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Spin polarization and relaxation in a semiconductor with impurity absorption of circularly polarized light

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Abstract

The approach based on kinetic equations is used to describe spin polarization of conduction electrons in a semiconductor doped with d or f atoms and subject to circularly polarized radiation. In the stationary state we find analytical expressions for the spin polarization of band electrons, ρ_e, and spin polarization of electrons in the impurity levels, ρ_i. It is shown that the degree of spin polarization of the band electrons is mainly determined by the polarization type of the light. On the basis of numerical results we conclude that ρ_e and ρ_i are practically independent of the long-term relaxation processes in the subsystem of magnetic impurities.

1. Introduction

The main issue in semiconductor spin electronics is the generation of spin polarized charge carriers and their manipulation and control over distances comparable to the size of a particular device. One of the most effective methods of spin control and spin manipulation in semiconductors is based on the optical excitation and optical pumping of spin polarized electrons [1, 2]. Using circularly polarized light one can create polarized electrons (holes) and also manipulate spin polarization of the photogenerated carriers [3–5]. The optical orientation of electron spin in semiconductors has been proposed long time ago [6, 7], and since then the main efforts were focused on the investigation of some peculiarities of various spin relaxation

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mechanisms. The latter problem is of particular importance as the spin relaxation processes determine the functionality range of many electronic devices. The corresponding results have been already surveyed in several review articles [4, 8], but some important details of the issue have not been addressed so far or are simply not well understood [9].

Recent interest in spin control and spin manipulation with optical methods is due to possible applications in modern semiconductor nanoelectronics and nanospintronics [10–12]. The optical methods turned out to be very useful because they offer possibility not only to generate a non-equilibrium spin density, but also to excite directly spin currents in semiconductor nanostructures [12, 13]. The optical methods also allow to polarize photogenerated electrons near the interface with a ferromagnet, which enables tunable control of spin polarization and an effective combination of the electric and spin injection mechanisms [14–17]. Apart from this, photoluminescence is commonly recognized as a powerful method of controlling magnetic states in semiconductors [18].

In order to describe a non-equilibrium electron state in a semiconductor subject to a polarized light, we apply the approach based on kinetic equations. We use a simple model which relies on the excitation of electrons from a deep level in the gap to the conduction band. We take into account spin polarization of electrons in the deep level and also different channels of spin relaxation accompanying the photoexcitation processes. Thus, our approach essentially generalizes a simplified picture based on a single spin relaxation time characterizing electronic states. In addition, the approach accounts for the spin relaxation in different electronic states and also variation of the spin density due to spin transport.

In section 2 of the paper we present the relevant kinetic equations and derive analytical solutions for the stationary spin polarization of conduction and impurity electrons in some limiting situations. Numerical results in a general situation and their detailed discussion are in section 3. Summary and final conclusions are presented in section 4.

2. Theoretical description

We consider a model semiconductor with shallow impurity levels, which are completely ionized. These levels are created by usual donor and acceptor impurities with concentrations N_d and N_a, respectively. In addition, we assume that impurities (of concentration N_T) with unfilled d or f shells create a deep level in the band gap. In the following we consider the case of $N_\mathrm{d} \gg N_\mathrm{a}$. Consequently, only the conduction band and deep impurity levels are taken into consideration, as the acceptors partially compensate the donors and do not affect the spin polarized electron transport. Typical examples of the materials, where such a situation can occur are GaAs:Mn, GaN:Mn, and InP:Fe [19–21]. For definiteness, we consider the case of InP:Fe [20, 21], where the iron impurities embedded in the tetragonal indium phosphate lattice exist in two different states: Fe^{2+} with the equilibrium concentration of localized electrons $n_{\mathrm{T}0}$, and Fe^{3+} with the equilibrium concentration of localized holes $p_{\mathrm{T}0}$.

