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Kinetics of current outflow from electron-hole plasma generated in silicon detectors by relativistic heavy ions

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Abstract. The investigation is focused on the processes associated with the detection of heavy ions of hundreds GeV energy in silicon p^+-n-n^+ detectors. In the study, the 1D simulation of the electric field and free carrier density evolution in the ^{238}U ion track during the first nanosecond was carried out, which demonstrated the initial appearance of narrow high electric field regions adjacent to the contacts and a strong reduction of the electric field *in between*. The kinetics of the electron-hole plasma dispersal was assigned to a track polarization within 100 ps followed by a delayed track destruction up to its disappearance. It was shown that the process at the p^+ contact was governed by the drift of electrons as a merged fraction of free carriers, which controls the hole current flowing between the track and the p^+ contact. The density of the current initiated by the track polarization was evaluated as $8 \cdot 10^3$ A/cm^2.

Keywords: silicon radiation detector, electron-hole plasma, electric field

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Материалы конференции
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Исследование кинетики истекания тока из электронно-дырочной плазмы, создаваемой в кремниевых детекторах релятивистскими тяжелыми ионами

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Аннотация. Основное внимание в исследовании уделяется процессам, связанным с регистрацией тяжелых ионов с энергией в сотни ГэВ в кремниевых p^+-n-n^+-детекторах. В работе проведено 1D-моделирование эволюции электрического поля и концентрации свободных носителей в треке иона ^{238}U в течение первой наносекунды, которое продемонстрировало начальное появление узких областей сильного электрического поля, прилегающих к контактам, и сильное снижение электрическое поле между ними. Кинетика разлета электронно-дырочной плазмы связывалась с поляризацией трека в течение 100 пс с последующим замедленным разрушением трека вплоть до его исчезновения. Показано, что процесс на p^+-контакте определяется дрейфом электронов как объединенной фракции свободных носителей, который контролирует дырочный ток, протекающий между треком и p^+-контактом. Плотность тока, инициируемого поляризацией трека, оценивалась как $8 \cdot 10^3$ А/см^2.

Ключевые слова: кремниевый детектор излучений, электронно-дырочная плазма, электрическое поле

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Introduction

The experiments planned in nuclear physics require the use of intense exotic ion beams with the known ion mass and energy [1]. The system for obtaining such beams includes an ion accelerator and the unit for the ion fragmentation. The fragments, i.e., ions with a certain combination of masses, energy and charge are the tool and the object of research and should be characterized in the on-line mode, i.e., directly in the beam. Taking into account high intensity of the primary beam, the ion on-line diagnostic system needs high speed operation. An ion separation system includes time-of-flight (ToF) spectrometers capable of operating at beam intensities up to 10^6 particles/cm^2 per a second and a time resolution of tens of ps, which will ensure the ion mass resolution per unit of atomic mass in the range from light elements to uranium at their energies from tens of MeV/u to several GeV/u.

For light ions of medium and high energy, the choice of Si detectors in this issue is obvious and based on the experience of their use in accelerator complexes, such as Large Hadron Collider at CERN. In this case the detector signal kinetics is predictable since the signal originates from generation of electron-hole (e-h) pairs with a low density inside the particle tracks and their collection. For detecting heavy ions, application of Si detectors requires special study, since the signal arises from a dense e-h plasma, which slows down charge collection and worsens the maximum detection rate of particles and the time resolution of Si detectors as well as and the ToF spectrometer on a whole. This topic was analyzed qualitatively in [2], and it was shown that the detector signal kinetics can be considered as a two-stage process: at the first stage the track is polarized, which creates the conditions for a subsequent slow escape of carriers during the second stage, and the latter determines the duration of the detector response.

