Observation of internal multiplication of nonequilibrium charge in irradiated silicon detectors at a temperature of 1.9K

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Abstract. The development of modern high-energy physics is a powerful incentive for the progress of its experimental base. The use of semiconductor devices is standard for large accelerators and experimental setups at LHC, CERN, and perspective as sensors for monitoring beam loss and radiation fields in superconducting magnets and accelerating resonators operating at superfluid helium temperature (1.9 K). In these problems, the optimal type of radiation sensor is a compact silicon detector, the use of which in harsh radiation environment in combination with helium temperatures is a non-trivial task. The most important characteristics of such devices are the distribution of the electric field in the volume and the parameters of charge carrier transport, which determines the detector signal. The study considers specific kinetics of charge collection in silicon detectors at a temperature of 1.9 K in situ irradiated by relativistic hadrons.

1. Introduction

In the largest modern particle accelerators, for example, the LHC (Large Hadron Collider, CERN), beam trajectories are formed by applying the magnetic field of the order of 10 T. To optimize power consumption, the coils of the magnets operate in a superconducting state at liquid helium temperatures. However, a situation may arise when the accelerating protons due to interaction with extraneous objects fall inside the coils of the magnets and cause local heating, which will lead to a breakdown of superconductivity and accident of the accelerator. Therefore, in order to ensure long-term safe operation of the system, the task of registering radiation near the coils arises, that is, at extremely low temperatures and under radiation with an increasing dose in time [1].

The monitoring of the radiation field in the LHC magnets was considered as an option to be carried out in the environment of superfluid helium at a temperature of 1.9 K, which significantly increases the control correctness and makes it possible to measure directly the radiation that affects the superconducting coils. For this purpose, it was proposed to use silicon $p^+/n/n^+$ radiation detectors. This stimulated the study of Si detector in situ irradiated by 23 GeV protons at 1.9 K, which in itself is a new field of radiation degradation physics [2].

The main characteristic of the detector is the charge collection efficiency, which is determined by the kinetics of transport of nonequilibrium charges depending on several factors: the distribution of the electric field, carrier lifetime, mobility, etc. All these parameters strongly depend on temperature. Therefore, the operation of silicon detectors at superfluid helium temperatures cannot be explained by simple extrapolation of experimental data within the framework of models of detector functioning at room temperature.
Based on the foregoing, the goal of this work was to study the transport of nonequilibrium charge carriers in Si detectors at superfluid helium temperatures.

2. Experimental technique

Silicon $p^+/n^n$ detectors with a sensitive area of 5x5 mm$^2$ processed on wafers with a resistivity of 10 k$\Omega$·cm and a thickness of 300 microns were used in the study. The detectors were in situ irradiated at the CERN PS beam line by 23 GeV protons. Irradiation of the detectors was carried up to the maximum fluence of $1\times10^{16}$ p/cm$^2$. The measurement points were within the range $5\times10^{13}$–$1\times10^{16}$ p/cm$^2$. The error in the fluence estimation was 7% [3].

Experimental results were obtained using Transient Current Technique (TCT) [4] with a LeCroy WavePro 7300A oscilloscope with an analog bandwidth of 3 GHz and a sampling rate of 10 GS/s. In this method, the current responses of the detector to the pulsed injection of charge carriers near one of the contacts of the detector were recorded. To generate a nonequilibrium charge in the detector, a picosecond red laser with a wavelength of 630 nm was used. A laser pulse with a duration of 45 ps and a rate of 10 kHz formed charge carriers in a spot with an area of 1×1 mm$^2$. Due to problems with the radiation hardness of the coaxial cables, the pulse signal was recorded only from the $n^+$ side of the detector. In order to ensure the spread of the generated charge at a temperature of 1.9 K, the aluminum contact was made as a mesh.

An additional feature of this experiment is the fact that TCT measurements were carried out during the direct transit of a 23 GeV proton beam through the sample (so-called proton spill). The duration of each spill was 400 ms. Thus, during the transit time in the detector electron-hole pairs were uniformly generated, which determined the occupancy of the deep levels of radiation defects and of the shallow levels of doping impurity.

Special attention was paid to the reduction of the pickup in the pulse signals. Since the measurement apparatus for TCT was located at a distance of 12 m from the cryostat in which the detectors were installed, the pickup and noise disturbed a small signal of the irradiated detector.

The analysis and processing of the current pulse is based on the proportionality of the current and the drift velocity $v_{dr}$, as well as on the dependence of the latter on the electric field $E$ and the carrier mobility $\mu$:

$$v_{dr} = \mu E.$$  \hspace{1cm} (1)

The mobility allows one to reconstruct the distribution of the electric field in the detector volume for any combination of external factors such as temperature or fluence. An important feature of this formal method is its self-consistency in terms of verifying the correctness of the performed procedure. The conditions for the conservation of the generated charge and the potential difference applied to the detector allow one to obtain the results directly from the experimental data without a priori models for the distribution of the electric field.

3. Experimental results and physical model

At a temperature of superfluid helium, the drift velocity is almost saturated even in the relatively low electric field [5]; therefore, the shape of the current pulse is close to rectangular. However, for detectors irradiated with a dose of $5\times10^{13}$ p/cm$^2$, the obtained pulses have a current increase in the range of time exceeding the carrier drift time. The current responses of the detector operated at different applied bias voltages and a temperature of 1.9 K are shown in figure 1.

