Saturation of absorption in *n—i—p—i* crystals

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ABSTRACT

Peculiarities of the absorption saturation in doping superlattices with *n—i—p—i* crystal type structure are established. Calculations are performed in the **k**-selection rule model taking into account the screening of the electrostatic potential by current carriers and the density state tails.

Keywords: *n—i—p—i* crystals, absorption, saturation, density state tails.

1. INTRODUCTION

As known, the saturation of the radiation absorption power in nonlinear semiconductor low-dimensional crystals is connected with the energy subband filling by non-equilibrium current carriers. As a result, the absorption coefficient k at a fixed light frequency ν decreases with increasing the electromagnetic field intensity. This effect is associated with the approach of the quasi-Fermi level difference ΔF to the photon energy $h\nu$ at increasing the monochromatic radiation intensity.

Peculiarities of the nonlinear light absorption and amplification have been earlier analyzed for bulk semiconductors [1-4] and for quantum-size two-dimensional systems as well [5-7]. For doping superlattices, having the *n—i—p—i* crystal type structure, this problem was investigated insufficiently [8, 9].

The *n—i—p—i* crystals exhibit the large optical non-linearity, especially the structures with embedded additional quantum wells [10, 11]. The main processes influencing the saturation of absorption in *n—i—p—i* crystals are (a) the filling of the energy states under an optical excitation of the crystal, (b) redistribution of the energy levels at the change of the potential relief depth, (c) the shortening of the density state tails, because of impurity concentration fluctuations, as result of the screening of the fluctuating impurity potential by non-equilibrium current carriers, (d) change in the life-time of current carriers due to changes in the overlap of the envelope wave functions of electrons and holes, (e) masking behavior of the free carrier absorption, (f) stabilizing action of the background screening, and (g) effects of narrowing the band gap and of changes in the effective band gap of the superlattice [12, 13].

2. BASIC EQUATIONS

The relation between the absorption or gain coefficient k and photon density S at the frequency ν is described by the standard equation [2]

$$\frac{\eta' j}{ed} = \frac{R_{sp}}{\eta_{sp}}\left[1-\exp\left(-\frac{\Delta F}{kT}\right)\right] \pm \nu k(\nu)\, S\,, \qquad (1)$$

where j is the current density, η' is the injection efficiency, η_{sp} is the internal spontaneous quantum efficiency, v is the group velocity of light, d is the superlattice period. The sign of minus or plus in Eq. (1) corresponds to absorption or gain processes. The spontaneous recombination rate R_{sp} is defined by the integration of the spectral spontaneous emission rate $r_{sp}(h\nu)$ all over the photon energies $h\nu$ at definite difference between quasi-Fermi levels ΔF and the crystal temperature T. The expression for $r_{sp}(h\nu)$ in the **k**-selection rule model has the form [12]

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Optics of Crystals, V. V. Shepelevich, N. N. Egorov, Editors, Proceedings of SPIE Vol. 4358 (2001)

$$r_{sp}(h\nu)=\frac{A_{cv}}{\pi\hbar^2 N_p d}\sum_i m_{ri\perp}\sum_n\sum_m\sum_\nu H_t\left(h\nu-h\nu_{nmiv}\right)I^2_{nmiv}f_e\left(E_{cnmiv}\right)f_h\left(E_{vnmiv}\right). \quad (2)$$

Here, A_{cv} is the Einstein coefficient, N_p is the number of the superlattice periods, I_{nmiv} is the overlap integral of the envelop wave functions of electrons and holes, $f_e(E_{cnmiv})$ and $f_h(E_{vnmiv})$ are the Fermi-Dirac functions for electrons and holes,

$$E_{cnmiv}=E_{c0}+\frac{m_{ri\perp}}{m_c}\left(h\nu-E_g^{'}\right)+\frac{m_{ri\perp}}{m_{vi\perp}}E_{cn\nu}-\frac{m_{ri\perp}}{m_c}E_{vim\nu}, \quad (3)$$

