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Quantum dynamics of spin polarized optoelectronic processes

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Abstract

We study the quantum dynamics of the emission of multimodal polarized light in light emitting devices (LED) due to spin polarized carriers injection. We present the equations for photon number and carrier numbers, and calculate the polarisation degree of the light generated by LED.

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Advances on control of spin degrees of freedom in electronic devices provide wide range of potential applications. Recently circularly polarized photon emission by injecting spin-polarized carriers into optoelectronic devices has been reported [1–4]. In this paper we study the quantum dynamics of spin polarized optoelectronic processes in such a spin-electronic device using microscopic quantum Langevin equations [5,6].

The model is based on the systems studied experimentally [1,3]. The spin polarized electrons are injected into a non-magnetic GaAs/AlGaAs light emitting diode (LED) in a magnetic field. The spin degeneracy of the GaAs bands is lifted in the magnetic field and light hole and heavy hole degeneracy is lifted by confinement. Due to selection rules, electrons with spin $\pm\frac{1}{2}$ in the conduction band recombine with holes of spin $\pm\frac{3}{2}$ or $\mp\frac{1}{2}$ in the valence band to emit photons in right (σ^+) or left (σ^-) circular polarization, respectively.

The Hamiltonian describing polarized multimode photons and carriers in the active layer of an LED in the presence of a magnetic field is given by

$$H = H_{\mathrm{c}} + H_{\mathrm{p}} + H_{\mathrm{d}} + H_{\mathrm{mb}} + H_{\mathrm{M}} + H_{\mathrm{bath}} + H_{\mathrm{bath\text{-}sys}}. \qquad (1)$$

The carriers free Hamiltonian is given by

$$H_{\mathrm{c}} = \sum_k \left(\sum_\mu \varepsilon_{ck\mu} c^\dagger_{k\mu} c_{k\mu} + \sum_{\mu'} \varepsilon_{vk\mu'} d^\dagger_{-k\mu'} d_{-k\mu'} \right). \qquad (2)$$

where $c_{k\mu}$ and $d_{-k\mu'}$ are fermionic annihilation operators for electron with momentum k and spin μ and holes with momentum $-k$ and spin μ', respectively; $\varepsilon_{ck\mu}$ and $\varepsilon_{vk\mu'}$ are the conduction and valence band energy, respectively. The multiphotonic process is characterized by the Hamiltonian

$$H_{\mathrm{p}} = \sum_{l\mu\mu'} \hbar\nu_l a^\dagger_{l\mu\mu'} a_{l\mu\mu'}, \qquad (3)$$

with $a_{l\mu\mu'}$ and $\nu'_{l\mu\mu}$ the bosonic annihilation operator and frequency for photons in mode l characterized by

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the allowed spin transition between μ and μ' contributing to photons circularly polarized, in σ^+ or σ^-.

The dipole interaction is given by

$$H_{\rm d} = \sum_{lk\mu\mu'} \hbar(g_{lk\mu\mu'} d^\dagger_{-k\mu'} c^\dagger_{k\mu} a_{l\mu\mu'} + \text{h.c.}), \tag{4}$$

where $g_{lk\mu\mu'}$ is the dipole coupling constant. Note that $\varepsilon_{ck\mu}$, $\varepsilon_{vk\mu'}$ and $g_{lk\mu\mu'}$ are renormalized to include the many-body interaction $H_{\rm mb}$ in a mean-field approximation [5]. The magnetic field acts as

$$H_{\rm M} = \mu_{\rm B}\mathbf{B}\cdot\sum_k\left(\sum_{\mu\nu}\mathscr{G}_{\rm e}\mathbf{S}_{{\rm c}\mu\nu}c^\dagger_{k\mu}c_{k\nu} + \sum_{\mu'\nu'}\mathscr{G}_{\rm h}\mathbf{S}_{{\rm v}\mu'\nu'}d^\dagger_{-k\mu'}d_{-k\nu'}\right), \tag{5}$$

where $\mu_{\rm B}$ is the Bohr magneton, $\mathscr{G}_{\rm e(h)}$ is the electron (hole) Landé g-factor and $\mathbf{S}_{\rm c}$ and $\mathbf{S}_{\rm v}$ are spin matrices for electrons and holes, respectively. The reservoir is constituted of three terms, one for photonic modes and the other two for electrons and holes. The corresponding terms of the Hamiltonian, $H_{\rm bath}$, are conveniently eliminated in a Markovian approximation for the reduced dynamics of the device. The photonic reservoir is assumed in a thermal distribution, while the carriers reservoir are considered in quasi-Fermi-Dirac distributions. The interaction with the carrier reservoir, $H_{\rm bath\text{-}sys}$ is considered in the Langevin approach, which include fluctuations in the carriers and photon populations.

