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Lifetimes of electrons and holes in pure Si at temperature 40 mK

I.D. Isakov [1,2]✉, E.M. Verbitskaya [1], I.V. Eremin [1], N.N. Fadeeva [1], V.K. Eremin [1]

[1] Ioffe Institute, St. Petersburg, Russia;

[2] St. Petersburg Electrotechnical University "LETI", St. Petersburg, Russia

✉ isakov-ivan.2016@yandex.ru

Abstract. The paper presents the study of experimental current responses of Si p^+-n-n^+ 3 mm thick structure operated at 40 mK. Analysis of the data showed reduction of carrier lifetimes in silicon to 50–70 ns for electrons and 350 ns for holes, which is the most critical factor for restriction of the internal thermal gain in bolometric detectors based on the Joule-Lenz effect and should be accounted for in the optimization of detector design.

Keywords: silicon, current response, carrier trapping, bolometric detector

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Конференционная статья
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Время жизни электронов и дырок в чистом Si при температуре 40 мК

И.Д. Исаков [1,2]✉, Е.М. Вербицкая [1], И.В. Еремин [1], Н.Н. Фадеева [1], В.К. Еремин [1]

[1] Физико-технический институт им. А.Ф. Иоффе РАН, Санкт-Петербург, Россия;

[2] Санкт-Петербургский государственный электротехнический университет «ЛЭТИ» им. В.И. Ульянова (Ленина), Санкт-Петербург, Россия

✉ isakov-ivan.2016@yandex.ru

Аннотация. В статье представлены результаты исследования экспериментальных токовых откликов кремниевой p^+-n-n^+-структуры толщиной 3 мм, работающей при температуре 40 мК. Анализ данных показал уменьшение времени жизни носителей заряда в кремнии до 50–70 нс для электронов и 350 нс для дырок, что является наиболее критичным фактором для ограничения внутреннего теплового усиления в болометрических детекторах, основанных на эффекте Джоуля-Ленца, и должно учитываться при оптимизации конструкции детектора.

Ключевые слова: кремний, токовый отклик, захват носителей, болометрический детектор

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Introduction

Bolometric radiation detectors (BDs), in which the signal is a change in the temperature of the semiconductor sensitive element (SE) due to the energy deposition by the detected particle, attract growing interest owing to the possibility to achieve unique sensitivity. Development of BD on high purity Ge and high resistivity Si is motivated by the search for dark matter particles (CDMS and EDELWEISS collaborations [1, 2]) and measuring the characteristics of neutrinos. In particular, the latter is planned within the scope of program No. 8 at the National Center for Physics and Mathematics, Sarov, aimed at building a silicon massive BD up to 10 kg operating at a temperature of tens of mK [3]. A productive idea was to record the change in the SE temperature arising from released particle energy instead of electrical signal generated at the contacts of semiconductor sensor acting as a sensitive element (SE) of BD. The factor in favor of achieving higher internal thermal gain (ITG) is that the heat capacity of Si decreases with temperature as T^3, so, for example, reducing the operational temperature of a SE from 10 K to 10 mK should increase the temperature signal by a factor of 10^9.

The ITG implementation is based on generation of the additional thermal energy ΔE_{dr} in the SE via the drift of nonequilibrium electrons and holes created by the particle, expressed as

$$\Delta E_{dr} = Q_e\left(t\right)\cdot\Delta V_e + Q_h\left(t\right)\cdot\Delta V_h, \tag{1}$$

where $Q_e(t)$, $Q_h(t)$ are respectively the charges of nonequilibrium electrons and holes, depending on time t, and ΔV_e, ΔV_h are the fractions of applied voltage V passed by electrons and holes that follows from the Shockley–Ramo theorem [4]. The drift energy ΔE_{dr} can be raised up to hundreds of times by applying the proper voltage, accordingly increasing the BD signal. The maximum gain is achieved if Q_e and Q_h remain constant during the drift due to the absence of carrier trapping. However, at temperatures < 100 mK this currently has no experimental confirmation.

Carrier trapping was earlier studied in Si SE with a thickness d of 300 μm and 1 mm [5, 6]. Here we extend this task to the sample with a 3 mm thickness using the same approach for obtaining experimental data and their processing.