Upon illumination of the semiconductor with circularly polarized light of the frequency corresponding to the impurity absorption (transitions from the deep level to the conduction band), the linear kinetics of spin polarized electrons in different states can be described by the following set of equations [11, 21, 22]:

$$\frac{\partial N_\uparrow}{\partial t} = -(S_n I_\mathrm{L} + \sigma)N_\uparrow - \beta_\uparrow N_\uparrow + \beta_\downarrow N_\downarrow + \gamma_\uparrow n_\uparrow (N_\mathrm{T} - N), \tag{1}$$

$$\frac{\partial N_\downarrow}{\partial t} = -(S_n I_\mathrm{R} + \sigma)N_\downarrow - \beta_\downarrow N_\downarrow + \beta_\uparrow N_\uparrow + \gamma_\downarrow n_\downarrow (N_\mathrm{T} - N), \tag{2}$$

$$\frac{\partial n_\uparrow}{\partial t} = (S_n I_\mathrm{L} + \sigma)N_\uparrow - \alpha_\uparrow n_\uparrow + \alpha_\downarrow n_\downarrow - \gamma_\uparrow n_\uparrow (N_\mathrm{T} - N) + \frac{1}{q}\frac{\partial j_\uparrow}{\partial z}, \tag{3}$$

$$\frac{\partial n_\downarrow}{\partial t} = (S_n I_\mathrm{R} + \sigma)N_\downarrow - \alpha_\downarrow n_\downarrow + \alpha_\uparrow n_\uparrow - \gamma_\downarrow n_\downarrow (N_\mathrm{T} - N) + \frac{1}{q}\frac{\partial j_\downarrow}{\partial z}, \tag{4}$$

$$\frac{\partial E}{\partial z} = \frac{q}{\epsilon\epsilon_0}(N_\mathrm{d} - N_\mathrm{a} - N - n), \tag{5}$$

$$j_{\uparrow,\downarrow} = q\left(n_{\uparrow,\downarrow}\mu_n E + D_n \frac{\partial n_{\uparrow,\downarrow}}{\partial z}\right), \tag{6}$$

where

$$n = n_\uparrow + n_\downarrow, \qquad N = N_\uparrow + N_\downarrow, \tag{7}$$

$$n_{\mathrm{T}0} = N_\mathrm{d} - N_\mathrm{a}, \qquad n_{\mathrm{T}0} + p_{\mathrm{T}0} = N_\mathrm{T}, \qquad N + P_\mathrm{T} = N_\mathrm{T}, \tag{8}$$

and

$$V_0 = \int_0^l E(z,t)\,\mathrm{d}z, \tag{9}$$

with V_0 being the bias voltage. The concentrations of electrons with up and down spin orientations in the deep level are denoted by $N_\uparrow$ and $N_\downarrow$, respectively, whereas $n_\uparrow$ and $n_\downarrow$ are the corresponding free electron densities (electrons in the conduction band). In the Gauss law (5), E stands for the electric field along the sample of length l due to the applied voltage V_0. All these quantities depend on the time t and coordinate z (not indicated explicitly, except of equation (9)). The other parameters in equations (1)–(6) are: the intensities I_L and I_R of the left and right polarized light, respectively; the cross-section S_n of the ionization centres; the thermal excitation rate σ; the inverse long-term relaxation (LTR) time $\beta_{\uparrow,\downarrow}$ of localized electrons (in the magnetic impurity system); the electron recombination rate via the impurity centres $\gamma_{\uparrow,\downarrow}$; the inverse LTR times for conduction electrons $\alpha_{\uparrow,\downarrow}$, and the current density $j_{\uparrow,\downarrow}$. Finally, the electron drift mobility μ_n is assumed to be independent of the spin orientation, and the density of non-equilibrium holes in the impurity centres is denoted by P_T. The other parameters in equations (1)–(6) have their usual meaning.

In diluted magnetic semiconductors with a sufficiently low concentration of Fe impurities, the exchange interaction between magnetic atoms is weak as compared to the spin–lattice interaction [23]. The parameters α and β are then equal to the inverse spin relaxation times due to the spin–lattice interaction. For the model described by equations (1)–(6) we use a phenomenological description of the interaction responsible for the long-term spin relaxation. The control parameters α, β, γ, and σ can be in general calculated from first principles [24]. In turn, $N_\mathrm{d} - N_\mathrm{a}$ and N_T are usually determined from comparison of the theory and experimental data on the temperature dependence of the corresponding Hall coefficient [25].