Choosing the Faraday configuration, where the magnetic field is orientated along the device, the Langevin equation for the dipole operator ($\sigma_k^{\mu\mu'} = d_{-k\mu'}c_{k\mu}{\rm e}^{{\rm i}\nu_l t}$) and for the photon annihilation operator $A_{l\mu\mu'} = a_{l\mu\mu'}{\rm e}^{{\rm i}\nu_l t}$ describing the LED are given by

$$\begin{aligned}\frac{\rm d}{{\rm d}t}\sigma_k^{\mu\mu'} &= -\frac{\rm i}{\hbar}(\varepsilon_{ck\mu} + \varepsilon_{vk\mu'} - {\rm i}\hbar\gamma - \hbar\nu_l)\sigma_k^{\mu\mu'} \\ &\quad -{\rm i}\sum_l g_{lk\mu\mu'}(1 - n^\mu_{{\rm e}k} - n^{\mu'}_{h-k})A_{l\mu\mu'} \\ &\quad -\frac{\rm i}{\hbar}\mu_{\rm B}B_z(\mathscr{G}_{\rm e}S^z_{c\mu\mu}\sigma_k^{\mu\mu'} + \mathscr{G}_{\rm h}S^z_{v\mu'\mu'}\sigma_k^{\mu\mu'}) + F^{\mu\mu'}_{\sigma k}\end{aligned} \tag{6}$$

and

$$\begin{aligned}\frac{\rm d}{{\rm d}t}A_{l\mu\mu'} &= \left[-\frac{\kappa_l^0}{2} + {\rm i}(\nu_l - \Omega_l)\right]A_{l\mu\mu'} \\ &\quad -{\rm i}\sum_k g^*_{lk\mu\mu'}\sigma_k^{\mu\mu'} + F_l.\end{aligned} \tag{7}$$

In these equations γ and κ_l^0 are the rates of the dipole dephasing and the field decay respectively, while $F^{\mu\mu'}_{\sigma k}$ and F_l are the fluctuation terms for the carriers and the field, respectively. In Eq. (7) Ω_l is the passive-cavity frequency. Taking the solution of Eq. (6) in the slow varying regime for the adiabatic approximation,

$$\sigma_k^{\mu\mu'} = \frac{{\rm i}\sum_{l'} g_{l'k\mu\mu'}(n^\mu_{{\rm e}k} + n^{\mu'}_{h-k} - 1)A_{l'\mu\mu'} + F^{\mu\mu'}_{\sigma k}}{\gamma + {\rm i}[\mu_{\rm B}B_z(\mathscr{G}_{\rm e}S^z_{c\mu\mu} + \mathscr{G}_{\rm h}S^z_{v\mu'\mu'}) + \varepsilon_{ck\mu} + \varepsilon_{vk\mu'} - \hbar\nu_l)]/\hbar} \tag{8}$$

and substituting it in Eq. (7), we obtain

$$\begin{aligned}\frac{\rm d}{{\rm d}t}A_{l\mu\mu'} &= [-\kappa_l^0/2 + {\rm i}(\nu_l - \Omega_l)]A_l \\ &\quad + \sum_{l'} G^{\mu\mu'}_{ll'}A_{l'\mu\mu'} + F^{\mu\mu'}_{\sigma l} + F_l,\end{aligned} \tag{9}$$

where the polarized gain matrix, $G^{\mu\mu'}_{ll'}$ is defined as

$$G^{\mu\mu'}_{ll'} = \sum_k \mathscr{D}_{lk\mu\mu'}\, g^*_{lk\mu\mu'}\, g_{l'k\mu\mu'}(n^\mu_{{\rm e}k} + n^{\mu'}_{h-k} - 1)$$

and

$$F^{\mu\mu'}_{\sigma l} = -{\rm i}\sum_k g^*_{lk\mu\mu'}\mathscr{D}_{lk\mu\mu'}F^{\mu\mu'}_{\sigma k}$$

with

$$\mathscr{D}_{lk\mu\mu'} = \frac{1}{\gamma + {\rm i}[\mu_{\rm B}B_z(\mathscr{G}_{\rm e}S^z_{c\mu\mu} + \mathscr{G}_{\rm h}S^z_{v\mu'\mu'}) + \varepsilon_{ck\mu} + \varepsilon_{vk\mu'} - \hbar\nu_l)]/\hbar}. \tag{10}$$

