Electron Spin Polarization In Led With Cdte As Active Layer; The Effect Of Magnetic Impurity

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Abstract: *In this paper we have presented a model based on quantum Langevin equation to investigate the variation of degree of spin polarization of electrons due to external magnetic field applied on a LED with and without magnetic impurity. Active layer of the proposed LED consists of quantum dots of CdTe. It is found that in a GaAs LED, if CdTe quantum dot layer is given then the degree of spin polarization of electrons increases considerably as compared to pure GaAs LED at the same applied magnetic field value. Again when magnetic impurity Manganese(Mn) doped CdTe quantum dot is placed in active region then the degree of spin polarization increases with increase of impurity fraction.*

Keywords: *Spintronics, CdTe quantum dot, LED, Spin polarization, electron phonon interaction, Magnetic impurity (Mn)*

I. INTRODUCTION

Spintronic and its device applications are of great importance because of exhaustion of purely electronic devices. Purely electronic devices produce more heat due to shortage of space for large data storage and communication. Compensation of above requirement can be done replacing charge of electron by spin or including spin with charge of electron for communication and storage of data. For this purpose degree of polarization of spin of electrons need to be more and it should sustain for considerable time and an optimum distance of communication, In this context it is found [1, 2, 3] that when an external magnetic field is applied in a LED, the degree of spin polarization increases , further the applied magnetic field brings change in degree of spin polarization when GaAs quantum dot is doped with magnetic impurity manganese(Mn) [2]. Here in this paper we have investigated the effect of magnetic field on the degree of spin polarization when GaAs LED containing a quantum dot layer of CdTe in its active region. Cadmium is a super conductor crystalline with T_c 0.52 and electron phonon coupling constant 0.38 [4], CdTe is a semiconductor with an energy gap of 1.5 eV, it is opaque in the visible range of the spectrum, but transparent to infrared region. The fundamental lattice vibration frequency is located at 141 cm^{-1} (70 micron). It is also found out that it has large (relative to GaAs and other III-V semiconductors) electro-optic coefficient [5], but it varies with the size of quantum dot of course. It is shown in [6] that Mn doped cdte quantum dot shows magneto-optical properties. Photo generated spin polarized electrons induce the polarization to spin of Manganese by many-body interaction which results into enhancement of degree of spin polarization. So we considered to take Mn doped CdTe in the active layer of LED for the investigation. To develop the mathematical model for the study of effect of magnetic field on the degree of spin polarization of electrons and hence light emitted out from the LED, Langevin quantum mechanical rate equations [7] are used. Unlike others in this investigation we have included electron-phonon interaction in the Hamiltonian in addition to the other interaction terms. Secondly the spin injection, spin relaxation and spin flip are studied in many literatures at low temperature but we have investigated the degree of spin polarization at high temperature under the effect of electron phonon interaction.

II. THE ORETICAL MODEL

The model consists of two cases. First when the active region of LED is a layer of CdTe quantum dots and second when Mn doped CdTe quantum dots layer is considered in the active region. The total Hamiltonian for the first case is [3]

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

HereH_c ,H_p, H_d and H_M are Hamiltonians [8] for free carrier interaction, photonic process, dipole interaction and magnetic field interactions respectively. H_{ph} is the Hamiltonian for phonon number given by $H_{ph} = \hbar\omega_{\mu\kappa} f^{\dagger}_{\kappa\mu} f_{\kappa\mu}$ and the Hamiltonian for electron phonon interaction [9] is $H_{e-ph} = M_{\kappa\mu} c_{\kappa\mu} c^{\dagger}_{\kappa\mu}\left(f_{\kappa\mu} + f^{\dagger}_{\kappa\mu}\right)$, here $f_{\kappa\mu} = \frac{Q_{\kappa\mu} n_\kappa}{\hbar(\gamma_q - i\omega_{\mu\kappa})}$ is the phonon annihilation operator [2] ,

n_κ is total number of free charge carriers, γ_q is coupling constant= 0.38 and $\omega_{\kappa\mu}$ is phonon frequency = $38.67X10^{12}$.