In this work, we consider the processes responsible for the formation of a signal in Si detector in the first nanosecond after the charge generation within the ion track, which is essential for advancing the ToF ion spectrometry to the range of picosecond time resolution. The investigation is performed by using original program for simulating the charge transfer in p^+-n-n^+ detector structures. The time interval of the processes in the ion track is within few ps to 1 ns, which does not allow their direct experimental study. Therefore, simulation is considered as an “objective physical experiment” that provides quantitative data for the analysis of ongoing processes.

Model of ion track

A track of high-energy ion traversing the total detector thickness is the electrical object in the volume of the detector characterized by specific ionization losses and representing geometrically a thin cylinder with a diameter corresponding to the region in which nonequilibrium electrons and holes arise. Although a large number of studies are devoted to the physics of the ion track formation, there are only rough estimates of its geometry yielding the diameter in the range hundredths of a μm to a μm, which results in the ambiguity of the concentration of charge carriers created by the ion [3].

In the simulations performed in this work, a track with a diameter of 1 μm and a uniform distribution of e-h pairs with initial concentrations of electrons and holes n_0 and p_0 equal to $8 \cdot 10^{15}$ cm^{-3} created by a heavy ion, is considered. This concentration corresponds to ^{238}U ions with energies in hundreds of GeV.

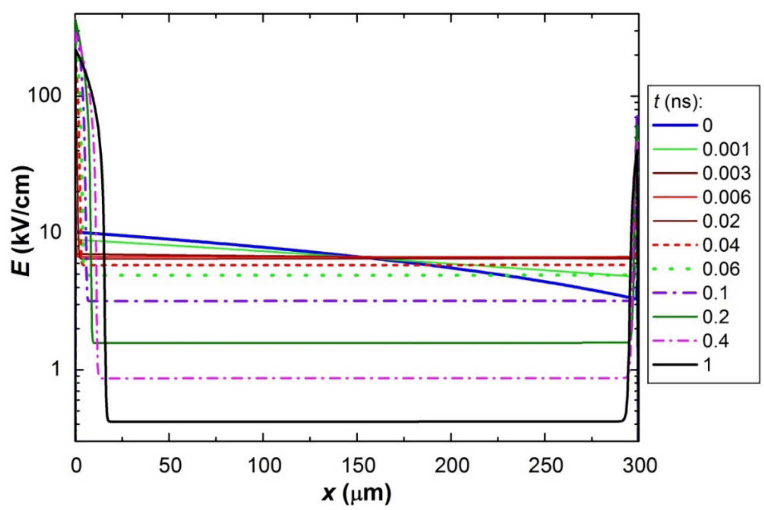


Fig. 1. Distribution of the electric field across the detector thickness. $V = 200$ V

The processes in the track were studied in a 1D model extending along the thickness of the detector (coordinate x). Simulations were carried out using original software package applied earlier for calculating the electric field profile $E(x)$ in Si p^+-i-n^+ structures [4]. The package included modeling the processes of carrier drift and diffusion along the x-coordinate and allowed tracking the kinetics of the redistributions of $E(x)$ and the electron and hole concentration n and p, respectively. The model structure was a silicon detector processed on the wafer with a resistivity of 3 kΩcm, a thickness d of 300 μm and degenerate p^+ and n^+ contacts. The generation of e-h pairs arose from a single heavy ion penetration inside the detector bulk normally to the surface and was uniformly distributed across the track cross-section. The profiles of the electron and hole densities were uniform over the structure thickness, turning into the degenerate layers at $x = 0$ and $x = d$ (the p^+ and n^+ contacts, respectively). The bias voltage applied to the detector was 200 V, which matches Si detector operation in the experiments with heavy ions at room temperature.

Evolution of the electric field profile in subnanosecond time range

Fig. 1 shows the electric field profiles obtained by simulation in the detector sensitive area over its total depth and corresponding to different moments of time from the appearance of the track ($t = 0$) up to $t = 1$ ns. It should be noted that this time interval is of significant importance. Indeed, with a target time resolution of the ToF spectrometer in tens of picoseconds, the electric field redistribution at $t < 1$ ns is vital, since it controls the kinetics of the current response to impinging ions. With that in mind, the study considers the high rate processes of the electric field redistribution in the regions adjacent to the contacts.

