LASER GAIN SPECTRA OF QUANTUM WELLS AND MULTIPLASMON OPTICAL TRANSITIONS

V. Gurau

State University of Moldova, Department of Physics, Chishinau, MD-2009, Mateevici 60, Republic of Moldova, virgurau@yahoo.com

Abstract

A novel multi-plasmon concept of a light absorption and laser gain of low-dimensional structures are comprehensively discussed. A Generalized Semiconductor Bloch Equations are derived with account of multi-plasmon optical transitions in direct gap quantum wells, using the cumulant expansion method and fluctuation-dissipation theorem. We present results of computer simulations concerning gain spectra of $In_{0.05}Ga_{0.95}As$ quantum wells with account of multi-plasmon optical transitions in two- dimensional systems.

Multi-quantum LO-phonon-plasmon optical transitions are investigated with account of coherent memory effects in quantum wells. It is shown that a red shift of the absorption edge can be caused, not only by known mechanism of band gap shrinkage, but also by multi-plasmon transitions. The electron-hole plasma properties in the active region of the laser device and its interaction with the optical field are studied on a microscopic level using obtained Generalized Semiconductor Bloch Equations.

The comparison with other theories and experimental data measured in $In_{0.05}Ga_{0.95}As$ quantum wells is performed. The gain value g=50 cm^{-1} in 8 nm $In_{0.05}Ga_{0.95}As$ quantum wells is obtained at a surface density of electrons $nd_0=1.64\ 10^{-12}\ cm^{-2}$.

1. Microscopic theory

The key step to understand the physical mechanisms governing semiconductor laser devices and to develop models capable to predict accurately the relevant experimental properties, is to investigate the potential for further progress in design of a wide variety of semiconductor lasers and light emitting diodes. The electron-hole plasma properties in the laser device active region and its interaction with the optical field are studied in this paper on a microscopic level.

The Coulomb interaction in the electron-hole plasma leads not only to the band gap energy renormalization and to the enhancement of the transition matrix element [1-5], but also causes, due to correlations, multi-plasmon optical transitions that have been investigated experimentally and theoretically in works [6-10]. Here we consider interband light absorption and radiation in quantum wells in two-band approximation, with account of electron-hole pair strong coupling with plasmons. Also, as for three-dimensional systems [6-10], we use the cumulant expansion method and fluctuation dissipation theorem, allowing to express correlation function density - density through a structure factor.

Generalizing the results of papers [6-10] at low-dimensional structures, we find for the coefficient of light interband absorption in the symmetric quantum wells of width d_0 the following expression:

$$\alpha(\omega)=\alpha_0\frac{\omega_g}{\omega}\sum_N\int_0^\infty\{1-f_N^e(\omega_{k_\perp})-f_N^h(\omega_{k_\perp})\}C(k_\perp)\mathrm{Re}\int_0^\infty e^{i\left(\omega-\omega_g-\omega_N-\omega_{k_\perp}\right)t-g(t)}dtd\omega_{k_\perp} \quad (1)$$

Gain spectrum is determined by a known relation $g(\omega)=-\alpha(\omega)$. Here $\hbar\omega_g=E_g$ is the band gap of semiconductor $\omega_{k_\perp}=\hbar k_\perp^2/2m_r$, $m_r=m_em_h/(m_e+m_h)$ is the reduced electron and a hole mass. f_N^e and f_N^h are Fermi-Dirac distributions of electrons and holes. The successions of energy subbands are labeled by the quantum numbers N=1,2,3… The constant α_0 looks like:

$$\alpha_0=\frac{2^{5/2}e^2P_{cv}^2m_r^{3/2}}{cnm_0^2\hbar^{5/2}\omega_g}\left(\frac{\hbar}{2m_rd_0^2}\right)^{1/2} \quad (2)$$

Here c is the speed of light, and n is refraction index , m_0 is mass, e is electron charge, P_{cv} is matrix element of the momentum projection on light polarization direction.

Functions C ($k_\perp$) and g (t) characterize the electron and hole interaction with plasma and lattice vibrations.

