Semiconductors, 2024, Vol. 58, No. 8

Drift transport of charge carriers in silicon p^+-n-n^+ structures at temperatures $\leq 100\,\mathrm{mK}$

© E.M. Verbitskaya[1], I.V. Eremin[1], A.A. Podoskin[1], V.O. Zbrozhek[2], S.O. Slipchenko[1],
N.N. Fadeeva[1], A.A. Yablokov[2], V.K. Eremin[1]

[1] Ioffe Institute,
194021 St. Petersburg, Russia
[2] Alekseev State Technical University,
603155 Nizhny Novgorod, Russia
E-mail: elena.verbitskaya@mail.ioffe.ru

Received September 11, 2024
Revised October 9, 2024
Accepted October 13, 2024

For the first time, the transient current technique is used to study the drift transport of charge carriers in silicon p^+-n-n^+ structures at temperatures $T \leq 100\,\mathrm{mK}$. The pulse current responses of the structure caused by the drift of laser-generated electrons and holes in the region of the electric field up to 10^4 V/cm are measured. It is found that the space charge concentration in the n-region decreases to a few percent of the phosphorus atom concentration. This fact indicates that the influence of phonons on the electron tunneling through the potential barrier of phosphorus atoms, reduced according to the Poole-Frenkel effect, becomes ineffective already at $T < 1.1\,\mathrm{K}$. The combination of the p^+-n-n^+ structure properties converts n-Si into an electrically neutral insulator with a small space charge and high carrier mobilities, which is important for building sensitive elements with internal thermal gain for a neutrino detector.

Keywords: silicon p^+-n-n^+ structure, current response, electric field, phonon-assisted tunneling, neutrino.

DOI: 10.61011/SC.2024.08.59888.7067

1. Introduction

Application of semiconductor devices at temperatures of tenths and hundredths of Kelvin appeared in the context of high-energy physics to search weakly interacting massive particles (WIMPs) as possible candidates for Dark Matter in the Universe that are capable of interacting with solid and liquid media [1–7]. Experiments on the search for WIMPs and the study of cosmic neutrinos are being performed, for example, by the Cryogenic Dark Matter Search [1–4] and Edelweiss [5] collaborations. Silicon and germanium bolometric detectors, which produce signals as a change in temperature of their sensitive elements (SEs) under the influence of a detected particle, are used in these experiments. In both cases, the semiconductor detectors operate at a temperature of tens of mK, which ensures a sensitivity better than 1 keV.

Similar instruments are planned to be used in studies of the magnetic moment of neutrinos, which are the part of research program No. 8„Hydrogen Isotope Physics“ of the National Center for Physics and Mathematics (NCPM) in Sarov. One of the projects within this program envisions the development of research methods in the field of neutrino physics and neutron-rich nuclei using hydrogen and helium isotopes for fundamental nuclear physics [8]. The members of this project are currently preparing an experiment with an intense tritium antineutrino source utilizing the reaction [9]

$$ {}^3_1H \to {}^3_2He + e^- + \bar{\nu}_e \qquad (1)$$

with a maximum neutrino energy of 18.6 keV and three types of detectors (including a cryogenic silicon one operating within the 10−50 mK temperature range with an expected detection threshold of a few eV). These measurements should allow detecting the effects of magnetic moment μ_ν of an electron antineutrino with a sensitivity of $(1.5-2.5)\cdot 10^{-12}\,\mu_\mathrm{B}$ (μ_B is the Bohr magneton), which is an order of magnitude better than the $\sim 3\cdot 10^{-11}\,\mu_\mathrm{B}$ value [5.10] achieved by using detectors based on liquid xenon and high-purity germanium in the registration of cosmic and reactor neutrinos, respectively.

The detection ability, which is specified by the absorber mass (i. e., the probability of interaction of a particle with the absorber) and the signal-to-noise ratio, is a critical parameter of detectors in the planned neutrino experiment. NCPM program No. 8 envisions building a prototype of silicon detector with internal thermal gain that should help in increasing its sensitivity. A particle interacting with the SE material in such a detector (silicon, (Si)), which is the energy absorber, produces both phonons, which induce primary heating of the absorber, and nonequilibrium carriers (NCs), electrons and holes. Internal gain is achieved due to the Neganov–Trofimov–Luke effect [11,12] that is observed when an electric field with a strength $F(x)$ arises in the absorber, causing the drift of NCs. In this case, specific energy $dE/dx = QF(x)$ is released at a point with coordinate x in the process of drift of, e. g., electrons, and additional energy $\Delta E = QV$, where Q is the charge of each of NC components and V is the applied voltage, is transferred to the sensitive element during the transport of carriers in the electric field region between the contacts. For example, thermal effect ΔE of a single electron-hole (e-h) pair generation in a SE operating at $V = 1000\,\mathrm{V}$

is as high as 1000 eV, which is equivalent to internal gain $G \approx 1000/3.6 \approx 300$ (3.6 eV is the *e-h* pair formation energy). This approach is most efficient if the following three conditions are satisfied:

– the electric field extends over the whole absorber volume (i. e., the entire mass of a silicon SE is active);

– the lifetime of NCs (in the present case, the time of their trapping at the energy levels of atoms and defects in the semiconductor) is much longer than the time t_{dr} of their drift to the corresponding contacts; and

– thermal generation of *e-h* pairs in the SE volume and surface leakage current do not raise the SE operating temperature due to the gain effect and do not produce an intense component of background signals.

In Program No 8, silicon was chosen as the SE material in consideration of future plans for experimental studies, where the overall weight of SEs may reach 160 kg. It is assumed that an individual SE with a mass of approximately 100 g and a working area thickness of several centimeters will be a p^+-i-n^+ structure (*i*where i is high-resistivity silicon) operating at a voltage up to 1000 V. Since a large number of identical SEs needs to be produced (up to 1600 elements), their design and fabrication rely on the widest possible use of processing and instruments of modern microelectronics.

