EFFECT OF ELECTRON-PHONON INTERACTION ON ELECTRON SPIN POLARIZATION IN A QUANTUM DOT LIGHT EMITTING DIODE:

Deepanjali Misra[1] and Sukanta Kumar Tripathy[2]

[1]Department of physics, Berhampur University, Odisha, INDIA
[1]Department of ECE, National Institute of Science and Technology, Berhampur, INDIA

ABSTRACT

This paper presents a theoretical model for the effect of electron-phonon interaction, temperature and magnetic field on degree of electron spin polarization in GaAs/InAs quantum dot LED. To describe the dynamics, quantum Langevin equation for photon number and carrier number is used. Simulation results show that degree of electron spin polarization in quantum dot decreases with increase of electron phonon interaction parameter at constant temperature and constant magnetic field which agrees with experimental results in literatures.

KEYWORDS

Electron-phonon interactions, Quantum dot, Spin polarization.

1. INTRODUCTION

High quality spin polarized electron sources are important for applications in quantum computation, spintronic devices, cryptographic optical communications, optical switching and biomedical engineering. In a spin polarized light source, spin population is transferred from a magnetic contact to a forward biased P-I-N diode. The injected spin reacts in the active region (of PIN), which usually comprises of quantum well structure or quantum dot layer, by both diffusion and drift through a spacer layer. The spin polarized carriers recombine radiatively with the unpolarized carriers injected from a magnetic contact. The resulting emission will exhibit circular polarization if the carriers do not lose their spin orientation due to various relaxation mechanisms. It is shown both by theory as well as experiment [1,2,3], that the degree of spin polarization in LED (GaAs) depends on temperature and magnetic field. In the theoretical investigation we started with formulation of Hamiltonian, which includes terms due to free carriers as well as different interactions. When polarization of electron spin is considered at room temperature, electron phonon interaction cannot be overlooked, since lattice vibration is a common phenomena at higher temperature. Again the interactions of electrons with phonons have been demonstrated to affect greatly the optical properties of semiconductor [4]. Phonons can participate in the nearband emission and in the absorption processes, which leads to enhanced absorption and broadens the emission peak [4]. So we have attempted to find out how the electron phonon interaction effects the polarization of electron spin during radiative recombination in the active zone. We have considered a quantum dot layer In the active region, for quantum dot can be a more suitable recombination media as the spin relaxation time in quantum dot is longer than that of quantum well [5]. Further phonon assisted hoping, where the electrons hop from one dot to a nearby dot by absorbing one or multiple photon proves to be the most likely charge transfer mechanism between two quantum dots [6]. We in this investigation studied the effect of electron phonon interaction on the spin polarization of a LED containing a layer of quantum dots in the active region. For this we model the quantum processes in spin polarized LEDs with a microscopic description using quantum Langevin equation for photon number and carrier number [7]. Particularly we extend the multimodal light emission treatment of [8] by including the effect of electron-phonon interaction on degree of spin polarization where a semiconductor quantum dot is in the epitaxial active region.

2. MODEL

We consider a GaAs LED whose active region comprises a quantum dot layer and model the degree of spin polarization of light emitted in the equilibrium condition with injected carriers. A magnetic field is applied perpendicularly to it to lift the degeneracy of spin and light-heavy hole degeneracy is lifted by confinement. In the presence of magnetic field, perpendicular to the layer, if electron phonon interaction is taken into account inclusion with the Hamiltonians for carriers, incident photons, the total Hamiltonian for the system is ref. [8]

$$H = H_c + H_p + H_d + H_m + H_{e-ph} + H_{ph} \qquad (1)$$

Where H_c is Hamiltonian for free carriers , H_p is the Hamiltonian due to multi photonic process ,the dipole interaction is described H_d using a mean field approximation and Magnetic field Hamiltonian is given by H_m ref [6]. In a quantum dot which is present in the active region, electrons interact with phonons making transition between electronic states. The Hamiltonian for phonon number is $H_{ph} = \hbar w_{\mu k} f_{k\mu}^{\dagger} f_{k\mu}$ and for electron phonon interaction can be written as [9]

$$H_{e-ph} = M_{k\mu} c_{k\mu}{}^{\dagger} c_{k\mu} \left(f_{k\mu} + f_{k\mu}{}^{\dagger} \right) \qquad (2)$$