In this paper we discuss the case of a stationary and homogeneous in space solution of equations (1)–(6), which in the following are labelled with the superscript '0' at the relevant variables. Let us introduce the following notation:

$$\begin{aligned} &n^0 = n^0_\uparrow + n^0_\downarrow, \qquad && n^0_- = n^0_\uparrow - n^0_\downarrow, \\ &N^0 = N^0_\uparrow + N^0_\downarrow, \qquad && N^0_- = N^0_\uparrow - N^0_\downarrow, \qquad R = (N_\mathrm{d} - N_\mathrm{a})/N_\mathrm{T} < 1 \end{aligned} \tag{10}$$

and the relative concentration, $\bar{n}^0 = n^0/N_\mathrm{T}$. Then, from equations (1)–(6) one finds

$$\bar{N}^0 = R - \bar{n}^0, \tag{11}$$

$$\bar{n}^0_- = \frac{1}{c_\downarrow\gamma_\uparrow - c_\uparrow\gamma_\downarrow}\left[N_\mathrm{T}\gamma_\uparrow\gamma_\downarrow(\bar{n}^0)^2 + (b_\uparrow\gamma_\downarrow + b_\downarrow\gamma_\uparrow)\bar{n}^0 - \frac{1}{N_\mathrm{T}}(a_\uparrow\gamma_\downarrow + a_\downarrow\gamma_\uparrow)\right], \tag{12}$$

$$\bar{N}^0_- = \frac{z_\beta - 1}{z_\beta + 1}\bar{N}^0 + \frac{\Delta_\alpha}{\Delta_\beta}\frac{(z_\alpha - 1)}{(z_\beta + 1)}\bar{n}^0 - \frac{\Delta_\alpha}{\Delta_\beta}\frac{(z_\alpha + 1)}{(z_\beta + 1)}\bar{n}^0_-, \tag{13}$$

where the concentration $\bar{n}^0$ is a solution of the equation

$$(\bar{n}^0)^3 + a(\bar{n}^0)^2 + b\bar{n}^0 - c = 0 \tag{14}$$

and

$$\Delta_\alpha = \alpha_\uparrow/\sigma, \qquad \Delta_\beta = \beta_\uparrow/\sigma, \qquad z_\alpha = \alpha_\downarrow/\alpha_\uparrow, \qquad z_\beta = \beta_\downarrow/\beta_\uparrow. \tag{15}$$

Explicit expressions for the coefficients a, b, c, $a_{\uparrow,\downarrow}$, $b_{\uparrow,\downarrow}$, and $c_{\uparrow,\downarrow}$ are presented in the appendix.

Having the solutions for n^0 and n^0_-, one can determine the stationary polarization degree of the band electrons,

$$\rho_e = \frac{n^0_-}{n^0}. \tag{16}$$

Similarly, one finds the stationary polarization of electrons in the impurity levels,

$$\rho_i = \frac{N^0_-}{N^0}. \tag{17}$$

The stationary polarizations ρ_i and ρ_e are related via the formula

$$\rho_i = \frac{z_\beta - 1}{z_\beta + 1} + \frac{\overline{n}^0}{R - \overline{n}^0}\frac{\Delta_\alpha(z_\alpha - 1)}{\Delta_\beta(z_\beta + 1)} - \frac{\overline{n}^0}{R - \overline{n}^0}\frac{\Delta_\alpha(z_\alpha + 1)}{\Delta_\beta(z_\beta + 1)}\rho_e. \tag{18}$$

If one neglects the LTR processes in the impurity system ($\beta_\uparrow = \beta_\downarrow = 0$ in equations (1)–(4)), then equation (18) takes the form

$$\rho_i = -\frac{\Delta_\gamma(1 - R + \overline{n}^0)\overline{n}^0}{2(I^*_L + 1)(I^*_R + 1)(R - \overline{n}^0)}\left\{z_\gamma(I^*_L + 1) - (I^*_R + 1) - \left[z_\gamma(I^*_L + 1) + (I^*_R + 1)\right]\rho_e\right\}, \tag{19}$$

with

$$\rho_e = (z_\alpha - 1)/(z_\alpha + 1), \tag{20}$$

$$z_\gamma = \gamma_\downarrow/\gamma_\uparrow, \qquad \Delta_\gamma = \gamma_\uparrow N_T/\sigma, \qquad I^*_{L,R} = SI_{L,R}/\sigma, \tag{21}$$

and $\bar{n}^0$ being the solution of equation

$$(\bar{n}^0)^2 + (1 - R + B)\bar{n}^0 - BR = 0, \tag{22}$$

where $B = (z_\alpha + 1)(I^*_L + 1)(I^*_R + 1)/\{\Delta_\gamma[z_\alpha(I^*_R + 1) + z_\gamma(I^*_L + 1)]\}$.

