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Parameterization of charge transport process with avalanche multiplication in irradiated Si p-i-n structures at T = 1.9 K

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Abstract. The study is devoted to the treatment of *in situ* radiation tests results for silicon p-i-n detectors of relativistic protons, which showed the two-stage process of charge transport with avalanche multiplication at a temperature of 1.9 K. The goal of the work is to extract the carrier transport parameters from the experimental data obtained by transient current technique. For that, the impact of a spatial nonuniformity of carrier generation by the laser and spreading of the drifting carrier cloud due to diffusion on the current pulse response formation were considered. The mathematical procedure proposed for the current pulse simulation showed a key contribution of avalanche multiplication in the signal formation and allowed direct estimation of the multiplication factor from the experimental pulses. It is found that this factor only slightly depends on the bias voltage, which suggests the electric field inside the detector to be affected by the space-charge-limited current.

1. Introduction

The analysis of the experimental results of the *in situ* radiation tests of silicon detectors carried out at Conseil Européen pour la Recherche Nucléaire (CERN) at the Proton Synchrotron (PS) accelerator [1, 2] allowed to observe the two-stage process of charge transport in sensors at the temperature of superfluid helium, T = 1.9 K. In the tests, silicon planar detectors were placed perpendicular to an intense 23 GeV proton beam segmented in time into 400 ms spills. The study was aimed at the development of silicon detectors designed to operate in a harsh radiation environment and intense generation of nonequilibrium charge carriers (NCC) in the detector. The $p^+/n/n^+$ structures were investigated, where the dopant concentration in the p^+ and n^+ layers is in the range of 10^{18} - 10^{19} cm⁻³, while in the n layer concentration is in the order of 10¹² cm⁻³. The measurements of current pulse responses using Transient Current Technique with a pulse 640 nm laser [3] illuminating the n⁺ contact was carried out at the unique conditions: at a temperature of 1.9 K and during interaction of the material with proton beam, which modifies the electric field profile. The electric field is formed by charge carriers produced by a proton spill interacting with the detector for 400 ms, while charge carriers generated by a laser drift for several nanoseconds. Therefore, a quasi-stationary distribution of the electric field in the TCT method is considered.

The concept of the detector current response formation was described in [2]. In the first stage of the two-stage process, holes drift to the p^+ contact of the detector and produce electron-hole (e-h) pairs via impact ionization in a thin layer near the contact. In the second stage, the drift of electrons generated as a result of the multiplication process takes place.

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To initiate the two-stage process of charge transport in the detector bulk, the electric field distribution should contain thin region of high electric field near the detector p^+ contact in which multiplication of holes occurs. During interaction with the material, high-energy protons produce radiation defects and generate NCC giving rise to the detector current response [4]. The defects with deep energy levels in the silicon bandgap effectively trap nonequilibrium free carriers. Due to these effects, a quasi-stationary distribution of the electric field arising in the sample leads to the avalanche multiplication of carrier near the detector p^+ contact, and thus, avalanche of holes in this experiment is controlled by the distribution of charged deep centers near the contact. It should be noted that at such low temperature, the term "deep levels" refers to all radiation defects and, additionally, to the traps, whose ionization energy is reduced by the electric field (the Poole-Frenkel effect), and the probability of carrier capture on these levels is affected by the tunneling.

The presented results extend the model of charge collection described in [2] by considering the charge cloud evolution during the carrier transport in the detector. The goal of this work is to obtain the parameters of the NCC transport at 1.9 K directly from the experimental data. The following mechanisms influencing on the detector current pulse shape were accounted in the simulation:

- trapping of holes and electrons on deep defect levels, which determines the smoothed shapes of the pulse top,
- nonuniformity of the e-h pairs density generated by laser light and diffusion spreading of the drifting carrier cloud,
- influence of avalanche multiplication occurring between two phases of charge transport on the current pulse shape.

