RECOMBINATION RADIATION IN SEMICONDUCTORS UNDER THE PINCH EFFECT UNDER CONDITIONS OF STRONG DEGENERACY OF BOTH THE ELECTRON AND HOLE GASES

PHYSICS

1969

SovietRxiv

Abstract

Full Text

UDC 537.226

PHYSICS

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RECOMBINATION RADIATION IN SEMICONDUCTORS UNDER THE PINCH EFFECT UNDER CONDITIONS OF STRONG DEGENERACY OF BOTH THE ELECTRON AND HOLE GASES

(Presented by Academician M. A. Leontovich, 12 V 1969)

1. In the present work the behavior of the frequency of the spectral maximum of recombination radiation under the pinch effect in semiconductors is investigated as a function of current, under conditions of strong degeneracy of both the electron and hole gases.

In the works of Shpotov et al. [1] it was shown that the pinch effect in a degenerate electron–hole gas of indium antimonide (InSb) is accompanied by intense recombination radiation ($\lambda \approx 5\mu$), whose spectral maximum shifts toward the short-wavelength side as the current increases. In these experiments, carried out at comparatively small currents $I \lesssim 10$ A, the plasma cord does not go deeply into the crystal, and the average density of nonequilibrium current carriers over the cross section of the cord corresponded to strong degeneracy of the electron gas; at the same time the hole gas remained nondegenerate, since in InSb $m_n^* \ll m_p^*$, where m^* is the effective mass of the current carriers. The shift of the maximum is caused by the rise of the Fermi level in the pinch channel as the current increases. A theory of recombination radiation under the pinch effect in semiconductors under conditions of strong degeneracy of the electron gas was constructed in [2]. At large currents, when in the process of the pinch the plasma cord goes deeply into the crystal and the carrier density increases, cases are possible in which the hole gas also becomes strongly degenerate. The condition for strong degeneracy of the hole gas in InSb ($m_p^* \approx 0.5\, m_0$, where m_0 is the mass of the free electron) has the form

$$p^{2/3}/kT \gg 10^{26} \text{ CGSE units,} \tag{1}$$

where p is the hole density and T is their temperature.

If $T \approx 10^{\circ}$ K, then strong degeneracy of the hole gas arises at $p \gtrsim 5 \cdot 10^{17}$ cm^{-3}. Let us estimate the conditions under which the average density in the plasma cord reaches such values. When the drift velocity is saturated at the moment of constriction of the pinch channel, the average carrier density in the plasma cord of radius R is determined by the relation [3]

$$p_R = p_d \theta^6, \quad \text{where } \theta = d/R = (I/I_0)^{1/4} \geq 1. \tag{2}$$

Here p_d is the average density of current carriers in the crystal at the moment of constriction, d is the crystal radius, and I_0 is the current at which constriction of the pinch channel begins.

Using (2), we find that the average density in the pinch channel reaches the indicated values at $\theta \gtrsim 2$, if one assumes $p_d \approx 10^{16}$ cm^{-3}. At such large densities ($p_R \gtrsim 5 \cdot 10^{17}$ cm^{-3}), the recombination radiation undergoes total internal reflection inside the cord from regions whose plasma frequency $\omega_p = \sqrt{4\pi e^2 p/m_n^*}$ is greater than the radiation frequency (ω).*

* The author' s attention was drawn to this fact by A. A. Vedenov.

In the case of InSb ($\omega \approx 3.8 \cdot 10^{14}$ s^{-1}, $m_n^* \approx 0.013\, m_0$) this effect arises at $p \gtrsim 6 \cdot 10^{17}$ cm^{-3}. The cutoff point of the radiation inside the filament, $x = r/R$, at which the condition

$$\omega_p(x) = \omega, \tag{3}$$

is satisfied, will be denoted by x''. Using (2) and the results of a numerical calculation of the density profile in the channel of a degenerate pinch [(3)], it is not difficult to determine the position of the point x'' as a function of the current (θ). The calculation for the case $p_d = 10^{16}$ cm^{-3} gave the following results:

θ	1.65	1.8	2	2.2	2.4	2.6	2.8	3
x''	0	0.41	0.62	0.75	0.78	0.83	0.87	0.9

As can be seen, the effect of plasma reflection arises at $\theta > 1.65$. We note that for $p_d \approx 10^{15}$ cm^{-3} this effect arises at $\theta \gtrsim 2.5$; therefore, under the conditions of Shottov' s experiments the plasma reflection of radiation is absent.

