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Relaxation process features of photoconductivity in p-i-n structures

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Abstract. We studied the relaxation processes of photoconductivity in Si(Li) *p-i-n* structures. It has been shown that a clearly pronounced "well" is observed in time dependences of the photovoltage pulse after photoexcitation of these structures. Our experimental data are indicative of abnormal relaxation of photoconductivity in silicon *p-i-n* diodes.

Keywords: photoconductivity, relaxation, well.

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1. Introduction

It is known that the most striking example of the inhomogeneous field created by a movable space charge in the semiconductor is the space charge region in *p-n*, *p-i-n* structures of a large size. Studied in [1, 2] was topography of the photo-emf signal associated with the heterogeneity of the electric field in the space charge region in germanium radiation detectors. Silicon *p-i-n* radiation detectors were studied using the topography of the amplitude spectrum by scanning with a collimated beam of alpha particles [3]. It is important that these studies enabled to reveal significant inhomogeneous distribution of impurities in certain local areas. Study of physical processes in these areas could find unknown physical processes as a base for new fundamental functional principles. Consequently, in semiconductor physics, they can cause a wide interest both of theoreticians and experimentalists [4, 5].

2. Experimental

In this paper, we consider the relaxation processes for charge carriers in the space charge region inherent to Si (Li) *p-i-n* structures. These structures were fabricated by us on the base of wafers made of a *p*-type silicon single crystal with the diameter 50 mm and thickness 2.5 mm, as well as initial parameters: resistivity $\rho = 5000$ Ohm·cm, carrier lifetime $\tau = 300$ µs. After certain chemical-and-technological operations, lithium diffusion was made on one of plate sides in vacuum at $T = 450$ °C down to the depths 320 to 350 µm. Then, to compensate the whole thickness of the plate, the drift of lithium ions was performed over the entire thickness of it. The drift was carried out in two stages: at $T = 80$-100 °C and reverse bias voltage 80 to 120 V and with increasing the latter up to approximately 300 V at the same temperatures. The end of the drift was fixed by a sharp increase in reverse current through the structure [6, 7]. The plates prepared using the above-mentioned method were used to measure photoconductivity in their various parts by probing all over the surface. When measuring the photoconductivity, we used LED AL-402 ($\lambda = 0.69$ µm) with a radiated power close to 5 mW. Features of the sample photoconductivity were studied using the relaxation curves both for the rise and decay of the photovoltage pulse [8].

3. Results and discussion

In separate parts of the investigated samples, the photoconductivity relaxation curves for the decaying photovoltage had a clearly pronounced "well". Fig. 1 shows a typical oscillogram for this type of photoconductivity relaxation. The time is scaled as 1 ms/10 mm and directed along the abscissa, while the ordinate corresponds to the voltage scaled as 0.05 V/10 mm.

After reaching the maximum photovoltage value 0.3 V, its drop occurs within 1.025 ms, the relaxation curve being of a usual form. Then, in 2.1 ms one can observe the following sharp drop, and the photovoltage reaches its minimum value equal to 0.05 V. At the beginning of this drop, the photovoltage value was

0.12 V. Thus, the slope of the relaxation curve in the interval 1.025-2.1 ms is –0.065 V/ms, while at the beginning of the recession in the interval 0-1.025 ms the slope of the curve was –0.175 V/ms. Consequently, the slope of the second drop is approximately 3 times less than that in the first recession. Between the first and second drops, in the time moment 0.425 ms the relaxation curve has a minimum slope and can be considered as nearly parallel to the abscissa.

In 2.1 ms after photoexcitation, the photovoltage is set at the level 0.05 V. In this point of oscillogram, the drop is changed by its growth, i.e., the slope of the curves changes its sign here. Then, in the interval 2.1 to 2.6 ms the photovoltage increases from 0.05 V up to 0.075 V, hence, the slope of the curves reaches 0.05 V/ms. Then again, a slow drop with a slope – 0.006 V/ms takes place. Thus, the relation curve demonstrates three specific turning points, with one of them where the drop is changed by a growth [3].

It is known that in presence of trapping levels in silicon, the photovoltage pulse value is decreased monotonically during these relaxation processes [9]. Studied in [10] is the influence of the saturation effect for the electron velocity on switching the n^+-p-p^+ structure in the quasi-neutral drift mode. It is noted that the effect of velocity saturation significantly slows down the passage of the Dean wave [11] of electrons through the base of n^+-p-p^+ structure, which causes the sharp drop. Proposed in [11] mechanism is rather suitable to explain the appearance of the well in the recession, if we assume that the band gap of silicon clusters contains deep recombination centers [12]. Then, the relaxation time has two components [6]

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \frac{1}{\tau_1}. \qquad (1)$$

Here, τ_0 is the relaxation time inherent to p-type semiconductor in the absence of deep recombination centers; τ_1 – relaxation time when only these centers are present. Then drop in voltage over time is determined by the formula

$$U = U_{st}\, e^{-\left(\frac{1}{\tau_0}+\frac{1}{\tau_1}\right)t}. \qquad (2)$$