Two features are clearly observed in the evolution of the $E(x)$ distribution in the subnanosecond range. At $t \geq 0.01$ ns, sharp electric field maxima E_{max} arise near the detector contacts. This is accompanied by a reduction in the electric field *in between*, i.e., in most of the detector volume that becomes eventually close to uniform and goes down in time.

Fig. 2 shows the details of the electric field rearrangement in the track in the interval 0-1 ns in the region adjacent to the p^+ contact. The formation of a region with a maximum electric field occurs within a few picoseconds. E_{max} rises with time and reaches hundreds of kV/cm (maximum value is ~350 kV/cm at ~100 ps), which significantly exceeds the initial E_{max} of 10^4 V/cm at $t = 0$. The following decay of the electric field from its maximum takes place within the region $x = 0$–16 μm, and the electric field gradient dE/dx is close to linear.

Transformation of the electric field profiles occurs in two time stages showing different tendencies:

- $0 < t < 100$ ps, E_{max} increases, while a subsequent linear decrease of the electric field with an almost constant slope is observed within a region with a width W of few μm (Fig. 2,*a*);
- 100 ps $< t <$ 1 ns, E_{max} drops, and an intensive expansion of the high electric field region takes place near the p$^+$ contact leading to the dE/dx decrease (Fig. 2,*b*).

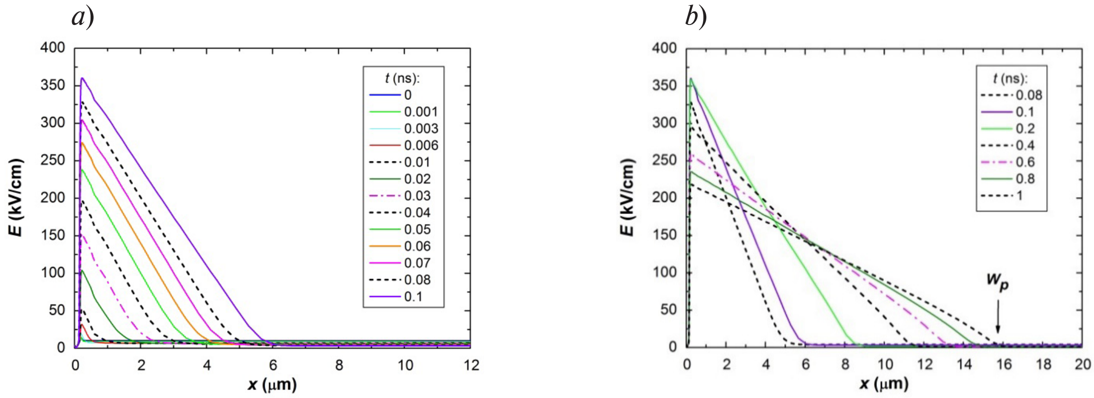


Fig. 2. Distribution of the electric field near the detector p^+ contact in the time intervals: 0–0.1 ns (*a*), and 0.08–1 ns. $V = 200$ V (*b*)

The appearance of the electric field maxima near the contacts is accompanied by the formation of a region with a constant field in the main part of the volume, whose value successively decreases with time to E below 1 kV/cm. It should be noted that such a redistribution of the electric field goes on at a constant bias voltage applied to the detector.

The nonmonotonic dependence of E_{max} on time is presented in Fig. 3. The maximal electric field ~350 kV/cm is achieved at $t \approx 150$ ps, and the width of the region with a linear $E(x)$ decay is 16 μm at $t = 1$ ns.