$$E_{vnmiv}=E_{v0}-\frac{m_{ri\perp}}{m_{vi\perp}}\left(h\nu-E_g^{'}\right)+\frac{m_{ri\perp}}{m_{vi\perp}}E_{cn\nu}-\frac{m_{ri\perp}}{m_c}E_{vim\nu}, \quad (4)$$

m_c and $m_{vi\perp}$ are the effective mass of electrons and effective mass transverse components for heavy ($i = h$) and light ($i = l$) holes, $m_{ri\perp} = m_c m_{vi\perp}/(m_c + m_{vi\perp})$ is the reduced mass, E_{c0} and E_{v0} are the energies of the bottom of the conduction band and top of the valence band. The summation in Eq. (2) is performed over the quantum numbers of minisubbands ν, electron n and hole subbands m. Transitions between the subbands of electrons and holes begin at the light quanta $h\nu_{nmiv} = E_g^{'} + E_{cn\nu} + E_{vim\nu}$ which is concerned with the effective band gap of the doping superlattice $E_g^{'} = E_{c0} - E_{v0}$ and the ground states of the subbands $E_{cn\nu}$ and $E_{vim\nu}$.

The function $H_t(y)$ is determined by the energy spectra broadening. If the broadening effects in the semiconductor structure are negligible, $H_t(y)$ is represented by the Heaviside unit-step function. For heavily doped superlattices, the impurity and intrinsic bands are to be overlapping. Therefore, tails of the density of states appear. In the case of the Gaussian-like tails the function $H_t(y)$ has the form $H_t(y) = \mathrm{erfc}(-y/\sigma_{cv})/2$ [13]. Here, $\sigma_{cv} = \sqrt{\sigma_c^2 + \sigma_v^2}$, σ_c and σ_v are the characteristic tail parameters of the density of electron and hole states which decrease with the increase of excitation level of the superlattice [12, 13]. The absorption coefficient $k(\nu)$ is connected with the spontaneous emission rate $r_{sp}(h\nu)$ by means of the universal relation [3]

$$k(\nu)=\frac{\exp\left(\dfrac{h\nu-\Delta F}{kT}\right)-1}{\nu\rho}\,r_{sp}(h\nu), \quad (5)$$

where $\rho(h\nu) = (h\nu)^2 n_0/\pi^2 c^2 h^3 \nu$ is the density of electromagnetic modes, n_0 is the refraction index of the semiconductor crystal. Therewith, the exciting radiation is considered to be isotropic.

The dependence $k(S)$ at the fixed photon energy $h\nu$ is defined by the features of the properties and characteristics of the active medium. As a rule, the relation between the absorption coefficient k and photon density S can be described by the simplified formula [1-7]

$$k=\frac{k_0}{1+h\nu\alpha S}, \quad (6)$$

where k_0 is the initial absorption coefficient, α is the non-linearity parameter. For the more detailed analysis of the saturation of absorption in definite semiconductor systems, it is necessary to use computer simulation.

3. RESULTS FOR GaAs *n—i—p—i* CRYSTALS

For doping superlattices, it is suitable to perform the calculations of the absorption saturation according to the following algorithm. At first, at a given value of ΔF and $S = 0$ it is necessary to determine the corresponding values of the initial absorption coefficient k_0 at a fixed frequency ν and current density j. At increasing the parameter ΔF, new values of the absorption coefficient k and spontaneous recombination rate R_{sp} are obtained. Then, from Eq. (1) the photon density S is determined. The iterative procedure is repeated until the quasi Fermi level difference ΔF is not equal to the photon energy $h\nu$. The similar algorithm has been also used for analysis of the gain saturation in quantum-well heterostructures [7].

The results of the self-consistent computations of the absorption saturation process are represented in Figs. 1 and 2 for the GaAs *n—i—p—i* crystal with the parameters $N_a = 10^{19}$ cm^{-3}, $N_d = 6\times10^{18}$ cm^{-3}, $d_p = 35$ nm, $d_n = 25$ nm, $d_i = 0$, $T = 300$ K,

$\eta' = 1$, $\eta_{sp} = 0.7$. The evaluations of the absorption coefficient are performed in the model of the Gaussian density state tail [13] in comparison with the no-broadening effect model.

