Proceedings Symposium IEEE/LEOS Benelux Chapter, 2004, Ghent

Polarization Characterized Band Model for Layered Semiconductors

W. Wang, K. Allaart and D. Lenstra

Department of Physics and Astronomy, Vrije University Amsterdam, De Boelelaan 1081, 1081 HV, and COBRA Research Institute, Eindhoven, The Netherlands

We propose a band model for layered III-V semiconductors, by reconfiguring the conventional band structure according to the polarization properties of the optical transitions of the carriers. This band model enables to conveniently investigate the light cross phase modulation and cross gain modulation with different polarizations in semiconductor optical amplifiers. It also provides a simple tool to study related ultrafast processes in terms of the carrier dynamics in polarization characterized bands, interacting with the corresponding TE or TM polarized optical fields. corresponding polarized optical field.

Introduction

The ultrafast dynamics of the polarization dependent gain in a semiconductor is attracting much interest. In the semiconductor band structure the optical transitions of the carriers have mixed polarization. This complicates the calculation of the polarization gain, especially for semiconductors with a band structure that is perturbed by, for instance, strain. We introduce a simplified picture, with an effective band structure characterized by polarization of the optical transitions. The carrier distribution dynamics in this polarization characterized band model is directly coupled to the corresponding polarization gain dynamics.

Theory

For a zinc blende semiconductor of direct band gap and large spin-orbit energy separation, the lattice periodic part of the Bloch functions of the heavy hole and light hole bands may be written for small electron wave vector $\vec{k}_e$ as [1]:

$$\Phi_{3/2,m'=\pm 3/2} = \frac{1}{\sqrt{2}}[(\cos\theta\cos\phi \mp i\sin\phi)|X\rangle + (\cos\theta\cdot\sin\phi \pm i\cos\phi)|Y\rangle - \sin\theta|Z\rangle]|\downarrow\uparrow\rangle \quad (1)$$

$$\Phi_{3/2,m'=\pm 1/2} = \frac{1}{\sqrt{6}}[(\cos\theta\cos\phi \mp i\sin\phi)|X\rangle + (\cos\theta\cdot\sin\phi \pm i\cos\phi)|Y\rangle - \sin\theta|Z\rangle]|\downarrow\uparrow\rangle - \frac{2}{\sqrt{6}}[(\sin\theta\cos\phi)|X\rangle + (\sin\theta\sin\phi)|Y\rangle + \cos\theta|Z\rangle]|\uparrow\downarrow\rangle \quad (2)$$

where $|X\rangle$, $|Y\rangle$ and $|Z\rangle$ are p-like functions, θ and ϕ represent the orientation of the electron wave vector $\vec{k}_e$, as shown in Fig. 1, $|\uparrow\downarrow\rangle$ are the spin functions for spin parallel or antiparallel to the direction of $\vec{k}_e$. The simplicity of these expressions is somewhat deceiving, as it uses two reference frames. The spin functions and the magnetic quantum numbers m' refer to a coordinate frame of which $\vec{k}_e$ is the z-axis, so a $\vec{k}_e$ dependent frame, whereas the three p-functions $|X\rangle$, $|Y\rangle$ and $|Z\rangle$ refer to the laboratory frame. For a layered

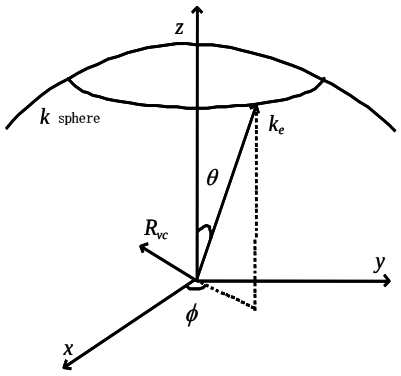

Figure 1: Coordinate system used in analysis, where the *y*-direction is the light propagation direction, the z-direction is the heterostructure growth direction and that of light TM polarization, the x-direction is that of TE polarization. k_e is the electron wave vector, θ and ϕ denote its orientation. R_{cv} is the optical transition dipole moment, which lies in the plane perpendicular to the k_e.

structure one chooses the growth direction as one axis, in the following the *z*-axis. For the direction of the light propagation, we adopt the *y*-axis and the *x*-axis is then transverse to the light propagation and parallel to the layers. A light wave with electric vector along this *x*-axis is called *x*-polarized light, or in the spirit of wave guiding TE light. Light with electric polarization along the *z*-axis will also be referred to as TM light. The merit of the given expressions for the heavy-hole and light-hole functions is that they display to which component of the electric light field vector each of the terms couples. For the components $|X\rangle$, $|Y\rangle$ and $|Z\rangle$ correspond to the *x*, *y* and *z* direction of the transition dipole matrix element $\vec{R}_{cv}$ of the recombination of the hole with a conduction electron and the interaction Hamiltonian is proportional to the scalar product of the electric field vector with this transition dipole: $\vec{E} \cdot \vec{R}_{cv}$. Particularly noteworthy is that for the heavy-hole band, which is dominant because of its large state density, the direction of $\vec{R}_{cv}$ is always orthogonal to the wave vector $\vec{k}_e$ of the electronic state, as shown in Fig. 1.