$M_{\kappa\mu}$ is the electron-phonon coupling matrix, which depends on the size of the quantum dot, given by $M_{\kappa\mu} = d\sqrt{\frac{\hbar}{\rho V \omega_{\mu k}}}|k| = d\sqrt{\frac{\hbar}{\rho V \omega_{\mu k}}}\left(\frac{n\pi}{a}\right)$, '$k$' is the phonon mode, '$n$' is a positive integer, 'a' is width of quantum dot layer, taken 0.5nm, 'd' is phonon deformation constant and is 22 for CdTe, 'ρ' is mass density and its value for CdTe is $5.5X10^3$kg/m^3, 'V ' is volume of the solid structure taken. Applied magnetic field causes spin flip besides Zeeman splitting. The photonic reservoir is considered in a thermal equilibrium distribution. The optical transition through the quantum dot layer requires momentum transfer from phonon to electron. This causes a spin current to be induced resulting electron-phonon or electron photon interaction in k-space. As electron phonon interaction is spin dependent causes spin polarization.

Applying Langevin rate equation to dipole operator $\sigma_k^{\mu\mu'}(= d_{-k\mu}\, c_{k\mu}\, e^{i\nu_l t})$ and photon annihilation operator $A_{l\mu\mu'}(= a_{l\mu\mu'} e^{i\nu_l t})$, and then solving it for rate of spontaneous emission, it can be shown that

$$R_{sp}^{\mu\mu'} = \frac{2\sum_k \gamma \left|g_{lk\mu\mu'}\right|^2 n_{ck}^{\mu} n_{d-k}^{\mu'}}{\gamma^2 \frac{1}{\hbar^2}\left\{\mu_B B_z\left(G_e S_{c\mu\nu} + G_h S_{\nu\mu\nu}\right) + \left(\varepsilon_{ck\mu} + \varepsilon_{\nu k\mu'} + \hbar\nu_l\right) M_{k\mu}\, Q_{k\mu}\, W_{k\mu}\right\}} \quad (2)$$

Here the electron phonon interaction parameter is

$W_{k\mu} = \frac{n_k}{\hbar}\left(\frac{2\gamma_q}{\gamma_q{}^2 + \omega_{\mu\kappa}{}^2}\right)$, where as $Q_{\kappa\mu}$ is the electron phonon interaction parameter for in active region.

μ and μ' represent the spin states and l is the mode of spontaneous emission. Using equation (2) the degree of spin polarization, $P = \frac{I^{\sigma^+} - I^{\sigma^-}}{I^{\sigma^+} + I^{\sigma^-}}$ in terms of rate of spontaneous emission is

$$P = \frac{\sum_l\left[R_{spl}^{-\frac{1}{2}\frac{3}{2}} + R_{spl}^{\frac{1}{2}\frac{1}{2}} - R_{spl}^{-\frac{11}{22}} - R_{spl}^{\frac{13}{22}}\right]}{\sum_l\left[\left(R_{spl}^{-\frac{1}{2}\frac{1}{3}} + R_{spl}^{\frac{1}{2}\frac{1}{2}} - R_{spl}^{-\frac{11}{22}} - R_{spl}^{\frac{13}{22}}\right) + 4n\bar{\nu}_l\right]} \quad (3)$$

Here $n(\bar{\nu}_l)$ represents thermal photon number given by $(\bar{\nu}_l) = 4\pi^2 V\left(\frac{k_\beta T}{hc^3}\right)$.

Due to addition of magnetic impurity Mn, the total Hamiltonian (1) for all interactions becomes

$$H = H_c + H_p + H_d + H_M + H_{ph} + H_{e-ph} + H_{imp} \quad (4)$$

Where

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

here $e_{k\mu}$ and $e_{k\mu}{}^{\dagger}$ are electron annihilation and creation operator

The Hamiltonian for magnetic impurity [2] is

$$H_{imp} = x\sum E_{\kappa\mu}^{e}\, e_{\kappa\mu}^{\dagger} e_{\kappa\mu} + x\sum V_e^c\left(c_{\kappa\mu}^{\dagger} e_{\kappa\mu} + e_{\kappa\mu}^{\dagger} c_{\kappa\mu}\right) + x\sum V_e^d\left(d_{-\kappa\mu}^{\dagger} e_{\kappa\mu}^{\dagger} + e_{\kappa\mu}\, d_{-\kappa\mu'}\right)$$

Where x is fraction of impurity, $E_{\kappa\mu}^{e}$ is single particle energy for impurity electron, V_e^c and V_e^d are the interaction energy coefficients for host electron and hole with impurity electron.