As shown, if the electrostatic potential fluctuations in a doping superlattice are small, the absorption coefficient k at the increase of the photon density S at a fixed frequency ν exhibits a non-monotonous behavior. The dependence $k(S)$ has a saw-tooth like form. The effect of "darkening", i.e. of increasing k versus S, occurs appreciably at photon energies near the semiconductor band gap value. The non-monotonous character of changes in k versus S is conditioned by redistribution of the subband levels, by changes in the overlap integral of electron and hole wave functions with the potential profile transformation, and by narrowing the effective band gap E_g' of the doping superlattice. The similar oscillation behavior of the absorption coefficient at fixed frequencies versus the two-dimensional electron concentration is manifested too [14].

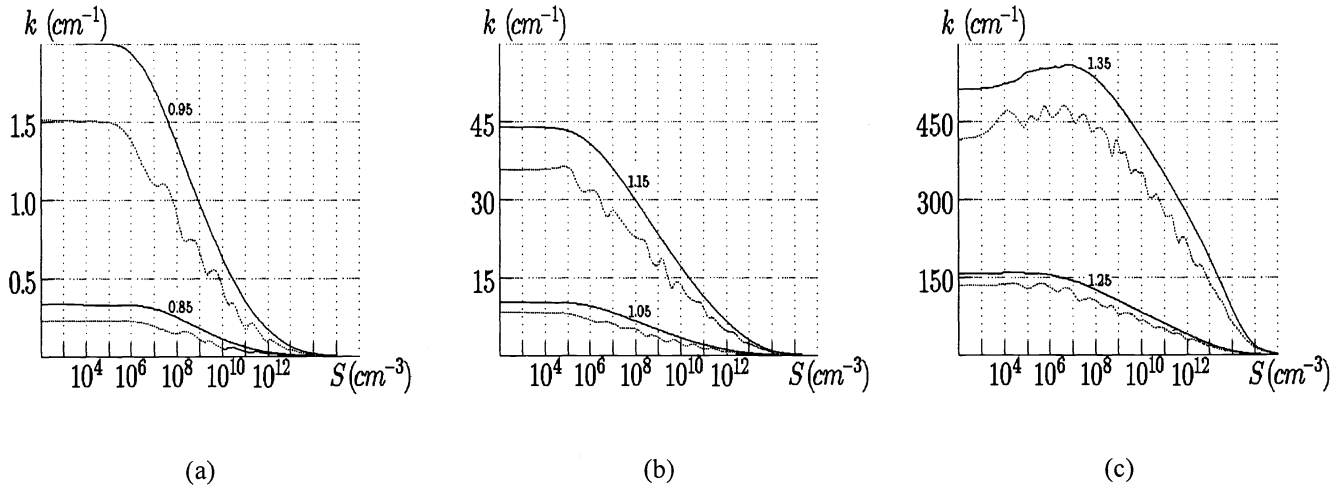

Fig. 1. (a, b, c) Curves of the saturation of absorption $k(S)$ calculated with taking into account (full curves) and without (dotted curves) density state tails. Numbers at the curves correspond to the photon energies $h\nu$, eV. $j \approx 0$.