In the other limiting case, $\alpha_\uparrow = \alpha_\downarrow = 0$, the expressions for ρ_i and ρ_e can be written as

$$\rho_i = \frac{z_\beta - 1}{z_\beta + 1}, \tag{23}$$

and

$$\rho_e = \frac{(R - \overline{n}^0)}{2\Delta_\gamma z_\gamma(1 - R + \overline{n}^0)}\{z_\gamma(I^*_L + 1) - (I^*_R + 1) - [z_\gamma(I^*_L + 1) + (I^*_R + 1)]\rho_i\}. \tag{24}$$

Here $\bar{n}^0$ is the solution of equation (22) for $B = [z_\beta z_\gamma(I^*_L + 1) + I^*_R + 1]/[\Delta_\gamma z_\gamma(z_\beta + 1)]$. It is worth noting that one should select only physical solutions of equation (22), i.e., those satisfying the condition $0 \leqslant \bar{n}^0 \leqslant 1$.

3. Numerical results and discussion

From equation (14) (and also equation (22)) follows that the system under consideration can have one, two or three stationary states for $0 \leqslant \bar{n}^0 \leqslant 1$, depending on the control parameters $I^*_{\mathrm{L,R}}$, R, z_α, z_β, z_γ, Δ_α, Δ_β, and Δ_γ. If we neglect the LTR processes in the magnetic impurity system (see equation (20)), the spin polarization ρ_e of band electrons is determined only by the ratio z_α of LTR times for the conduction electrons. At the same time, the degree of spin polarization ρ_i of electrons in the impurity levels increases with ρ_e under the arbitrary polarization of the light wave, see equation (19). We emphasize that illumination of the system with the left polarized light may lead to negative ρ_i, while for the right polarized light the spin polarization ρ_i is positive. As follows from equation (19), ρ_i as a function of $\bar{n}^0$ reaches a maximum at $\bar{n}^0_{\mathrm{extr}} = R + \sqrt{R} < 1$.

In the other limiting case, when the LTR processes for magnetic impurities are taken into account, while those for band electrons are neglected, the value of ρ_i is determined by z_β (in agreement with equation (23)), whereas ρ_e is determined by the concentration of band electrons, polarization of incident light, and semiconductor parameters. It is important to note that the increase of ρ_i leads to smaller values of ρ_e and this does not depend on the polarization type of incident light.

In a general case, when we take into account all possible LTR processes, the analysis is more complex and only numerical analysis is can be performed. We found that the increase of ρ_e results then in a decrease of ρ_i, as follows from equation (18). When $\bar{n}^0 = 0$, the value of ρ_i is determined only by the LTR processes in the magnetic impurity system. If the relaxation rates for spin up and down electrons in the conduction band and the relaxation rates in the impurity levels are equal, $z_\alpha = z_\beta = 1$, the spin polarization ρ_i has the sign opposite to ρ_e.

Qualitative analysis of equations (18)–(23) leads to the conclusion that our results are in agreement with general considerations of the physical processes taking place in the electron spin system under the influence of polarized light (see, e.g., [6, 7]). On the other hand, our considerations show the importance of LTR processes. We assume that the LTR parameters can be determined using the $\rho_\mathrm{i} = f(\rho_\mathrm{e})$ data from non-optical methods such as for instance EPR measurements [26].

