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Abstract

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RECOMBINATION RADIATION UNDER THE PINCH EFFECT IN A NONDEGENERATE ELECTRON-HOLE PLASMA OF SEMICONDUCTORS

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In semiconductors with bipolar conductivity, as in a gas plasma, when a strong electric current passes through them a pinch effect is possible: under the action of the magnetic field of the current, carriers are drawn from the periphery of the crystal toward the center ([1,2]). As a rule, the pinch effect in a solid is realized under conditions in which the main part of the current carriers has been injected into the crystal as a result of breakdown or through contacts. In this case the concentrations of holes p and electrons n are practically equal to each other and greatly exceed the equilibrium concentration of current carriers. Nonequilibrium electrons and holes recombine, and in a number of semiconductors a substantial fraction of the recombination is radiative. The study of recombination radiation can serve as a means of diagnosing the state of the electron–hole plasma in the crystal.

Let us consider a semiconductor in the form of an infinite plate ($-d \le y \le d$), through which a current is passed in the x direction. With the chosen geometry the problem becomes one-dimensional: all quantities depend only on the coordinate y; the longitudinal electric field E_x, by virtue of the condition $\operatorname{rot} \mathbf{E} = 0$, does not depend on the coordinates.

The problem of recombination radiation in a semiconductor plate under pinch-effect conditions is similar to the problem of the radiation of a plane layer with a nonuniform temperature distribution in the layer ([3]). In work ([4]) it was shown that the intensity of the radiation arising in direct interband transitions can be expressed directly through the optical constants of the semiconductor. We consider the case in which the time of radiative recombination appreciably exceeds the lifetime of the carriers. Under these conditions the reabsorption of light may be neglected, and the absorption of radiation in the bulk is determined only by the magnitude of the absorption coefficient and by the path length of the individual rays. In the case considered by us, the spectral density of the energy emitted per unit time from a unit lateral surface $y = \pm d$ has the form

$$I(\Omega, \pm d) = A\Omega e^{-a\Omega^2} \int_{-1}^{1} f^2(\xi) \left\{ E_2[\Omega(1 \mp \xi)] - \sqrt{1-q^{-2}}\, E_2\left[\Omega(1 \mp \xi)(1-q^{-2})^{-1/2}\right] \right\} d\xi. \tag{1}$$

Here

$$E_2(z) = \int_1^{\infty} e^{-tz} t^{-2} dt = e^{-z} + z\,\mathrm{Ei}(-z); \qquad A = h^4 E_g^3 q^2 p_0^2 \,[4\pi^2 c^2 \times$$

$$\times (m_n m_p)^{3/2} (kT_e)^3]^{-1}; \quad \Omega = \chi(\nu) d; \quad \chi(\nu) = \chi_0 (h\nu/E_g - 1)^{1/2}$$

is the absorption coefficient; E_g is the band-gap width; ν is the frequency of the emitted light (we consider the frequency range $h\nu - E_g \ll E_g$); q is the refractive index (in indium antimonide $q \simeq 4$); $m_{n,p}$ are the effective masses

electrons, holes; T_e is the carrier temperature;

$$a = \frac{E_g}{kT_e} \cdot \frac{1}{(\chi_0 d)^2},$$

$$\xi = \frac{y}{d}; \qquad f(\xi) = \frac{p(y)}{p_0};$$

p_0 is the mean carrier concentration in an infinitely thick plate, where the pinch effect is suppressed by volume recombination. Under symmetric conditions at the boundaries of the plate, $I(\Omega, +d) = I(\Omega, -d) = I(\Omega)$. In deriving (1) it was taken into account that only those rays leave the crystal whose angle with the normal to the side surface of the plate is less than $\arcsin \frac{1}{q}$; all other rays undergo total internal reflection.

