neglected, then $\nu' \sim s/L$, where L is the minimum dimension of the sample. A formula for ν_{ph-e} is given in [1]. Numerical estimates for bismuth show that for $T \sim 10^{-15}$ erg (10°K) and $L \sim 0.1$ cm, $\tilde{\omega}$ lies in the interval between 10^6 and 10^{10} cps. Conditions (12) can be realized in experiments.

A similar calculation for optical phonons under strong-dragging conditions leads to

$$\tilde{\omega}_H = \frac{5}{64(3\pi^2)^{2/3}} \frac{|e|H\omega_0^2}{cTN^{2/3}}$$

(ω_0 is the end-point frequency of the optical phonons). It is apparently a much more complicated matter to observe optical phonons than acoustic ones. We note that the predicted resonance can be readily distinguished from cyclotron resonance, owing to the specific temperature dependence of the resonance frequency.

The author thanks I. B. Levinson and Ya. B. Fainberg for valuable remarks.

[1] L. E. Gurevich and I. Ya. Korenblit, FTT 6, 856 (1964), Soviet Phys. Solid State 6, 661 (1964).

PHOTO-EMF OF p-n JUNCTION IN A STRONGLY EXCITED SEMICONDUCTOR

L. M. Blinov, V. S. Vavilov, and G. N. Galkin
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 7 March 1966
ZhETF Pis'ma 3, No. 9, 361-365, 1 May 1966

Most theoretical and almost all experimental studies of the photo-emf in crystals with p-n junctions have been confined to cases of relatively weak excitation (Δn, $\Delta p \ll n_n$, n_p) 1). Under these conditions the photo-emf depends logarithmically on the light intensity [1].

It follows, however, from simple theoretically-verified considerations [2] that in the case of strong excitation (Δn, $\Delta p \gg n_n$, n_p) the potential barrier of the p-n junction practically vanishes, and the photo-emf should approach the contact potential difference (c.p.d.).

Saturation of the photo-emf under the influence of laser emission pulses was observed experimentally in silicon photocells [3], where it was concluded, in view of the decrease of the limiting emf with increasing sample temperature and resistivity of the p region, that the c.p.d. can be determined with the aid of a laser; however, no quantitative results were given.

We have investigated the variation of the photo-emf with the radiation power incident on a silicon crystal with p-n junction. The light source was a Q-switched ruby laser ($\lambda = 0.69\ \mu$). A set of filters calibrated at high and low radiation power made it possible to cover the light-intensity range from 10^{-1} to 5×10^6 W/cm^2, corresponding to a maximum photogeneration rate $g \approx 10^{29}$ sec^{-1}cm^{-3} (the depth of penetration of the light is approximately 3μ) 2).

We investigated first p-n junctions obtained by diffusion of phosphorus in p-type silicon. The donor surface density in these samples was the same, $n_n' = 5 \times 10^{20}$ cm^{-3}, but the density p_p varied. The n region was illuminated, and the p-n junction was at a depth of 5 - 6 μ from the surface of the n-layer. For simplicity, the c.p.d. was assumed equal to $(kT/e) \ln (n_n' p_p / n^2)$. Allowance for the degeneracy of the n-type Si increases the theoretical c.p.d. by approximately 100 μV. A typical plot of the photo-emf vs. the light intensity is shown in Fig. 1 (curve 1). The corresponding c.p.d. is marked on the figure with a short horizontal line. Curve 1 was obtained for a diffusion p-n junction ($p_p = 5 \times 10^{17}$ cm^{-3}, $n_n' = 5 \times 10^{20}$ cm^{-3}), $t_{pulse} \approx 5 \times 10^{-8}$ sec, n-region illuminated. Curve 2 is for a shallow p-n junction obtained by ion bombardment ($p_p = 1.7 \times 10^{15}$ cm^{-3}, $n_n = 10^{19}$ cm^{-3}): a - $t_{pulse} \approx 5 \times 10^{-8}$ sec; b - $t_{pulse} \approx 10^{-3}$ sec, n-region illuminated; c - $t_{pulse} \approx 5 \times 10^{-8}$ sec, p-n junction illuminated from the end. Figure 2 shows the maximum values of the photo-emf (U_{max}) vs. the density p_p of the original material (curve 1). We see that a correlation between U_{max} and the calculated c.p.d. (curve 2) exists, but the former is much lower (diffusion p-n junctions, $n_n' = 5 \times 10^{20}$ cm^{-3}).