The basic issue in this concept is the fabrication of p^+-i-n^+ diodes with thickness W of the electric field region reaching units of centimeters at a voltage of several hundred volts. Specifically, the available high-resistivity pure n-type silicon (*n*-Si) with a resistivity of $\sim 10\,\mathrm{k\Omega\cdot cm}$ is characterized by difference $N_0 \approx 3.5 \cdot 10^{11}\,\mathrm{cm}^{-3}$ in concentrations between charged donors and acceptors (ionized atoms of phosphorus and boron, respectively, with the former being predominant). Within the standard temperature T range for Si detectors (from room temperature to 77 K), this translates into W limited to 0.2 cm at $V = 1000$ V, while N_0 needs to be reduced to $\sim 1 \cdot 10^9\,\mathrm{cm}^{-3}$ to achieve a thickness of 3–5 cm. Therefore, the condition of SE operation within the range of tens of mK, which is needed for noise minimization, is also proposed to be used to create a uniform electric field by freezing the electrically neutral state of silicon existing at $V = 0$ in the *i*-region of the structure with subsequent application of reverse voltage. It is important to note that voltage applied to the SE triggers the transition to a non-steady state of the structure, and the electroneutrality of silicon in the *i*-region may be maintained only under the condition of invariableness of the charge state of each acceptor and donor energy levels present in it (i. e., with a time constant of carrier emission from these levels being several orders of magnitude greater than the time of continuous SE operation).

The aim of the present study is to investigate the drift transport of carriers in silicon p^+-n-n^+ structures at temperatures $T \leq 100$ mK. Current responses of the structure measured using the transient current technique and caused by the drift of non-equilibrium electrons and holes under the application of a reverse voltage to the structure and an electric field up to 10^4 V/cm are presented. Their shape is analyzed to estimate effective space charge concentration N_{eff} at $T = 40$ and 100 mK. The features of signal waveforms in measurements within a wider temperature range of 14 mK–4 K are revealed.

2. Experimental samples and response measurement technique

Detector p^+-n-n^+ structures based on *n*-Si with a resistivity of $7\,\mathrm{k\Omega\cdot cm}$ ($N_0 \approx 6 \cdot 10^{11}\,\mathrm{cm}^{-3}$) and a thickness of $d = 300\,\mu$m were used in experiments. Heavily doped plane-parallel contact p^+- and n^+-layers were produced by implantation of boron and phosphorus atoms, respectively, with concentrations of at least $10^{18}\,\mathrm{cm}^{-3}$, which are sufficient for material degeneracy. The contact p^+-layer with an area of $2.5 \times 2.5\,\mathrm{mm}^2$ had metallization in the form of an aluminum mesh with a line width of $20\,\mu$m and a pitch of $200\,\mu$m and was surrounded by a structure of p^+-rings to stabilize the current–voltage characteristics at room temperature. Windows with an area of $1 \times 1\,\mathrm{mm}^2$ were etched in the continuous metallization of the n^+-contact with a size of 6×6 mm (chip size) in order to measure the response of the structure to hole drift. Two samples (A and B) identical in topology were used in the studies.

Their current response under deep cooling was measured at the Nizhny Novgorod State Technical University using a closed-loop dilution cryostat. The test samples, temperature sensors, and heating elements for temperature stabilization were positioned at the working lower flange of the cryostat, which is cooled to the lowest possible temperature. The time of cooling the cryogenic head from room temperature ($\sim 20^\circ$C) to the target temperature of 30–50 mK was 20 h.

The transient current technique (TCT) [13] was used to study the response. Electron-hole *e-h* pairs were generated by illuminating one of the contacts with laser pulses. Pulsed signals were recorded using a RIGOL MS08000 digital oscilloscope with an analog bandwidth of 2 GHz. The sample signal was output to vacuum SMA connectors at the warm flange of the cryostat via four series-connected semi-rigid cryogenic cables with a wave impedance of $50\,\Omega$. To interrupt the flow of heat to the working lower flange, the connectors at the ends of cables had thermal contacts with four intermediate inner flanges of the cryostat maintained at 50, 4, 1, and 0.1 K. The total length of the cryogenic cable line was ~ 2 m.

The results of electrical tests revealed stable operation of the cable line and cryogenic sample holders at voltages up to 1000 V. No excess noise, electromagnetic pick-up, or baseline fluctuations were observed. The noise signal level at the oscilloscope input did not exceed 0.1 mV; with an oscilloscope input impedance of $50\,\Omega$, this is equivalent to a noise current of $\pm 2\,\mu$A.

The TCT measurement of current responses of silicon p^+-n-n^+ structures was performed using lasers with wavelength $\lambda = 670$ or 850 nm and a peak power of 25 and 2–10 W at a half-amplitude pulse duration of 73 and 120 ps, respectively. The measurement procedure included all the preparatory operations needed to commission a detector in a physical experiment with a neutrino source. All tests with the sample mounted in the cryostat were performed at room temperature. Cooling was performed with a voltage source connected and ensuring that $V = 0$ at the sample. With the target temperature reached and stabilized, the reverse voltage was raised to the required level, and one side of the structure was illuminated with laser pulses. The voltage was varied within the $0-300$ V range at a fixed temperature. Negative voltage was applied to the p^+-contact from which the signal was read out, while the n^+-contact was grounded.

