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Fig. 1

Figure 1: Fig. 1

Abstract

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On the Question of the Photomagnetic Effect at a $(p-n)$-Junction

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In ([1]) some experimental data were presented concerning the appearance of a photomagnetic effect upon illumination of a $(p{-}n)$-junction placed in a magnetic field (Fig. 1).

Additional investigations have shown that the occurrence of an odd photomagnetic effect at a $(p-n)$-junction may be explained by the circumstance that the ordinary photomagnetic effect in the homogeneous n- and p-parts of a sample with a $(p-n)$-junction adds a certain number of current carriers entering the space-charge region of the $(p{-}n)$-junction. If, for example, a part of the n-region is illuminated (Fig. 1), at a distance from the $(p-n)$-junction much greater than the diffusion length, then under open-circuit conditions the presence of the $(p-n)$-junction should not affect the magnitude of the photomagnetic effect. The presence of the $(p-n)$-junction, like that of the p-region, leads only to the appearance of an additional resistance connected in series with the illuminated n-region.

Fig. 1

The situation is different when the illuminated part of the n-region is at a distance from the $(p-n)$-junction not exceeding the diffusion length L_p. In this case the holes constituting the hole component of the photomagnetic current, entering region II (see Fig. 1), diffuse from it into the space-charge region, and the component of the hole current of the photomagnetic effect in the homogeneous part of the sample enters the p-region. It should be expected that electron–hole pairs generated in region II will not affect the magnitude of the photo-emf at the $(p-n)$-junction, since even without a magnetic field they all reach the space-charge region. This is illustrated by the following experiment. The sample under investigation, with a $(p-n)$-junction in the middle, was illuminated through a narrow slit parallel to the plane separating the n- and p-regions. This slit could be moved along the sample (the x-axis). The

Fig. 2

Figure 2: Fig. 2

dependence of the potential difference at the ends of the sample on the position of the slit x was measured. This dependence is presented by the curve in Fig. 2. The minimum on the curve corresponds to the position of the slit directly above the $(p-n)$-junction; at this position the photo-emf itself passes through a maximum*. This means that when the formation of electron-hole–

Fig. 2

* In (1) this minimum was not observed because of its small width (less than 0.5 mm).

pairs occurs near the space-charge region, the influence of the magnetic field on the photo-emf is small.

In a rigorous treatment of the problem of the formation of the photomagnetic effect at a $(p-n)$-junction, one should find the electron and hole currents, having first solved the problem of the concentration distribution near the $(p-n)$-junction. But from the data presented it is clear that the concentration distribution in region II, immediately adjacent to the space charge, is immaterial for us. The hole component of the photomagnetic current in the n-region, up to distances equal to the diffusion length (but not less), can be calculated without taking into account region II, adjacent to the barrier layer.

These considerations make it possible, in calculating the photomagnetic effect at a $(p-n)$-junction, to use S. M. Ryvkin' s phenomenological theory of the photodiode. The formula for the current J through the photodiode, as is known (2), has the form

$$J = J_f - J_s \left(e^{qU/kT} - 1 \right), \tag{1}$$

where U is the potential difference arising upon illumination of the space-charge region; J_s is the dark saturation current of the photodiode; J_f is the number of electron-hole pairs separated per unit time at the $(p-n)$-junction. $J_f = J_f^+ + J_f^-$, where J_f^+ and J_f^- are determined by the number of holes and, respectively, electrons generated at a distance of one diffusion length or less from the space-charge region. If the surface recombination velocity is not taken into account, then $J_f^+ = I_0 \beta q L_p L_1$, where I_0 is the number of quanta incident per unit surface area per unit time; β is the quantum yield; L_p is the diffusion length for holes; L_1 is the sample dimension indicated in Fig. 1. Correspondingly, J_f^- is determined by the equation $J_f^- = I_0 \beta q L_n L_1$ (L_n is the diffusion length for electrons). If the surface recombination velocity is different from zero, then J_f^+ and J_f^- must be correspondingly reduced.

The calculation shows that, in the absence of a magnetic field, the photocurrent magnitude, taking into account the surface recombination velocity, is equal to

$$J_f^+ = \frac{qI_0L_pL_1\beta}{\sqrt{1-v_p^2}}\left\{1 - \frac{2}{\pi}\operatorname{arc\,tg}\sqrt{\frac{v_p^2}{1-v_p^2}}\right\} \quad \text{for} \quad v_p = \frac{L_ps}{D_p} < 1,$$

$$J_f^+ = \frac{qI_0\beta L_pL_1}{\pi\sqrt{v_p^2-1}}\ln\frac{v_p+\sqrt{v_p^2-1}}{v_p-\sqrt{v_p^2-1}} \quad \text{for} \quad v_p > 1, \tag{2}$$

where s is the surface recombination velocity on the illuminated side, and the sample thickness $L_2 \gg L_p$. Analogous expressions are obtained for J_f^-.

If, through a plane parallel to the plane separating the n- and p-regions and separated from the space-charge region by the distance L_p (or L_n in the p-region), some additional number of carriers enters per unit time, then it is obvious that these carriers must also reach the space-charge region. Consequently, in this case J_f^+ must be replaced by $J_f^+ + J_p'$, and correspondingly J_f^- by $J_f^- + J_n'$. In our case the additional carriers enter the region of interest to us as a consequence of the photomagnetic effect in the p- and n-parts of the sample.