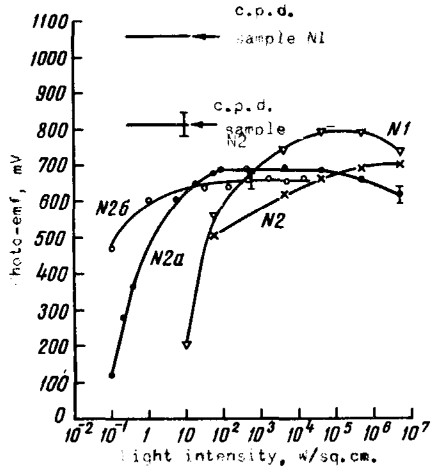

Fig. 1. Photo-emf vs. light intensity

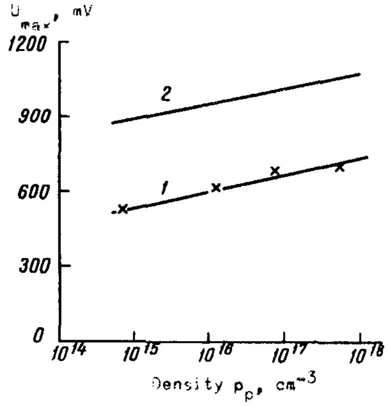

Fig. 2. Maximum photo-emf (1) and calculated c.p.d. (2) vs. the density p_p.

Inasmuch as the donor distribution in the n-region of the diffusion p-n junction is extremely uneven, the "photo-emf deficit" may indicate that the part of the potential barrier of the n-region due to this inhomogeneity is not lifted.

We have therefore performed additional experiments with a shallow p-n junction obtained by bombarding p-type silicon with phosphorus, followed by annealing of the radiation defects [4]. In this case the p-n junction was at a depth ~ 1 μ from the surface, and the donor distribution was relatively homogeneous, with $n_n \approx 10^{19}$ cm^{-3} and no degeneracy. Figure 1 shows the photo-emf of this sample with illuminated n-region (curve 2a).

The exciting pulse was of short duration ($t_{pulse} \approx 5 \times 10^{-8}$ sec), thus explaining the unusual variation of curves 1 and 2 in the region of low light intensities (large slope, small photo-emf). However, under saturation conditions the photo-emf does not depend on the duration of the pulse, as evidenced by curve 2b, obtained by excitation with a laser without Q switching, where $t_{pulse} \approx 10^{-3}$ sec.

The measurement results lead to the following conclusions:

1. The emf tends to saturate with increasing light intensity. This tendency begins with intensities of the order of 1 W/cm^2 in the "stationary" case (curve 2b). This is to be expected, since the condition $(\Delta n)_p \ll p_p$ is violated. Indeed, a rough estimate under the assumption that the electron lifetime in the p region is $\tau_n \approx 10^{-6}$ sec yields $\Delta n = g\tau_n \approx 10^{16}$ cm^{-3} (here $g \approx 10^{22}$ cm^{-3} cm^{-1}).

2. The saturation of the photo-emf extends over several orders of magnitude of the radiation power. The decrease in the emf in the region of highest light intensities is due apparently to the occurrence of a Dember emf of opposite sign, since no drop in the photo-emf was observed when the p-n junction was irradiated from the end.

3. In no case did the limiting photo-emf's coincide with the calculated values of the c.p.d., being always smaller. Apparently part of the potential barrier of the p-n junction is not lifted even at maximum photogeneration. This question is presently under study, but it is clear that the c.p.d. in silicon p-n junctions can not be determined by measuring the saturation photo-emf.

The authors are grateful to Corresponding Member B. M. Vul of the Academy of Sciences and V. D. Egorov for very useful remarks, and also to N. M. Borodina and V. V. Titov for supplying the samples of silicon with p-n junctions.

[1] R. L. Cummerow, Phys. Rev. 95, 16 (1959).
[2] P. N. Keating, J. Appl. Phys. 36, 564 (1965).
[3] D. Girton, Proc. IEEE 51, 938 (1963).
[4] V. M. Gusev, M. I. Guseva, V. S. Zolotarev, V. I. Kuritskii, V. G. Naumenko, V. V. Titov, and V. S. Tsyplenkov, Preprint IAE-1020, Kurchatov Atomic Energy Institute, 1965.

[1)] n_n and p_p are the equilibrium densities of the electrons in the n region and of the holes in the p region; Δn and Δp are the density increments due to the nonequilibrium carriers.

[2)] An increase of the light intensity to 5 x 10^7 W/cm^2 by focusing damaged the sample surfaces.

ANOMALOUS BEHAVIOR OF j_c(H, T) OF HEAT-TREATED Nb - 75% Zr ALLOYS

I. N. Goncharov and I. S. Khukhareva
Joint Institute for Nuclear Research
Submitted 8 March 1966
ZhETF Pis'ma 3, No. 9, 365-369, 1 May 1966

In spite of the tremendous number of investigations devoted to hard superconductors, the temperature dependence of the critical density has barely been studied. Kim et al. [1] measured at various temperatures the magnetization of cylinders of Nb and of Nb - 25% Zr alloy annealed at 1125°C, and obtained on this basis a linear dependence of the critical current