Using the experimental results, we determine the time dependence. First of all, let us analyze the function U at the points of extremum, where the first derivative of U with regard to t is equal to zero. In these points, we have

$$\left(\frac{d\tau_1}{dt}\right)_{t_i} = \frac{\tau_1}{t_i}\left(\frac{\tau_1}{\tau_0} + 1\right). \qquad (3)$$

Here, t_i is the value of t when one observes a minimum of U. The experiment shows that the functional dependence of U on time t has a three-point extremal value. This means that the empirical formula U is a curve of the third power. The equation (3) determines the conditions where the function U has zero derivative. Analyzing the various options for empirical formulas describing the dependence of U on time t, we have drawn the conclusion that the following formula is rather convenient for calculations

$$-\ln\left(\frac{U}{U_{st}}\right) = y_1 + k_2\left(\frac{t-t_k}{t_k}\right)^2 + k_3\left(\frac{t-t_k}{t_k}\right)^3. \qquad (4)$$

Here, k_2 and k_3 depend on the parameters of the function U at the points of extremum:

$$k_2 = y_0 - y_1 + k_3;\quad k_3 = \frac{y_2 - y_1}{a^2(a+1)} - \frac{y_0 - y_1}{(a+1)};$$

$$a = \frac{t_2 - t_k}{t_k};\quad y = \ln\left(\frac{U}{U_{st}}\right).$$

Then $y_0 = 0$, as in the beginning of recession $U = U_{st}$. We designate $y_1 = \ln\left(\frac{U}{U_{st}}\right)$ at $t = t_k$, there t_k corresponds to a voltage minimum and t_2 to maximum t. The initial time is determined in a point of recession, therefore $t_1 = 0$. At $t = t_2$, one can obtain that k_2 and k_3 are defined by the formulas

$$k_2 = \frac{t_k^3 y_2}{t_2(t_2 - t_k)^2} - \frac{t_k + t_2}{t_2} y_1,$$

$$k_3 = \frac{t_k^3}{t_2(t_2 - t_k)^2} y_2 - \frac{t_k}{t_2} y_1. \qquad (5)$$

As

$$-\ln\left(\frac{U}{U_{st}}\right) = t\left(\frac{1}{\tau_0} + \frac{1}{\tau_1}\right), \qquad (6)$$

it follows from (4) that

$$t\left(\frac{1}{\tau_0} + \frac{1}{\tau_1}\right) = y_1 + k_2\left(\frac{t-t_k}{t_k}\right)^2 + k_3\left(\frac{t-t_k}{t_k}\right)^3. \qquad (7)$$

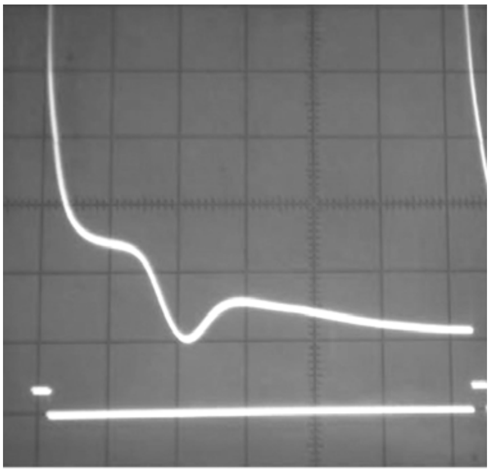

Fig. 1. A relaxation of photoconductivity of p-i-n structures, $y = 0.05$ V/10 mm, $x = 1$ ms/10 mm.

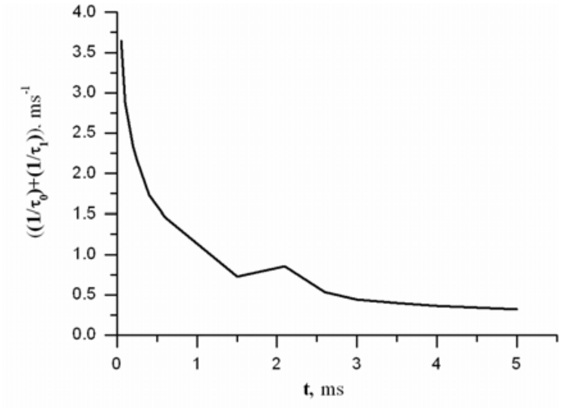

Fig. 2. Graphic dependence of time of a relaxation.

The graphic plot of τ_1 versus time is shown in Fig. 2.

As seen, in the process of approach to the abscissa the pulse photovoltage value takes its minimum, time of relaxation starts to decrease, when the speed of reduction in τ_1 value with time up to the certain value determined using the formula (3) reaches its minimal value. Here, τ_1 begins to increase up to a certain maximum, after that one can observe a quasi-stationary value of the relaxation time. As it was noted above, the account of trapping levels does not give extreme points in the range of recession in the pulse photovoltage value [9]. More exact calculation of dynamic characteristics n^+-p-p^+ structures, by means of Dean waves for electrons gives monotonic recession of a photovoltage on time, too [10]. However, to ascertain the specific nature of defects causing this non-monotonic drop in conductivity inherent to *p-i-n* diodes, additional investigations are necessary.

4. Conclusions

Thus, our experimental data are indicative of abnormal relaxation of photoconductivity in silicon *p-i-n* diodes.

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