{rev}=600 \text{ V}$, the intrinsic layer of the PiN diode is completely depleted and the electric field decreases linearly starting from the $P-N^-$ to the N^-N^+ junction. Since the alpha sources are collimated within the active area of the PiN diode, the singularities of the electric field occurring at the terminations of the device can be completely neglected. Fig. 5a reports the impact ionization coefficients of the electrons from the *Van Overstraeten* and *De Man* model and the resulting ionization current as simulated by *TCAD*.

Fig. 4. Doping concentration and thickness of the intrinsic layer of the PiN diode as calculated from the *capacitance-to-voltage* curve.

Fig. 5. (a) Electron impact ionization coefficients in the depletion layer of the *PiN* diode as from *TCAD* simulation [22] (*Van Overstraeten De Mann* model) at different reverse bias levels. (b) Impact ionization current in the depletion layer of the *PiN* diode as simulated by *TCAD*. Up to the rated voltage, the component of the ionization current due to the holes is negligible.

The simulation also confirms the assumption that impact ionization due to the holes is negligible over the whole voltage range of interest. In fact, the impact ionization coefficients at $V_{rev}=600\text{ V}$ and $V_{rev}=1200\text{ V}$ are six, respectively three orders of magnitude smaller than the impact ionization coefficients of the electrons at the same bias level. Fig. 5b shows how the impact ionization current develops along the depletion region of the *PiN* diode. At high reverse bias levels, because of the trapezoidal shape of the electric field, the ionization current increases rapidly within about $30\text{ }\mu\text{m}$ from the P+N junction. Beyond this point, it stays almost constant, since just little generation by ionization impact occurs.

F. The collimated alpha sources

Two alpha emitters have been used in the present setup: Po^{210} and Am^{241} . Exempt quantity sources have been used to avoid safety issues and to prevent the occurrence of pile up. Po^{210} is an almost pure alpha emitter, with a main decay channel resulting in alpha particles at 5.305 MeV and a half-life of 138 days. The energy spectrum measured with a silicon detector is shown in Fig. 3d. A rod source is used, where the radioactive isotope is deposited at the top of a thin steel needle with 0.7 mm diameter. After collimation, the activity of the source is $0.01\text{ }\mu\text{Ci}$. Since the emission characteristics of the naked source is almost hemispherical, a collimator had to be used to reduce the lateral emission, in order to confine the irradiation spot within the active area of the *PiN* diode. As published in a previous work [23], [24], the collimator in Fig. 3c consists of a quartz capillary with 0.7 mm inner and 1.0 mm outer diameter. The rod source can slide along the axis of the capillary, such that the distance from the bottom of the capillary can be finely adjusted to achieve the optimum trade-off between beam spot and the luminosity of the source. The optimum beam spot has a diameter of 1.2 mm (at the chip surface) and the impinging angle of the emitted alpha particles ranges from -20° to 20° . Since, the bottom of the electrically insulated collimator is in direct contact with the diode surface, no energy loss occurs in air. The location, where the collimated source has been placed on the diode surface is shown in Fig. 3b. Under these conditions, the spectrometer has to process two events per second.

Besides the gamma emission at 59.9 keV that is negligible in this case, the Am^{241} is an alpha emitter at 5486 keV with a half-life of 432 years. The energy spectrum of the emitted alpha particles (not shown here) is quite similar to that in Fig. 3d. The activity of the naked button source (in Fig. 6a) is $0.1\text{ }\mu\text{Ci}$. The radioactive isotope is plated on the top of a small disk with 2 mm diameter that is mounted in a steel frame with 6 mm

mm outer diameter. The emission characteristics of this planar source exhibits a reduced angular spreading, that can even be reduced down to -5° to 5° by the use of the collimator in Fig. 6a. As shown in the radio-photographic map in Fig. 6b, the resulting full width at half maximum (*FWHM*) of the beam spot at the chip surface is 2 mm , such that the alpha irradiation is completely confined within the active area of the device. Besides this, the scope of the lead collimator is the reduction of the flux of alpha particles, in order to reduce the probability of pile-up events. The planar button source, mounted in the collimator, is placed directly on the top of the chip. The thickness of the resulting air gap is about 1 mm , producing an energy loss to the alpha particles of about 40 keV . Under these conditions, the spectrometer has to process twenty events per second.

