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Abstract

Full Text

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PHOTOCONDUCTIVITY AT LARGE LIGHT FLUXES AND THE EFFECTIVE CROSS SECTION OF BIMOLECULAR RECOMBINATION IN SILICON*

PHYSICS

1. Along with simple trap recombination according to the Shockley—Read scheme, theory considers recombination processes of higher order in semiconductors—bimolecular (radiative interband recombination of an electron and a hole; impact recombination at traps) and trimolecular (impact interband recombination) processes ($^{1-3}$). In the simplest case of uniform steady-state excitation ($n \simeq p \gg n_0 + p_0$)

$$\beta k I = n/\tau + A_1 n^2 + A_0 n^3. \quad (1)$$

It follows from purely kinetic considerations that recombination processes of higher orders can manifest themselves only at high generation levels. From the physical point of view, the optimal method for investigating purely concentration dependences is photogeneration, since in this case the distortions introduced by the formation of a p—n junction and the field effects inevitably arising under strong injection are absent. However, as far as we know, until now there have been almost no experimental works on the study of photoconductivity over a wide range of light-intensity values up to such large values that simple trap recombination ceases to play the dominant role. Only for tellurium at 100° K did Moss (^{4}), Ridfield (^{5}), and Loferski (^{6}) observe, apparently, a transition from linear to quadratic recombination. Ridfield associates this result with interband transitions and explains it by the small forbidden-band width of tellurium (0.34 eV). However, according to Moss' s estimates (^{7}), the radiative lifetime in tellurium at 100° K is of the order of 1 sec, whereas the experimentally determined lifetime was of the order of 50 sec. Consequently, the fraction of interband radiative recombination in these experiments is very small. Ridfield did not succeed in experimentally detecting recombination radiation.

Experiments on the study of photoconductivity at high light intensities were also carried out on germanium (^{8}). However, the results indicate simple trap recombination for all experimentally realized values of I, corresponding to $\Delta n/(n_0 + p_0) \leqslant 100$.

In the present work, the photoconductivity of silicon has been investigated over a wide range of light-intensity values, up to

$$\Delta\sigma/\sigma_0 \sim 10^3.$$

2. According to the Shockley—Read theory (^{9}), the dependence of the photoconductivity $\Delta\sigma$ on the light intensity I in the case of simple trap recombination has the form

$$\frac{\Delta\sigma}{\sigma_0} = \frac{n_0+p_0}{bn_0+p_0}\frac{b+1}{2}\left[\sqrt{\left(\frac{\Delta\sigma_2}{(b+1)\sigma_0}\frac{bn_0+p_0}{n_0+p_0}\frac{I}{I_2}-1\right)^2+\lambda_1\frac{4}{b+1}\frac{\Delta\sigma_2}{\sigma_0}\frac{bn_0+p_0}{n_0+p_0}\frac{I}{I_2}}+\frac{\Delta\sigma_2}{(b+1)\sigma_0}\frac{bn_0+p_0}{n_0+p_0}\frac{I}{I_2}-1\right. \qquad (2)$$

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At such generation levels, when the lifetime determined by simple trap recombination turns into τ_∞ according to Shockley—Read, while trimolecular processes have not yet manifested themselves, from (1) we obtain

$$\frac{\Delta\sigma}{\sigma_0} = \frac{b+1}{2\lambda_2}\left[\sqrt{1+4\lambda_2\frac{\Delta\sigma_2}{(b+1)\sigma_0}\frac{I}{I_2}}-1\right]. \qquad (3)$$

Formulas (2) and (3) constitute a piecewise representation of the family of curves $\Delta\sigma(I)$, depending on two parameters

$$\lambda_1 = \tau_0/\tau_\infty, \qquad \lambda_2 = A_1\tau_\infty(p_0+bn_0), \qquad (4)$$

valid at such light intensities as long as impact interband recombination remains insignificant. The introduction of certain fixed values I_2 and $\Delta\sigma_2 = q\mu(b+1)\Delta n_2 = q\mu(b+1)\beta k\tau_\infty I_2$, corresponding to the second linear region ($\tau = \tau_\infty$) according to Shockley—Read, makes it possible to avoid the need for absolute measurements of I, β, k, τ. Without dwelling on the general study, which will be carried out separately, let us consider the case when: 1) $\tau_0 < \tau_\infty$ and 2) the trap τ turns into τ_∞ earlier (at smaller I) than substantial quadratic recombination sets in. One of the theoretical curves of this type is shown by the solid line in Fig. 1. The straight-line segment CD belongs to both parts of the curve $\Delta\sigma(I)$, and the continuation of formulas (2) (section $ABCD$) and (3) (section $CDEF$) into the region where they cease to be valid is shown by dashed lines.