Without taking into account a Coulomb interaction, in free carrier approximation C ($k_\perp$) = 1 and g (t) = 0 and we obtain the known result for the coefficient of interband absorption in quantum wells as a superposition of step functions [1-5]. At low concentrations of plasma Coulomb or Sommerfeld factor C ($k_\perp$) looks like [1]:

$$C(k_\perp)=\frac{\exp\{q(k_\perp)\}}{\cosh\{q(k_\perp)\}},\quad q(k_\perp)=\frac{\pi}{a_Bk_\perp},\quad a_B=\frac{\hbar^2\varepsilon_0}{m_re^2}, \quad (3)$$

Let's consider, that for a screened two-dimensional exciton, C ($k_\perp$) also looks like (3), but q we shall calculate with account of interaction with plasma. Using screened Coulomb interaction as perturbation, we find:

$$q(k_\perp)=\frac{2}{\pi}\frac{\lambda_0}{a_B}\int\frac{1}{1+\lambda_0|k'_\perp-k_\perp|}\frac{dk'_\perp}{k'^2_\perp-k_\perp^2}=4\frac{\lambda_0}{a_B}\mathrm{Re}\frac{1}{\sqrt{1-4\lambda_0k_\perp^2}}\ln\frac{1+\sqrt{1-4\lambda_0k_\perp^2}}{2\lambda_0k_\perp} \quad (4)$$

When the screening length λ_0 satisfies the inequality $\lambda_0 k_\perp \gg 1$, function q ($k_\perp$) (4) transfers in $q(k_\perp)=\pi/a_Bk_\perp$ (3). According to expression (4), plasma screening decreases the influence of Coulomb electron and a hole attraction on the transition probability. As a result of screening, near to the light absorption threshold ($k_\perp$ = 0), the power dependence $q \sim 1/k_\perp$ (3) is replaced logarithmic (4). The screening length is determined by the expression:

$$\frac{1}{\lambda_0}=\frac{2}{a_B}\left\{\frac{m_e}{m_r}\sum_N f_N^e(0)+\frac{m_h}{m_r}\sum_N f_N^h(0)\right\} \quad (5)$$

At performance of the inequality $\hbar^2 k_\perp^2 / 2m\, k_0 T << 1$ the screening length depends on electron and hole number, which momentum $\hbar k_\perp$ along the interface is equal to zero.

In case of electron - hole pair weak interaction with plasma and lattice oscillations, the main contribution to integral on time (1) is given by values t→ ∞, but absorption coefficient $\alpha(\omega)$ can be represented as a superposition of Lorentzian lineshape functions. At a strong e-h pair coupling with plasma, the limit of small t is actual, but function g(t) can be represented by expression:

$$g(t) = \frac{1}{2}\sigma t^2 + N_{LO} e^{i\omega_{LO} t}, N_{LO} = \alpha_e \left(1 + \sqrt{\frac{m_h}{m_e}}\right) n(\omega_{LO}) \qquad (6)$$

Here the weak coupling with longitudinal optical phonons is taken into account. α_e is Frohlich coupling constant for electrons, n (ω_{LO}) is phonon number , and σ is the second moment of absorption band that looks like:

$$\sigma = \frac{2}{\pi\hbar} \sum_{\kappa_\perp} V_{\kappa_\perp} \int_0^\infty \mathrm{Im}\left\{\frac{\varepsilon_0}{\varepsilon^*(\kappa_\perp, \omega)}\right\} cth\, \frac{\hbar\omega}{2k_0 T} d\omega\,, \quad V_{\kappa_\perp} = \frac{2\pi e^2}{\varepsilon_0 A \kappa_\perp} \qquad (7)$$

Two-dimensional Coulomb interaction $V_{\kappa_\perp}$ (7) is dynamically screened by plasma, which oscillation frequencies are determined by zeros of the dielectric function $\varepsilon(k_\perp, \omega)$.

At high temperatures $k_0 T > \hbar\omega_p$, $\omega_p = \left(\frac{4\pi n e^2}{\varepsilon_0 m_r}\right)^{1/2}$, using the approximation

$cth\, \frac{\hbar\omega}{2k_0 T} \approx \frac{2k_0 T}{\hbar\omega}$ and a sum rule one obtains :

$$\sigma = \frac{e^2 k_0 T}{\hbar^2 \varepsilon_0} \int_0^\infty d\kappa_\perp \left(1 - \frac{\varepsilon_0}{\varepsilon(\kappa_\perp, 0)}\right) = \frac{4^{5/3}\pi^{4/3}}{3^{3/2}\hbar^2} Ry\, k_0 T \left\{\frac{d_0 a_B^2}{m_r}(m_e + m_h) n\right\}^{1/3} \qquad (8)$$

Here n is the concentration of plasma. Substituting g (t) (6) in expression (1) for the absorption coefficient and integrating on time, we find with account of LO-phonon satellites:

$$g(\omega) = \sqrt{\frac{\pi}{2\sigma}} \alpha_0 \frac{\omega_g}{\omega} \sum_{N0} \int C(k_\perp) \{f_N^e(k_\perp) + f_N^h(k_\perp) - 1\} \sum_{j=0}^\infty \frac{(N_{LO})^j}{j!} \exp\{-\frac{(\omega - \omega_g - \omega_N - \omega_{k_\perp} + j\omega_{LO})^2}{2\sigma}\} d\omega_{k_\perp} \qquad (9)$$