3. Pulsed response of silicon p^+-n-n^+ structures under charge carrier drift

Building large-volume neutrino detectors with thermal gain requires total depletion of Si p^+-n-n^+ structures several centimeters in thickness. As was noted above, this may be achieved by reducing effective (i. e., difference) concentration N_{eff} of positive and negative charged impurities and defects to $\leq 10^9\,\text{cm}^{-3}$. Compensation of silicon by, e. g., radiation defects with deep energy levels in the band gap (BG) of silicon leads invariably to an increase in the concentration of charged traps for NCs and, accordingly, to carrier trapping, suppressing the useful signal amplitude. It should be noted that shallow levels of phosphorus and boron atoms also act as effective carrier traps at liquid helium temperatures. Therefore, the only way to maintain near-zero N_{eff} in the electric field region is to cool the detector to the temperature of electron and hole freezing at the energy levels for the entire ensemble of impurity atoms under the conditions of electroneutrality of the sensitive volume at $V = 0$ and subsequent application of voltage. Silicon then turns into an insulator with electric field $F = V/d$ remaining uniform at any V. Deep cooling of the entire detector to tens of mK is also necessary for high-sensitivity bolometric measurements and is generally consistent with the concept of neutrino detection.

Unfortunately, reliable experimental data on the characteristics of high-resistivity silicon at such low temperatures are currently unavailable. Specifically, a study of Si p^+-n-n^+ detectors designed for monitoring a beam of relativistic protons at the Large Hadron Collider at CERN demonstrated that under cooling phosphorus atoms in the electric field region remain positively charged at temperatures down to $T = 6$ K due to the ionization energy E_i reduction from 46 to 6 meV [13,14]. This fact cannot be attributed solely to the electrostatic Poole–Frenkel effect that is associated with lowering of the energy barrier for the ionization of phosphorus atoms in the BG under the influence of an electric field: at $T = 6$ K and $F = 10$ kV/cm, the barrier height decreases just to 23 meV, and the probability of ionization is negligible at $\sim 10^{-10}\,\text{s}^{-1}$. Therefore, the ionized state of phosphorus atoms observed experimentally below 10 K may be associated with carrier tunneling through the potential barrier of an impurity center, which involves phonons and leads to a further E_i reduction. Extrapolation of the experimental data for 6 K to lower temperatures provides estimated data only, necessitating an experimental study of the charge state of shallow impurities in high-purity n-Si at the target operating temperature of the neutrino detector sensitive element (below 100 mK) in electric fields up to 10 kV/cm.

In the measurements of the pulse current response of a p^+-n-n^+ structure containing useful data on the drift transport of NCs, the following conditions must be satisfied.

– to consider the drift of NCs as the one of a package of electrons or holes with thickness L_{gen}, a laser pulse producing NCs should be much shorter than time t_{col} of carrier collection at the structure contacts;

– to make a one-dimensional drift model applicable, the light spot within which e-h pairs are excited should be much larger than the thickness of their generation layer and larger than (or at least commensurate with) the distance between the p^+- and n^+-contacts; and

– the time constant of the oscilloscope input circuit should be much shorter than the drift time of non-equilibrium carriers between contacts, and the analog bandwidth should be sufficient to examine the signal kinetics in detail.

The thickness of the region in which NCs are generated is a parameter important for the analysis of the response shape. Owing to the lack of experimental data for light absorption coefficient α and, accordingly, absorption depth $L_{\text{gen}} = \alpha^{-1}$ at such low temperatures, the latter is hard to determine. At $\lambda = 660$ nm and $T = 1.9$ K, it is estimated at $L_{\text{gen}} \sim 10-15\,\mu$m [15]. However, reliable data on α for light with a wavelength of 850 nm are limited from below by temperature $T = 77$ K, where $\alpha \approx 600\,\text{cm}^{-1}$ and, accordingly, $L_{\text{gen}} \approx 17\,\mu$m [16]. Since α decreases with decreasing temperature, L_{gen} is expected to increase at $T \leq 100$ mK (presumably, to several tens of micrometers).

Therefore, at $\lambda = 670$ nm, the drift of a cloud of non-equilibrium electrons or holes is similar to the drift of a thin package of carriers with charge q parallel to the electrodes in the region of an electric field of$F(x)$ formed by the voltage applied to the structure. Under these conditions, the value of transient current i for moving charge q at a point with coordinate x and time t is specified by the Shockley–Ramo theorem and is written as [17]

$$i(x) = qF_w(x)\mu(F, T)F(x), \tag{2}$$

where μ is the carrier mobility that depends on F and T, x is the coordinate normal to the sample surface, and F_w is the weighting electric field that determines the efficiency of charge induction to the contact (at which the signal is read out) as a result of charge coordinate variation: $dx/dt = \mu(x)F(x)$. $F_w(x)$ is calculated as the electric field at the point where the charge is located at voltage $V = 1$ V applied to this contact and the other contacts being grounded. In general, F_w depends on their geometry, and $F_w = 1/d$ for a structure with two plane-parallel contacts. It follows from expression (2) that in the case of a uniform field (i. e., at constant drift velocity $\upsilon_{dr} = \mu F(x)$) the current