Experimental results and analysis

The p^+-n-n^+ structure was processed on the 3 mm thick wafer of pure n-type silicon with a resistivity of ~ 40 kΩ·cm (concentration of phosphorus atoms < 10^{11} cm^{-3}) using planar technology. The measurements of the responses were performed in a closed-loop dilution cryostat at T = 40 mK. The sample was mounted on a copper holder ensuring its thermal connection to the cryostat plate. The holder and sample were screened by aluminum foil from the cryostat warmer component radiation. The measurements of the current response, whose procedure was described in [5, 6], were carried out using the Transient Current Technique with electron-hole pairs generation by illuminating the sample contacts with a 670 nm, 47 ps laser pulse. Current signals were recorded by a digital oscilloscope with an analog bandwidth of 2 GHz and an input impedance of 50 Ω. Negative bias voltage V was applied to the p^+-contact while the n^+-contact was grounded.

In the measurements the current responses originated from the drift of carriers (either electrons or holes) to the contact opposite to the illuminated one. Fig. 1, *a* shows examples of the responses arising from electron drift from the p^+- to the n^+-contact. The pulse shapes observed at $V \leq 160$ V exhibit the following regions: a small narrow peak adjacent to the sharp pulse front, a smooth signal growth to the maximal current, clearly defined descending pulse tops and gradual

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signal decay. The current in the narrow peak near the front (oval in Fig. 1, *a*) and the region of slow current growth are presumably due to the space charge limited current (SCLC) process [6], which forms an extended cloud of drifting electrons. Narrow peak disappears at $V > 240$ V. Within the time range of slow current reduction on the pulse top the current occurs as the drift of the extended electron cloud between the p^+-n-n^+ structure contacts. At $V \geq 140$ V the pulse tops demonstrate a slope close to a linear increase with the voltage, and a sharp drop of the signals. Transition of the final gradual current decay to a sharp drop is the evidence that electrons reach the n^+-contact.

For the responses from holes (Fig. 1, *b*) the signal appeared at $V = 40$ V and at higher voltages displayed a clearly defined sharp front and abrupt decay. No peak was observed near the pulse front. The pulse tops showed a superlinear increase in the current at $V = 40$–300 V and a nearly linear rise at $V \geq 300$ V.

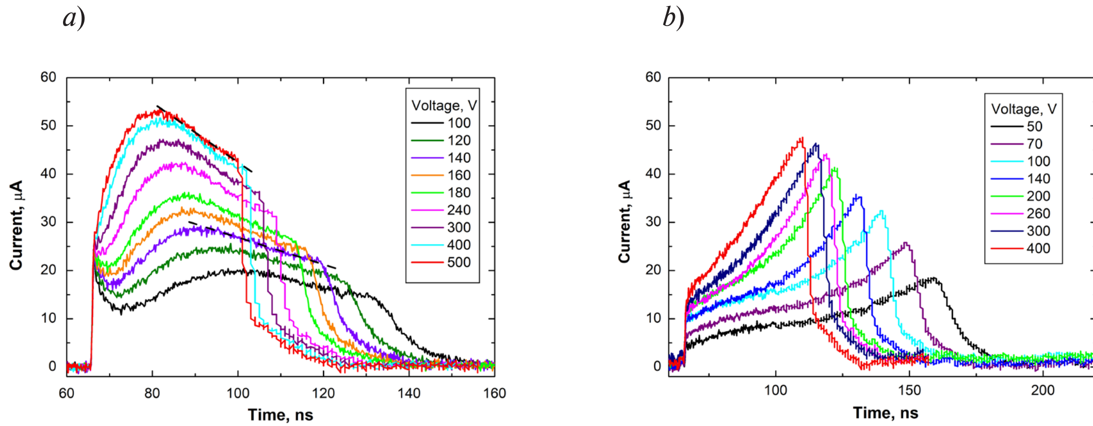

Fig. 1. Current pulse responses of Si p^+-n-n^+ structure to electron drift (*a*) and hole drift (*b*). Dashed lines in (*a*) show linear top slopes at $V = 140$ and 500 V

Drift of nonequilibrium carriers in the Si SE occurs in the electrically neutral material due to low operational temperature, at which thermal activation of charge carriers even from shallow energy levels of boron and phosphorus with an activation energy of about 46 meV is impossible. Thus, in the external circuit of the sample the current originated from the drift of charge cloud acts as the displacement current arising from a change in the charge position in the volume between the contacts. The depth δ of carrier generation near the contacts at temperatures of a few mK is ~ 10 μm [6], which enables considering the process of charge collection as the drift of a flat carrier layer in a 1D-geometry. Then, the resulting drift current *i* when the charge *q* moves at the coordinate x at the time t is described by the Shockley-Ramo expression [4]:

$$i(x) = q(t) F_w(x) \mu(F, T) F(x), \tag{2}$$

where μ is the mobility of drifting carriers depending on the electric field *F* and *T*, and F_w is the weighting electric field, which determines the efficiency of charge induction on the contacts, and in plane-parallel geometry is $1/d$.