Fig. 6. (a) Button planar Am^{241} source with the related lead collimator. (b) Contour plot (parameter is the percent of the peak intensity) of the beam spot of the alpha particles impinging at the chip surface as measured by photo-radiography. The *FWHM* is 2 mm , the peak is completely confined within the active area of the *PiN* diode.

G. The spectroscopy chain

Measuring the onset of charge multiplication requires a spectrometer with sufficient dynamics to cope with typical multiplication factors starting from 1 up to 50. In addition, the spectrometer needs to be capable of resolving every single ionization event produced by single alpha particles. This can be achieved on one side by reducing the flux of the impinging alpha particles, on the other side by finding an optimum trade-off between speed and accuracy of the spectrometer. The block diagram of the detection chain is represented in Fig. 7. The preamplifier stage shown in Fig. 8 converts the charge pulse from the power diode into an exponential voltage pulse. It employs a high-bandwidth (250 MHz) trans-impedance amplifier followed by a second high-bandwidth amplifier with gain 6.6. In the second stage (pulse shaper) shown in Fig. 9, the pulse bandwidth is adapted to the sampling rate of the fast 14bit analog to digital converter (ADC). This is carried out by a *Sallen-Key* second order active low-pass filter with pole-zero cancellation. The digitized waveform related to every single detected ionization event is saved in a mass-storage unit for offline processing. Offline multichannel pulse height analysis by a dedicated software is preferred here, since it enables better fine-tuning of the algorithms for noise cancelling, pile up suppression, and pulse-height extraction than on-the-flight techniques. The final pulse charge spectrum is built by forming the histogram of the frequency of the pulse amplitudes. This detection chain is linear over the full operating range and can deal with high-voltage devices rated up to 3.5 kV DC. Adjustment of the sensitivity range to the specific task, system calibration, and linearity check are completed before starting data acquisition.

Fig. 7. Block scheme of the spectroscopy chain used to measure the signal in the low multiplication range ($M=1-50$) with 1 fC resolution. The hardware consists of a pre-amplifier, a pulse shaper, and a fast 14bit analog to digital converter. The acquired waveforms are processed offline by a dedicated software. The spectrometer is designed to operate up to 3.5 kV input voltage.

Fig. 8. Detailed scheme of the dedicated two-stages transimpedance amplifier (TIA) used as pre-amplifier in the spectroscopy chain. The reverse-biased device is connected at the input in box 1 and capacitively coupled to a high-gain charge sensitive amplifier (box 3), where the feedback resistor and capacitor are 100 MΩ and 1.4 pF, respectively. The amplitude of the 140 μs output pulses is proportional to the detected charge. The second stage (box 4) is a low-gain voltage amplifier used to calibrate the spectroscopy chain in conjunction with the 1 pF injection capacitor (box 2) and the voltage amplifier in the pulse shaper.

Fig. 9. Detailed scheme of the dedicated pulse shaper aimed to format the output pulse into a double-exponential for optimum conversion in the 14bit analog to digital converter. A second order *Sallen-Key* filter is implemented by four stages based on operational amplifiers. The first stage is a differentiator, which includes a *pole-zero* cancellation function to cancel possible undershoots in output pulses. The second stage is an integrator, followed by a low-pass filter with programmable gain the third stage. The final stage acts at the same time as filter and as buffer.

III. RESULTS AND DISCUSSION

A. Multiplication: analytical and Monte Carlo models

The multiplication factors obtained from the *Van Overstraeten* and *De Man*, *Okuto* and *Crowell*, *Lackner*, *New Bologna*, *Fulop* and *Baliga* models summarized in Table II, are compared in Fig. 1c. At all voltage levels, the *Van Overstraeten-De Man* model and the *Fulop* approach deliver the maximum and the minimum value of the multiplication, respectively. All other models predict quite similar results (within a factor of two of the mean value). In particular, it can be noted that the multiplication factors from the *New Bologna* model are systematically 20-30% larger than the multiplication value from the *SMC Monte Carlo* simulation.

B. The Collimated Po^{210} and Am^{241} sources

The measurements with the Po^{210} and Am^{241} sources have been carried out at 700 V, 900 V, 1000 V, 1200 V and 1250 V. The intrinsic noise of the spectrometer has been suppressed by setting the lower cut-off at 10 fC. Under these conditions, charge pulses have been acquired up to 1.2 pC, except for the case at 1250 V, where some pulses caused the saturation of the pre-amplifier. Fig. 10a and 10b show the resulting spectra. Test measurements have been performed at voltages lower than 700 V to confirm that 700 V is the maximum reverse bias, at which no multiplication occurs and that this curve can be assumed as p_{CCO} in Eq. (4). In both cases, the spectra acquired at higher reverse bias clearly show an evident smearing effect due to the statistical distribution of the multiplication factor. Up to 1100 V the distributions are quite tight. Starting from 1200 V, the charge pulses cover a broad interval of values, indicating an increasing variance in the number of scattering events of the electrons.