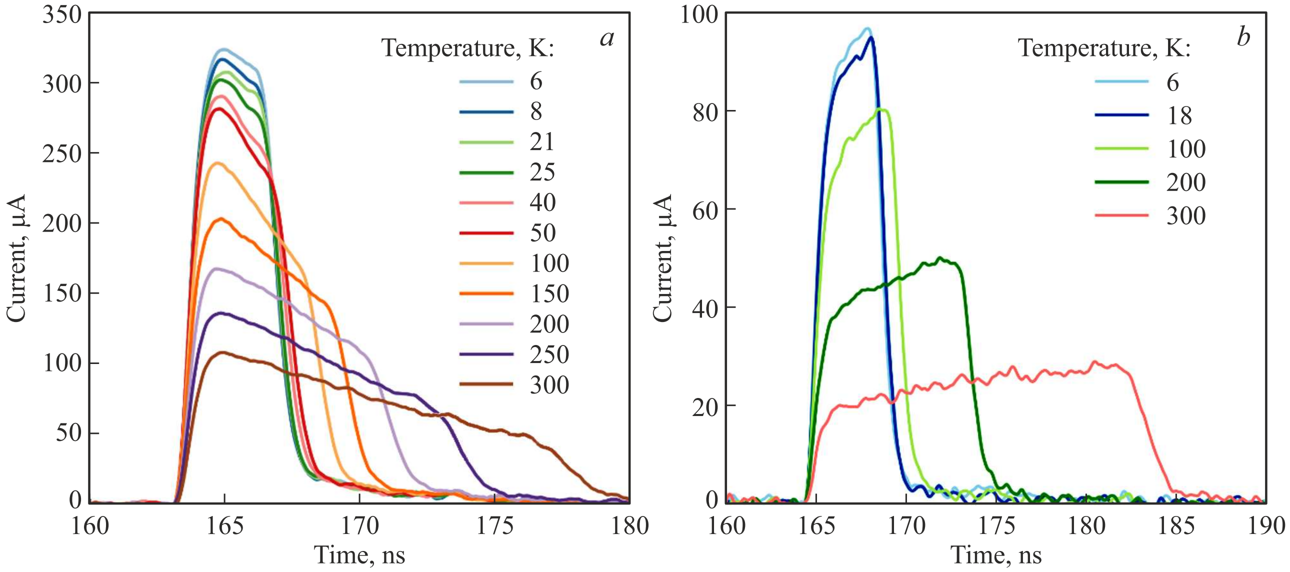

Figure 1. Experimental current pulses of a 300-μm-thick silicon p^+-n-n^+ structure based on n-Si with a resistivity of $10\,\mathrm{k\Omega\cdot cm}$ at different temperatures: a — electron drift, $V = 50\,\mathrm{V}$; b — hole drift, $V = 100\,\mathrm{V}$, $\lambda = 660\,\mathrm{nm}$. (A color version of the figure is provided in the online version of the paper).

should remain constant within the $0 < t < t_{dr}$ time interval, where t_{dr} is the carrier drift time.

In a p^+-n-n^+ structure with a uniform electric field $\operatorname{div} F = 0$, and, consequently, N_{eff} in the region of the electric field is also zero. If N_{eff} is nonzero and does not depend on the coordinate and the mobility is also independent of F, the current at the top of the pulse reaches its maximum and decreases exponentially afterward with drift time constant τ_{dr} set by the effective concentration. Thus, the current pulse for the drift of an electron package is written as

$$i_e(t) = \frac{q}{d}\mu_e F(0)\exp\left(-\frac{t}{\tau_{dr}}\right), \tag{3}$$

where $F(0)$ is the electric field at the p^+-contact and τ_{dr} depends on mobility:

$$\tau_{dr} = \frac{\varepsilon\varepsilon_0}{e\mu_e N_{\mathrm{eff}}}, \tag{4}$$

where ε and ε_0 are the permittivities of silicon and vacuum, respectively, and e is the elementary charge. Therefore, the sign of derivative $di(t)/dt$ at the top of the pulse depends on the sign of the space charge in the drift region. The relation between $i(t)$ and N_{eff} is used widely in TCT studies of nuclear radiation detectors with a weak dependence of carrier mobility on F. Experimental data on $\mu(F)$ and $\upsilon_{dr}(F)$ at temperatures of hundreds of mK and below this range are lacking; however, the objective trend toward saturation of the drift velocity to $\sim (1-1.4)\cdot 10^7$ cm/s [18] should lead to weakening of the $\upsilon_{dr}(x)$ dependence and flattening of the current pulse top.

Figure 1 shows an example of experimental current responses of a silicon p^+-n-n^+ structure cooled from 300 to 6 K and irradiated by a laser with a wavelength of 660 nm [13,19]. According to expression (3), pulses caused by the electron drift from the p^+-contact to the n^+-contact in a p^+-n-n^+ structure with positive N_{eff} (the electric field is maximal at the p^+-contact) should have a top revealing a decrease in current, while the current should increase in the case of hole drift from the n^+-contact where F is minimal. This is fully consistent with Figures 1, a and b. It should be noted that the pulse duration is clearly bound by the moments when the process of carrier package drift is initiated (e-h pairs are generated) and when these carriers reach the opposite contact. Owing to the increase in carrier mobility, this duration decreases with decreasing temperature.

4. Experimental data on the response of silicon p^+-n-n^+ structures at $T \leq 1\,\mathrm{K}$

Current responses of the silicon structure were studied within two temperature intervals: detailed measurements at $T \leq 100\,\mathrm{mK}$, which is the range including the target operational temperature of Si sensitive elements, and in addition, measurements within the extended range of $14\,\mathrm{mK}-4\,\mathrm{K}$.

Figure 2 shows the current responses for sample A at voltages of 0–90 V and $T = 100\,\mathrm{mK}$ with e-h pairs generated by the laser with a wavelength of 670 nm (a photon energy of 1.85 eV). The pulse series shown in Figures 2, a and b are produced as a result of drift of electrons and holes under irradiation of p^+- and n^+-contacts, respectively. The characteristic features of pulses relevant to the aim of the study are as follows.

– Current responses $i(t)$ contain four regions: a rapid signal growth at the moment of generation of e-h pairs,