The peculiarity of the recombination radiation of a degenerate pinch, as is seen from Fig. 1, which presents the Fermi-level profile over the cross section of the plasma filament [(5)], consists in the following: transitions with energy $h\nu - E_g < \mu_n(x') + \mu_p(x')$ [(4)], which contribute to the radiation from the crystal surface at $x > x''$, in the region of the crystal $x'' \leq x \leq x'$, occur under conditions of population inversion; photons with such energy pass through this region of the crystal under conditions of negative absorption [(5)], being multiplied on emerging

Fig. 1

Figure 1: Fig. 1

to the point x'. In the region of the crystal $x' \leq x \leq d/R$, the photons pass under conditions of positive absorption. The behavior of the spectral maximum with increasing current (θ) will be determined by the competition between the processes of positive and negative absorption. At different stages of the pinch, determined by the radius of the plasma filament, these processes will play either a dominant or a secondary role.

Fig. 1

2. The radiation intensity (the energy emitted per unit time by a unit volume of the plasma filament) in the spectral interval $d\nu$, for the case of direct band-to-band transitions, has the form [6]:

$$I(\nu)\,d\nu = 8\pi h\nu^3 (c/n)^{-2} \left(\chi\sqrt{h\nu - E_g}\right)\sqrt{h\nu - E_g}\, f_n f_p\, d\nu, \tag{4}$$

where

$$f_{n,p} = \left[\exp\left(\frac{E_{n,p} - \mu_{n,p}}{kT}\right) + 1\right]^{-1}, \qquad \chi = \frac{\chi_0 E_g^{1/2}\sqrt{h\nu - E_g}}{h\nu}$$

is the absorption coefficient, n is the refractive index, E_g is the band gap (in InSb $\chi_0 \approx 7 \cdot 10^3$ cm^{-1}, $n \approx 4$, $E_g \approx 0.24$ eV at $T \approx 10$°K [6,7]), ν is the transition frequency, and $E_{n,p}$ are the energies measured from the bottom of the corresponding band.

For direct transitions,

$$E_n = (h\nu - E_g)/(1+\varepsilon), \qquad E_p = \varepsilon E_n, \tag{5}$$

where $\varepsilon = m_n^*/m_p^*$. In what follows it is assumed that $\varepsilon \ll 1$.

Under conditions of strong degeneracy of the electron and hole gases, for transitions $h\nu - E_g < \mu_n(1+\varepsilon) \approx \mu_n$, formula (4) takes the form

$$I(\nu)\,d\nu = 8\pi\chi_0 E_g^{1/2} c^{-2} n^2 \nu^2 \sqrt{h\nu - E_g}\, d\nu. \tag{6}$$

As has already been noted, optical transitions at frequencies $h\nu - E_g \lesssim \mu_n(x')$ occur under conditions of population inversion, and photons with such energy pass through the region of the crystal $x'' \leq x \leq x'$ with a negative absorption coefficient (undergoing total internal reflection at the point x''), and through the region $x' \leq x \leq d/R$ with a positive one. Taking this into account, the spectral density of radiation from a unit length of the crystal for inverted transitions has the form

$$W(d,\nu) = 16\pi^2\chi_0 E_g^{1/2} R^2 \left(\frac{n}{c}\right)^2 \left(\frac{\varphi}{2\pi}\right) \nu^2 \sqrt{h\nu - E_g}\, \exp\left[-\chi R\left(\frac{d}{R} - 2x' + x''\right)\right]$$
$$\times \int_{x''}^{x'} x\ \mathrm{ch}\,\chi R(x - x'')\,dx \propto \exp\left[-\chi R\left(\frac{d}{R} - 2x' + x''\right)\right]$$
$$\times \left\{x'\,\mathrm{sh}\,\chi R(x' - x'') - \frac{1}{\chi R}\left[\mathrm{ch}\,\chi R(x' - x'') - 1\right]\right\}, \tag{7}$$

where φ is the solid angle in which the rays emerging from the crystal propagate; its magnitude is determined by the conditions of total internal reflection at the surface of the crystal. In deriving this formula we assumed that the propagation direction of the individual rays is close to radial, since the angle of total internal reflection in crystals with a large refractive index is small. The position of the point x' is determined by the condition

$$h\nu - E_g = \mu_n(x'). \tag{8}$$

In view of the strong absorption of radiation in the region $x' \leq x \leq d/R$, one should expect the maximum of the function W to correspond to the frequencies (8), where $x' \approx 1$, since in this case the photons traverse the greatest distance under conditions of negative absorption. The calculation confirms this assumption. As was shown in Ref. ([3]), near the boundary of the plasma filament $(0.7 \leq x \leq 1)$:

$$p(x)/p_R \approx (1 - x^2)^{3/2}. \tag{9}$$

Using (2), (8), and (9), one can obtain:

$$x' = 1 - \Omega/2\theta^4, \qquad \text{where } \Omega = (h\nu - E_g)/\mu_n(p_d). \tag{10}$$