The strong electron and hole coupling with plasmons is valid at performance of the inequality :

$$k_0 T Ry < (\hbar\omega_p)^2 \quad \left(Ry = \frac{e^2}{2\varepsilon_0 a_B}\right) \qquad (10)$$

2. Results and discussion

The light gain frequency dependence in case of strong charge carrier interaction is determined by processes of absorption and radiation of several oscillation quanta of two-dimensional plasma and several optical phonons.

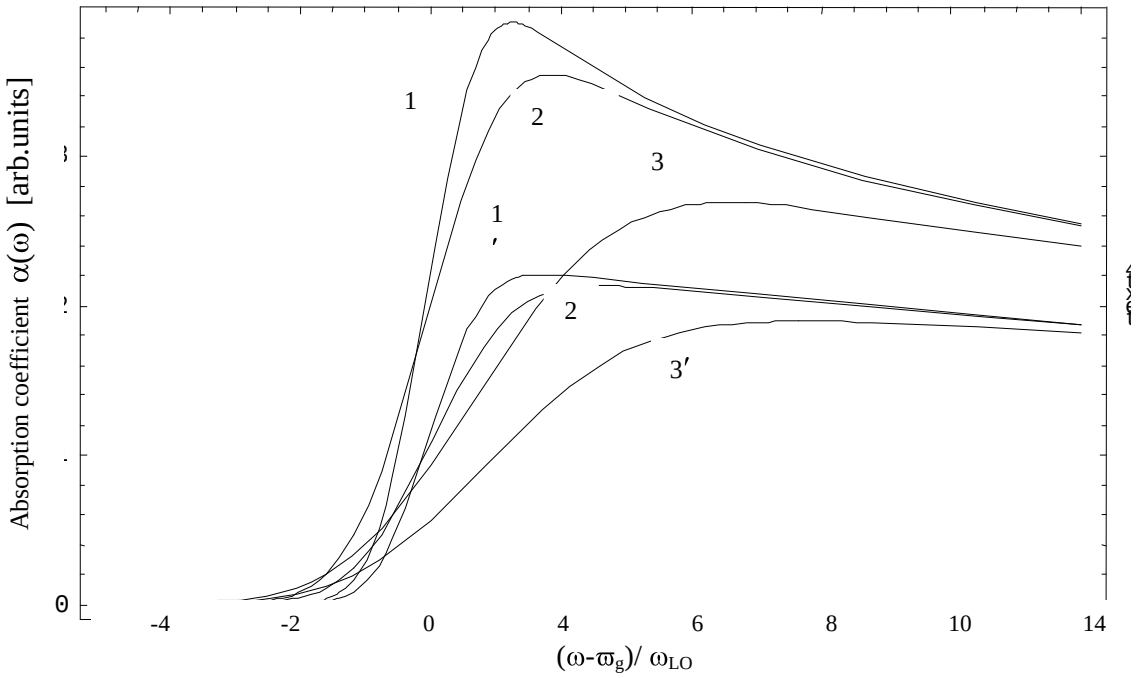


Fig.1. Absorption coefficient $\alpha(\omega)$ frequency dependence of 10 nm GaAs quantum well at T=300K and at different plasma concentrations 1,1′- n =10^{16}cm^{-3}, 2,2′- n =10^{17}cm^{-3} and 3,3′- n=10^{18}cm^{-3} , $\hbar\varpi_g=E_g+\hbar^2\pi^2/2m_rd_0^2$.

Figure.1 is a plot of the absorption spectra for different plasma concentration. In the absence of doping, the total carrier density is the same for electrons and holes. For each of two groups the top curves 1,1′ are for n =10^{16}cm^{-3}, the middle 2,2′ for n =10^{17}cm^{-3} and the bottom 3,3′ for n=10^{18}cm^{-3}. Curves 1,2,3 are the absorption spectra calculated with account of Sommerfeld enhancement factor, 1′, 2′, 3′ at C ($k_\perp$) = 1. The attractive Coulomb interaction between electrons and holes is responsible for the absorption increase, when compared to the free-carrier approximation C ($k_\perp$) = 1, but plasma screening leads to the decrease in it. At low plasma concentrations n = 10^{16} – 10^{17} cm^{-3} the absorption coefficient $\alpha(\omega)=-g(\omega)$ (9) looks like a step. With growth of plasma concentration n, the frequency dependence is flattened, and the absorption threshold is shifted in the long-wave region of a spectrum. These features are represented in figure1. And at last, at n ≅2· 10^{18} cm^{-3} there is an amplification.