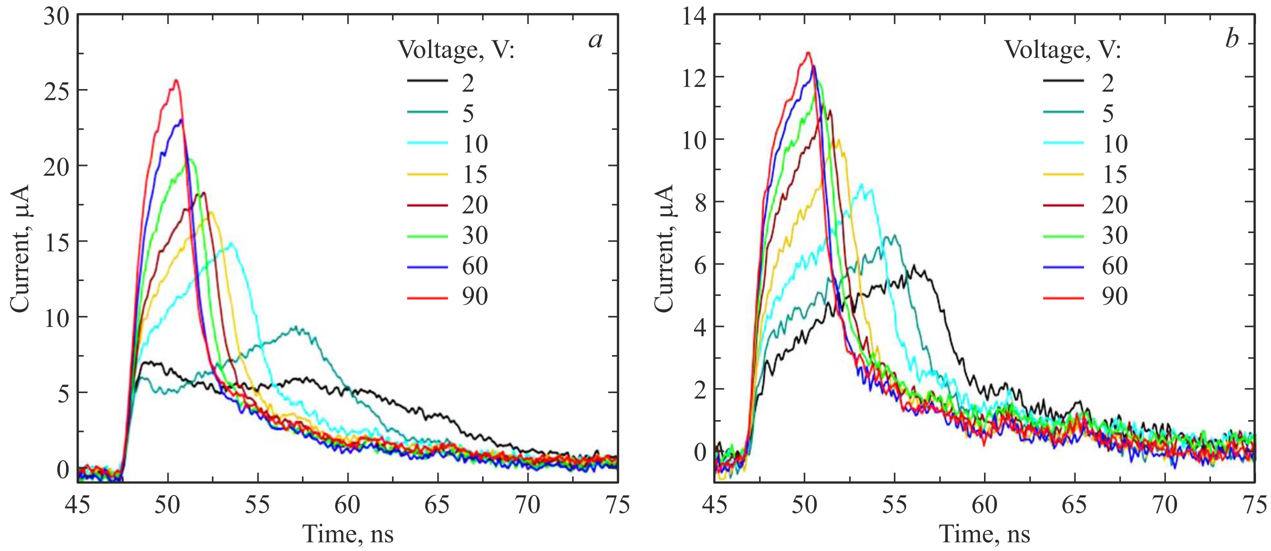

Figure 2. Current responses of sample A during electron and hole drift (fragments a and b, respectively). $\lambda = 670$ nm; $T = 100$ mK.

a smooth increase in current at the top of the pulse, and a sharp signal fall with subsequent slow fade-down. The pulse duration decreases with increasing voltage and drops to 4–4.5 ns at the maximum $V = 90$ V.

– Moments of current generation correspond to the onset of carrier package drift (i. e., detachment of an electron package from the p^+-contact or holes from the n^+-contact).

– A small peak is observed at a voltage of 5 V at the front of the pulse shown in Figure 2, a. This peak may be associated with visualization of the drift current of holes from the NC generation layer at the p^+-contact. Its duration is ~ 1 ns and is set by the time of hole escape from the generation layer with a thickness of $\sim 10\,\mu$m into the adjacent p^+-contact. At higher voltages, the peak is not visible due to an increase in electron current and a reduction in pulse duration.

– The onset of pulse decay in Figure 2, a corresponds to the moment when the electron package reaches the n^+-contact (i. e., the point when the charge drifting in the region of the electric field starts decreasing). Regardless of the pulse top shape, a rapid response decay is observed at almost all V values, which provides direct evidence of an electron package transport from the p^+-contact to the n^+-contact.

– Similar shapes of current pulses are also observed in the drift of a hole package when NCs are generated near the n^+-contact (Figure 2, b). The top of pulses is also characterized by an increase in current over time with a subsequent sharp fall. The pulse features include a subnanosecond rise time, with the front formed already at $V = 2$ V, and a sharp drop in current at this voltage, which indicates that the hole package has reached the p^+-contact. This character of pulse decay does not vary with the type of drifting carriers and is a direct consequence of the presence of an electric field permeating the entire region between the contacts.

– The responses with current increasing over time arising from the drift of electron and hole packages are qualitatively similar. However, they differ from pulses with a flat top expected for a uniform $F(x)$ distribution with carriers frozen at the energy levels of shallow impurity atoms in the n-region of the sample.

– The observed increase in current over time with the pulse shape interpreted formally as $i \propto q\mu F$ (expression (2)) either leads to a dependence of the sign of dF/dx on the sign of drifting carriers, which appears paradoxical, or requires an increase in charge over time arising from unclear reasons.

The existence of an electric field over the entire structure at $V \approx 2$–4 V is indicative of concentration of $N_{\text{eff}} = 2.9 \cdot 10^{10}\,\text{cm}^{-3}$, which follows from the expression for the electric field region depth W in the p^+-n junction equal to d and total depletion voltage $V_{fd} \approx 2$ V:

$$d = \left(\frac{2\varepsilon\varepsilon_0 V_{fd}}{eN_{\text{eff}}}\right)^{0.5}. \qquad (5)$$

The listed features of the response shape and the N_{eff} estimate, which yields a value ~ 20 times lower than concentration N_0 measured at room temperature, provide direct evidence that the charge state of the ensemble of shallow donor and acceptor levels in high-resistivity n-Si is close to electroneutrality already at $T = 100$ mK.

In view of the importance of this conclusion, similar measurements were carried out for a silicon p^+-n-n^+ structure based on n-Si promising for the production of a large-scale neutrino detector (sample B). A laser with a wavelength of 670 nm was used in this case. It produced pulses of greater power (25 mW), while their duration remained unchanged. The current responses for this sample with a laser pulse illuminating the n^+-contact, which ensures maximum sensitivity to the presence of an electric field in

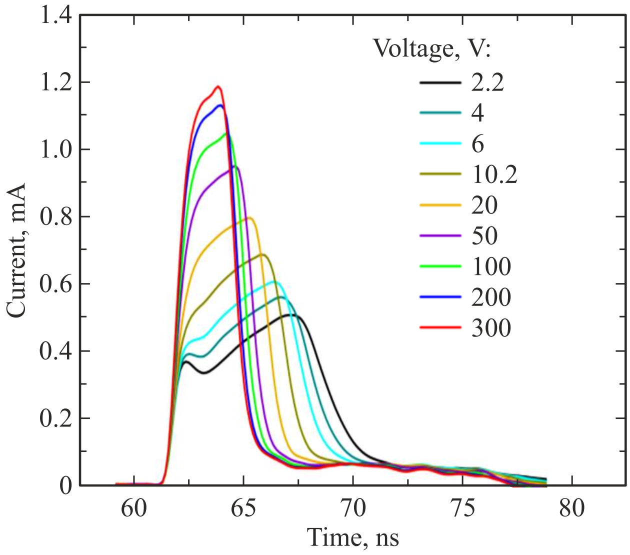

Figure 3. Responses of sample B at laser illuminating the n^+-. $T = 40\,\text{mK}$; $\lambda = 670\,\text{nm}$.

the region of its possible minimum, are shown in Figure 3. Measurements were performed within the 0–300 V voltage range at $T = 40\,\text{mK}$, which corresponds to the target temperature.