The considered control parameters can be divided into two classes. The first class includes the external parameters; like the polarization type and intensity of the light $I^*_{\mathrm{L,R}}$, as well as the type and concentration of magnetic impurities (accounted via the parameter $R = (N_\mathrm{D} - N_\mathrm{A})/N_\mathrm{T}$). The second class includes the internal semiconductor parameters; z_α, z_β, z_γ, Δ_α, Δ_β, and Δ_γ. The proposed model allows us to calculate the spin polarization degrees ρ_i and ρ_e as a function of all the control parameters. In figure 1 we show the results of our calculation of ρ_e and ρ_i as a function of Δ_α and Δ_β for linear (LR), left (L), and right (R) polarized light. In the numerical calculations we assumed [19, 21]: $\gamma = 4 \times 10^{-14}$ m^3 s^{-1}, $\sigma = 8 \times 10^4$ s^{-1}, $N_\mathrm{d} - N_\mathrm{a} = 2 \times 10^{22}$ m^{-3}, $N_\mathrm{T} = 7 \times 10^{22}$ m^{-3}. The values of $z_{\alpha,\beta,\gamma}$ are characteristic for III–V semiconductors [20]: $z_\alpha = 2.5$, $z_\beta = 4/3$, $z_\gamma = 1.25$, and the value of $I^*_0 = 3$ was chosen to fit the theoretically calculated spin polarization degree for electrons, ρ_e, to the experimental data ($\rho_\mathrm{e} = 0.42 \pm 0.08$ for GaSb [6] and $\rho_\mathrm{e} = 0.46 \pm 0.06$ for $Ga_{0.7}Al_{0.3}As$ [27]).

Figure 1(a) shows that the dependence of ρ_e on the parameters Δ_α and Δ_β is non-linear with respect to both arguments. For the same values of the remaining control parameters, the magnitude of ρ_e for the left (L), linear (LR), and right (R) polarized light obeys the relation $\rho_\mathrm{e}^\mathrm{L} > \rho_\mathrm{e}^\mathrm{LR} > \rho_\mathrm{e}^\mathrm{R}$, which is in qualitative agreement with [7]. Moreover, the calculated values of ρ_e agree well with the experimental results presented in [28–30]. In turn, figure 1(b) presents the dependence of ρ_i on the parameters Δ_α and Δ_β, and shows that ρ_i behaves qualitatively

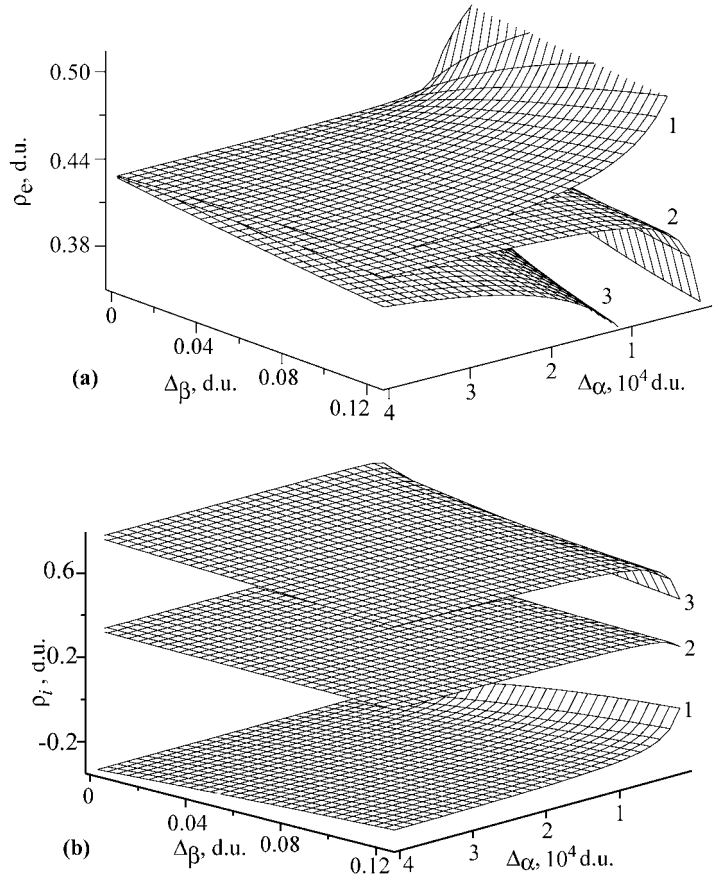

Figure 1. Spin polarization degree of the band electrons (a) and the impurity electrons (b) as a function of the long-term relaxation times for the different polarization of the incident light wave: 1 for $I_{\mathrm{L}}^{*} = I_{0}^{*}$, $I_{\mathrm{R}}^{*} = 0$; 2 for $I_{\mathrm{L}}^{*} = I_{\mathrm{R}}^{*} = I_{\mathrm{LR}}^{*} = I_{0}^{*}/\sqrt{2}$; 3 for $I_{\mathrm{L}}^{*} = 0$, $I_{\mathrm{R}}^{*} = I_{0}^{*}$.