Results of numerical calculation of laser amplification spectrum of 8 nm $In_{0.05}Ga_{0.95}As$ quantum well under formula (9), using (3), (4) and (8) formulas, at a surface plasma density $nd_0 = 1.56, 1.60, 1.64 \cdot 10^{12}$ cm $^{-2}$ are shown in figure 2. Apparently from the figure, the theoretical results and experimental data [11] shown on a parenthesizing of figure 2, are in agreement between themselves.The gain value $g = 50$ cm $^{-1}$ is obtained at $nd_0 = 1.64 \cdot 10^{12}$ cm $^{-2}$, that approximately is twice less, than in the theory [11]. The experimental value of n in paper [11] is not given. Injection currents have been 5, 7.5, 10, 15, 20 mA [11].

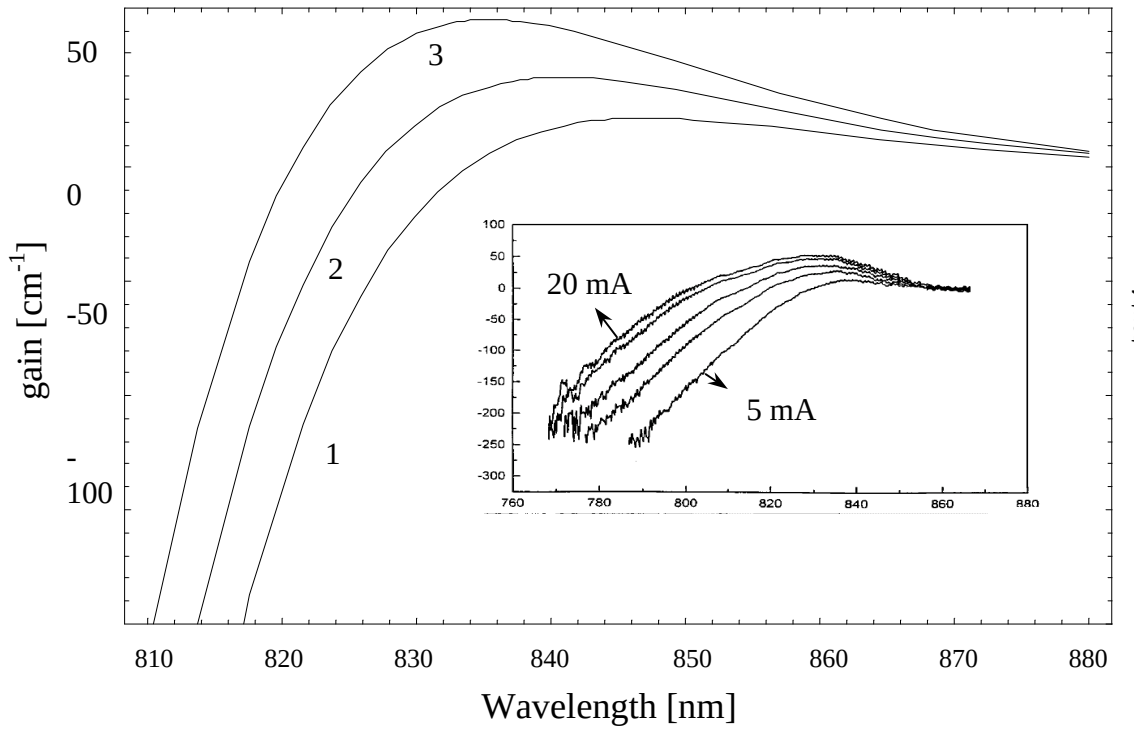


Fig.2. Laser gain spectra designed unde formula (9) with account of transitions between two subbands (N = 1) and functions (3), (4) and (8) at the following values of parameters: T = 300 K, m_e = 0,0648 m_o, m_h = 0,476 m_o, E_g = 1,42 eV, $\hbar\omega_{LO}$=35meV, α_e=0,07, ε_0=13,13 ε_∞=11,1. Surface density of electrons are 1-1.56, 2-1.60, 3-1.64×10^{12}см$^{-2}$. Experimental gain spectra are measured at the following injection currents 5, 7.5, 10, 15, 20 mA [11].