The signal waveforms with a significantly better signal-to-noise ratio are similar to those shown in Figure 2, *b*. Just as for sample A, a signal with a subnanosecond front and a sharp fall is recorded already at a voltage of 2.2 V, which is indicative of the existence of an electric field at the n^+-contact sufficient for effective hole drift. The paradox mentioned above for sample A, which consists in the fact that the pulse-top slope formally corresponds to negative N_{eff} and is virtually independent of voltage, is also observed. At a higher concentration of generated NCs in the pulse series in Figure 3 at $V \leq 6\,\text{V}$, a peak corresponding to the drift of electrons from the layer of their generation to the nearby n^+-contact is found beyond a sharp increase in the signal (this peak is not seen in Figure 2, *b*).

The same sample was studied under illumination by a laser with a wavelength of 850 nm (photon energy of 1.46 eV) which provides a greater length of generated carriers package than at $\lambda = 670\,\text{nm}$. Therefore, when any of the contacts is irradiated with light, a pulsed signal is formed as a result of drift of both electrons and holes that produce different partial contributions to the signal. The shape of current responses is characterized by the same four regions that were noted above; however, significant differences are also evident.

– A sharp drop in current is seen at voltages starting from 8 and 4 V (Figures 4, *a* and *b*, respectively).

– The above-mentioned peaks at the pulse front remain visible within almost the entire range of voltages when light is illuminating the n^+-contact, but are seen only at $V \leq 25\,\text{V}$ in the case of the p^+-contact.

– The pulse-top slopes corresponding to irradiation of different contacts are the same, but, unlike those in Figures 2 and 3, indicate a decrease in current over time. The latter feature is apparently related to the fact that the escape of a fraction of extended carrier packages from the drift region into the contacts at $\lambda = 850\,\text{nm}$ initiates a reduction in drift charge q and current (in accordance with expression (2)) at the early stages. The discussed change in the response pulse-top slope represents the main difference between the effects of light with a wavelength of 670 and 850 nm.

Figure 5 illustrates the constancy of collected charge Q_{col} for sample B with an increase in voltage within the 0–300 V range at $T = 40\,\text{mK}$ and various λ. The charge was determined by integrating the current over the time of complete carrier collection ($\sim 15\,\text{ns}$). Using expression (5) with an average value of $V_{fd} = 3\,\text{V}$, one finds the following estimate of the equivalent concentration: $N_{\text{eff\_}eq} \approx 4.4 \cdot 10^{10}\,\text{cm}^{-3}$ ($\sim 7\%$ of N_0), which is comparable with N_{eff} determined above. It should be noted that, provided that there are no drift charge losses, Q_{col} is specified by the number

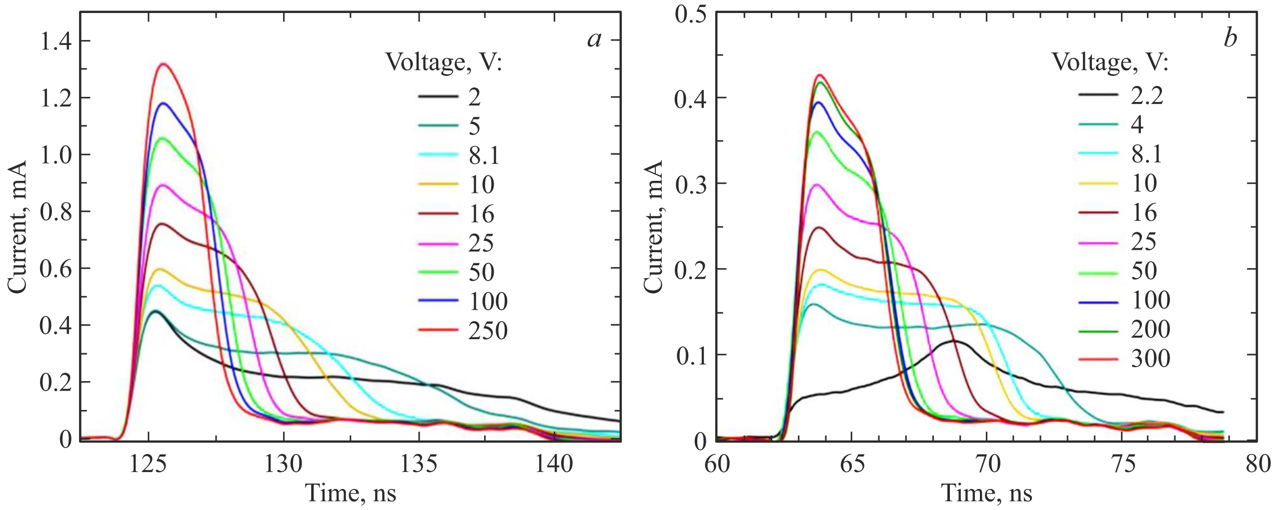

Figure 4. Responses of sample B at laser illuminating p^+- and n^+- contacts (fragments *a* and *b*, respectively). $T = 40\,\text{mK}$; $\lambda = 850\,\text{nm}$.