Using Langevin rate equations, one can express dipole operator $\sigma_k^{\mu\mu'}$ in terms of photon annihilation operator$\left(A_{\iota\mu\mu'} = a_{\iota\mu\mu'} e^{i\nu_\iota t}\right)$ as

$$\sigma_\kappa^{\mu\mu'} = \frac{\left[i\sum_l g_{\iota\kappa\mu\mu'}\left(n_{c\kappa}^{\mu} + n_{d-\kappa}^{\mu'} - 1\right)A_{\iota\mu\mu'} - \frac{i}{\hbar}xV_e^d\left(n_{c\kappa}^{\mu} + n_{d-\kappa}^{\mu'}\right) + F_{\sigma\kappa}^{\mu\mu}\right]}{\left\{\gamma + \frac{i}{\hbar}\left[\mu_B B_z\left(G_e S_{c\mu\nu} + G_h S_{V\mu'\nu'}\right) + \left(\varepsilon_{c\kappa\mu} + \varepsilon_{V-\kappa\mu'} - \hbar\nu_\iota\right)\left(Q_{\kappa\mu} + Q_{\kappa\mu}'\right)W_{\mu\kappa} + x\left(E_{\kappa\mu}^{e} + V_e^c\right)\right]\right\}} \quad (5)$$

Here $n_{c\kappa}^{\mu}$ and $n_{d-\kappa}^{\mu'}$ are number of electrons and holes in conduction and valence bands respectively, $F_{\sigma\kappa}^{\mu\mu'}$ is the fluctuation term for careers, $Q_{\kappa\mu}'$ is the coefficients for electron phonon interaction for impurity Mn and $W_{\mu\kappa}$ is electron phonon interaction parameter, given by

$$W_{\mu\kappa} = \left(\frac{Q_{\kappa\mu}\, n_\kappa}{\hbar}\right)\left(\frac{2\gamma}{\gamma^2 + \omega_q^2}\right) = f_{\kappa\mu} + f_{\kappa\mu}^{\dagger} \quad (6)$$

In this case the rate of spontaneous emission can be shown as

$$R_{spl}^{\mu\Delta'} = \frac{2\sum_\kappa \gamma\left|g_{\iota\kappa\mu\mu'}\right|^2 n_{c\kappa}^{\mu} n_{d-\kappa}^{\mu'} x\, n_{e\kappa}^{\mu}}{\gamma^2 + \frac{1}{\hbar^2}\left\{\mu_B B_z\left(G_e S_{c\mu\nu} + G_h S_{V\mu'\nu'}\right) + \left(\varepsilon_{c\kappa\mu} + \varepsilon_{d-\kappa\mu'} + \hbar\nu_\iota\right) + \left(Q_{\kappa\mu} + Q_{\kappa\mu}'\right)W_{\mu\kappa} + x\left(E_{\kappa\mu}^{e} + V_e^c\right)\right\}^2} \quad (7)$$

This expression when used to calculate degree of spin polarization using equation(3), it gives

$$P = \frac{\sum_l\left[R_{spl}^{-\frac{1}{2}\frac{3}{2}} + R_{spl}^{\frac{1}{2}\frac{1}{2}} - R_{spl}^{-\frac{11}{22}} - R_{spl}^{\frac{13}{22}}\right]}{\sum_l\left[\left(R_{spl}^{-\frac{1}{2}\frac{1}{3}} + R_{spl}^{\frac{1}{2}\frac{1}{2}} - R_{spl}^{-\frac{11}{22}} - R_{spl}^{\frac{13}{22}}\right) + 4k_\iota n\bar{\nu}_l\right]} \quad (8)$$

Here k_ι is the rate of field decay and is 130ps [10].