Let us consider a number of cases. In the high-frequency limit $\chi R \gg 1$, or $\chi\Omega^{1/2} \gg \theta$, where $\chi = \chi_0 d\sqrt{\mu_n(p_d)/E_g}$, the function W takes the form

$$W(d,\nu) \propto \left(1 - \frac{\theta}{\chi\Omega^{1/2}}\right) \exp\left\{-\frac{\chi\Omega^{1/2}}{\theta}\left(\theta - 3 + 2x'' + \frac{3\Omega}{2\theta^4}\right)\right\}. \tag{11}$$

The frequency of the spectral maximum of this function Ω_m is determined by the equation

$$\Omega_m^2 + {}^2/_9\theta^4(\theta - 3 + 2x'')\Omega_m - 2\theta^6/9\chi^2 = 0, \tag{12}$$

whose positive root is

$$\Omega_m = \frac{\theta^4}{9}(3 - \theta - 2x'') + \frac{\theta^4}{9}|3 - \theta - 2x''|\sqrt{1 + \frac{18}{\chi^2\theta^2(3 - \theta - 2x'')^2}}. \tag{13}$$

In the case where the effect of plasma reflection is absent ($x'' = 0$), the position of the spectral maximum for $\theta < 3,\ \chi \gg 1$ is described by the formula:

$$\Omega_m = 2\theta^4(3 - \theta)/9. \tag{14}$$

An analogous formula in this current range (θ) describes the position of the spectral maximum also in the case where only the electron gas is degenerate ([2]).

At large currents θ, the spectral maximum of the function W shifts to the low-frequency region: $\chi R \ll 1$.

In this limit the function W has the form

$$W(d, \nu) \propto \Omega^{1/2} \exp\left[-\frac{\chi\Omega^{1/2}}{\theta}(\theta - 2 + x'')\right]. \tag{15}$$

The position of the spectral maximum of this function is determined by the relation

$$\Omega_m = \chi^{-2}\left(\frac{\theta}{\theta - 2 + x''}\right)^2. \tag{16}$$

For $\theta \gg 1$ the frequency of the spectral maximum (16) coincides with the frequency of the spectral maximum of the recombination radiation of a nondegenerate pinch (8): $h\nu_m - E_g = E_g/(\chi_0 d)^2$.

Figure 2 (curve I) shows the dependence of Ω_m on the current θ, plotted from function (13) with the aid of the table given above. The transition to the low-frequency region occurs at $\theta > 2$. The shift of the spectral maximum to the short-wavelength region occurs up to currents $I \lesssim 9I_0$ ($\theta \lesssim 1.7$), at which plasma reflection is not significant. Curve II (Fig. 2) shows the dependence of Ω_m on the current for the case in which plasma reflection is not taken into account: $x'' = 0$. All calculations are given for the case $p_d = 10^{16}$ cm^{-3}, $\chi_0 d = 10^2$. The shift of the spectral maximum to the long-wavelength side in the case $x'' = 0$ begins at much larger currents: $I \gtrsim 33I_0$ ($\theta \gtrsim 2.4$), which is due to the increase

Fig. 2

Figure 2: Fig. 2

in the path traversed by the quanta in the region of negative absorption in the absence of plasma reflection.

Fig. 2

As is seen from Fig. 2, on the curves of the dependence of the position of the spectral maximum on the current one can distinguish three clearly expressed regions:

a) The region in which the spectral maximum shifts to the short-wavelength side with increasing current. In this region the processes of negative absorption play the dominant role, since the plasma cord has not yet gone deeply into the crystal.

b) The region of currents in the vicinity of the largest value of the frequency of the spectral maximum, where the processes of positive and negative absorption compete.

c) The region in which the frequency of the spectral maximum decreases sharply with increasing current. In this region the processes of positive absorption dominate. When plasma reflection is taken into account, the dominant role of positive absorption arises at smaller currents, which is due to the decrease in the distance traversed by the rays in the region of negative absorption.

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Received
17 IV 1969

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