Here $M_{k\mu}$ is the electron-phonon coupling matrix, which depends on the size of the quantum dot and $f_{k\mu} = \dfrac{Q_{k\mu} n_k}{\hbar(\gamma_q - i\omega_q)}$ is the annihilation operator for electron-phonon interaction, where $Q_{k\mu}$ is the phonon interaction parameter, n_k is total number of free charge carriers, γ_q is coupling constant and ω_q is phonon frequency. To find out the degree of spin polarization of emitted light, dynamics of dipole operator and photon number is considered here and their interactions with carriers and photons is found out by using 2nd quantization method in a Langevin approach. Solving Langevin rate equation for the dipole operator $\sigma_k^{\mu\mu'}\left(=d_{-k\mu'}c_{k\mu}e^{i\nu_l t}\right)$ and following the same procedure as in ref [8], for the slow varying region under adiabatic approximation, we get

$$\sigma_k^{\mu\mu'}=\frac{i\sum_l g_{lk\mu\mu'}(1-n_{ck}^{\mu}-n_{d-k}^{\mu'})A_{l\mu\mu'}+F_{\sigma k}^{\mu\mu'}}{\gamma+\frac{i}{\hbar}\left[\left(\varepsilon_{ck\mu}+\varepsilon_{Vk\mu'}+\hbar\upsilon_l\right)+\mu_B B(G_e S_{ck\mu}+G_h S_{Vk\mu'})+M_{k\mu}Q_{k\mu}W_{kq}\right]} \quad (3)$$

Where, $W_{kq}=\frac{n_k}{\hbar}\left(\frac{2\gamma_q}{\gamma_q^2+\omega_q^2}\right)$ is the electron phonon interaction parameter arrises due to addition of electron phonon interaction in the total Hamiltonian $g_{lk\mu\mu'}$ is the dipole coupling constant, $n_{ck}^{\mu}\left(n_{d-k}^{\mu'}\right)$ is total number of electrons (holes) in conduction (valance) band, $\varepsilon_{ck\mu}$ and $\varepsilon_{Vk\mu'}$ are the conduction and valence band energy respectively, μ_B is Bohr magnetron, $G_{e(h)}$ is electron (hole) Landau g-factor and $s_{c\mu\nu}$ and $s_{\nu\mu'\nu'}$ are spin matrices of electrons and holes. B_z is the magnetic field strength, γ is the rate of dipole dephasing and $F_{\sigma k}^{\mu\mu'}$ is the career fluctuation term. In the denominator, an extra term $M_{k\mu}Q_{k\mu}W_{kq}$ arises due to addition of electron phonon interaction. Similarly solving the langevin rate equation for the photon annihilation operator $A_{l\mu\mu'}\left(=a_{l\mu\mu'}e^{i\nu_l t}\right)$ in a similar way, the rate equation for photon operator is given by

$$\frac{dA_{l\mu\mu'}}{dt}=\sum_l-\left(\frac{k_l^0}{2}+i\left(\nu_l-\Omega_l\right)\right)A_{l\mu\mu'}-\frac{i}{\hbar}\frac{A_{l\mu\mu'}}{a_{l\mu\mu'}}n_k\left(M_{k\mu}+\frac{Q_{k\mu}\omega_q}{(\gamma_q-i\omega_q)}\right)+\sum_{l'}G_{ll'}^{\mu\mu'}A_{l\mu\mu'}+F_{\sigma l}^{\mu\mu'}+F_l$$

(4)

where k_l^0 is rate of field decay and F_l is the fluctuation term for field.

$$G_{ll'}^{\mu\mu'}=\sum_l D_{lk\mu\mu'}g_{lk\mu\mu'}^{*}g_{lk\mu\mu'}\left(n_{ck}^{\mu}+n_{dk}^{\mu'}-1\right)$$

$$F_{\sigma l}^{\mu\mu'}=-i\sum_k g_{lk\mu\mu'}^{*}D_{lk\mu\mu'}F_{\sigma k}^{\mu\mu'}$$