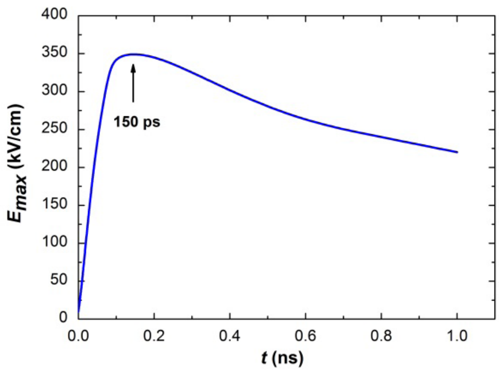


Fig. 3. Time dependence of E_{max}

Evolution of space charge and carrier concentration due to polarization inside the track

At $t = 0$, the maximum electric field at the p^+ contact E_0 of 10 kV/cm is determined by the effective space charge concentration $N_{eff0} = 1 \cdot 10^{12}$ cm^{-3} in the sensitive n-type region of the detector. In the track generated by impinging ion, the e-h plasma is electrically neutral and only slightly affects the initial electric field distribution. Further, E_{max} at the p^+ contact increases and dE/dx gradient goes down, while remaining close to linear, which evidences a change in N_{eff} with time in the region with a width W. The N_{eff} dependence on the width W is determined by the Poisson equation:

$$\frac{dE}{dx} = -\frac{eN_{eff}}{\varepsilon\varepsilon_0}, \tag{1}$$

where e is the elementary charge, ε and ε_0 are permittivities of Si and vacuum, respectively, and is shown in Fig. 4. The dependence demonstrates two regions. In the first one, in the interval $0 < t < 60$ ps, i.e., at $W \le 3.8$ μm, N_{eff} is positive and equals $4.7 \cdot 10^{15}$ cm^{-3}. In the second region, at $t \ge 60$ ps N_{eff} goes down as W rises, which implies changing the mechanism of the electric field distribution.

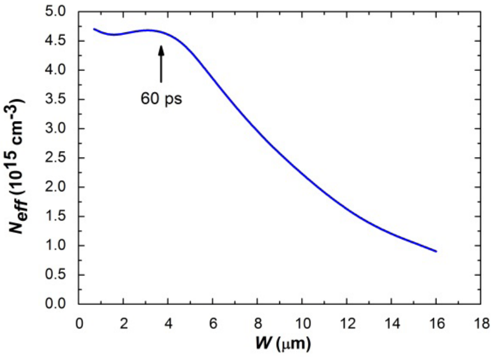
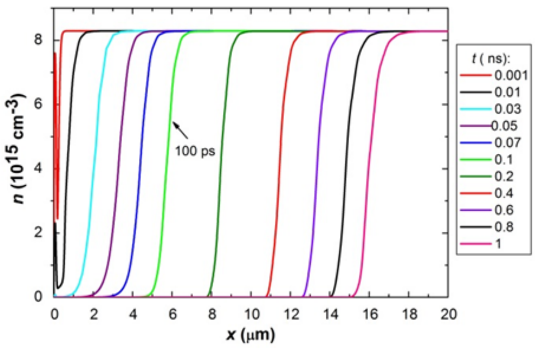


Fig. 4. Dependence of N_{eff} in the region
with a linear electric field gradient on its width W

Evolution of the electric field profile at p^+ contact originates from the time distribution of the electron and hole concentrations in the region adjacent to the p^+ contact. The primary process is the drift of the electron column as a whole in the electric field E_c in the central region of the detector ($E_c \leq 6$ kV/cm at $t \geq 10$ ps). It can be seen that the column border stays sharp and shifts in time (Fig. 5,***a***), which expands the region deeply depleted with electrons; for example, at $x < 5$ μm, the concentration n is below $1 \cdot 10^4$ cm^{-3}. In turn, positive charge of free holes in this region (Fig. 5, *b*) determines the distribution of the electric field. Obviously, free holes will drift in the electric field towards the p^+ contact, creating conduction current. This process is visualized in the hole concentration distribution as a region with a decrease in p from $8 \cdot 10^{15}$ cm^{-3} to $\sim 5 \cdot 10^{15}$ cm^{-3} within the interval 40–100 ps. This concentration of holes is still high and comparable with its value in the electrically neutral track.

