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Spin polarization in GaAs LED, the effect of phonon interaction

Sukanta Kumar Tripathy [a,*], Deepanjali Misra [b]

[a] Department of Electronics and Communication Engineering, National Institute of Science and Technology, Palurhills, Berhampur, Odisha 761008, India
[b] Department of Physics, National Institute of Science and Technology, Palurhills, Berhampur, Odisha 761008, India

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ABSTRACT

We present a model based on quantum Langevin equation for degree of spin polarization of the light emitted from GaAs LED. Using this model the effect of electron–phonon interaction on spin polarization at constant magnetic field and room temperature is investigated. Variation of degree of polarization with temperature and magnetic field for different values of electron–phonon interaction is also studied. It is found that electron–phonon interaction favors the degree of polarization at given temperature and magnetic field.

1. Introduction

Spin injection from a spin filter in to a semiconductor is one of the hot topics in spintronics. Number of materials are investigated for spin aligner, for example $Be_xMn_yZn_{1-x}Se_{1-y}$, ZnMnSe, $Ga_{1-x}Mn_x$ As, ferromagnetic materials are used as spin polarized source for GaAs light emitting devices. Experiments using these materials were only at low temperature. Besides selection rules for radiative recombination process, which directly relate the spin orientation of the carriers transported to the active region to the polarization of photons emitted, there are other factors like temperature dependence of 'g' factor, noise due to thermal light emission, blur the detected light degree of polarization which are to be considered while investigating such devices. Temperature dependence of 'g' factor results in low efficiency in spin polarization carrier injection at high temperature. Further external magnetic field applied to a bulk material lifts the degeneracy. Thus a thorough investigation of the temperature and magnetic field effects on the spin polarization photon emission and detection is necessary. There are few references [1,3,4] where temperature and magnetic field dependence of spin polarization in GaAs LED have been investigated.

Recently, the effect of electron–phonon interaction on spin polarization in Metal Insulated Semiconductor (MIS) LED is investigated experimentally [9]. Based on these findings, it is obvious to assume that efficiency of spin polarization photon emission from GaAs LED, to be effected by electron–phonon interaction.

In this paper, we analyze the temperature and magnetic field dependence of GaAs emitted light degree of polarization with respect to electron–phonon interaction. We used quantum Langevin equation, where the Hamiltonian is expressed as a sum of different charge carriers and their interaction in second quantization. Our investigation is different from Ref. [1], in the sense that, we have included the electron–phonon interaction for the first time to investigate its role in spin polarization of the emitted light from LED.

This paper is organized as follows. In Section 2, theoretical formulation of our model is presented. The degree of polarization is obtained in terms of rate of absorption and emission from allowed transitions mentioned in Fig. 1. Simulation results and analysis are presented in Section 3. Finally, conclusions made in Section 4.

2. Theoretical model

In the presence of magnetic field the polarized photons and carrters in the active layer of LED is given by the Hamiltonian [1]

$$H = H_c + H_p + H_d + H_m + H_{mb} \tag{1}$$

where H_c is Hamiltonian for free carriers and is given as

$$H_c = \sum_k \left(\sum_\mu \varepsilon_{ck\mu} c^\dagger_{k\mu} c_{k\mu} + \sum_{\mu'} \varepsilon_{v-k\mu'} d^\dagger_{-k\mu'} d_{-k\mu'} \right) \tag{2}$$

where $c_{k\mu}$ and $d_{-k\mu'}$ are annihilation operators for electron with momentum k and spin μ and holes with momentum $-k$ spin μ' respectively. $\varepsilon_{ck\mu}$ and $\varepsilon_{v-k\mu'}$ are the conduction and valence band energy respectively.

* Corresponding author. Tel.: +91 680 249 2421/2422; fax: +91 680 249 2627.
E-mail addresses: sukantakutrpathy@yahoo.co.in (S.K. Tripathy), deepanjali.misra@gmail.com (D. Misra).

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H_p is the Hamiltonian due to multi photonic process and is represented by the Hamiltonian

$$H_p = \sum_{l\mu\mu'} \hbar \nu_l a^{\dagger}_{l\mu\mu'} a_{l\mu\mu'} \tag{3}$$

Here ν_l is the frequency of photon in lth mode for spin transition μ to μ' and $a_{k\mu\mu'}$ is the bosonic annihilation operator.