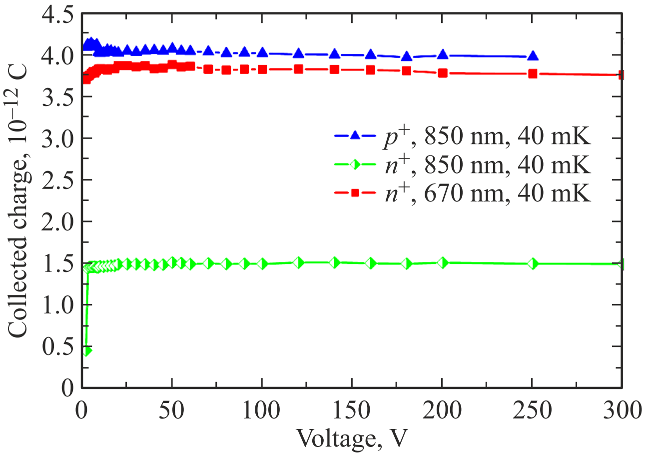

Figure 5. Dependence of the collected charge on voltage for sample B at different λ.

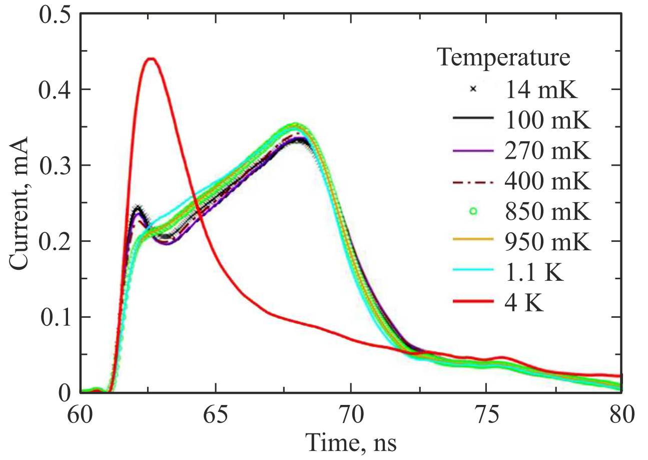

Figure 6. Effect of temperature on the response of sample B with the p^+-contact illuminated. $V = 7$ V; $\lambda = 670$ nm.

of generated NCs (i. e., the laser pulse energy absorbed in the sample) and the geometry of light incidence onto the sensitive surface of the sample. The constancy of these factors was impossible to control in the discussed experiments, and a correct comparison of the absolute values of Q_{col} thus cannot be performed. Relying on the value of $Q_{\text{col}} \approx 4 \cdot 10^{-12}$ C, we may estimate the laser light energy absorbed in the samples at $7.4 \cdot 10^{-12}$ and $5.8 \cdot 10^{-12}$ J for $\lambda = 670$ and 850 nm, respectively.

The responses of sample B were also measured with the p^+-contact irradiated with 670 nm light and the temperature increasing from 14 mK to 4 K (Figure 6). A transition of the n-region of the structure from an insulator-like state to a state typical of temperatures causing thermal ionization of phosphorus atoms in the electric field region is possible within this range. Following this transition, N_{eff} becomes equal to N_0, which should induce a change in the response shape at low voltages.

The measurement data revealed that the shape of pulses associated with electron drift at $V = 7$ V remains unchanged within the $T = 14{-}400$ mK range and is similar to the one presented in Figure 2, *a*, which corresponds to a concentration of ionized phosphorus atoms of several % of N_0. A further increase in temperature to 1.1 K leads to a slight reduction in the rate of current growth at the same pulse duration, and the peak near the response front, which was interpreted above as the drift current of holes from an NC package to the p^+-contact, vanishes.

Unfortunately, owing to certain design features of the cryostat, the process of increasing the temperature of the flange with the sample holder was uncontrolled and quite fast ($<$ 1 min in duration), precluding us from performing a thorough recording temperature-induced changes in the signal shape. The response at $T = 4$ K shown in Figure 6 illustrates a radical change in its shape: transformation of the pulse top into a peak. Following a rapid signal growth within $\sim$ 1 ns to the peak value, a smooth extended decay is observed, which is typical of partial depletion of the p^+-n-n^+ structure and corresponds qualitatively to expression (3). Thus, N_{eff} is positive at $T = 4$ K and increases significantly due to the ionization of a significant fraction of phosphorus atoms, terminating the state of electroneutrality of the n-Si volume.

The obtained data correlate well with the results reported in [13,19], where the effective concentration in the region of the electric field was found to remain equal to N_0 at a temperature decreasing down to 6 K, while the ionization energy of phosphorus atoms decreased to 6 meV due to phonon-assisted tunneling of electrons through the potential barrier of phosphorus atoms. The obtained results reveal that the critical temperature below which the tunneling-stimulated emission mechanism becomes ineffective is within the range of 1–4 K.

5. Conclusion

The drift transport of carriers in 300-μm-thick p^+-n-n^+ silicon structures was examined using the transient current technique under pulsed laser illumination and the application of a reverse voltage within the temperature range of 14 mK–4 K, which includes the target temperature of 30–50 mK for sensitive elements of neutrino detectors. It was demonstrated that the experimental current responses are determined by the drift of non-equilibrium electrons and holes produced by laser radiation. It was revealed that N_{eff} in n-Si at $T \leq 100$ mK is only a few percent of the concentration of phosphorus atoms, which is the key finding of the present study. The response shapes measured within the extended temperature range of 14 mK–4 K showed that the influence of phonons on the tunneling of electrons through the lowered (due to the Poole–Frenkel effect) potential barrier of phosphorus atoms at an electric field up to 10^4 V/cm, which should result in a reduction in N_{eff}, becomes ineffective at temperatures below 1.1 K. This is confirmed by a sharp fall of pulsed signals at voltages as low as $\sim$ 2–4 V, which corresponds to the extension of the electric field region across the entire thickness of the structure.

Owing to this combination of properties, silicon in the sensitive volume of a detector may be regarded as a semiconductor close to an electrically neutral insulator, but with high electron and hole mobility, which is necessary for the production of sensitive elements with internal thermal gain for a neutrino detector. At $T \leq 100\,\mathrm{mK}$, the current pulse-top slope, which formally characterizes the sign of effective charge, depends on the wavelength of laser light. The available data provide no ready explanation for this fact, necessitating additional experiments.