a)



b)

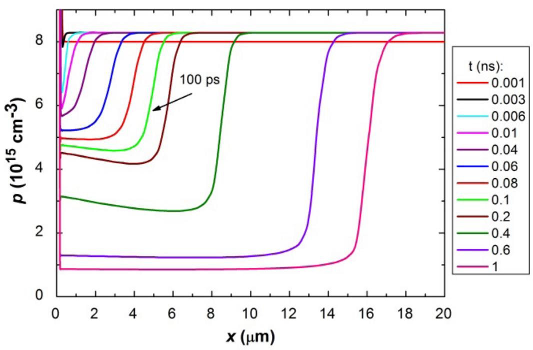


Fig. 5. Evolution of the carrier concentration in the ion track in time:
(*a*) electrons, and (*b*) holes

The process of plasma drift in the electric field can be described by two equations. The first one determines the relation between the displacement velocity of the electron column border W_e, dW_e/dt, and the density of hole charge dq_h/dt outflowing from the track:

$$\frac{dq_h}{dt} = en\frac{dW_e}{dt}. \tag{2}$$

The second yields the dependence of hole current density J_h on the hole concentration:

$$J = e\mu_h E_p, \tag{3}$$

where μ_h is the hole mobility. A displacement of the electron column border via its drift is a basic process determining the current dq_h/dt at $t < 100$ ps. Then, at $t = 0.1$ ns, W_e is 5 μm and n equals $8 \cdot 10^{15}$ cm^{-3}, while J is $8 \cdot 10^3$ A/cm^2 that corresponds to the current of $7.5 \cdot 10^{-5}$ A outflowing from the track with a diameter of 1 μm. It should be noted that this estimation corresponds to the time when the electric field at the p^+ contact reaches its maximum of about 350 kV/cm. Then, considering $\mu_h E = v_{sat}$ (where $v_{sat} = 7.5 \cdot 10^6$ cm/s is the hole saturated velocity) and using Eq. (3), the mean hole concentration in the layer W is $6 \cdot 10^{15}$ cm^{-3} that is in the reasonable agreement with p at $t < 100$ ps.

At $t = 1 \cdot 10^{-10}$ s E_{max} starts decreasing, and the expansion of the high electric field region slows down (Figs. 2,*b* and 3). The above two stages in the $E(x)$ transformation can be attributed to two qualitatively different processes:

track polarization which manifesting itself as a rapid change in the electric field distribution, which occurs in the 0—100 ps interval and leads to the formation of the polarization charge layer with a thickness W_{pol}. This results in the electric field rise to the maximum E_{max} and is accompanied by a significant decrease in the electric field in the detector volume outside the W_{pol} layer;

slower expansion of the depleted layer to the central part of the detector (Fig. 2,*b* and 5,*a*) that finalizes with the disappearance of the track due to the escape of all nonequilibrium carriers to the contacts.

It should be noted finally that the presented results do not affect the electric field formation at the ohmic n^+ contact, whose analysis requires an additional software resource and is included in further research plan. However, the overview $E(x)$ plot (Fig. 1) shows a qualitative similarity of the processes at the n^+ contact with those at the p^+-n junction, which allows us to consider the current results as a basis for further study.

Conclusion

The performed simulation of the electric field distribution demonstrated the following.

- In the range of few ps, the track polarization is a dominating process.
- The polarization at the p^+ contact is characterized by deep depletion of the narrow layer by electrons, while the concentration of holes only reduces.
- Both processes, electron column shift and the hole current flow, are balanced and characterized by the high current density in the range of thousands A/cm^2.
- The hole concentration is nearly constant in time, which predicts the constant current flow during the polarization phase controlled by the hole saturated velocity.
- The modeling enables a physically justified parameterization of the high resolution timing characteristics of Si detectors.

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