Generally, the current shape may not have a flat top if it is controlled by the non-uniform $F(x)$ profile and the $q(t)$ reduction due to the capture of carriers on electrically active centers. However, according to [5], $F(x)$ distribution in a p^+-n-n^+ structure is uniform at $T < 800$ mK since the energy levels of shallow impurities of phosphorus and boron (positively charged donors and negatively charged acceptors respectively) in silicon at *F* up to $3 \cdot 10^4$ V/cm cannot be thermally activated. Cooling of the sample at zero bias voltage freezes electrical neutrality of the silicon bulk and maintains this state in the range of electric field corresponding to the SE operation, and $F(x)$ profile still holds its uniformity. In turn, reduction of $q(t)$ due to trapping and its kinetics are dependent on the carrier capture probability $1/\tau_{tr} = \sigma v_{th} N_{tr}$ (where τ_{tr} is the trapping time constant (carrier lifetime), σ and v_{th} are carrier capture cross section and thermal velocity respectively, and N_{tr} is the trap concentration), which violates the flat pulse shape.

Two approaches, both based on the trapping phenomenon of the drifting carriers, were used to determine τ_{tr}.The first is fitting the current response tops using the relationship $i(t) \propto \exp(-t_{col}/\tau_{tr})$ (where tcol is the carrier collection time), which is only possible for electron pulses with decay in the top. The exponential fits of the current response tops at low (140 V) and high (500 V) bias voltage, at which the SCLC effect is negligible, are illustrated in Fig. 1, *a* by dashed lines. Reduction of the current on the pulse top is well fitted, which proves the interpretation of its origin. The result of the analysis in the full range of bias is presented in Fig. 2 as the dependence of τ_{tr} on the average electric field in the sample determined as $F = V/d$. The obtained τ_{tr} values for electrons are in the range 60–80 ns, rising only insignificantly with the electric field increase at $F > 0.7$ kV/cm. It should be noted here that the applied approach was based on the analysis of carrier package drift and required the knowledge of the electric field distribution inside the sample bulk.

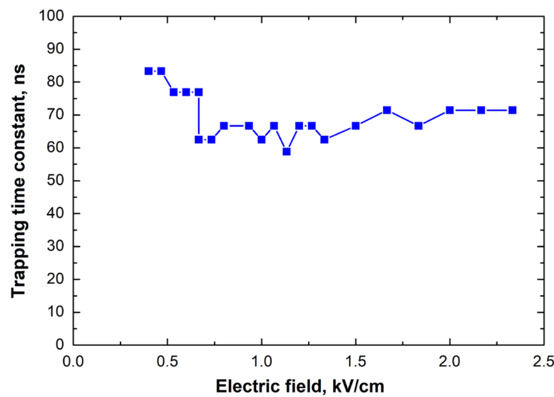

Fig. 2. Dependence of the electron trapping time constant on the average electric field

The second approach to evaluation of τ_{tr} is based on the relation between the collected charge and carrier collection time. According to the Shockley-Ramo expression that considers induction of the current on the sample contacts by drifting charge changing in time, the charge was determined by integrating the current response over t_{col}. This parameter was estimated as the duration between the time points at half of the pulse front and half of the decay. The experimental dependences for electrons and holes as well as their fits are shown in Fig. 3 as normalized charge $Q_{col\text{-}n}$ vs. t_{col}. For electrons, using simple proportionality between $Q_{col\text{-}n}$ and $\exp(-t_{col}/\tau_{tr})$ fails fails to properly fit the experimental data in the total range of tcol. Therefore $Q_{col\text{-}n}$ vs. t_{col} dependence was treated by using the Hecht equation [7, 8], which is only correct in the case of significant trapping and expressed as

$$Q_{col} = \frac{\tau_{tr}}{t_{col}}\left[1 - \exp\left(\frac{t_{col}}{\tau_{tr}}\right)\right]. \tag{3}$$

The fit shows reasonable agreement with the experimental data at $\tau_{tr_e} \approx 50$ ns. It should be noted that disagreement between the curves at $t_{col} \geq 100$ ns ($V \leq 60$ V) may be due to the influence of space charge limited current; however, the trends of the experimental data and the fit well correlate. The matching results obtained with different approaches for data treatment give a clear indication of the distribution of electric field through the entire thickness of the sample and the efficient charge drift between the p^+- and n^+-contacts.

