PHYSICS

Academician of the Academy of Sciences of the Uzbek SSR É. I. ADIROVICH, P. I. KNIGIN, Yu. S. KOROLEV

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Fig. 1

Figure 1: Fig. 1

Abstract

Full Text

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A NEW HYSTERESIS EFFECT

IN SILICON p-n JUNCTIONS

1. In studying the behavior of silicon photodiodes in the steady-state regime at sufficiently large reverse voltages, we discovered a hysteresis effect which, as far as we know, had not previously been observed in p-n junctions. Starting from a certain value of the current (point a in Fig. 1), the current-voltage characteristic (CVC) $V(I)$, taken point by point by stabilizing it with a sufficiently large load resistance, follows different paths depending on the sequence in which the current is varied.

Fig. 1

The first branch of the CVC, oab, can be traversed many times upward and downward, provided that the critical point b is not reached. When this point is reached, a jump occurs to the second branch dca, and under no load can the transition $b \to c$ be stabilized. When the external resistance is increased, point c shifts downward in accordance with the change in the slope of the load curve bc, and in the generator-current regime it is found at position c'. However, even in this regime the transition $b \to c'$ occurs abruptly. The second branch of the CVC, dca, can likewise be traversed many times upward and downward, provided that the second critical point a is not reached. When this point is reached, further changes in current and voltage again occur along the first branch of the CVC, and so on.

Below we describe the experiment, present the results obtained in studying the breakdown of silicon p-n junctions in the dark and under illumination, and also set forth theoretical considerations concerning the nature of the effect discovered.

2. The studies were carried out on diffusion silicon photodiodes with a p-type base. The junctions were obtained by the usual method employed in fabricating silicon photocells for solar batteries. The samples investigated were analogous to those described in paper (^{1}).

Fig. 2 and Fig. 3

Figure 2: Fig. 2 and Fig. 3

A voltage $\mathcal{E}$ of up to 250 V was supplied from a rectifier with a small ripple factor to a series circuit consisting of the photodiode and a load resistance $R = 5 \div 200$ ohms. The values of the currents and voltages were measured with high-accuracy pointer instruments (M-104 and M-106). Both dark and illuminated characteristics of the photodiodes were obtained. Illumination was provided by a 400-W incandescent lamp with a concentrated filament. The light beam could be focused on the sample by means of a condenser. To maintain constancy of the ambient temperature, the sample was soldered to a copper holder through which water was passed. The temperature of the holder T_0 was monitored with a thermocouple.

The experimental CVCs for one of the photodiodes investigated are shown in Fig. 2. All of them were taken at an ambient temperature $T_0 = 25°$. Comparison with Fig. 1 shows that both the dark characteristic (curve 1) and the illuminated characteristics (curves 2, 3) exhibit hysteresis of the type described above.

Figure 3 gives experimental curves taken on the same sample under changed experimental conditions in order to determine the physical nature of the hysteresis. The static dark current-voltage characteristic 1 was obtained at a higher ambient temperature ($T_0 = 75°$). Curve 2 shows the static light current-voltage characteristic, also taken at $T_0 = 75°$. Plot 3 in Fig. 3 is a dynamic characteristic when a sawtooth voltage with a pulse duration of 10^{-4} sec is applied. The ambient temperature corresponding to this curve is 25°, i.e., the same as for the characteristics shown in Fig. 2. As can be seen from Fig. 3, hysteresis is absent on the current-voltage characteristics taken under changed experimental conditions.

Fig. 2 **Fig. 3**

3. The shift of the state of electrical breakdown into the region of lower voltages, which occurs when T_0 is increased, and the non-Ohmic character of the dynamic characteristic show that the current-voltage characteristics shown in Fig. 2 are caused by some interaction of thermal and electrical processes developing in p-n junctions in strong electric fields. These hysteretic current-voltage characteristics, however, cannot be explained by the mechanism of thermoelectric breakdown (^{2}). In thermoelectric breakdown the current is a multiplicative function formed from thermal and field parts: $I = Ae^{-B/T} \cdot f(V)$. Noting that the multiplication coefficient $f(V)$ is a nondecreasing function of V, we shall show that, owing to the multiplicative character of I, the voltage in thermoelectric breakdown cannot be a two-valued function of the current.

Let V be a two-valued function of I, as is observed in hysteresis (Fig. 2).

Fig. 4

Figure 3: Fig. 4

Consider two points with the same value of I, for example α and β in the schematic Fig. 1. Since $V_\alpha > V_\beta$, and $I = f(V)Ae^{-B/T}$, it must be that $T_\alpha \leq T_\beta$. But from the heat-balance equation

$$\chi(T - T_0) = VI \tag{1}$$

it follows that T_α must be greater than T_β. Consequently, two-valuedness of V in thermoelectric breakdown is impossible, since it requires the fulfillment of two mutually exclusive conditions.

The results we have obtained can be explained if it is assumed that: 1) breakdown develops not over the whole cross section of the p–n junction, but in some "weak" region located at the place where the p–n junction emerges at the surface; 2) breakdown and the prebreakdown regime of the "weak" region are thermal in character and occur at such voltages that, in the remaining part of the p–n junction, appreciable electrical multiplication of charges already arises; 3) heat removal from the "weak" region to the surroundings occurs faster than heat exchange with the rest of the diode.