Where $$D_{lk\mu\mu'}=\frac{1}{\gamma+\frac{i}{\hbar}\left[\mu_B B_z\left(G_e S_{c\mu\nu}+G_h S_{V\mu'\nu'}\right)+\left(\varepsilon_{ck\mu}+\varepsilon_{\nu k\mu'}+\hbar\nu_l\right)+M_{k\mu}Q_{k\mu}W_{kq}\right]}$$

As photon number density is $n_{lk\mu\mu'} = A_{l\mu\mu'} A^{\dagger}_{l\mu\mu'}$ [10], and the rate of change of photon number is

$$\frac{dn_{l\mu\mu'}}{dt} = \frac{dA_{l\mu\mu'}}{dt} A^{\dagger}_{l\mu\mu'} + A_{l\mu\mu'} \frac{dA^{\dagger}_{l\mu\mu'}}{dt} \tag{5}$$

Number of photons generated due to radiative recombination of charges in the presence of electron phonon interaction and in the low injection limit is $n_{l\mu\mu'} = n(\nu_l) + \left(R^{\mu\mu'}_{spl} / k^0_l \right)$ (6)

Where $n(\nu_l)$ is the thermal photon number with frequency ν in mode 'l', $R^{\mu\mu'}_{spl}$ is the rate of spontaneous emission given by

$$R^{\mu\mu'}_{spl} = \frac{2\sum_k \gamma \left| g_{lk\mu\mu'} \right|^2 n^{\mu}_{ck} n^{\mu'}_{d-k}}{\gamma^2 + \frac{1}{\hbar^2}\left\{ \mu_B B_z \left(G_e S_{c\mu\nu} + G_h S_{V\mu'\nu'} \right) + \left(\varepsilon_{ck\mu} + \varepsilon_{vk\mu'} + \hbar \nu_l \right) + M_{k\mu} Q_{k\mu} W_{kq} \right\}^2} \tag{7}$$

If $V^{\mu\mu'}_l$ is the photon flux at the active layer, then from input output theory, $V^{\mu\mu'}_l \alpha \ k^0_l n_{l\mu\mu'}$.

At the detector, photon flux $N^{\mu\mu'}_l = \beta_0 V^{\mu\mu'}_l$ and for a broad band frequency detector intensity of light is

$$I = \frac{N^{\mu\mu'}_l}{\beta_0} = V^{\mu\mu'}_l \alpha \ k^0_l n_{l\mu\mu'} \tag{8}$$

Here μ and μ' represent the spin states and l is the mode of spontaneous emission. In this case conduction band has two spin states $+\frac{1}{2}$ and $-\frac{1}{2}$ where as the valance band has four spin states given as $+\frac{3}{2}, -\frac{3}{2}$ (heavy hole) and $+\frac{1}{2}, -\frac{1}{2}$ (light hole). By selection rule the possible transitions from $+\frac{1}{2}$ to $-\frac{1}{2}$, $-\frac{1}{2}$ to $-\frac{3}{2}$ giving σ^+ circularly polarized light and the transition from $+\frac{1}{2}$ to $+\frac{3}{2}$, $-\frac{1}{2}$ to $+\frac{1}{2}$ giving σ^- polarized light. Now from equation (8) intensity of right circular polarized light is $I^{\sigma^+} = k_l^0\left(n_{l-\frac{1}{2}-\frac{3}{2}} + n_{l\frac{1}{2}-\frac{1}{2}}\right)$ and left circularly polarized light is $I^{\sigma^-} = k_l^0\left(n_{l-\frac{1}{2}\frac{1}{2}} + n_{l\frac{1}{2}\frac{3}{2}}\right)$.