In addition, the influence of readout electronic circuit on the rise and fall of the current pulse was taken into account. This procedure allowed obtaining the carrier transport parameters and the dependence of the multiplication factor on voltage.

2. Spatial distribution of carrier cloud

The charge drifting in the detector decreases proportionally to the term $\exp(-t/\tau)$, where τ is the trapping time constant. Charge cloud spreading due to diffusion usually affects only the decay of the pulse; however, in this experiment it affects additionally the front of the second stage of the current pulse, since multiplication of carriers from the cloud occurs gradually as the holes reach thin multiplication region near the detector p⁺ contact.

The diffusion changes the shape and spatial size of drifting carrier cloud, and this change is time dependent. To calculate the effect of diffusion, the distribution associated with the nonuniformity of carrier generation by the laser is taken as the initial shape of the carrier cloud.

Thus, the algorithm for the current pulse simulation includes several steps:

- the calculation of hole concentration in the cloud at any time taking into account the initial spatial nonuniformity and diffusion spreading of the carrier cloud,
- the calculation of the collected charge inside the detector over the drift time,
- building the simulated pulse shape taking into account the finiteness of carrier lifetime,
- the convolution of the simulated pulse shape and the RC response function of the readout electronics.

According to [5], at t = 0 initial distribution of the hole concentration p(x,t) generated by the laser is: $p(x, 0) = p_0 e^{-\alpha x}$, (1)

where p_0 is the initial concentration and α the light absorption coefficient. Following the Fick's second law of diffusion, the hole cloud distribution at any time p(x, t) can be obtained as a convolution of (1) and a Gaussian function:

$$p(x,t) = \frac{1}{\sqrt{4\pi Dt}} \int_0^\infty p_l(x') \exp\left(-\frac{x-{x'}^2}{4Dt}\right) dx',$$
(2)

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where D is the hole diffusion coefficient and $\sqrt{2Dt}$ is denoted below as σ . Combining (1) and (2) yields the integral:

$$p(x,t) = \frac{1}{\sigma\sqrt{2\pi}} p_0 \int_0^\infty \exp\left(-\alpha x'\right) \exp\left(-\frac{x-{x'}^2}{2\sigma^2}\right) dx'.$$
(3)

The integral (3) can be evaluated using a complementary error function:

$$\operatorname{erfc}(z) = \frac{2}{\sqrt{\pi}} \int_{z}^{\infty} e^{-t^{2}} dt.$$
(4)

The final expression for p(x,t) is:

$$p(x,t) = \frac{1}{2}p_0 \exp\left(\frac{\alpha^2 \sigma^2}{2} - \alpha x\right) \operatorname{erfc}\left(\frac{\alpha \sigma^2 - 2x}{2\sigma}\right).$$
(5)

Thus, equation (5) is carrier distribution at any time within the drift time. The time dependence of p(x,t) is defined by σ controlled by a temperature dependent diffusion coefficient *D*. According to [6], at T around 10 K the diffusion coefficient of holes in silicon reaches 500 cm²/s that is used to evaluate the diffusion spreading of the carrier cloud. For calculation α is set to be 500 cm⁻¹ [5].

Assuming that charge carriers are drifting with a saturated drift velocity v_s , the position of hole cloud depends on time as $x = v_s t$. The saturated drift velocity of holes at T = 1.9 K is around 1×10^7 cm/s, and the total drift time through the detector volume with a thickness of d = 0.03 cm is $t_{dr} = d/v_s = 3$ ns. Figure 1 demonstrates the evolution of the hole cloud distribution depending on the position in the detector volume. The curves are shown at different moments of time disregarding hole diffusion (equation 1, dashed) and taking it into account (equation 5, solid).



Figure 1. Evolution of hole distribution over the drift time. Dash - without diffusion, solid - taking into account the diffusion.

Figure 2. Normalized charge inside the detector over the drift time.

