EFFECT OF A STRONG MAGNETIC FIELD ON RECOMBINATION RADIATION IN SEMICONDUCTORS

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EFFECT OF A STRONG MAGNETIC FIELD ON RECOMBINATION RADIATION IN SEMICONDUCTORS

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The effect of a strong magnetic field on the shift of the long-wavelength absorption edge in interband transitions in semiconductors has been investigated in a number of works ([1-3]). This effect is associated with the formation of Landau levels for carriers having the smaller effective mass. In a strong magnetic field a change in the line shape of the recombination radiation of indium arsenide ([4]) and a decrease in the generation threshold in an injection laser made of this material ([5]) were also observed. It was shown ([6]) that, under the assumption of radiative recombination from the conduction band to an impurity level, the value of the transition matrix element does not depend on the magnetic field up to field strengths that are practically unattainable, and the supposition was made that the effect of the magnetic field is manifested in a change in the density of states.

In the present work we calculate the intensity of recombination radiation in a magnetic field for an interband transition in semiconductors and determine the line shape of the radiation, taking as given the distribution functions of electrons and holes in the conduction and valence bands.

The number of quanta of frequency $\hbar\omega$ emitted per unit time in a spontaneous transition into the interval $d\omega$ is determined by the expression

$$\frac{\partial N_\omega}{\partial t}\,d\omega = \rho(\omega)d\omega \sum_{ab} \frac{2\pi}{\hbar}\left|H_{ab}\right|^2 f_a(\varepsilon_e, \mathbf{k}_e) f_b(\varepsilon_h, \mathbf{k}_h), \tag{1}$$

where the index a corresponds to an electron in the conduction band, b to a hole in the valence band and to the appearance of a photon $\hbar\omega$; the energies ε_e and ε_h are measured from the bottoms of the corresponding bands (for field $\mathbf{H} = 0$) in opposite directions, so that

$$\varepsilon_{e,h} = (n_{e,h} + {}^1/_2)\hbar\omega_{e,h} + \frac{\hbar^2 k_{ze,h}^2}{2m_{e,h}}, \qquad \omega_{e,h} = \frac{eH}{m_{e,h}c}. \tag{2}$$

The summation in (1) is carried out over all states satisfying the law of conservation of energy

$$\hbar\omega - \Delta - \varepsilon_e - \varepsilon_h = 0. \tag{3}$$

The matrix element H_{ab} is decomposed into the product of two matrix elements —the usual matrix element associated with photon emission (it does not depend on the magnetic field), and the matrix element taken over the wave functions of the electron and the hole:

$$H_{eh} = i\hbar \int \Psi_h(\mathbf{k}_h, \mathbf{r})\, \mathbf{e}_\lambda \nabla \Psi_e(\mathbf{k}_e \mathbf{r})\, d^3 r. \tag{4}$$

The wave function of an electron (hole) in a magnetic field is represented in the form (the field H is directed along z, and the vector potential of the field is taken in the form $A_y = xH,\ A_x = A_z = 0$):

$$\Psi_e(\mathbf{k}_e, \mathbf{r}) = B u_{0e}(\mathbf{r}) e^{i(k_y y + k_z z)} \varphi_n(x), \tag{5}$$

where B is a normalization constant; $u_0(\mathbf{r})$ is the Bloch factor at $\mathbf{k} = 0$, having the periodicity of the lattice,

$$\varphi_n(x) = \frac{e^{-\frac{1}{2}((x-x_0)/\lambda)^2}}{\sqrt{\lambda}}\, H_n\Big(\frac{x - x_0}{\lambda}\Big). \tag{6}$$

The magnetic length is $\lambda = (\hbar c/eH)^{1/2}$, and H_n is the Hermite polynomial of order n. Substituting (5) into (4) and retaining only the leading terms (the photon momentum is neglected), we obtain

$$H_{eh} = i\hbar \int u^*_{0h}(\mathbf{r})\, \mathbf{e}_\lambda \nabla u_{0e}(\mathbf{r})\, d^3 r\, \delta(k_{ye} - k_{yh})\, \delta(k_{ze} - k_{zh})\, \delta_{n_e n_h}. \tag{7}$$

The integral in (7) is taken over the volume of the elementary cell and does not depend on the magnetic field, since the linear dimensions of the elementary cell are small in comparison with the magnetic length even in fields of millions of oersteds. In this case the square of the matrix element of the momentum operator can be expressed in terms of the effective mass of the electron and the width of the forbidden band in the absence of a magnetic field:

$$\hbar^2 \left| \int_V u^*_{0h}(\mathbf{r})\, \mathbf{e}_\lambda u_{0e}(\mathbf{r})\, d_0 r \right|^2 = \frac{3m^2\Delta}{m_e}. \tag{8}$$