If we restrict the discussion to the frequency region where $\Omega/2q^2 \ll 1$, and assume $q^2 \gg 1$, expression (1) is appreciably simplified. In this approximation we obtain:

$$I(\Omega) = A\Omega e^{-a\Omega^2 - \Omega} \frac{1}{2q^2} \int_{-1}^{1} f^2(\xi)\, \mathrm{ch}\, \Omega\xi \, d\xi. \tag{2}$$

In works ([2]) it was shown that in a plate whose thickness is small or comparable with the bipolar diffusion length L, the spatial distribution of carriers has the form

$$f(\xi) = f(0)\, \mathrm{ch}^{-2}(\xi/R), \tag{3}$$

Fig. 1 and Fig. 2

Figure 1: Fig. 1 and Fig. 2

where

$$R = [2/af(0)]^{1/2}; \qquad a = 2\pi kT_e p_0 \times \left(\frac{u_n + u_p}{c}\frac{eE_x d}{kT_e}\right)^2;$$

$u_{n,p}$ are the mobilities of electrons and holes. Under conditions

Fig. 1. Spatial distribution of current carriers for different values of α in the case of quadratic volume recombination ($\mu = 2$)

Fig. 2. Spectral distribution of recombination radiation for
$a = 4 \cdot 10^{-3}$, $\mu = 2$. $F(\Omega) = g_{1,2}(\Omega)e^{\Omega - a\Omega^2}$.
1 $-R \gg 1$, $g_1(\Omega) = \operatorname{sh}\Omega$, $\Omega_a \simeq 2.33$;
2 $-R \ll 1$, $g_2(\Omega) = \Omega$, $\Omega_a \simeq 1$

of constant injection and in the absence of surface generation–recombination, the carrier distribution is normalized in the following way:

$$\int_0^1 f^\mu(\xi)\, d\xi = 1, \tag{4}$$

where $\mu = 1$ if the volume recombination of carriers is mainly linear (monomolecular), and $\mu = 2$ for quadratic (bimolecular) recombination. Figure 1 shows the function $f(\xi)$, constructed for the case $\mu = 2$ at different values of the parameter α.

In the case of a weak pinch ($R \gg 1$), from (2)–(4) we obtain

$$f(0) \simeq 1 + \alpha/6; \qquad R \simeq (2/\alpha)^{1/2};$$

$$I(\Omega) \simeq \frac{A}{q^2} e^{-a\Omega^3 - \Omega}\left\{\operatorname{sh}\Omega + \alpha\left[\frac{\operatorname{sh}\Omega}{6} - \frac{(\Omega^2+2)\operatorname{sh}\Omega - 2\Omega\operatorname{ch}\Omega}{\Omega^2}\right]\right\}. \tag{5}$$

The integral radiation intensity for $R \gg 1$ is equal to

$$\int_{E_g^*/h}^{\infty} I[\Omega(\nu)]\, d\nu = \frac{AE_g}{2ah(\varkappa_0 d)^2 q^2}. \tag{6}$$

For a developed pinch ($R \gg 1$), neglecting terms $\sim R^3$, from (2)–(4) we obtain

$$I(\Omega) \simeq \frac{2A}{3q^2} Q(\alpha)\mathcal{L}(\Omega), \tag{7}$$

where

$$Q(\alpha) = [2f^3(0)/\alpha]^{1/2}; \qquad \mathcal{L}(\Omega) = \Omega e^{-a\Omega^2 - \Omega}. \tag{8}$$

It follows from (3) and (4) that $Q(\alpha) \simeq \alpha/2$ for $\mu = 1$ and $Q(\alpha) \simeq 3/2$ for $\mu = 2$. As we see, the linear and quadratic recombination laws lead to a completely different dependence of the radiation intensity on α. At the same time, for a developed pinch the form of the spectral distribution, determined by the function $\mathcal{L}(\Omega)$, does not depend on the character of the bulk recombination. For $a \ll 1$, the function $\mathcal{L}(\Omega)$ reaches an extremum at the point $\Omega \simeq 1$.