Charge collected inside the detector volume is the integral of expression (1) or (5) from $-\infty$ to $d - v_s t$ in a coordinate space. Figure 2 shows the dependence of the nonequilibrium charge in the detector volume on the drift time. The red line shows the drift of hole cloud as a charged plane. The yellow line takes into account nonuniformity of carrier distribution generated by the laser. The green line shows the charge dependence on time taking into account the diffusion spreading of hole cloud. It can be seen that at the end of the drift the charge does not decrease to zero instantaneously, as it should be for holes drifting like a plane. Distortion of the falling edge of rectangular pulse affects the last 1 ns of the drift, i.e., about 30% of the drift time. For $t > t_{dr}$, the dependence (5) can be simplified by an exponential function $y(t) = A \exp(-(t-t_{dr})\tau_{diff}^{-1})$, where τ_{diff} is the time constant describing the diffusion process determined by D. International Conference PhysicA.SPb/2021

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The second stage of the pulse is drift of electrons arising via charge multiplication, and spreading of electron cloud affects the pulse decay. This region of the current pulse is the least informative concerning the physics of the charge transport studied in this article. Therefore, it can be assumed that the spreading of the electron cloud is also described by equation (5) with the same values of parameters. The last physical mechanism distorting the current pulse is the emission of electrons from deep levels. Since at T = 1.9 K the time constant of this process significantly exceeds all other constants, the electron emission from deep levels is negligible.

3. Signal simulation

Estimation of various physical factors influencing on the formation of a current pulse enables to derive the simulated pulse shape generated by the device taking into account the finiteness of carrier lifetime and changing of charge inside the detector. The drifting charge decreases proportionally to $\exp(-t/\tau)$. Thus, the pulse stages corresponding to the carrier drift are defined by τ_e for electrons and τ_h for holes.

An undistorted current signal *s*(*t*) is:

$$s(t) = \begin{cases} I_h, & 0 < t < t_m \\ I_e, & t_m \le t \le t_{dr}. \\ 0, & t > t_{dr} \end{cases}$$
(6)

where t_m is the time corresponding to the moment of hole multiplication, i.e., hole drift time, t_{dr} the total drift time, I_h the hole current amplitude, and I_e the electron current amplitude.

Taking into account the distortions described above and the boundary conditions at t_m and t_{dr} , it can be obtained:

$$s(t) = \begin{cases} I_{h}e^{-\frac{t}{\tau_{h}}}, & 0 < t \le t_{m} \\ s(t = t_{m})[1 + Mf(t)]e^{-\frac{t - t_{m}}{\tau_{e}}}, & t_{m} < t \le t_{dr}, \\ s(t = t_{dr})e^{-\frac{t - t_{dr}}{\tau_{diff}}}, & t > t_{dr} \end{cases}$$
(7)

where *M* is the multiplication factor and f(t) the function defined by the change of charge in the detector volume corresponding to figure 2. *M* equals the ratio of the electron current just after $t = t_m$ to the hole current at $t = t_m$. The function f(t) can be obtained correctly as a convolution of function (5) with a function that describes the dependence of the multiplication factor on the electric field. For simplicity, it is assumed that the multiplication near the detector p⁺ contact occurs instantly that only little affects the accuracy of simulation. Consequently, f(t) = 1 - g(x, t) where the latter is the integral of (5) over the interval $(-\infty; d - v_s t]$ calculated at any time.

The influence of the readout electronics is taken into account by convolution of function (7) with the RC response function of the readout electronics $h(t) = \exp(-t/\tau_{RC})$, where τ_{RC} is the time constant of the circuit. The output signal y(t) is:

$$y(t) = \int_0^t s(t')h(t-t')dt',$$
 (8)

The set of parameters that describes the result (8) is τ_{RC} , τ_h , τ_e , τ_{diff} , t_m , t_{dr} , I_h and M. The task is finding the values of all parameters that minimize *in toto* the standard deviation between the experimental and simulated pulses. A complete numerical solution for many parameters is the complicated task, therefore, some of them need to be extracted from the experimental pulse, e.g., τ_{RC} , τ_h , τ_e , τ_{diff} , t_m , and t_{dr} . It can be done via approximating the shapes of the pulse stages using exponential and linear functions. This approach is illustrated in figure 3. Therefore, only I_h and M should be evaluated from the numerical minimization of the standard deviation.

