of the sample and the thermostat is such that the new distributions $T^{(1)},^{(2)}(z)$ transform into one another on increase in $|\lambda a|$ ($\lambda a < 0$) and they do not transform to $T^{(3)}(z)$ representing the formation of a "drop" in the current-voltage characteristics (curve 3 in Fig. 2). Finally, if $T^{(3)}(z)$, then for any current the profile ensures sufficient heat transfer and there is no instability (curve 4 in Fig. 2).

4. It is important to point out that the transport coefficients found experimentally may depend on T and this makes it much more difficult to obtain analytic criteria of the type given by Eq. (6). However, the possibility of control of the parameters $\eta$ and s by a special surface treatment or by the field effect[8,9] should lead to an experimental detection of an instability. Moreover, experimental studies of an instability of electrons can provide information on nonlinear thermal properties of the surface. For example, in the case of Si with a carrier density $n \sim 10^{14}$-$10^{15}$ cm$^{-3}$ when $|\mu|/T_0 \sim 10$ it is found that in the range of characteristic currents $|\lambda a| \sim 1 (\lambda a > 0)$ the necessary conditions of Eq. (6) reduce to the inequalities $s > 2$ and $\eta a/\kappa > 1 (1-2/s)^{2-s}$. The first of them is the requirement in respect of the surface treatment. The second inequality is satisfied by thin Si films [$a \sim 10^{-2}$-$10^{-3}$ cm, $\eta/n \sim 6 \cdot 10^6$ cm/s (Ref. 8), and $T_0 \lesssim 77$ K] by a large margin. It should be noted that, because of the dependence of $\kappa$ on the magnetic field, the quantity $\eta a/\kappa$ [i.e., H in Eqs. (6)-(8)] can be changed in experiments in a contactless manner by applying a longitudinal (along j) magnetic field.

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# Estimate of the lifetimes of nonequilibrium carriers in a semiconductor irradiated with heavy ions

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An important task in modern picosecond optoelectronics is a major reduction in the lifetime of carriers in semiconductor materials without a change in its main optical properties. This have been achieved[1] by introducing into the matrix of an original crystal a number of local regions with a high rate of capture of nonequilibrium carriers, but these regions occupy only a small proportion of the volume of the whole crystal. Such regions can be created by irradiation with heavy ions.[1,2] It is assumed that such irradiation creates filaments of an amorphized material along the slowing-down tracks; the transverse size of such filaments amounts to several lattice constants and the average distance between the filaments is governed by the radiation dose.

Measurements of the nonequilibrium carrier lifetime in GaAs irradiated with oxygen ions are reported in Ref. 2 and it is shown that, after doses of $\phi > 10^{11}$ ions/cm$^2$, the lifetime $\tau$ decreases to values of the order of $10^{-12}$ s without a significant change in the optical properties of this compound.

Simple approximate expressions will be obtained below for the lifetime in a semiconductor containing filaments characterized by a high rate of capture of nonequilibrium carriers. We shall assume that these filaments are cylinders of radius a and height h, and that the average distance between them is $l = \sqrt{\phi^{-1}}$, where $\phi$ is the radiation dose. Under the experimental conditions of Refs. 1 and 2 the inequalities $a \ll l \ll h$ and $a \ll L$ are satisfied, where L is the mean free path of nonequilibrium carriers in a crystalline substance.

According to Ref. 3, the density of a particle flux flowing through a body of size $a \ll L$ is independent of the shape of the body and equal to

$$j = n_0 v/4. \qquad (1)$$

Here, $n_0$ is the concentration of particles far

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from a body and $\bar{v}$ is the average absolute velocity of the particles for which a uniform distribution of the velocity directions is assumed. In the case of a Maxwellian distribution of particles of mass m and temperature T, we have

$$\bar{v} = 4\,(kT/2\pi m)^{1/2}. \tag{2}$$

In considering determination of the nonequilibrium carrier lifetime we shall assume steady-state generation (for example, optical generation 0 of carriers in the intervals between the filaments at a constant rate G such that $\tau = \langle n\rangle/G$, where $\langle n\rangle$ is the average density of carriers in the investigated material and if $a \ll L$, then $\langle n\rangle \approx n_0$.

Assuming that all the particles reaching the surface of the cylinder are caputred by the cylinder and ignoring the recombination in the bulk of the material, we shall assume that the flux of particles reaching one cylinder is equal to the number of particles generated per unit time in the volume occupied by this cylinder:

$$\frac{n_0\bar{v}}{4}\,2\pi ah = Gl^2h,$$

so that

$$\tau = 2l^2/\pi a\bar{v}. \tag{3}$$

In order to allow for the finite rate of capture by such a cylinder, we shall introduce the average reflection coefficient R of particles incident on the cylinder surface.