Two - dimensional plasma approach is valid for a narrow quantum well. For an arbitrary width well one obtains:

$$\omega_p^2(\kappa_\perp) = \frac{4\pi n e^2}{\varepsilon_0 m_r}\left(1 - e^{-\frac{\kappa_\perp d_0}{2}}\right) \qquad (11)$$

For $\kappa_\perp d_0 < 1$ formula (11) gives known result for two-dimensional plasma $\omega_p^2 = 2\pi n e^2 d_0 \kappa_\perp / \varepsilon_0 m_r$ [1-5], whereas at $\kappa_\perp d_0 > 1$ plasma behaves as volumetric. In a

three-dimensional case plasma oscillations are similar to longitudinal optical lattice oscillations and multi-plasmon processes determine an equidistant thin structure of emission bands [6-10]. Thus, the multi-plasmon satellites of radiation lines, under condition of plasma oscillation existence $\omega\tau \gg 1$ where τ is the plasmon lifetime , may be also allowed in case of wide quantum wells. Optical properties of wide quantum wells have been explored in papers [12-14]. Gossard with co-authors [14] have found out, that photoexcitation spectra of wide (4000 E) $GaAs/Al_xGa_{1-x}As$ quantum wells in which x was incremented from zero near the interface, up to x = 0,3 in the middle of the well, consist of a series of equidistant peaks, parted energy distance about 3 meV. This equidistant structure has been attributed by authors of paper [14] to the parabolic shape of the quantum well and to the equidistant electron and hole energy spectrum . In our opinion the equidistant structure may be caused by resonant radiation of several plasmons alongside with a photon. For the benefit of our guess quantity of plasmon energy $\hbar\omega_p \cong 3$ meV meets to a surface density of electrons $nd_0 \cong 10^{12}$ cm^{-2} given in paper [14] speaks, first. Except for that in work [14] the magnification of distance between peaks was observed at a doping of donor silicon strata which can be also easily explained by the multi-plasmon mechanism of radiation, namely - magnification of energy plasmon with increasing of an electron plasma concentration.

References

[1] H.Haug and S.W.Koch, *Quantum Theory of the Optical and Electronic Properties of Semiconductors*, (World Scientific 1990, Second edition), 1993.

[2] W.W.Chow, S.W.Koch, M.Sargent, *Semiconductor Laser Physics.* (Springer, Berlin, Heidelberg), 1994.

[3] M.Kira, W.Hoyer, S.W.Koch, *Phys. Stat. Sol.* (*b*), V.238,N3, P.443-450, (2003).

[4] G.Bastard. *Wave mechanics applied to semiconductor heterostructures*, (Ed. de Phys., Lesulis), 1988.

[5] A.Shik. *Quantum Wells*,(World Scientific), 1988.

[6] A. A. Klyukanov, N. A. Loiko, I. V. Babushkin, V. Gurau, *Proceedings of SPIE*, V. 47-48, p. 301-312, (2002)

[7] A. A. Klyukanov, N. A. Loiko, I. V. Babushkin, *Laser Physics* ,V.11, N.3, 318, (2001).

[8] В.С.Вавилов, А.А.Клюканов, К.Д.Сушкевич, М.В.Чукичев, А.З.Ававдех, Р.Р.Резванов, *ФТТ*, Т.41, N.7, 1176, (1999) .

[9] В.С.Вавилов, А.А.Клюканов, К.Д.Сушкевич, М.В.Чукичев, А.З.Ававдех, Р.Р.Резванов, *ФТТ*, Т.43, N.5, 776, (2001).

[10] А.А. Клюканов. *ФТТ*, Т.29. С.1529, (1987).

[11] C. Ellmers, M.Hofmann, W.W.Ruhle, A. Girndt, F.Jahnke, W.W.Chow, A. Knorr, S.W.Koch, C Hanke, L.Korte, C.Hoyler, *Phys. Stat. Sol. (b)*, V.206, P.407-412, (1998).

[12] I.H. Burnett, H.H. Cheong, W. Paul, P.F. Hopkins, A.S. Gossard, *Phys.Rev. B.*, V.48, N.11, pp.7940-7943, (1993-I).

[13] H. Fritze, W. Chen, A.V. Nurmiko, J. Jo, M. Santos and Sheyegan, *Phys.Rev. B.* V.48, N20, 15103 – 15111, (1993-II).

[14] I.H. Bunett, H.H. Cheong, W. Paul, P.F. Hopkins, E.G. Gwinn, A.I. Rinberg, R.M. Westervelt, M. Sundaram, A.S. Gossard, *Phys.Rev. B.* V.43, N.14, pp.12033-12035, (1991).