in a similar way as the spin polarization ρ_{e} of band electrons. However, it obeys the relation $\rho_{\mathrm{i}}^{\mathrm{R}} > \rho_{\mathrm{i}}^{\mathrm{LR}} > \rho_{\mathrm{i}}^{\mathrm{L}}$, which is different from the corresponding one found for ρ_{e}. It is worth noting that the resulting $\rho_{\mathrm{i}}^{\mathrm{L}}$ is negative for the assumed values of the parameters, as predicted by equation (18).

According to the results presented in figure 1(a), the spin polarization degree of band electrons remains constant for Δ_{β} varying in a relatively wide range. Assuming constant σ, one may consider this as a demonstration of the independence of spin polarization degrees ρ_{e} and ρ_{i} on the LTR times for the impurity electrons (i.e. on specific mechanisms of the LTR processes leading to finite $\beta_{\uparrow,\downarrow}^{-1}$).

Variation of the spin polarization of conduction and impurity electrons, ρ_{e} and ρ_{i}, with the spin anisotropy of the LTR processes (described by the parameters z_{α} and z_{β}) is shown in figure 2. Both ρ_{e} and ρ_{i} strongly depend on the spin asymmetry of the LTR processes in the conduction band, and only weakly on the spin asymmetry of the LTR processes in the impurity band. Moreover, for the parameters assumed in figure 2, the polarization of conduction electrons is only weakly dependent on the light polarization type (see figure 2(a)), while the spin polarization of impurity electrons is very sensitive to the light polarization, as follows from figure 2(b).

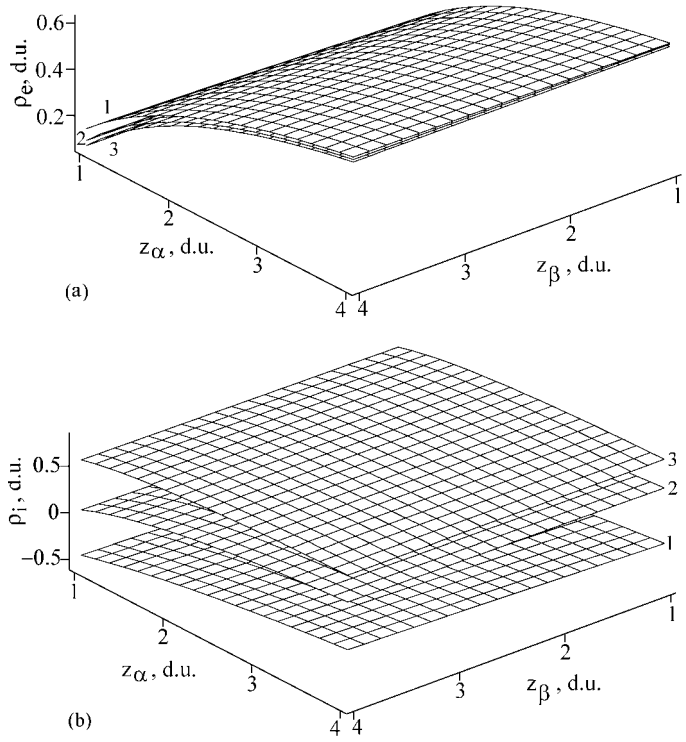

Figure 2. Spin polarization degree of the band electrons (a) and the impurity electrons (b) as a function of the anisotropy of long-term relaxation times, z_α and z_β, for $\Delta_\alpha = 3 \times 10^4$, $\Delta_\beta = 0.06$ and different polarization of the incident light wave: 1 for $I_{\mathrm{L}}^* = I_0^*$, $I_{\mathrm{R}}^* = 0$; 2 for $I_{\mathrm{L}}^* = I_{\mathrm{R}}^* = I_{\mathrm{LR}}^* = I_0^*/\sqrt{2}$; 3 for $I_{\mathrm{L}}^* = 0$, $I_{\mathrm{R}}^* = I_0^*$.