Fig. 1: plot of $\lg\Delta\sigma/\sigma_0$ versus $\lg I/I_2$, with experimental points and theoretical curve.

Fig. 1

Comparison with experiment can be carried out as follows. Fixing I_2 and $\Delta\sigma_2$, we choose the origin and the scale along the I axis (the scale along the $\Delta\sigma$ axis is set by the value σ_0).

The criterion for agreement between theory and the experimental conditions is the possibility of choosing such parameters λ_1 and λ_2 that the experimental points fall on the theoretical curve $ABCDEF$ over its entire length. An even stricter check can be made by measuring three values of the lifetime τ_0, τ_∞, and τ_b (the bimolecular τ) in the regions AB, CD, and EF, since in this case no free parameters remain in the theory.

3. The experiment (Fig. 2a) was carried out on p-type silicon ($\rho \approx 1000 \div 3000\ \Omega\cdot\text{cm}$, $\tau \sim 50\ \mu\text{sec}$, $l \sim 0.5$ mm). Light pulses (~ 2 msec), produced by a 400-watt incandescent lamp S with a concentrated filament, a condenser K, and a disk chopper D, generated photoconductivity in the Si samples under study, to which a voltage was applied from the audio generator ZG and the bias battery B. The current-voltage characteristics were observed directly on the oscilloscope screen (Fig. 2b), with the photoconductivity measured from the slope of the characteristic in its linear part. Differential probing by a small signal (Fig. 2c) ensured verification of the linearity of the current-voltage characteristic and the accuracy of measurement of $\Delta\sigma$. In this way it was possible to exclude the influence of contact nonlinearity without resorting to probe measurements, which are inconvenient under pulsed excitation. Heat removal by means of a massive copper washer ensured that the sample remained at room temperature. The dark conductivity and photoconductivity at low light intensities, when there was no need for pulsed excitation, were measured by the probe method under direct current.

Experimental data for one of the samples ($\rho = 2800\ \Omega\cdot\text{cm}$, $\tau = 50\ \mu\text{s}$) are given in Fig. 1. Agreement with the theoretical curve is achieved for the parameter values

$$\lambda_1 \equiv \tau_0/\tau_\infty = 0.25, \qquad \lambda_2 \equiv A_1\tau_\infty p_0 = 0.009. \tag{5}$$

The maximum concentrations of nonequilibrium carriers n were 10^{15} cm^{-3}. At larger n, one must take into account the change in mobilities with increasing concentration (^{10}, ^{11}).

Fig. 2

Fig. 2

From the condition $n_{\text{cr}}/\tau_\infty = A_1 n_{\text{cr}}^2$, we find that the critical concentration value corresponding to equality of the rates of mono- and bimolecular recombination is

$$n_{\text{cr}}/p_0 = 1/\lambda_2 \approx 100. \tag{6}$$

Knowing that the lifetime in the samples investigated is $\tau_0 \approx 5 \cdot 10^{-5}$ s, we find the coefficient and effective cross section of bimolecular recombination in silicon at room temperature:

$$A_1 = \lambda_1 \lambda_2 / (p_0 \tau_0) = 1.15 \cdot 10^{11}\ \text{cm}^3\,\text{s}^{-1},$$
$$S = A_1/u \sim 10^{-18}\ \text{cm}^2. \qquad (7)$$

4. Both bimolecular processes—radiative interband recombination and impact recombination at traps—proceed in parallel, and therefore the larger of the two corresponding effective cross sections is determined experimentally. For silicon, a theoretical estimate of interband radiative recombination according to the Roosbroeck-Shockley theory ($S = R/(n_i^2 u)$ (^{12})) was made by Burstein and Egli (^{13}) and by Hall (^{14}). The experimental values obtained by us agree well with the data of Burstein and Egli, but differ substantially from Hall' s results.

We attempted an experimental observation of recombination radiation in the silicon samples studied. The experiment was carried out in the Semiconductor Physics Laboratory of the P. N. Lebedev Physical Institute of the Academy of Sciences of the USSR, using the method described in the paper by V. S. Vavilov, E. L. Nolle, V. D. Egorov, and S. I. Vintovkin (^{15}). Excitation was produced by a pulsed electron beam with an energy of 110 kV. The current density in the pulse was of the order of 0.5 A/cm^2. At room temperature we observed radiation whose spectrum had a single maximum at 1.09 eV and a half-width of 0.078 eV, which corresponds to radiative interband recombination in silicon. The slit width corresponded to a spectral resolution of 0.014 eV. Although, unlike the work on tellurium (^{5}), where the experimental detection of quadratic recombination was not accompanied by observation of recombination radiation, in our experiments on silicon such radiation was observed···

it turned out that the question of the dominant bimolecular process can be resolved only by determining the quantum yield of the radiation.

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