The photon number Langevin equation is obtained immediately from Eq. (9) and reads as

$$\begin{aligned}\frac{\rm d}{{\rm d}t}n_{l\mu\mu'} &= -\kappa_l^0 n_{l\mu\mu'} + \sum_{l'}(G^{\mu\mu'}_{ll'}A^\dagger_{l\mu\mu'}A_{l'\mu\mu'} + \text{h.c.}) \\ &\quad + \left[\left(\sum_{\mu\mu'}F^{\mu\mu'}_{\sigma l} + F_l\right)A^\dagger_{l\mu\mu'} + \text{h.c.}\right].\end{aligned} \tag{11}$$

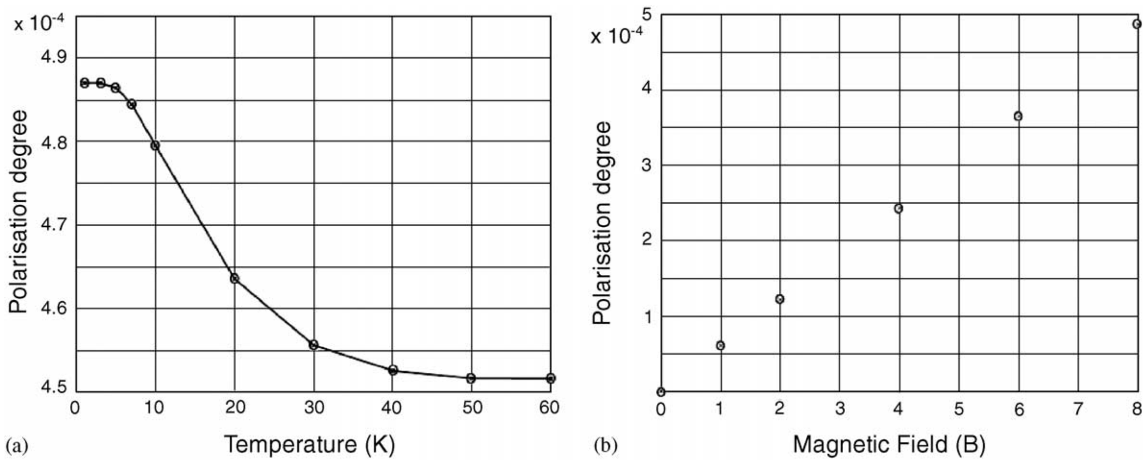

Fig. 1. The degree of circular polarization of the electroluminescence results from the Zeeman effect in intrinsic GaAs: (a) the magnetic field dependence at $T = 4.2$ K; and (b) temperature dependence at $B = 8$ T.

Assuming that there is no correlation between distinct modes, and the quasi-equilibrium condition

$$\frac{\mathrm{d}}{\mathrm{d}t}\langle n^{\mu}_{\mathrm{e}k}(t) n^{\mu'}_{h-k}\rangle \ll 2\gamma\langle n^{\mu}_{\mathrm{e}k}(t) n^{\mu'}_{h-k}\rangle, \tag{12}$$

we finally obtain the steady-state photon number in the model l as

$$\bar{n}_{l\mu\mu'} = \frac{\kappa^0_l \bar{n}_0(\nu_l) + \langle R^{\mu\mu'}_{\mathrm{sp},l}\rangle}{\kappa^0_l + (\langle R^{\mu\mu'}_{\mathrm{abs},l}\rangle - \langle R^{\mu\mu'}_{\mathrm{sp},l}\rangle)}, \tag{13}$$

where $R^{\mu\mu'}_{\mathrm{sp},l}$ is the spontaneous emission rate into the mode l due to the transition $\mu\mu'$, and defined as