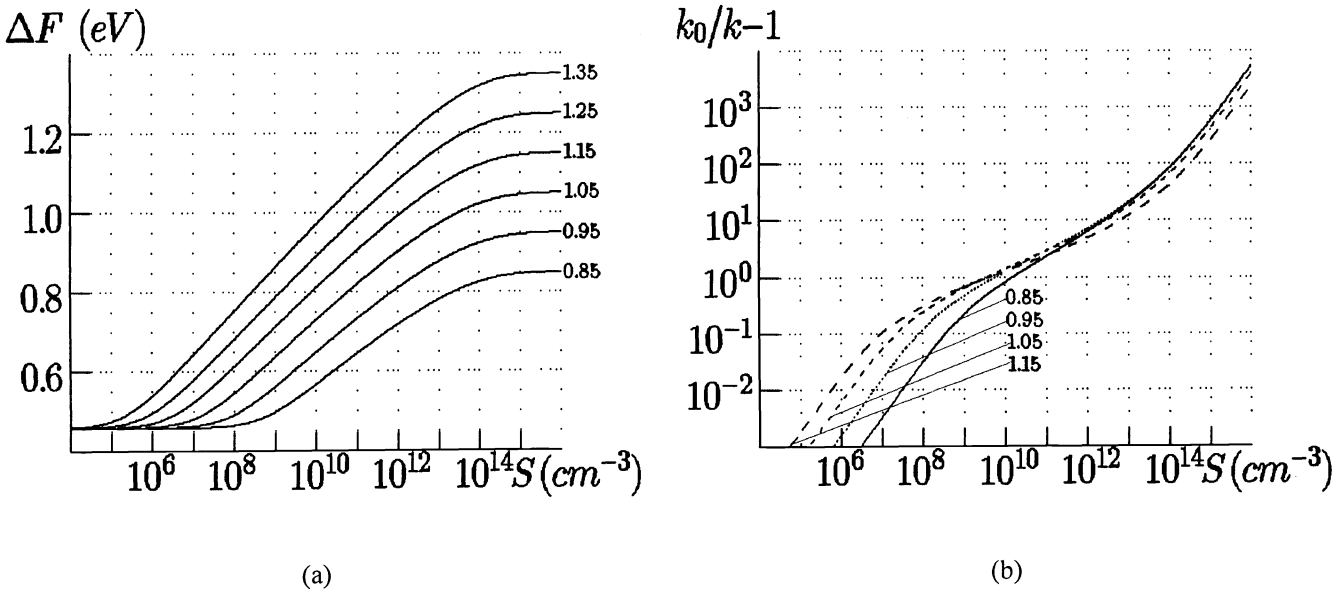

Fig. 2. Dependencies (a) of the quasi Fermi level ΔF and (b) variable (k_0/k)-1 on the photon density S. Numbers at the curves correspond to the photon energies $h\nu$, eV. $j \approx 0$.

Usually, the electrostatic potential fluctuations in doping superlattices spread a step-like structure of the density of states that provides smooth absorption spectra. As a result, the dependence $k(S)$ becomes smooth as well but the "darkening" region at a sufficiently high $h\nu$ does not disappear. A non-monotonous character of the absorption saturation is also put into effect in δ-doped superlattices. For bulk semiconductors, this effect can be found when including the free carrier absorption [2].

In general case, the dependence $k(S)$ is not defined by Eq. (6). However, at low and higher photon densities the curve $k(S)$ can be approximated by Eq. (6) with two different non-linearity parameters α_0 and α_∞, correspondingly. Often, in Eq. (6) the light flux density is used, instead of the photon density S, and the non-linearity parameter equaled to α/v. The evaluation of the respective quantities α_0/v and α_∞/v is suitable to be performed in the double logarithmic scale [2] (Fig. 2).

In particular, the non-linearity parameter values at the temperature of 300 K for the photon energies $h\nu$ = 0.95, 1.05, and 1.15 eV are equal to $\alpha_0/v = 1.37$ cm^2/W and $\alpha_\infty/v = 0.46$ cm^2/kW, $\alpha_0/v = 4.93$ cm^2/W and $\alpha_\infty/v = 0.29$ cm^2/kW, and $\alpha_0/v = 11.8$ cm^2/W and $\alpha_\infty/v = 0.16$ cm^2/kW, accordingly. As seen, the value of α_0 increases and of α_∞ decreases with increasing $h\nu$. Therewith, the saturation radiation flow density, when the absorption coefficient is reduced in two times, is sufficiently low and makes up in the order of 5 W/cm^2.

Large non-linearity of the absorption in *n—i—p—i* crystals can be used in optical switches, bi- and multi-stable elements and for tunable lasers with a widen wavelength range. The non-linear effects also have an influence on the performance characteristics of *n—i—p—i* crystal photo-detectors under high optical excitation.

ACKNOWLEDGEMENT

This work was supported by the Belarusian Republican Foundation for Fundamental Research under the Project No. Ф99R–119.

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