In the study, the laser illuminated the $n^+$ contact of the detector thus the hole drift was observed. At the applied bias voltage of 250 volts the detector is totally depleted and the mean electric field in the bulk of about 8 kV/cm. Therefore, the drift velocity of the holes is close to saturated in the entire detector volume. Obviously, at bias voltages greater than 250 V, the drift velocity is also saturated. Since the saturated drift velocity of holes at a temperature of 1.9 K is in the order of $10^7$ cm/s, the total drift time through the 300 microns is about 3 ns. The corresponding time is shown in Figure 1 by the
dashed lines. A further increase of the current cannot be associated with the drift of the initially generated charge carriers.

![Figure 1](image1.png)

**Figure 1.** Current pulse response of the detector irradiated to $5 \times 10^{13}$ p/cm$^2$ at 1.9 K and operated at reverse bias voltages.

The shape of a current signal can only be explained as the kinetics of a two-stage process. It is schematically shown in figure 2. The first classical stage is determined by the drift of the hole cloud generated by a picosecond laser pulse at the detector n$^+$ contact and drifting towards the p$^+$ contact (red arrow). Within the hole drift time, the pulse shows insignificant decay and becomes almost flat at the highest voltage of 400 V.

The second stage, registered for the first time, has a shape different from the rectangular and demonstrates a threefold amplitude rise. The increase in the electron current is not instantaneous, i.e. its rising edge ($\sim 1$ ns) is larger than the rise time of the pulse at $t=0$. This is apparently due to the fact that the holes reach the contact as a cloud expanded by diffusion. The duration of this stage is about 3-4 ns. The stage looks as associated with the generation inside the sensitive area of additional negative charge created by a cloud of holes at the p$^+$ contact and then drifting towards the n$^+$ contact (blue arrows).

![Figure 2](image2.png)

**Figure 2.** The model of the two-stage charge transport process in the detector under study.

![Figure 3](image3.png)

**Figure 3.** Kinetics of the current pulse response of the two-stage charge transport process.

The current pulse induced by such two-step process is schematically shown in figure 3. The holes initially generated by the laser drift in the electric field with a saturated drift velocity inducing the current whose decay is due to hole trapping (red line). Reaching the p$^+$ contact, the holes cause the generation of electrons whose charge is greater than the initial. Then the electrons drift with a saturated drift velocity, which also should give a constant current (blue dashed line). However, in the
irradiated semiconductor due to electron trapping on deep levels of radiation-induced defects, the current pulse response reduces (blue solid line). This model of charge transport qualitatively corresponds to the experimental pulses shown in figure 1.

Thus, the main issue of the kinetics of this process is the generation of electrons near the p⁺ contact, the number of which is greater than the initial holes. It should be noted that this assumption is based on the similarity of the observed current response shape and the experimental and simulated pulse signals from Low-Gain Avalanche Detectors (LGADs) processed on p-type Si. The LGAD structure contains a built-in p⁺-layer with a moderate boron doping and the electric field at its border with the n⁺ contact is high enough to initiate avalanche multiplication. The shape of the current pulses of LGAD demonstrated two-stage process related to the sequence of processes: drift of electrons, charge multiplication, drift of holes arising due to impact ionization [6,7].

To explain the two-stage process, the following physical model is proposed, which makes it possible to qualitatively explain the physics of such process. The holes generated by a laser near the n⁺ contact drift in the electric field of a totally depleted detector with a saturated drift velocity. Therefore, in accordance with equation (1), the current pulse response has an almost flat top. That is observed in Figure 1 between the dashed lines. The time of this drift corresponds to the value of the saturated drift velocity and the detector thickness. Then a hole cloud reaches the p⁺ contact.

The possible mechanism of the electron charge arising near the p⁺ contact in the second stage of the pulse and its enhanced value is avalanche multiplication. Holes that reach p⁺ contact cause impact ionization of silicon atoms, which leads to the appearance of a large number of free charge carriers. The electrons from this region are drawn by the electric field into the sensitive volume and then their drift induces a current. However, the mean electric field in the detector operated at 400 V is 15 kV/cm, which is essentially low for evolving the avalanche multiplication via band-to-band transitions. Therefore it seems reliable to assume that the electric field profile is vastly non-uniform in the detector volume and in the local region the electric field reaching ~10⁵ V/cm evolves near the p⁺ contact. This region can arise due to polarization effects associated with the trapping of free carriers typical of semiconductor structure with high concentration of deep levels. The electron component of the pulse is about three times larger than the hole one; however, the saturated drift velocities of both types of charge carriers at T=1.9 K are almost equal. Consequently, the initial charge of drifting electrons is three times more than the charge of holes, and the multiplication factor, in this case, should be equal to three.

4. Conclusion
This article discusses the results of a unique experiment performed by TCT with additional features, such as registration of the current pulse responses of detector during the direct transit of a proton beam with the particle energy of 23 GeV through the detector volume (in situ irradiation). A physical model was proposed to explain a non-standard shape of the current pulse with two stages of carrier transport.

The core of the model is the assumption of the process with two-stage kinetics of the pulse signal observed at superfluid helium temperatures. The first stage is the hole drift in the detector volume. In the second phase, the observed enhanced charge is assigned to the drift of electrons in the opposite direction presumably arising due to the avalanche multiplication. The duration of each stage is 3 ns that correspond to the carrier drift with a saturated velocity. Currently, the mechanism of charge multiplication the p⁺ contact is not completely clear and further studies of Si detector characteristics at extremely low temperatures aimed at solving these issues are ongoing.

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