J_p' and J_n' are determined by the value of the photomagnetic current:

$$J_p' = qD_p \operatorname{tg}\theta_p \Delta p(0) L_1,$$

$$J_n' = qD_n \operatorname{tg}\theta_n \Delta n(0) L_1, \tag{3}$$

where $\Delta p(0)$, $\Delta n(0)$ are the concentrations of minority carriers at the surfa-

in regions I, IV of the $(p-n)$-junction; $\theta_p = \mu_p H/c$, $\theta_n = \mu_n H/c$ are the Hall angles for holes and electrons, respectively; μ_p, μ_n are the mobilities of holes and electrons; H is the magnetic-field strength. The magnetic field is assumed to be weak.

Instead of formula (1) we now obtain

$$J = J_f + J_p'\delta_p + J_n'\delta_n - J_s\left(e^{qU/kT} - 1\right). \tag{4}$$

The quantities δ_p and δ_n are determined by the position of the light spot. When only the n-region is illuminated, $\delta_n = 0$, $\delta_p = 1$; when the entire $(p-n)$-junction is illuminated, $\delta_n = \delta_p = 1$. The exact dependence of δ_n and δ_p on the method of illumination can be found only by a rigorous solution of the given problem, which, of course, would complicate consideration of the phenomenon and is therefore not pursued here, especially since the qualitative character of this

Fig. 3

Figure 3: Fig. 3

Fig. 4

Figure 4: Fig. 4

dependence is evident and makes it possible to explain the experimental results observed. We note that J_f is also a function of the position of the light spot.

Consider the case in which short-circuit current conditions are realized; then $U = 0$, and the change in current, odd with respect to H, when the magnetic field is switched on is determined by the relation

$$\Delta J_H = J_p'\delta_p + J_n'\delta_n. \tag{5}$$

In the experiments described in [1], where the illumination of the sample was varied by moving a solid screen along the direction of the measured potential difference,

Fig. 3

Fig. 4

the dependence of ΔJ_H on the position of the screen has, according to (5), the form of a step spread over a length $\sim L_n + L_p$, which is in agreement with the experimental curve shown in Fig. 3. This dependence was obtained on a drawn $(p-n)$-junction.

To obtain the total voltage drop across the whole sample under open-circuit conditions ($J = 0$), it is necessary also to take into account the photomagnetic emf arising in the homogeneous parts of the sample (in regions I and IV).

It follows from (4) that the odd component of the photomagnetic emf at the $(p-n)$-junction is equal to

$$\Delta U_H^{(1)} = \frac{kT}{q} \ln\left(1 + \frac{J_p'\delta_p + J_n'\delta_n}{J_f + J_s}\right), \tag{6}$$

and in the homogeneous p- and n-parts of the sample

$$\Delta U_H^{(2)} = \frac{(J_p' + J_n')L_3^{(n)}}{q\mu_n n_0 L_2 L_1}\,\delta_p^* + \frac{(J_p' + J_n')L_3^{(p)}}{q\mu_p p_0 L_2 L_1}\,\delta_n^*, \tag{7}$$

where n_0 and p_0 are, respectively, the equilibrium concentrations of electrons in the n-region and holes in the p-region. It is assumed throughout that the injection level is low and the magnetic field weak.

The quantities δ_n^* and δ_p^* again characterize the method of illumination of the $(p-n)$-junction: $\delta_p^* = 1$ when the entire region I is illuminated, and $\delta_n^* = 1$ when region IV is illuminated.

In our experiments on extended $(p-n)$-junctions, as a rule, the inequality $(\Delta U_H^{(1)})_{\max} \gg (\Delta U_H^{(2)})_{\max}$ holds. Formula (6), in a weak magnetic field, takes the form

$$\Delta U_H^{(1)} \simeq \frac{kT}{q} \frac{(J_p'\delta_p + J_n'\delta_n)}{J_f + J_s}. \tag{8}$$

If the rate of surface recombination is not taken into account, for a fully illuminated specimen this formula may be rewritten as follows:

$$\Delta U_H^{(1)} = \frac{kT}{q} \frac{(L_p\theta_p + L_n|\theta_n|)}{L_p + L_n + J_s/qI_0\beta L_1}. \tag{9}$$

An estimate of $\Delta U_H^{(1)}$ by this formula leads to quantitative agreement with experiment.

Figure 4 gives the experimental dependence of $\Delta U_H^{(1)}$ on the position of the moving screen. The origin of the maximum is explained by a drop in the differential resistance of the $(p-n)$-junction owing to an increase in the photocurrent. So long as only region I is illuminated (Fig. 1), the photomagnetic effect reaches its maximum value. In this case its magnitude is determined by the dark differential resistance (by the current J_s). With further displacement of the light boundary toward the p-region, the photocurrent J_f increases sharply, and the differential resistance of the $(p-n)$-junction correspondingly decreases, while $J_p'\delta_p$ remains unchanged and $J_n'\delta_n$ has not yet begun to increase. This leads to a decrease of $\Delta U_H^{(1)}$. After the passage of regions II and III, the growth of $J_n'\delta_n$ will begin to have an effect. However, if $J_n'\delta_n$ is small in comparison with J_f, the change will not be noticeable. It is easy to see from formula (6) that a maximum on the curve appears only in the case when, upon displacement of the screen, J_f becomes much larger than J_s. This circumstance is in agreement with the experimentally observed disappearance of the maximum on going from nitrogen temperatures to room temperatures. It was precisely for this case that the curves of $\Delta U_H^{(1)}$ were presented in the preceding paper ([1]), on which there is no maximum, but only a potential jump.

In conclusion, the authors take the opportunity to express their gratitude to Acad. I. K. Kikoin and S. M. Ryvkin for useful discussion of the results of the present work.

When these investigations had been completed, it became known to us that a similar theory of the photomagnetic effect at a $(p-n)$-junction, based approximately on the same considerations as those set forth above, had been developed by Yu. I. Ravich. He drew our attention to paper (3), in which an analogous question is considered.

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Note: Figure translations are in progress. See original paper for figures.