III. SIMULATION RESULTS

We used equation (3) and (8) for simulation, using MATLAB. The simulation result for LED containing CdTe quatum layer in the active region is shown in Fig. 1 and Fig.2. The same result is shown for LED containing GaAs quantum dots instead of CdTe [3]. Simulations in both the cases are done at 300K. It is interesting to note that in both the cases degree of spin polarization increases with the increase of magnetic field but the nature of variation is just opposite to one another. The value of degree of spin polarization in CdTe case is comparatively higher than GaAs, at the same magnetic field. This suggests that CdTe quantum dots can be better candidate compared to GaAs to attain degree of spin polarization easily. To investigate the role of electron phonon interaction on the degree of spin polarization, we take three different values of electron-phonon interaction parameter Q = 2, 3, 4. As shown in Fig.1 with the increase of electron phonon the degree of spin polarization decreases. This can be explained as follows;

Landau 'g' factor for the material increases with the increase of temperature and may be responsible for decrease of degree of degree of spin polarization. As other investigation is carried out at low temperature, the results in these investigation are quite opposite. Other reason for decrease of polarization degree may be due to the spin – de phasing, which is due to the electron-phonon interaction. The most interesting result is shown in figure 3, which is plotted using equation (8). The graph is plotted between applied magnetic field and degree of spin polarization for a given electron-phonon interaction (Q=2) but different values of impurity (Mn) in fraction, x= 0.1,0.2 and 0.3. With the increase of magnetic impurity amount the degree of spin polarization increases. It may be noted that the addition of magnetic impurity Mn, restores the nature of variation of the graph similar to GaAs. This may be due to ferromagnetic nature of Mn. However this investigation needs to be extended to other ferromagnetic materials in the active region before coming to a final conclusion.

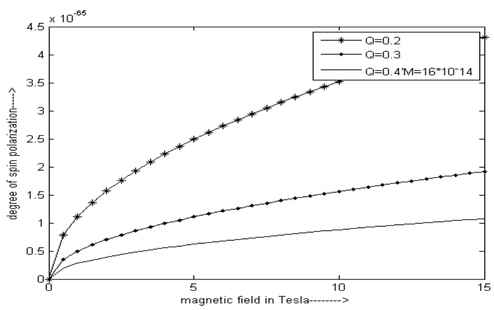

Fig:1.Variation of degree of spin polarization with applied magnetic field in LED containing CdTe quantum dot layer as active region giving highest value of degree of spin polarization $3.3*10^{-65}$ at magnetic field 8T

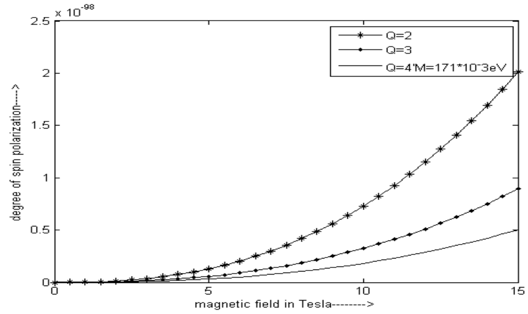

Fig.**2.** Variation of degree of spin polarization with applied magnetic field in LED containing GaAs quantum dot layer as active region giving highest degree of spin polarization $4.3*10^{-99}$ at magnetic field8T[3]

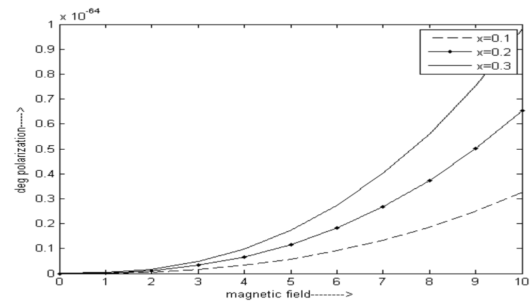

Fig.3: variation of degree of spin polarization with magnetic field at different concentration of doping impurity Mn at constant electron-phonon interaction parameter Q=2

IV. CONCLUSION

The results obtained in this investigation leads us to conclude that degree of spin polarization can be controlled either by changing electron-phonon interaction or impurity fraction. Increase of impurity amount or decrease of electron phonon interaction favors the degree of spin polarization, while the material used in the active region plays a crucial role in deciding the degree of spin polarization.

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