The dipole interaction is described by

$$H_d = \sum_{lk\mu\mu'} \hbar (g_{lk\mu\mu'} d^{\dagger}_{-k\mu'} c^{\dagger}_{k\mu} a_{l\mu\mu'} + g^{*}_{lk\mu\mu'} d_{-k\mu'} c_{k\mu} a^{\dagger}_{l\mu\mu'}) \tag{4}$$

where $g_{lk\mu\mu'}$ is the dipole coupling constant. The effect of the many body interaction is included in the renormalized parameters of $\varepsilon_{ck\mu}$, $\varepsilon_{v-k\mu'}$ and $g_{lk\mu\mu'}$ using a mean field approximation.

Magnetic field Hamiltonian is given by

$$H_m = \mu_B B_z \sum_{k} \left(\sum_{\mu\nu} G_e S_{c\mu\nu} c^{\dagger}_{k\mu} c_{k\mu} + \sum_{\mu'\nu'} G_h S_{c\mu'\nu'} d^{\dagger}_{-k\mu'} d_{-k\mu'} \right) \tag{5}$$

Here μ_B is Bohr magnetron, $G_e(h)$ is electron (hole) Landau g-factor and $S_{c\mu\nu}$ and $S_{v\mu'\nu'}$ are spin matrices of electrons and holes. B_z is the magnetic field strength.

In addition to the above interactions, we consider phonon interaction, which is represented by the Hamiltonian

$$H_{ph} = \sum_{q\mu\mu'} \hbar \omega_q f^{\dagger}_{q\mu\mu'} f_{q\mu\mu'} + i \sum_{kq} D_q [f_{q\mu\mu'} (c^{\dagger}_{kq\mu} c_{k\mu} + d^{\dagger}_{-kq} d_{-k\mu'}) - f^{\dagger}_{q\mu\mu'} (c^{\dagger}_{k-q\mu} c_{k\mu} + d^{\dagger}_{-k-q\mu'} d_{-k\mu'})] \tag{6}$$

where $f_{q\mu\mu'}$ is bosonic annihilation operator for lattice vibration or phonon. D_q is phonon interaction co efficient and ω_q is the natural frequency for lattice vibration. When the magnetic field is oriented along the device, the Langevin equation for the dipole operator $\sigma^{\mu\mu'}_k (= d_{-k\mu'} c_{k\mu} e^{i\nu_l t})$ and for the photon annihilation operator $A_{l\mu\mu'} (= a_{l\mu\mu'} e^{i\nu_l t})$ describing the LED can be expressed as

$$\frac{d\sigma^{\mu\mu'}_k}{dt} = \gamma + \left[\frac{-i}{\hbar} (\varepsilon_{ck\mu} + \varepsilon_{v-k\mu'}) \sigma^{\mu\mu'}_k - i \sum_{l} g_{lk\mu\mu'} (1 - n^{\mu}_{ck} - n^{\mu'}_{h-k}) A_{l\mu\mu'} - \frac{i}{\hbar} \mu_B B_z (G_e S_{c\mu\nu} + G_h S_{v\mu'\nu'}) \sigma^{\mu\mu'}_k - \frac{4i}{\hbar^2} \frac{D_q^2 \omega_q n_k}{(\gamma_1^2 + \omega_q^2)} \right] + F^{\mu\mu'}_{\sigma k} \tag{7}$$

And

$$\frac{dA_{l\mu\mu'}}{dt} = \left[-\frac{k^0_l}{2} + i(\nu_l - \Omega_l) \right] A_{l\mu\mu'} - i \sum_{k} g^{*}_{lk\mu\mu'} \sigma^{\mu\mu'}_k + F_l \tag{8}$$

in above two equations γ is rate of dipole dephasing and k^0_l is field decay, $F^{\mu\mu'}_{\sigma k}$ and F_l are the fluctuation terms for the carriers and the field respectively, Ω_l is the passive cavity frequency, n_k is number operator for charge carriers and γ_1 is a constant introduced phenomenological. In the slow varying regime for adiabatic approximation, the solution of Eq. (7) can be obtained as