Averaged over all directions of $\vec{k}_e$ the weight of the components $|X\rangle$, $|Y\rangle$ and $|Z\rangle$ is equal in the heavy hole as well as in the light hole states. So with random orientation of the $\vec{k}_e$ of the charge carriers there will be no anisotropy of light emission or absorption. This situation changes when there is a preferred direction in the semiconductor material, usually the growth direction, for instance due to strain. Then there may be an energy splitting δ between the $p_{3/2}$ valence bands already at the Γ point, $k_e = 0$. Together with the well known Luttinger Hamiltonian with parameters γ_1 and $\bar{\gamma} = \gamma_2 = \gamma_3$ [2] the energy of the bands now depends on the direction of $\vec{k}_e$ as

$$E(k_e) = -\frac{\hbar^2}{2m_0}\gamma_1 k^2 \pm \{\frac{\hbar^4}{4m_0}\bar{\gamma}^2 4k^4 + \frac{\delta\hbar^2\bar{\gamma}}{2m_0}(2k_z^2 - k_x^2) + \frac{\delta^2}{4}\}^{1/2}. \quad (3)$$

This band structure is plotted in Fig. 2, in which the positive horizontal axis gives the value of k_x and the negative axis the value of k_z. The explicit expression of the corresponding wave functions becomes rather complicated and thereby lacks transparency regarding the polarization properties of the emitted light. One may however resort to a

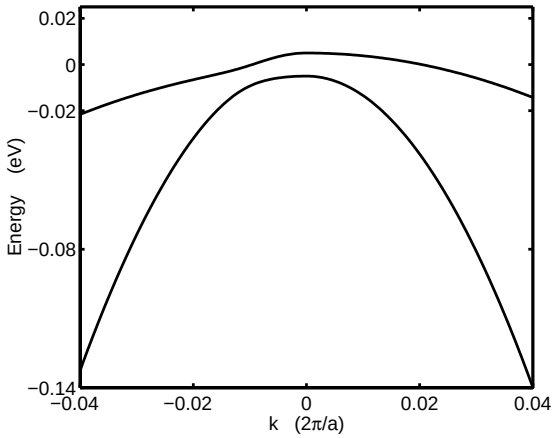

Figure 2: Calculated band structure of strained bulk semiconductor. The positive horizontal axis gives k_x and the negative axis k_z.

simple and transparent model based on the picture shown in Fig. 2. The energies of the upper bands with heavy effective mass are not symmetric in the two directions of $\vec{k}_e$; the z and the x direction. For $\vec{k}_e$ in the z direction it is to a good approximation δ higher than for $\vec{k}_e$ in the x direction. Because of the orthogonality of $\vec{k}_e$ and the transition dipole $\vec{R}_{cv}$, this implies that the states of the heavy-hole band that couple to TE polarized light are higher in energy than those that couple to TM polarized light, which will give rise to anisotropic gain or absorption. The same is true for the lower, light hole, band in Fig. 2.

As an effective model, which exposes the polarization dependent properties of the semiconductor in a simple and clear way, we therefore introduce an effective two-band model. One band contains carrier states that couple to x-polarized (TE) light and which is shifted in energy by a certain amount δ with respect to the other band which couples only to z-polarized (TM) light. These bands may be given an effective model mass $1/m^* = 1/m_h + 1/m_l$, to include approximately the contribution of the light-hole band. In this way we have obtained a simple and fertile, yet realistic model to simulate gain and absorption anisotropy in semiconductors in which, for some reason, for instance strain, the growth direction is singled out and thereby the full intrinsic anisotropy broken.

This band model enables to easily calculate the polarization dependence of the gain in terms of the carrier distribution over these effective TE and TM bands. In Fig. 3 we show a calculated carrier density anisotropy as a function of the total carrier density for an assumed splitting of 5 meV between the TE and TM band. At small carrier density, that is low pump current, the ratio of the carrier densities in both bands is 0.83; at higher density it becomes 0.9 or more, due to band filling effects. In the study of the ultrafast polarization dependent gain dynamics, this band model simplifies the gain calculation by following the temporal carrier density in each band. A similar method has been adopted in a phenomenological rate equations approach, assuming two kind of holes characterized by the light polarization that they give rise to [3].

Our effective two-band model also lends itself to easy simulation of polarization dynamical processes, that may be represented as transitions of the carriers between the TE and TM band. These processes are expected to lead to ultrafast gain and phase dynamics.

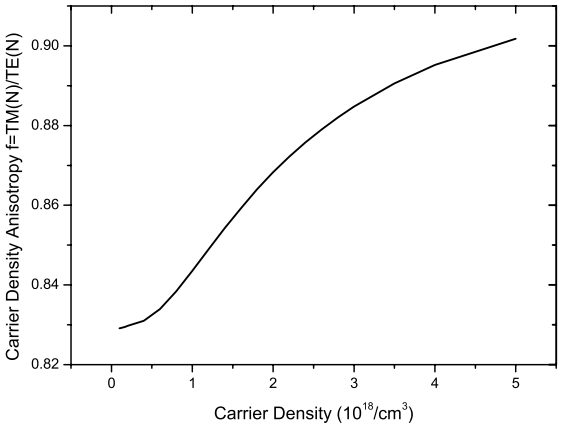

Figure 3: Carrier density anisotropy f as a function of the total carrier density. This factor f is the ratio between the carrier density attributed to the TM mode amplification and that of the TE mode amplification

Conclusion

We propose a III-V semiconductor band structure model, by reconfiguring the conventional band structure according to the polarization properties of the optical transitions of the carriers. This effective band structure model enables to conveniently investigate the light gain according to its polarization by studying the carrier distribution in the corresponding bands.

References

[1] M. Yamanishi and I. Suemune, "Comment on polarization dependent momentum matrix elements in quantum well laser," *Japanese J. Appl. Phyisics.*, vol. 23, pp. L35-L36, Jan. 1984

[2] W. W. Chow, S.W. Koch and M. Sargent, Semiconductor-Laser Physics, *Springer-Verlag*, Berlin, 1994

[3] X. Yang, D. Lenstra, G.D. Khoe, and H.J.S. Dorren, "Nonlinear polarization rotation induced by ultrashort optical pulses in a semiconductor optical amplifier," *Optics Communications*, vol, 223, pp. 169-179, 2003