After carrying out preliminary calculations one can find the explicit form of expression (1):

$$\left(\frac{\partial N_\omega}{\partial t}\right) d\omega = \frac{6D^{1/2}e^2\omega\Delta}{m_e c^3}\, d\omega \int g(\varepsilon_e)\, \delta(\varepsilon_e + \varepsilon_h + \Delta - \hbar\omega)\, f_e(\varepsilon_e) f_h(\varepsilon_h)\, d\varepsilon_e. \quad (9)$$

In expression (9), $g(\varepsilon_e)$ is the density of states in the conduction band [8]:

$$g(\varepsilon_e) = \frac{(2m_e)^{1/2} eH}{(2\pi\hbar)^2 c} \sum_{n_e} \left[\varepsilon_e - (n_e + \tfrac{1}{2})\hbar\omega_e\right]^{-1/2}. \quad (10)$$

Taking into account that in (9) $k_{ze} = k_{zh}$, we use the properties of the delta function:

$$\left(\frac{\partial N_\omega}{\partial t}\right) d\omega = \frac{(2m^*)^{1/2} e^3 \omega \Delta H}{(2\pi\hbar)^2 m_e c^4} \sum_n \frac{f_e(\varepsilon_e) f_h(\varepsilon_h)}{\left[\hbar\omega - \Delta - (n + \frac{1}{2})\hbar(\omega_e + \omega_h)\right]^{1/2}}, \quad (11)$$

where

$$\varepsilon_e = (n + \tfrac{1}{2})\hbar\omega_e + \frac{m^*}{m_e}\left[\hbar\omega - \Delta - (n + \tfrac{1}{2})\hbar(\omega_e + \omega_h)\right],$$

$$\varepsilon_h = (n + \tfrac{1}{2})\hbar\omega_h + \frac{m^*}{m_h}\left[\hbar\omega - \Delta - (n + \tfrac{1}{2})\hbar(\omega_e + \omega_h)\right], \quad (12)$$

$$\frac{1}{m^*} = \frac{1}{m_e} + \frac{1}{m_h}.$$

In the limiting case $H \to 0$, expression (11) goes over into the expression obtained in the absence of a magnetic field. It is clear that the presence of the magnetic field will be essential if $\hbar\omega_e \gg kT$, where T is the lattice temperature of the semiconductor.

If one assumes that, in some energy interval close to the level $n = 0$, the distribution function for electrons and holes is constant and close to unity, as is the case when approaching the generation threshold, then the emission line shape will be determined by the denominator of the last factor in expression (11), and instead of the sum over n only one term with $n = 0$ will enter (we assume $f_e(\varepsilon_e) \to 0$ for $\varepsilon_e > \hbar\omega_e/2 + kT$, with $kT \ll \hbar\omega_e$). In this case the shape of the recombination-radiation line is proportio-

is proportional to the factor

$$\frac{\partial N_\omega}{\partial t} \sim \left[\hbar\omega - \Delta - \frac{\hbar(\omega_e + \omega_h)}{2}\right]^{-1/2} \quad (13)$$

and formally tends to infinity when the expression in brackets is equal to zero. Since the Landau levels are broadened, owing to the interaction of the carriers with the lattice and with one another, by an amount $\sim \hbar/\tau$, the intensity of the radiation remains finite; the half-width of the emission line γ is determined by the level broadening ($\gamma \sim 4/\tau$).

If one assumes that the characteristic time $\tau \sim 10^{-11}$ sec, then the level width is expressed in terms of an effective temperature ($kT_\gamma \sim 4\hbar/\tau$) and is $T_\gamma \sim 3^\circ$K, which, at a sample temperature $T > T_\gamma$, leads to narrowing of the emission line. In the absence of a magnetic field, however, the width of the emission line in an interband transition cannot be less than several kT. As is known ([9]), the half-width of the emission line enters into the self-excitation condition of a quantum generator, and its decrease leads to a lowering of the generation threshold. Apparently, it is precisely this that explains the achievement of generation in indium antimonide in a magnetic field ([10]) and the lowering of the generation threshold in indium arsenide upon application of an external magnetic field ([5]). For a final quantitative comparison with experiment it is necessary to determine the value of τ, which can be done by measuring the half-width of the absorption line or the emission line in a magnetic field.

In conclusion, we note that the form of the emission line obtained remains valid also in the case of a transition from the conduction band to an acceptor level and to the valence band, when the magnetic field still has no substantial influence on the energy spectrum of the holes. The only essential fact is that the spacing between neighboring Landau levels for conduction-band electrons is greater than the energy interval in this band occupied by nonequilibrium carriers.

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