After allowance for such reflection, we obtain

$$\tau = 2l^2/\pi\bar{v}\,(1-R). \tag{4}$$

We can relate the value of R to another phenomenological parameter which is the surface recombination velocity S:

$$\frac{n_0\bar{v}}{4}(1-R) = \frac{n_0(1-R)}{2}S. \tag{5}$$

Then,

$$\tau = \frac{1}{\pi}\frac{l^2}{a\bar{v}} + \frac{1}{2\pi}\frac{l^2}{aS}. \tag{6}$$

It should be noted that it follows from Eq. (5) that the largest possible value of S (corresponding to R = 0) is $S_{max} = \bar{v}/2$, in good agreement with the results obtained in Ref. 4 by a rigorous microscopic analysis.

Equation (6) is obtained on the assumption that the filaments are not charged. However, since $\bar{v}_e > \bar{v}_h$, in reality they become charged to a certain (negative) potential U.

We shall assume that R = 0 applies to both types of carrier. According to Ref. 3, a generalization of Eq. (1) for the electron flux density reaching a repulsive center yields

$$j_e = \frac{n_0\bar{v}_e}{4}\exp\left(-\frac{eU}{kT}\right). \tag{7}$$

The density of the hole flux is correspondingly

$$j_h = \frac{n_0\bar{v}_h}{4}\exp\left(\frac{eU}{kT}\right)\left(1-\frac{4}{\sqrt{\pi}}\int_0^{\sqrt{eU/kT}} t^2\exp(-t^2)\,dt\right). \tag{8}$$

The value of U is found by equating the electron and hole fluxes reaching the cylinder. We then obtain

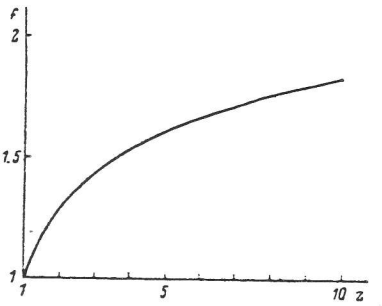

FIG. 1. Functional dependence f(z) used in Eqs. (9) and (10).

$$j_e = j_h = \frac{n_0\bar{v}_h}{4}f\left(\frac{\bar{v}_e}{\bar{v}_h}\right). \tag{9}$$

Here,

$$f(z) = \exp[x_0(z)]\left(1-\frac{4}{\sqrt{\pi}}\int_0^{\sqrt{x_0(z)}} t^2\exp(-t^2)\,dt\right),$$

where $x_0(z)$ is a root of the equation

$$\exp(2x)\left(1-\frac{4}{\sqrt{\pi}}\int_0^{\sqrt{x}} t^2\exp(-t^2)\,dt\right) = z.$$

A graph of the function f(z) is plotted in Fig. 1.

It follows from the above discussion that the lower limit to the lifetime under conditions of escape of particles to filaments is

$$\tau = \frac{2}{\pi a\bar{v}_h f(\bar{v}_e/\bar{v}_h)}. \tag{10}$$

In the case of GaAs, we have $\bar{v}_e/\bar{v}_h = \sqrt{m_h/m_e} = 2.5$ and $f(2.5) \approx 1.4$, i.e., $\tau \approx 3\cdot 10^{-12}\cdot(300\ \mathrm{K}/T)^{1/2}(10^{-7}\ \mathrm{cm/a})(10^{11}\ \mathrm{cm^2}/\phi)$ s.

The above treatment is based on the assumption that nonequilibrium carriers behave as classical particles. An allowance for the quantum properties within the framework for the quantum properties within the framework of the two-dimensional analogy of the nonresonance model of nuclear reactions [5] has the effect that the radius of the cylinder capturing the particles should be regarded as equal to a + λ*, where $\lambda^* = \lambda/2\pi$, and λ is the de Broglie wavelength of carriers; this reduces further the calculated lifetime. However, since for the values of T and φ considered here the flux reaching this cylinder is mainly due to carriers characterized by $\lambda^* \lesssim a$, this reduction is not very large. The expression obtained gives the lifetime which is of the same order of magnitude and which depends in the same way on T and φ as the experimental results reported in Ref. 2. The calculated lifetimes are somewhat less than the experimental values and this is primarily due to the reflection of carriers from filaments.