For $\Omega \gg 1$, the expressions obtained for the spectral distribution require refinement. This is due to the fact that for $R \ll 1$ formula (2) incorrectly describes the spatial distribution of carriers near the crystal boundaries. In the region $1 \geq |\xi| \gg R$, the carrier distribution is essentially determined by the bulk recombination time τ_{rec} and has the form

$$f(\xi) = \frac{\beta^2}{\alpha\mu} \left(\frac{\alpha}{3}\right)^{(\mu-1)/3} \left[1 - |\xi| + \frac{1}{\alpha} \left(\frac{\alpha}{3}\right)^{(\mu-1)/3}\right]. \tag{9}$$

Here $\beta = d/L$, where the bipolar diffusion length is

$$L = \left(2\frac{kT_e}{e} \frac{u_{nu} p}{u_n + u_p} \tau_{\text{rec}}\right)^{1/2}.$$

Estimates show that the region in which the spatial distribution is described by expression (9) does not make a noticeable contribution to the long-wavelength part of the spectral distribution and to the integral intensity of recombination radiation. In the short-wavelength part, however, the contribution of radiation from near-surface regions may exceed the contribution of radiation from the central region of the crystal, where the spatial carrier distribution is described by expression (3). For $\alpha = 6$, $\beta = 1$, the contribution of the near-surface regions is significant beginning with frequencies at which $\Omega \simeq 11$. In the frequency region where the condition $\Omega/2q^2 \ll 1$ is still not too strongly violated, the spectral distribution of radiation from the near-surface regions has the form

$$I(\Omega) \simeq \frac{A}{2q^2} \left(\frac{\beta^2}{\alpha\mu}\right)^2 \left(\frac{\alpha}{3}\right)^{2(\mu-1)/3} e^{-a\Omega^2} \tag{10}$$

or, in dimensional units,

$$I(\nu) \sim \exp\left(\frac{E_g - h\nu}{kT_e}\right).$$

The integral intensity of recombination radiation for $R \ll 1$ is equal to

$$\int_{E_g^*/h}^{\infty} I[\Omega(\nu)]\, d\nu = \frac{8E_{gAQ}(\alpha)}{3h(\varkappa_0 d)^2 q^2}. \tag{11}$$

Figure 2 presents the spectral distribution of the radiation for the cases of a weak ($R \gg 1$) and a strong ($R \ll 1$) pinch. In comparison with the radiation distribution for a weak pinch, in the case of a strong pinch the radiation band is appreciably narrowed, and the radiation maximum is shifted toward the long-wavelength side. This is due to the fact that, under a strong pinch, only a small part of the short-wavelength radiation reaches the boundaries of the plate.

Experimental data on recombination radiation in InSb are given in Ref. (5). In a crystal at the temperature of liquid nitrogen ($T = 78^\circ$ K), under pinch-effect conditions the carrier temperature is $T_e \sim 250^\circ$ K, $p_0 \sim 10^{16}$ cm^{-3}. We used the given values to estimate, by means of (6) and (11), the effective radiation temperature T_{eff}. Note that, owing to the strong nonparabolicity of the electron band, the mean effective mass of the electrons depends on the carrier temperature. According to (6), $m_n \simeq 0.018\, m_0$ at $T_e \sim 250^\circ$ K. If, in the estimate, one sets $m_p = 0.5\, m_0$, $\chi_0 d = 50$, then for a weak pinch ($R \gg 1$) $T_{\text{eff}} \simeq 160^\circ$ K, and for a strong pinch ($R \ll 1$) $T_{\text{eff}} \simeq 70^\circ$ K.

A substantial increase in the intensity of the recombination radiation can be achieved by applying to the crystal a constant magnetic field oriented in the z direction. In this case the pinch layer with the increased carrier concentration is brought out to one of the xz faces of the plate.

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REFERENCES

1. Glicksman, R. A. Powlus, Phys. Rev., **121**, 1659 (1961); B. Anker-Jonson, T. E. Drummond, Phys. Rev., **131**, 1961 (1963); A. P. Shotov, S. P.

Grishechkina, R. A. Muminov, ZhETF, **50**, 1525 (1966).

2. I. I. Boiko, FTT, **9**, 2929 (1967); A. E. Stefanovich, FTT, **9**, 2035 (1967).

3. Ya. B. Zel' dovich, Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, "Nauka," 1966.

4. W. V. Roosbroeck, W. Shockley, Phys. Rev., **94**, 1558 (1954).

5. B. P. Osipov, A. N. Khvoshch, ZhETF, **43**, 1179 (1962).

6. M. Glicksman, W. A. Hicinbothem, Phys. Rev., **129**, 1572 (1963).

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