A direct confirmation of breakdown at a "weak" spot is provided by the fact that, in the hysteresis region of the current-voltage characteristic, as a rule, it was possible visually to detect a microscopic luminous region-

current arising, apparently, at the point where the p–n junction emerges at the surface. If the development of breakdown was not limited by a sufficiently large load resistance, irreversible destruction occurred in this region.

With such a mechanism of breakdown and of the prebreakdown regime, the current is formed additively from the current $I_1 = Ae^{-B/T}$ through the "weak" region and the current I_2 through the rest of the p–n junction. If internal heat exchange prevailed over heat transfer to the external medium, both current components would make a common contribution to the heating of the sample, and, as a result of the increase in the number of thermally generated primary charge carriers that form the avalanche in the main part of the p–n junction, one would have $I_2 = f(V)A'e^{-B'/T}$. But in that case the current I would again turn out to be a multiplicative function of thermal and field factors, which, as shown above, does not correspond to the experimental facts.

Fig. 4

When heat transfer outward predominates over internal heat exchange, the current regimes in the "weak" region and in the rest of the p–n junction are, to a first approximation, independent. In this case the current I is composed of the purely thermal current I_1 through the "weak" region, determined only by its own Joule heat,

$$I_1 = Ae^{-B/T}, \qquad \varkappa(T - T_0) = VI_1, \tag{2}$$

and of the field current $I_2(V)$ through the rest of the p-n junction. Since thermal breakdown occurs before electrical breakdown, the current $I_2(V)$ can be approximated by the expression

$$I_2 = \begin{cases} 0 & \text{for } V \leqslant V_1, \\ \Gamma(V - V_1) & \text{for } V \geqslant V_1, \end{cases} \tag{3}$$

where Γ is a sufficiently large number.

Figure 4 shows the partial currents I_1, I_2, and the total current I, obtained by adding them. The theoretical current-voltage characteristic agrees well with experiment and has the required hysteresis.

The curves in Fig. 4 could have been constructed from formulas (2), (3) and $I = I_1 + I_2$. We proceeded, however, differently, modeling the proposed breakdown mechanism by means of an equivalent circuit consisting of a silicon diode with purely thermal breakdown (an analogue of the "weak" region) and a Zener diode (an analogue of the rest of the p-n junction). The diode and Zener diode, connected in parallel, were connected through a load R to a rectifier. Curve 1 was taken with the Zener diode disconnected; curve 2 with the diode disconnected; and curve 3 with current flowing through the entire modeling structure. By varying $\mathcal{E}$, we were able to produce in the model the same breaks and transitions from one section of the current-voltage characteristic to another as in the photodiodes investigated.

A comparison of the dark and light current-voltage characteristics (Fig. 2) also speaks in favor of the proposed mechanism. If there are no weak spots, or if internal heat exchange dominates over heat transfer, then the balance equation (1) is valid. But in that case the light characteristic could not intersect the dark one, since, owing to the equality of the temperatures at the intersection point, the total current on the light characteristic must be equal to the thermal current, which is impossible.

Further, if the prebreakdown thermal current and the photocurrent flow in the same places of the p—n junction, then the ratio of the ordinates of two light characteristics must increase with increasing V or, as long as the thermal currents are small compared with the photocurrents, remain constant. If, however, the photocurrent and the thermal current flow in parallel in different parts of the p—n junction, then the ratio of the ordinates must decrease with increasing V. This is precisely how the ratio of the currents changes for the two light characteristics in Fig. 2.

4. Electrical breakdown of the sample, determined by the condition $dI/dV = \infty$, occurs at the same V as breakdown of the electrically isolated weak section, since $I = I_1 + I_2$. The maximum of $I(V)$ is reached when $dI_1/dV = -dI_2/dV = -\Gamma$, and since Γ is large and the slope of the curve $I_1(V)$ decreases rapidly, the "loop" caused by the superposition of the avalanche current on the thermal current must be very narrow. Therefore the nonuniformity of the section *ab* (cf. Fig. 1 and Fig. 4) is not manifested in the experiment, especially since, on reaching point *b*, a jump occurs to the branch *dca* of the current-voltage characteristic. To reveal this nonuniformity, a special experiment was carried out, based on an analysis of the processes that cause, at point *a*, a transition from the branch *dca* to the branch *oab* when recording the experimental current-voltage characteristics.

According to the proposed mechanism, point a in fact denotes two close states a' and a'', differing slightly in temperature (cf. Figs. 2 and 4). Recording again the dark current-voltage characteristic (curve 1 in Fig. 2), we approached point a along the branch *ca*, still remaining in such a state that an increase of the input voltage $\mathcal{E} = V + IR$ was accompanied by traversal of the same branch in the reverse direction. Then we applied a cold pulse by briefly cooling the copper holder by $3 \div 5^\circ$. After this, an increase of $\mathcal{E}$ was accompanied instead by a change of the current along the segment *ab* of the current-voltage characteristic.

Then, bringing the sample again to point *a*, this time along the section *oa*, we applied a heat pulse by briefly heating the holder. Upon a further increase of $\mathcal{E}$, a transition to the branch *ac* occurred immediately, and the section *ab* did not appear on the current-voltage characteristic. Thus, experimental transfers of the system between the states a' and a'' were carried out.

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