As the degree of polarization by definition is given as $P = \frac{I^{\sigma^+} - I^{\sigma^-}}{I^{\sigma^+} + I^{\sigma^-}}$ which for transition between spin states 1/2, -1/2 in conduction band to 1/2, -1/2, 3/2, -3/2 in valance band can be expressed as

$$P = \frac{\sum_l R_{spl}^{-\frac{1}{2}-\frac{3}{2}} + R_{spl}^{\frac{1}{2}-\frac{1}{2}} - R_{spl}^{-\frac{1}{2}\frac{1}{2}} - R_{spl}^{\frac{1}{2}\frac{3}{2}}}{\sum_l\left[\left(R_{spl}^{-\frac{1}{2}-\frac{3}{2}} + R_{spl}^{\frac{1}{2}-\frac{3}{2}} + R_{spl}^{-\frac{1}{2}\frac{3}{2}} + R_{spl}^{\frac{1}{2}\frac{3}{2}}\right) + 4n\left(\bar{\nu}_l\right)\right]} \quad (9)$$

Using equations (9) and (7) we have plotted graphs to show the dependence of degree of spin polarization on temperature and applied magnetic field for different values of electron-phonon interaction parameter. We have also shown the variation of spin polarization with electron-phonon interaction at constant magnetic field of 8T and room temperature for a LED containing quantum dot in active region.

3. SIMULATION RESLTS

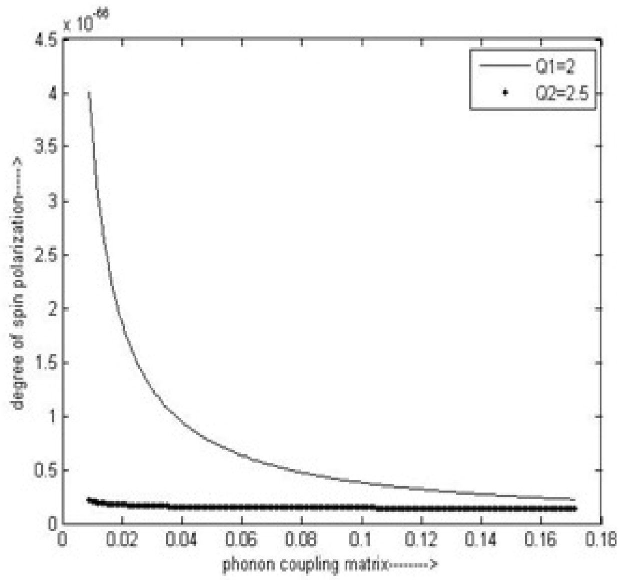

Figure:1(a):Variation of spin polarization with change in coupling matrix

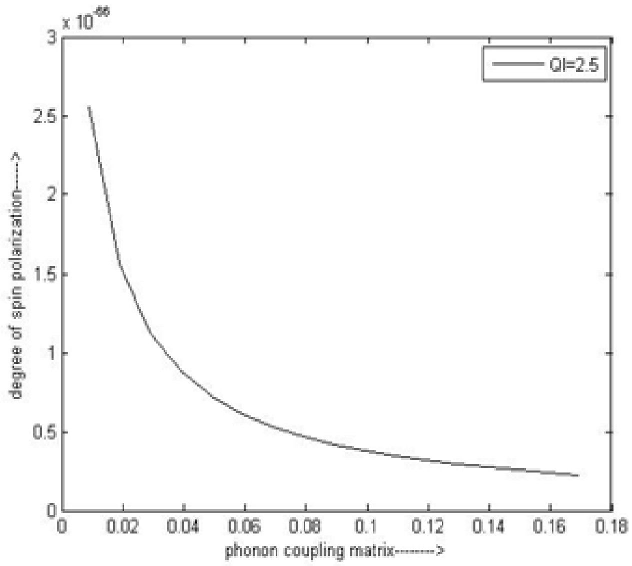

figure1(b): shows concavity of graph decreases with increase of electron phonon interaction parameter.

