order of 10 keV, and this number does not depend on the energy of the primary electrons. The latter is a consequence of the fact that the thickness of the block is smaller than the coherence length. We now take into account the fact that the angle scatter of the electrons incident on the crystal lattice was $\sim 10^{-3}$ in our experiments. Therefore only 5×10^{-5} of the electrons passing through the crystal can produce coherent bremsstrahlung. Consequently, the contribution of coherent bremsstrahlung amounts to $\sim 2.5 \times 10^{-4}$ quantum per primary electron in the crystal under consideration. Thus, in spite of the fact that we used relatively thick crystals, in our experiments the coherent bremsstrahlung was negligibly small, since the crystals were not sufficiently ideal.

Calculation of the Bethe-Heitler bramsstrahlung gives for these crystals about 10^{-3} photon per primary electron. On the other hand, it is seen from the table and from Fig. 2 that the background measured by us was of the order of 10^{-1} photon per primary electron. We can therefore conclude that η_{backgr} is due to the background in the laboratory and should not depend on the thickness and type of radiator, as is also seen from the table.

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FEASIBILITY OF OPTICAL ORIENTATION OF EQUILIBRIUM ELECTRONS IN SEMICONDUCTORS

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The first experiments on optical orientation of free carriers in semiconductors were performed recently [1 - 4]. In materials of p-type, with which most of the experiments were performed, the oriented electrons were those propelled into the conduction band by circularly polarized light (there is practically no orientation of holes in the valence band, owing to the rapid relaxation of their spin). Thus, only the spins of non-equilibrium carriers become oriented. Their number is proportional to the intensity of the light, but the degree of orientation does not depend on the intensity. The phenomenon is analogous to optical orientation of excited atoms of a gas [5].

The purpose of the present paper is to show that in semiconductors, just as in a gas, it is possible to attain optical orientation of the ground state (optical pumping). Namely, in an n-type semiconductor (with a simple conduction band that is doubly degenerate in the spin) it is possible to obtain a considerable degree of electron orientation even at exciting-light intensities at which the concentration of the non-equilibrium carrier is still small

compared with the orientation of the equilibrium electrons. To this end it is necessary that the spin-relaxation time τ_s be large compared with the lifetime of the minority carriers τ. The experimental results [1 - 4] show that such a relation is quite realistic.

Circularly polarized light propels into the conduction band mostly electrons with a single spin direction. At the same time, the electron recombination rate is independent of their spin. It is clear that this will result in accumulation of oriented electrons in the conduction band. If $\tau \ll \tau_s$, then the electrons oriented in the stationary state will be the equilibrium ones.

The kinetics of the spin orientation is described by the equations

$$\frac{dn_\pm}{dt} = -\alpha(n - n_0)n_\pm \mp \frac{n_+ - n_-}{2\tau_s} + J_\pm, \tag{1}$$

where n_+ and n_- are the densities of the electrons with spins "up" and "down," respectively, J_+ and J_- are the numbers of electrons with spin "up" and "down" produced in the conduction band upon absorption of light, per unit volume and per unit time, $n = n_+ + n_-$, n_0 is the equilibrium electron density, and α is the recombination coefficient. From (1) we get the stationary degree of electron orientation $P = (n_+ - n_-)/n$:

$$P = P_0 J\tau_s (J\tau_s + n)^{-1}, \tag{2}$$

where $J = J_+ + J_-$ and $P_0 = (J_+ + J_-)/J$ is the orientation of the electron at the instant of its production by the light. For example, for the $\Gamma_6 \to \Gamma_8$ transition with excitation by circularly polarized light we have $P_0 = 1/2$. The stationary concentration of the electrons is $n - n_0 = J\tau$, where $\tau = (\alpha n)^{-1}$ is the lifetime of the non-equilibrium carriers.

The orientation P saturates at a level P_0 when $J \sim n/\tau_s$ and then the ratio $(n - n_0)/n \sim \tau/\tau_s$ is still small if $\tau \ll \tau_s$.

Usually the light is absorbed in a narrow layer near the surface of the crystal, and the conditions of the experiment set not the value of J but of I, the number of electrons produced by the light per unit surface area. In this case the excess carriers penetrate a distance equal to the diffusion length $L = \sqrt{D_p \tau}$ (where D_p is the hole diffusion coefficient). On the other hand, the orientation penetrates a depth $L_s = \sqrt{D_e \tau_s}$ (where D_e is the diffusion coefficient of the electrons; we shall henceforth assume that $L_s \gg L$). Indeed, in a layer of thickness L we can neglect the relaxation, since diffusion removes the electron from this layer within a time shorter than τ_s if $L \ll L_s$. On the other hand, recombination by itself cannot change the degree of orientation. At a depth $z > L$, the degree of orientation falls off like $P(z) = P(0)\exp(-z/L_s)$. The degree of orientation near the surface, P(0), can be determined from the balance equation

$$(I_+ - I_-)/2 = P(0)I/2 + n_0 L_s P(0)/(2\tau_s). \tag{3}$$

The left hand represents here the total spin of all the electrons produced by the light in a unit time. The first term in the right side is the rate of vanishing of the spin by recombination in the layer L, where all the excess carriers are annihilated, and the second term is the rate of spin relaxation in the layer L_s, where the electron density is already equal to the equilibrium value n_0. From (3) we obtain

$$P(0) = P_0 I\tau_s (I\tau_s + n_0 L_s)^{-1}. \tag{4}$$

Formula (5) has the same form as (2), with the role of J played by I/L_s.

We emphasize that an orientation of the order of P(0) penetrates in a depth L_3, where there are no excess carriers.

Interesting phenomena arise when the electrons are degenerate. If the energy relaxation is rapid enough, then the Fermi levels ζ_+ and ζ_- will be different for electrons with different spins following optical orientation. This leads to circular dichroism for interband absorption in the corresponding frequency interval.

Since the mobility depends on the position of the Fermi level, the photoconductivity will be different after excitation with circularly polarized and unpolarized light of the same intensity.

We note, finally, that the presence of an orientation gradient leads to the appearance of an emf $\mathcal{E}$ between two points 1 and 2 of the semiconductor. Indeed, the expression for the current density is

$$\mathbf{j} = -\sigma\nabla(\chi/e - \phi) - (\sigma_+ - \sigma_-)\nabla\eta/e. \tag{5}$$

where $\sigma_\pm = e\mu_\pm n_\pm$, $\sigma = \sigma_+ + \sigma_-$, $2\chi = \zeta_+ + \zeta_-$, $2\eta = \zeta_+ - \zeta_-$, ϕ is the potential, and $\mu_\pm$ the mobility of electrons with "up" or "down" spins. This yields (if $\eta << \zeta$)

$$\mathcal{E} = \frac{1}{2e\sigma}\frac{d\sigma}{d\zeta}(\eta_2^2 - \eta_1^2). \tag{6}$$

This emf can be called spin emf.

If the electrons are degenerate, then

$$\mathcal{E} = \frac{2\zeta^2}{9e\sigma}\frac{d\sigma}{d\zeta}(P_2^2 - P_1^2). \tag{7}$$

In the absence of degeneracy, $\mathcal{E} = (kT/2e)(P_2^2 - P_1^2)$. The direction of the spin emf is such that if $d\sigma/d\zeta > 0$, then in the presence of an external circuit the current in the sample flows in a direction opposite to the orientation gradient.

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