The last note is the argument to use only the $Q_{col}(t_{col})$ approach for evaluating the trapping time constant for holes when the impact of the charge trapping on the current pulse shapes is not resolved. The current responses corresponding to the hole collection (Fig. 1, *b*) have specific shapes with intensively rising current, which can be explained based on the model of carrier drift in an electric field strongly disturbed by the carrier cloud itself [6]. In the case of non-intensive trapping of drifting carriers, the mechanism of the electric field distortion can dominate, and analysis of the current responses becomes insensitive to trapping. Thus, the $Q_{col_p}(t_{col})$ approach was used for fitting experimental data for holes, and the result is presented in Fig. 3 (black dashed line). The fit with the Hecht function matches the experimental data and yields $\tau_{tr_h} \approx 350$ ns. In toto, in the range of smaller tcol the fits for electrons and holes nicely match the experimental data, whereas at $t_{col} > 100$ ns coincidence is observed with large errors, although the trend in the change of the experimental Q_{col} values corresponds to the calculation.

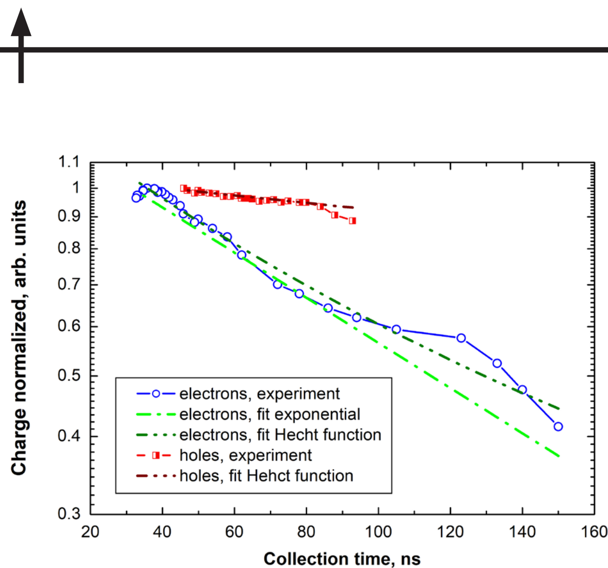

Fig. 3. Dependences of normalized collected charge of electrons and holes on collection time

Going back to estimated τ_{tr}, it should be emphasized that the determined values are 4–5 orders of magnitude smaller than the values of several milliseconds typical for pure high-resistivity silicon at room temperature. Such intensive trapping might be related to the high probability of shallow impurity levels of boron and phosphorus with an activation energy of about 46 meV to capture charge carriers at a temperature of tens of mK, since the time of carrier emission to the corresponding energy band drastically increases. The problem is to resolve the individual contribution of Ntr and □, which is hardly possible at the moment due to the lack of □(T) dependences at a temperature of a few K and below. This issue is the subject for further study.

Conclusion

1. The determined electron lifetimes were obtained using two methods of processing the experimental results: the current pulse kinetics and the dependence of the collected charge on the collection time. Therefore, the fact that the electron lifetime decreases by up to 5 orders of magnitude compared to room temperature has a high degree of reliability.
2. The decrease in the hole trapping time by 4 orders of magnitude confirms the trend of significant carrier lifetime drop, which requires physical understanding and additional study.
3. The measured trapping times should be taken into account when developing bolometric detectors with internal thermal gain.

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THE AUTHORS

ISAKOV Ivan D.
isakov-ivan.2016@yandex.ru

VERBITSKAYA Elena M.
elena.verbitskaya@mail.ioffe.ru
ORCID: 0000-0002-2313-1789

EREMIN Vladimir K.
vladimir.eremin@mail.ioffe.ru

FADEEVA Nadezda N.
fadeevanadezda@gmail.com
ORCID: 0000-0002-1282-4619

EREMIN Igor V.
Igor.Pti@mail.ioffe.ru

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