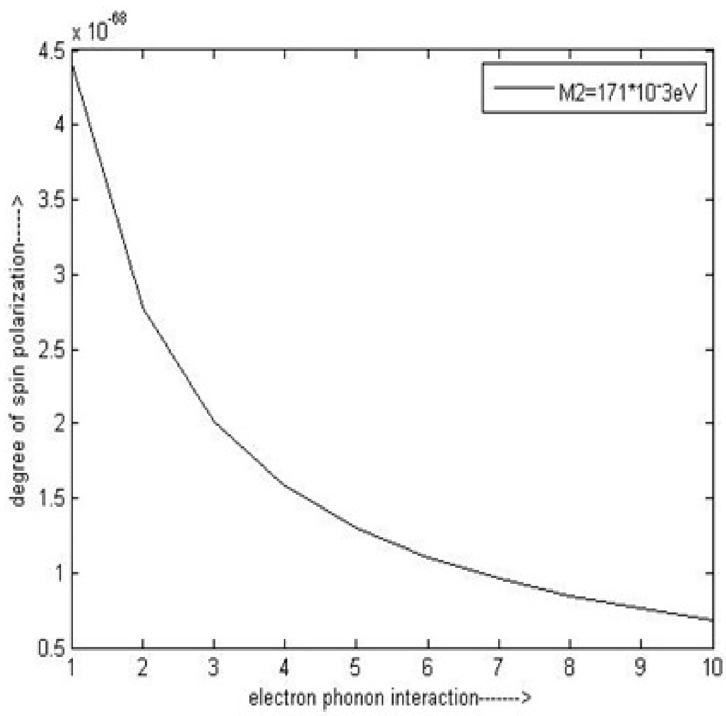

figure:2 Variation of degree of polarization when eph interaction parameter is varied keeping electron phonon coupling matrix constant.

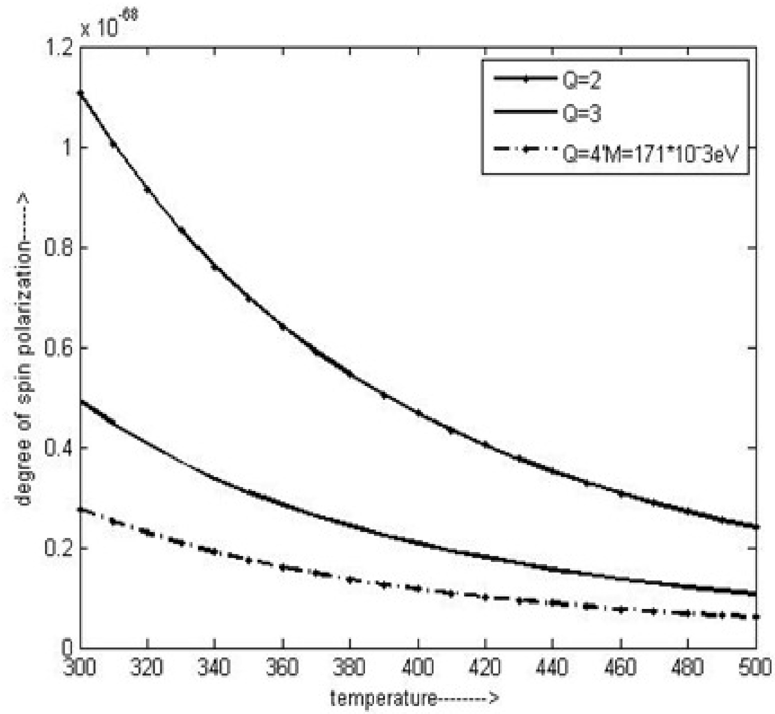

figure:3 variation of degree of spin polarization with temperature for different eph interaction parameter and constant electron phonon coupling matrix.