4. Summary

We have described behaviour of electron spin polarization in the conduction band and in the magnetic impurity system of diluted magnetic semiconductors under the influence of polarized light. Some analytical expressions have been obtained for the corresponding stationary spin polarization degrees, ρ_{e} and ρ_{i}, induced by the incident light of various polarizations.

The analytical and numerical results show that the spin polarization of conduction and impurity electrons is determined not only by the polarization type of incident light, but also by other system parameters. In particular, the results clearly demonstrate the importance of LTR processes, and show that both ρ_{e} and ρ_{i} strongly depend on the LTR processes in the conduction band, while LTR process in the impurity band are less important. Detailed analysis of the spin polarizations ρ_{e} and ρ_{i} as a function of spin anisotropy of LTR process in the conduction and impurity bands has also been performed.

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Appendix

The coefficients in equations (12)–(14) are defined as:

$$a = \frac{1}{N_{\mathrm{T}}}\left(\frac{c_{\downarrow}+b_{\downarrow}}{\gamma_{\downarrow}}+\frac{c_{\uparrow}+b_{\uparrow}}{\gamma_{\uparrow}}\right), \tag{25}$$

$$b = \frac{1}{N_{\mathrm{T}}^2\gamma_{\uparrow}\gamma_{\downarrow}}\left[2(b_{\uparrow}c_{\downarrow}+b_{\downarrow}c_{\uparrow})-(\gamma_{\uparrow}a_{\downarrow}+\gamma_{\downarrow}a_{\uparrow})\right], \tag{26}$$

$$c = \frac{2}{N_{\mathrm{T}}^3\gamma_{\uparrow}\gamma_{\downarrow}}\left[c_{\uparrow}a_{\downarrow}+c_{\downarrow}a_{\uparrow}\right],$$

where

$$\begin{aligned}
a_{\uparrow} &= \sigma N_{\mathrm{T}}\frac{I_{\mathrm{L}}^{*}+1}{z_{\beta}+1}z_{\beta}R,\\
a_{\downarrow} &= \sigma N_{\mathrm{T}}\frac{I_{\mathrm{R}}^{*}+1}{z_{\beta}+1}R,\\
b_{\uparrow} &= \sigma\left[\frac{I_{\mathrm{L}}^{*}+1}{z_{\beta}+1}z_{\beta}+\frac{1}{2}\Delta_{\alpha}(1-z_{\alpha})\left(\frac{I_{\mathrm{L}}^{*}+1}{\Delta_{\beta}(z_{\beta}+1)}+1\right)+\frac{1}{2}\Delta_{\gamma}(1-R)\right],\\
b_{\downarrow} &= \sigma\left[\frac{I_{\mathrm{R}}^{*}+1}{z_{\beta}+1}-\frac{1}{2}\Delta_{\alpha}(1-z_{\alpha})\left(\frac{I_{\mathrm{R}}^{*}+1}{\Delta_{\beta}(z_{\beta}+1)}+1\right)+\frac{1}{2}\Delta_{\gamma}z_{\gamma}(1-R)\right],\\
c_{\uparrow} &= \frac{1}{2}\sigma\left[\Delta_{\alpha}(1+z_{\alpha})\left(\frac{I_{\mathrm{L}}^{*}+1}{\Delta_{\beta}(z_{\beta}+1)}+1\right)+\Delta_{\gamma}(1-R)\right],\\
c_{\downarrow} &= \frac{1}{2}\sigma\left[\Delta_{\alpha}(1+z_{\alpha})\left(\frac{I_{\mathrm{R}}^{*}+1}{\Delta_{\beta}(z_{\beta}+1)}+1\right)+\Delta_{\gamma}z_{\gamma}(1-R)\right].
\end{aligned} \tag{27}$$

The explanation of all other quantities is given in the main text of the paper.

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