B.1. Multiplication factor

In the following, the techniques are described that have been used to extract the multiplication factor either as an

Fig. 10. Spectrum of the charge pulses, as obtained by (a) the collimated Po^{210} and (b) the collimated Am^{241} source. The total number of collected charge pulses is the same for the different reverse bias values. The highest peak has been measured at 700 V and is in excellent agreement with the *Monte Carlo* simulations in Fig. 2(b) and 2(c). Since it does not exhibit charge multiplication, it is used as reference spectrum for the charge generation (p_{CCO}) to estimate the multiplication factors in Fig. 11(a), 11(b), and 12.

Fig. 11. (a) Peak and minimum electric field in the depletion region as function of the reverse bias. The curves of the multiplication factors for Po^{210} and Am^{241} are calculated from the *median* of the cumulated distributions in Fig. 8b and normalized to the 700 V case (no multiplication). The curves have been fitted with the double exponential function $M(V) = a_1 \exp(b_1 V) + a_2 \exp(b_2 V)$, where for the Po^{210} : $a_1 = 0.5565$, $b_1 = 0.0008211$ 1/V, $a_2 = 7.546e-08$, $b_2 = 0.01453$ 1/V, and for the Am^{241} : $a_1 = 0.5565$, $b_1 = 0.0008211$ 1/V, $a_2 = 7.546e-8$, $b_2 = 0.0143$ 1/V. (b) Cumulated probability distribution functions of the multiplication factor of the charge pulses for each reverse voltage have been built and normalized to the cumulated distribution from the 700 V measurement to obtain the multiplication factor. Mean, median, and maximum values of the distributions are summarized in Table III.

TABLE III. Multiplication factors as extracted from the charge normalization in Fig. 11(a), from the cumulated distributions in Fig. 11(b), and from deconvolution in Fig. 12.

Vbias / Vrated	Charge norm.		Mean		Median		Max		Deconv. median		Deconv. max	
	Po	Am	Po	Am	Po	Am	Po	Am	Po	Am	Po	Am
0.6	1	1	0.92	0.93	0.94	0.95	1.75	2.39	/	/	/	/
0.8	1.47	1.39	1.37	1.30	1.37	1.33	2.91	3.59	/	/	/	/
0.9	2.04	1.93	1.93	1.83	1.87	1.88	5.54	5.23	/	/	/	/
1	4.25	3.45	6.61	3.07	5.45	3.29	28.35	13.87	3.48	4.47	15.29	8.77

average value, or as a statistical distribution. The summary of the extracted average values is presented in Fig. 14.

B.1.1. Normalizing to the reference charge

A first raw estimate of the multiplication factor is obtained by normalizing the total collected charge for a given reverse bias to the total charge collected at 700 V, i.e. at no multiplication. The results are shown in Fig. 11a, in conjunction with the maximum and minimum electric field values in the depletion region. It can be noticed from Table III that the measured multiplication factors are lower than the values predicted by *Monte Carlo* simulation and by the New Bologna model in Table II. The value at 1250 V has been censored, because of the saturation of the detection chain.

B.1.2. Normalizing to the reference peak

A second estimate of the multiplication factor is carried out by normalizing the charge axis to the peak of the 700 V distribution. The cumulated distributions at 1000 V, 1100 V and 1200 V after normalization are shown in Fig. 11b. The related mean, median, and maximum values are summarized in Table III for both the Po^{210} and Am^{241} sources.

B.1.3. Extraction by deconvolution

A more accurate extraction of the multiplication factor is obtained by the deconvolution procedure presented in Section II.B. For sake of simplicity, following considerations are limited to the 1200 V case for both sources. In this case, the (smearing) distribution p_{MULT} is searched that transforms by convolution the 700 V distribution (p_{CCO} , no multiplication)

Fig. 12. Probability distribution (p_{MULT}) and the related cumulated distribution as calculated by deconvolution at 1200 V reverse bias with the (a) Po^{210} source, (b) the Am^{241} source.