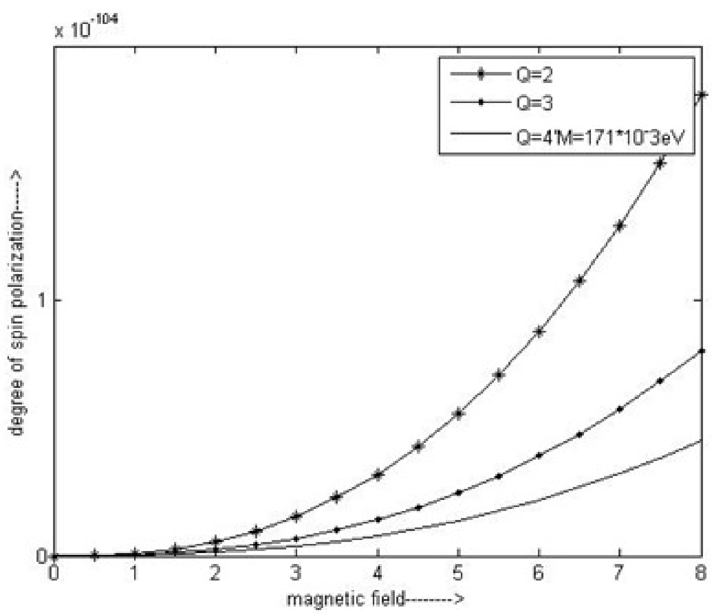

figure:4 variation in degree of spin polarization with applied magnetic field for different eph interaction parameter and constant eph coupling matrix.

4. RESULT ANALYSIS

In fig.1(a) we have shown the variation of degree of spin polarization with electron phonon coupling matrix for a given electron phonon interaction parameter. As electron phonon coupling matrix depends on the size of the quantum dot, fig.1(a) suggests that degree of spin polarization decreases with the increase of the size of the quantum dot. Another important feature, which is interesting is shown in figure 1(b), where the graph is plotted by changing the EPI parameter from Q_1=2 to Q_2=2.5. As shown in figure 1(b) the concavity of the graph increases implying a strong decay of spin polarization compared to fig.1(a) where Q_1=2. The results are direct consequence of equation (3), where dipole operator depends inversely on electron phonon coupling matrix and electron phonon interaction parameter. So a similar graph is also expected for the variation of degree of spin polarization with interaction parameter at a constant coupling matrix value. This is shown in fig.(2). Thus the analysis made so far lead us to conclude that either increase in the size of the quantum dot or electron phonon interaction parameter decreases the degree of spin polarization. The above observations can be explained by using dynamics of coherent inter band polarization. In the absence of phonons polarization is dephased by virtual emissions and radiation damping. On the other hand in the presence of phonons polarization is dephased rapidly by inclusion of phonon scattering with virtual emission and radiation damping. Thus the role of electron phonon interaction here is to decrease the degree of spin polarization. Further increase in size of quantum dots leads to decrease in upper level population density and hence polarization. Increase in temperature, causes spin distortion which also decreases polarization degree. This is shown in Fig:2. Further from Fig:2 it is observed that as the EPI increases, the degree of polarization decreases. Interestingly these results agree with experimental results in ref [2] and ref. [10]. We attribute the decrease in degree of spin polarization with increase of temperature, to the dependence of Landau-g factor on temperature which increases with increase in temperature.

One of the important parameter on which the spin polarization depends is applied magnetic field. This is important because of its use in magneto spintronic devices. In Fig:3 , we have plotted the variation of degree of spin polarization with magnetic field at 300K for different electron phonon interaction. Here the degree of spin polarization increases with increase of strength of applied magnetic field. This agrees with the experimental result in [2].

5. CONCLUSION

We have presented a theoretical model based on quantum Langevin equation to investigate the effect of electron phonon interaction on electron spin polarization in a spin polarized quantum dot LED. The quantum dot is assumed to be in the epitaxial layer of active region. It is found that increase in the electron phonon interaction decreases electron spin polarization. As the electron phonon coupling matrix depends on the size of the quantum dot, the spin polarized light emitted from these LED can be controlled by changing the size of the quantum dot. Thus this investigation reveals a new concept of controlling the spin polarization in quantum dot LED by controlling the size of quantum dot.

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AUTHORS

Deepanjali Misra is a Ph.D. scholar in Berhampur University in Physics.

Sukanta Kumar Tripathy is Prof. in Dept. of ECE in NIST,Berhampur, IEEE member, has about 20 publications in different journals, guided 7 Ph.D. scholars and 5 M.Tech. scholars, has published 2 books and the reviewer of 3 journals.
Short Biography.