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Figure 3. Illustration for the evaluation of the carrier transport parameters.



Figure 4. The result of simulation for the detector irradiated to $F = 5 \times 10^{13} \text{ p/cm}^2$ at different bias voltages.

4. Carrier transport parameters

The described procedure was performed for the pulses recorded from Si detector irradiated to the fluence of 5×10^{13} p/cm² and operating at different bias voltages. The experimental responses and results of simulation are shown in figure 4, and the parameters are summarized in table 1. Within the maximum error of about 4%, there is a good agreement between the simulated and experimental pulses. The most important result is that the multiplication factor is about 11 and independent on V_{bias} .

$V_{bias}(V)$	$\tau_{RC}(ns)$	$\tau_h(ns)$	$\tau_e(ns)$	$\tau_{diff}(ns)$	$t_m(ns)$	$t_{dr}(ns)$	$I_h(\mu A)$	М
250	0.3	2.5	3.2	1.7	5.2	8.4	7	10.84
280	0.3	6	2.5	1.7	4.7	7.9	9.6	10.93
300	0.3	9	2.45	1.7	4.75	7.6	9.4	10.92
350	0.3	10	2.4	1.7	4.8	7.8	10.6	10.90
400	0.3	12	2.6	1.7	4.37	7.2	14.2	11.01

 Table 1. Carrier transport parameters.

The transport parameters of holes in the first stage of the pulse arising from the hole drift, τ_h , t_m and I_h , shown in figure 5 in which the parameters are normalized to the corresponding values at the maximum bias voltage of 400 V.



Figure 5. Dependences of normalized hole transport parameters on the bias voltage.

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The parameters τ_{RC} and τ_{diff} are independent on the applied bias. The electron trapping time constant, as well as the electron drift time $t_e = t_{dr} - t_m$, is insensitive to the bias voltage. This means that the transport of electrons through the detector volume proceeds with the saturated drift velocity.

5. Summary

In the study, formation of the current pulse signal in irradiated silicon detectors with avalanche multiplication of carriers at a temperature of 1.9 K was considered. The influence of drifting carrier cloud nonuniformity and readout electronics on the interpretation of experimental results was demonstrated. The proposed mathematical procedure of data processing allowed calculating such important transport parameters as the holes and electrons trapping time constants and the multiplication factor.

The current pulse shape analysis was performed in detail including transformation of the drifting carrier cloud and avalanche multiplication. The results show that the processes of avalanche multiplication and carrier trapping lead to self-stabilization of the multiplication factor independent on the bias voltage due to the influence of the Space Charge Limited Current (SCLC) [7]. Near the detector contacts, especially p+ (the region of multiplication of holes), due to the trapping the concentration of free carriers becomes high and the quasi-stationary current becomes limited mainly by the amount of charge carriers. Consequently, with a change in the bias voltage, the electric field practically does not change. This mechanism can explain the constancy of the multiplication factor in this model. This result allows concluding that SCLC controls charge collection and operating conditions of irradiated *p-i-n* structures at superfluid helium temperature and, finally, the scenario of the detector sensitivity variation under irradiation.

The fact that the multiplication factor does not depend on the applied bias is nontrivial. Since the measurements were carried out during the interaction of an intense proton beam with a sample, the electric field in the bulk of the semiconductor is redistributed due to the trapping of electrons and holes on the deep levels of radiation-induced defects. The electric field in the region of hole multiplication changes insignificantly with the bias voltage increase, which stabilizes multiplication factor.

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