Fig. 13. Comparison of the (averaged) multiplication factors extracted experimentally for 700 V, 900 V, 1000 V, 1200 V to the multiplication factor predicted by (a) the New Bologna Model, (b) the SMC Monte Carlo code. (c) Comparison of the (averaged) multiplication factors extracted experimentally with the Am^{241} and the Po^{210} source.

into the 1200 V distribution (p_{CCM}). p_{MULT} as calculated by numerical deconvolution for the Po^{210} and Am^{241} sources is shown in Fig. 12a and 12b, respectively.

C. Comparison of the different extraction procedures

C.1. Comparison models to experimental data

The Fig. 13a and 13b show the correlation of the experimental multiplication factors acquired with both sources to the multiplication factors predicted by the more representative models, namely the *New Bologna model* and the *SMC Monte Carlo code*. Over the whole voltage range, the experimental and the values from both models and sources are in excellent agreement. The only deviation is observed at 1200 V (rated voltage of the *PiN* diode), where the multiplication factor obtained by the Am^{241} source is about 15% lower than the values obtained from the models and by the Po^{210} source. Due to the better collimation of the Am^{241} source and to the better statistical significance of the related spectrum, it can be argued that the lower multiplication value better reflects the reality. C.2. Comparison Am^{241} to Po^{210} source

The Fig. 13c shows the correlation of the experimental multiplication factors as acquired with the Am^{241} and the Po^{210} sources. Up to 1000 V (80% of the rated voltage of the *PiN* diode), both data sets are in excellent agreement. On the contrary, the multiplication factors obtained by the Po^{210} source (normalization and median) differ from each other by about 20%. This is the result of an artifact that arises due to the fact that the spectrometer uses a cut-off for low charge pulse values. In fact, at low reverse voltages, the events, where the deposited charge falls below the cut-off, do not appear in the spectrum. However, when the reverse bias is increased, “weak charge pulses” are multiplied exceeding the cut-off value and being included in the statistics. This leads to an

overestimation of the multiplication at high reverse bias values. This unwanted effect can be suppressed by reducing the angular spread of the impinging alpha particles by proper collimation, as it has been done for the Am^{241} source, where the obtained multiplication factors are much more consistent.

C.3. Averaged vs. extreme values of the multiplication

The data in Table III. and the probability distributions from Fig. 12a and b show that, starting from 80% of the rated voltage, the maximum value of the multiplication can exceed by up to a factor four or five the average multiplication factor. This variability, due to the scattering of “lucky electrons”, can become an issue when defining the safe operating area of devices, where avalanching is not allowed. This can be the case of the derating criteria used to define the maximum reverse DC voltage to avoid Single Event Burnout failures, which is a very strong function of the maximum multiplication factor.

Fig. 14. Comparison of the multiplication factors as obtained from the different extraction procedures.

IV. SUMMARY AND CONCLUSIONS

Exempt quantity Am^{241} and Po^{210} alpha sources have been proposed to measure the average value and the probability distribution of the carrier multiplication factor in a commercial silicon PiN power diode. Electron-hole pairs are generated by single ionization events in a small portion of the depletion region of the reverse-biased device and separated by the local electric field. The resulting charge pulses are collected by a dedicated spectrometry chain that can be easily implemented even under industrial conditions. In a first phase, the average value of the multiplication factor has been extracted by different techniques and compared with the outcome of the most popular analytical models and *TCAD* tools. Finally, the probability distribution of the multiplication factor has been extracted by the deconvolution of spectra, where no multiplication occurred, to spectra with multiplication. The obtained experimental distributions have been compared to distributions obtained by *Monte Carlo* simulation. The transport of alpha particles through the semiconductor, as well as the local charge generation by ionization have been validated by *Monte Carlo* simulations. The experimental average multiplication factors are in excellent agreement with the values predicted by the theoretical values up to 80% of the rated voltage of the device. At higher voltages the deviation from the theoretical values is in the 15% range. The average multiplication factors calculated from the experimental probability distributions at the rated voltage of the device are also in good agreement with the theoretical models. The extreme values of the extracted probability distributions show that at the rated voltage of the device, events are present with multiplication factors, which are a factor four up to five larger than the average value of the multiplication. The collimated planar Am^{241} button source has been shown to be better suited for the scope than the Po^{210} rod source, since it exhibits a narrower angular emission and a larger useful activity.

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