$$R^{\mu\mu'}_{\mathrm{sp},l} \equiv \frac{2}{\gamma}\sum_k |g_{lk\mu\mu'}|^2\gamma^2|\mathscr{D}_{lk\mu\mu'}|^2 n^{\mu}_{\mathrm{e}k} n^{\mu'}_{h-k} \tag{14}$$

and $R^{\mu\mu'}_{\mathrm{abs},l}$, the absorption rate is

$$R^{\mu\mu'}_{\mathrm{abs},l} \equiv \frac{2}{\gamma}\sum_k |g_{lk\mu\mu'}|^2\gamma^2|\mathscr{D}_{lk\mu\mu'}|^2 (1 - n^{\mu}_{\mathrm{e}k})(1 - n^{\mu'}_{h-k}). \tag{15}$$

The Eq. (13) shows how the absorption and emission rate contribute to the photon number in mode l, and the influence of the number of thermal photons $\bar{n}_0(\nu_l)$.

Finally, we study the measurement of spin polarization by detection of polarized light from the LED. To analyze the polarization degree of the emitted light, we focus on the l-mode photon flux N_l at the photo-detector. Following the input–output theory [7], the photon flux at the detector is given by $\bar{N}^{\mu\mu'} = \beta_0 \sum_l (\kappa^0_l \bar{n}_0(\nu_l) + R^{\mu\mu'}_{\mathrm{sp},l})$ where β_0 is the transference efficiency of the detection. The dipole matrix elements are given by the $\mathbf{k}\cdot\mathbf{p}$ theory in the parabolic band model, being

$$g_{k1\mu\mu'} = \frac{ie\,p_{\mu\mu'}}{m_0}\frac{1}{\varepsilon_g + \frac{\hbar^2k^2}{2}\left(\frac{1}{m_\mu} + \frac{1}{m_{\mu'}}\right)}. \tag{16}$$

The polarization degree of the detected light, $P \equiv (\bar{I}^{\sigma^+} - \bar{I}^{\sigma^-})/(\bar{I}^{\sigma^+} + \bar{I}^{\sigma^-})$, given in terms of the integrated intensities $\bar{I}^{\sigma^+}$ and $\bar{I}^{\sigma^-}$, in the limit $\kappa^0_l \gg R^{\mu\mu'}_{\mathrm{abs},l} - R^{\mu\mu'}_{\mathrm{sp},l}$, can be written as

$$P = \frac{\sum_l (R^{-1/2-3/2}_{\mathrm{sp},l} + R^{1/2-1/2}_{\mathrm{sp},l} - R^{-(1/2)(1/2)}_{\mathrm{sp},l} - R^{(1/2)(3/2)}_{\mathrm{sp},l})}{\sum_l [(R^{-1/2-3/2}_{\mathrm{sp},l} + R^{1/2-1/2}_{\mathrm{sp},l} + R^{-(1/2)(1/2)}_{\mathrm{sp},l} + R^{(1/2)(3/2)}_{\mathrm{sp},l}) + 4\bar{n}_0(\nu_l)]}. \tag{17}$$

The roles of the magnetic field and the material dipole matrix for the polarization degree is clear trough the spontaneous emission rate, $R^{\mu\mu'}_{\mathrm{sp},l}$ from Eq. (14).

We also see the dependence on the thermal photon number $\bar{n}_0(v_l)$. As the temperature is raised the unpolarized thermal photons become more important in the process, decreasing the polarization efficiency. The numerically calculated results are plotted in Fig. 1. Fig. 1(a) shows the magnetic field dependence of the intrinsic polarization degree (absolute value) which contributes to the decline of the total degree of the circular polarization of the light from the LED with the injection of spin polarized electrons, because the spin splitting of GaAs is opposite in sign to that of the spin aligner [3,4]. Fig. 1(b) presents the temperature dependence of the polarization degree (absolute value) which reflects the influence of the thermal photons and the carrier concentrations. The temperature dependence of the g-factor is not included yet.

In summary, we have demonstrated that the Langevin approach is useful to describing the dynamics in spin polarized optoelectronic process. The more complete work including the spin polarized carrier pumping, non-radiative recombination and fluctuations is ready in the formalism and will be presented in a larger publication.

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