The obtained results provide new insights into semiconductor device physics, since the operation of silicon p^+-n-n^+ structures was considered within a previously unexplored temperature range and at high electric field.

Funding

This study was conducted within the scientific program of the National Center for Physics and Mathematics, section # 8. Stage 2023-2025.

Acknowledgments

The authors express their sincere gratitude to A.F. Kardo-Sysoev and G.G Zegrya for their interest in the research and discussions of the obtained results.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] S. Cebrián. J. Phys.: Conf. Ser., **2502**, 012004 (2023). DOI: 10.1088/1742-6596/2502/1/012004

[2] M.F. Albakry, I. Alkhatib, D.W.P. Amaral, T. Aralis, T. Aramaki, I.J. Arnquist, I. Ataee Langroudy, E. Azadbakht, S. Banik, C. Bathurst, D.A. Bauer, R. Bhattacharyya, P.L. Brink, R. Bunker, B. Cabrera et al. Phys. Rev. D, **105**, 112006 (2022). https://doi.org/10.1103/PhysRevD.105.112006

[3] D.W. Amaral, T. Aralis, T. Aramaki, I.J. Arnquist, E. Azadbakht, S. Banik, D. Barker, C. Bathurst, D.A. Bauer, L.V.S. Bezerra, R. Bhattacharyya, T. Binder, M.A. Bowles, P.L. Brink, R. Bunker et al. Phys. Rev. D, **102**, 091101(R) (2020). https://doi.org/10.1103/PhysRevD.102.091101

[4] Q. Arnaud, E. Armengaud, C. Augier, A. Benoît, L. Bergé, J. Billard, A. Broniatowski, P. Camus, A. Cazes, M. Chapellier, F. Charlieux, M. De Jésus, L. Dumoulin, K. Eitel, E. Elkhoury et al. Phys. Rev. Lett., **125**, 141301 (2020). https://doi.org/10.1103/PhysRevLett.125.141301

[5] J. Aalbers, S.S. AbdusSalam, K. Abe, V. Aerne, F. Agostini, S. Ahmed Maouloud, D.S. Akerib, D.Y. Akimov, J. Akshat, A.K. Al Musalhi, F. Alder, S.K. Alsum, L. Althueser, C.S. Amarasinghe, F.D. Amaro et al. J. Phys. G: Nucl. Part. Phys., **50**, 013001 (2023). https://doi.org/10.1088/1361-6471/ac841a

[6] E. Aprile, J. Aalbers, K. Abe, S. Ahmed Maouloud, L. Althueser, B. Andrieu, E. Angelino, J.R. Angevaare, V.C. Antochi, D. Antyn Martin, F. Arneodo, M. Balata, L. Baudis, A.L. Baxter, M. Bazyk et al. arXiv:2402.10446v1 [physics.ins-det] 16 Feb 2024.

[7] V.A. Allakhverdyan, A.D. Avrorin, A.V. Avrorin, V.M. Aynutdinov, R. Bannasch, Z. Bardačová, I.A. Belolaptikov, I.V. Borina, V.B. Brudanin, N.M. Budnev, V.Y. Dik, G.V. Domogatsky, A.A. Doroshenko, R. Dvornický, A.N. Dyachok et. al. PoS(ICRC2021)1144.

[8] A.A. Yukhimchuk, A.N. Golubkov, I.P. Maksimkin, I.L. Malkov, O.A. Moskalev, R.K. Musyaev, A.A. Selezenev, L.V. Grigorenko, V.N. Trofimov, A.S. Fomichev, A.V. Golubeva, V.N. Verbetskii, K.A. Kuzakov, S.V. Mitrokhin, A.I. Studenikin, A.P. Ivashkin, I.I. Tkachev. Fizmat, **1** (1), 5 (2023). (in Russian). DOI: 10.56304/S2949609823010057

[9] Y. Giomataris, J.D. Vergados. Nucl. Instrum. Meth. A, **530**, 330 (2004). https://doi.org/10.1016/j.nima.2004.04.223

[10] G. Beda, V.B. Brudanin, V.G. Egorov, D.V. Medvedev, V.S. Pogosov, M.V. Shirchenko, A.S. Starostin. Advances in High Energy Phys., **2012**, 350150. DOI: 10.1155/2012/350150

[11] B.S. Neganov, V.N. Trofimov. *Sposob kalorimetricheskogo izmereniya ioniziruyushchikh izluchenii.* SU Patent No. 1037771. (in Russian).

[12] P.N. Luke. J. Appl. Phys., **64**, 6858 (1988). https://doi.org/10.1063/1.341976

[13] V. Eremin, A. Shepelev, E. Verbitskaya, C. Zamantzas, A. Galkin. J. Appl. Phys., **123**, 204501 (2018). https://doi.org/10.1063/1.5029533

[14] A. Shepelev, V. Eremin, E. Verbitskaya. J. Phys.: Conf. Ser., **1697**, 012067 (2020). DOI: 10.1088/1742-6596/1697/1/012067

[15] V. Eremin, A. Shepelev, E. Verbitskaya. JINST, **17**, P11037 (2022). DOI: 10.1088/1748-0221/17/11/P11037

[16] S.M. Sze, K.K. Ng. *Physics of semiconductor devices.* 3rd edn (J. Wiley & Sons, Inc., Hoboken-N.J., 2007).

[17] S. Ramo. Proc. IRE, **27**, 584 (1939).

[18] C. Jacoboni, C. Canali, G. Ottaviani, A.A. Quaranta. Solid-State Electron., **20**, 77 (1977).

[19] A.S. Shepelev. Candidate's Dissertation in Mathematics and Physics (SPb., Ioffe Inst., 2023). (in Russian).

Translated by D.Safin