$$\sigma^{\mu\mu'}_k = \frac{i \sum_l g_{lk\mu\mu'} (n^{\mu}_{ck} + n^{\mu'}_{d-k} - 1) A_{l\mu\mu'} + F^{\mu\mu'}_{\sigma k}}{\gamma + i/\hbar [\mu_B B_z (G_e S_{c\mu\nu} + G_h S_{V\mu'\nu'}) + (\varepsilon_{ck\mu} + \varepsilon_{vk\mu'} - \hbar\nu_l) - 4/\hbar (\omega_q D_q^2 n_k / \gamma_1^2 + \omega_q^2)]} \tag{9}$$

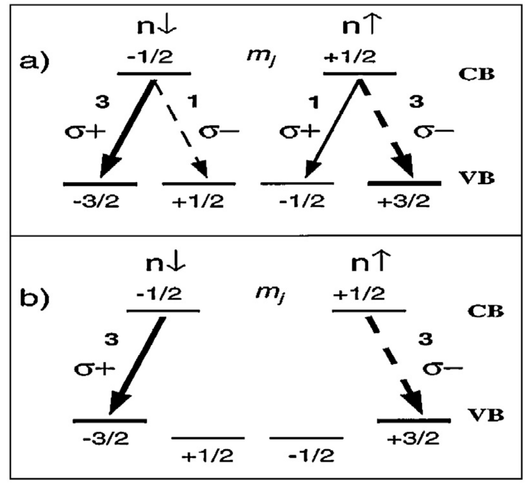

Fig. 1. Allowed transition of spin states.

Substituting Eq. (9) in Eq. (8) and then simplifying it becomes

$$\frac{dA_{l\mu\mu'}}{dt} = \sum_{l} - \left[\frac{k^0_l}{2} + i(\nu_l - \Omega_l) \right] A_{l\mu\mu'} + \sum_{l'} G^{\mu\mu'}_{ll'} A_{l\mu\mu'} + F^{\mu\mu'}_{\sigma l} + F_l \tag{10}$$

where

$$G^{\mu\mu'}_{ll'} = \sum_{l} D_{lk\mu\mu'} g^{*}_{lk\mu\mu'} g_{lk\mu\mu'} (n^{\mu}_{ck} + n^{\mu'}_{dk} - 1)$$

$$F^{\mu\mu'}_{\sigma l} = -i \sum_{k} g^{*}_{lk\mu\mu'} D_{lk\mu\mu'} F^{\mu\mu'}_{\sigma k}$$

and

$$D_{lk\mu\mu'} = \frac{1}{\gamma + (i/\hbar)[\mu_B B_z (G_e S_{c\mu\nu} + G_h S_{V\mu'\nu'}) + (\varepsilon_{ck\mu} + \varepsilon_{vk\mu'} - \hbar\nu_l) - 4/\hbar (\omega_q D_q^2 n_k / \gamma_1^2 + \omega_q^2)]} \tag{11}$$

Defining $d_q = \omega_q D_q^2 n_k / \gamma_1^2 + \omega_q^2$, Eq. (11) can be written as

$$D_{lk\mu\mu'} = \frac{1}{\gamma + (i/\hbar)[\mu_B B_z (G_e S_{c\mu\nu} + G_h S_{V\mu'\nu'}) + (\varepsilon_{ck\mu} + \varepsilon_{vk\mu'} - \hbar\nu_l) - (4/\hbar) d_q]} \tag{12}$$

Here d_q represents the phonon interaction.

As photon number density is $n_{lk\mu\mu'} = A_{l\mu\mu'} A^{\dagger}_{l\mu\mu'}$ and the photon number Langevin equation is

$$\frac{dn_{l\mu\mu'}}{dt} = -k^0_l n_{l\mu\mu'} + \sum_{l'} (G^{\mu\mu'}_{ll'} n_{l\mu\mu'} + G^{\mu\mu' *}_{ll'} n_{l\mu\mu'}) + (F^{\mu\mu'}_{\sigma l} + F_l) A^{\dagger}_{l\mu\mu'} + H.C \tag{13}$$