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# Change in the lithium concentration gradient in the course of compensation of semiconductors by the ion drift method

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The dynamics of establishment of the concentration of drifting lithium ions in an electric field was considered theoretically in Ref. 1. The present paper deals with the change in the lithium concentration gradient during the compensation process. We shall show that in the vicinity of a p-n junction the gradient should decrease exponentially with time. We shall give the results of an experimental check of this prediction and discuss its practical consequences.

1. According to Ref. 1, the dynamics of the change in the concentration $N_{Li}(t)$ in a drifting lithium layer is independent of the translational motion in the field and can be described by

$$N_{Li}(t) = \frac{N_A}{1 + [N_A/N_{Li}(0) - 1]\exp(-t/\tau)}, \quad (1)$$

where $N_A$ is the concentration of acceptors in the original material; $N_{Li}(0)$ is the concentration of lithium at an arbitrarily initial moment; $\tau = \varepsilon\varepsilon_0/e\mu N_A$; $\varepsilon$ and $\varepsilon_0$ are the permittivities of the material and of vacuum; e is the electron charge; $\mu$ is the ion mobility. Equation (1) does not include a coordinate dependence because it applies to the case when the "observer" moves together with the layer.

We shall now obtain an expression for the change in the lithium gradient in the region where p-n conversion takes place. We shall do this by assuming that the origin $\xi = 0$ of the selected coordinate system is at the drifting boundary of the p-n junction (inset in Fig. 1) and we shall select such a region of $\xi$ which will allow us to assume that the distribution of lithium is linear: $N_A - N_{Li}(\xi, 0) = a(0)\xi$. Then, if $a(0)\xi/N_{Li}(\xi, 0) \ll 1$, we find that Eq. (1) yields

$$N_{Li}(\xi, t) = N_A\left[1 - \frac{a\xi}{N_{Li}(\xi, 0)}\exp\left(-\frac{t}{\tau}\right)\right]. \quad (2)$$

To within terms linear within $\xi$, we find that Eq. (2) gives $N_A - N_{Li}(\xi, t) = a(t)\xi$, where

$$a(t) = a(0)\exp(-t/\tau). \quad (3)$$

The final expressions describes the dynamics of the change in the concentration gradient observed in the p-n junction plane.

2. We checked experimentally Eq. (3) by a study of the drift of lithium from a layer established by diffusion, which was deposited on silicon

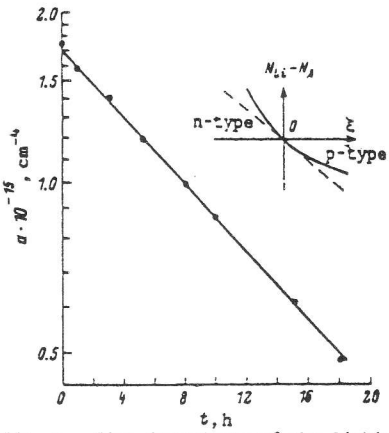


FIG. 1. Time dependence of the lithium concentration gradient in the region of a drifting p-n junction. The inset shows the selection of the origin of the coordinate axis $\xi$ moving together with the p-n junction.

characterized by $N_A = 2.8\cdot10^{12}$ cm$^{-3}$ at 89°C when the bias voltage was 200 V. The cross sectional area of the sample was S = 1.11 cm$^2$. The capacitance-voltage characteristics of the p-n junction being formed were determined during the drift process. The capacitance C was measured at a frequency of 1 kHz using an E8-2 capacitance bridge. A sample was first cooled to room temperature. The concentration gradient was determined from the capacitance measurements using the dependence of $1/C^3$ on V and the expression[2]

$$a = \frac{12}{e(\varepsilon\varepsilon_0)^2 S^3}\left(\frac{d(1/C^3)}{dV}\right)^{-1}. \quad (4)$$

The slope $d(1/C^3)/dV$ and the error in its value were calculated by the least-squares method[3] for the range of voltages corresponding to the linear part of the dependence.

The behavior of a(t) is plotted in Fig. 1 on a semilogarithmic scale. We can see that a(t) decays exponentially. The characteristic time constant is $\tau = 14.2 \pm 0.2$ h. It should be noted that the experiment confirms the predictions of the theory of Ref. 1 not only qualitatively but even quantitatively. In fact, the value of the mobility of $Li^+$ ions determined after a time $\tau$ was $\mu = \varepsilon\varepsilon_0/e\tau N_A = 0.46\cdot10^{-10}$ cm$^2\cdot$V$^{-1}\cdot$s$^{-1}$, in good agreement with the published data.

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