Generation of the pure spin current \textit{via} Auger recombination in Rashba quantum wells

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Abstract. We propose new non-optical mechanism of the pure spin current generation \textit{via} Auger recombination in the quantum wells with Rashba spin-orbit coupling. It is shown that such process is allowed due to interference between the Coulomb matrix elements corresponding to two different transitions during Auger recombination, leading to non-diagonal transversal components of the spin current tensor, \( J_R = J_{xy} = J_{yx} \). In the limit of low temperatures the total spin current is proportional to the Rashba constant \( R \), spin relaxation time \( \tau_s \) and the third power of both the concentration \( n \), inverse quantum well width \( a^{-1} \) and \( E_g^{-2} \). Estimations show that typical magnitude of the generated spin current by this way is much greater than the ones obtained using intraband optical excitation mechanisms and comparable with spin currents driven by interband optical excitation, provided that the quantum well bandgap is narrow enough (\( E_g < 0.5 \text{ eV} \)).

1. Introduction

Intensive development of the modern spin physics of low-dimensional semiconductor structures is primarily associated with the idea of creation of electronics based on carriers spin. One of the main goals of research in this area is the invention of an effective mechanism for creation of spin currents. The flow of electrical current may be accompanied by the transfer of spin if carriers are polarized. But it is more interesting to consider situation when directed motion of spin polarized carriers leads to zero charge current i.e. a pure spin current flows. Spin polarization in semiconductor structures can be created using spin-orbit splitting of bands in inversion-asymmetric materials. In two-dimensional structures spin splitting of conduction band is linear with respect to in-plane wave vector. This can be described by effective Rashba Hamiltonian [1] related to structural asymmetry of confining potential. In case of [001] quantum well growth direction Rashba term is given by

\[
\hat{H}_R = \gamma_R (\hat{\sigma}_x q_y - \hat{\sigma}_y q_x),
\]

with corresponding dispersion relation

\[
E_{\mu}(q) = \frac{\hbar^2 q^2}{2m^*} + \mu \gamma_R q,
\]

where \( q \) is the in-plane component of wave vector, \( \gamma_R \) is the Rashba constant describing splitting value, \( \mu = \pm 1 \) is the spin index, \( \hat{\sigma} \) – Pauli matrixes. Rashba spin splitting leads to opposite...
Figure 1. Spin and velocity vector fields in wave vector space, obtained from effective Hamiltonian (1). Green arrows correspond to velocity field, red and blue— to spin fields for energy branches (2) $\mu = 1, \mu = -1$ respectively.

motion of carriers with opposite spin direction (see Fig.1). In equilibrium, contributions to spin current from the energy branches (2) compensate each other and the total pure spin current flow vanishes.

Most proposed spin currents generation methods are based on optical excitation of carriers. In this paper non-equilibrium distribution required for generation of pure spin currents is excited by non-optical method. Consider a junction with the quantum well. Applying bias causes carrier injection into the well followed by Auger recombination. We consider the most probable type of Auger recombination in quantum wells— so-called CHCC— process [2] illustrated on Fig. 2. There are two electrons 1 and 2 in the initial state on one quantization level in the quantum well. One of them recombines with heavy hole 3 and transfers energy to another electron by the Coulomb interaction, which is excited to state 4 in the continuous spectrum with an energy near bandgap.

Figure 2. Generation of spin current-carrying states due to Auger recombination.

In two dimensional structures Auger recombination is significantly enhanced since energy
threshold is removed due to lack of momentum conservation in growth direction. Spatial confinement results in modification of $E_g$ functional dependence of the rate of Auger recombination in comparison with the bulk semiconductor. In quantum wells Auger recombination rate contains $E_g^{-n}$ term \cite{2,3} while for bulk it is proportional to $\exp(-E_g/kT)$. We consider the quantum well with narrow bandgap and high carrier concentration. This let us neglect other types of recombination in comparison with Auger recombination.

High-energy electrons 4 are weakly influenced by well potential and hence $q-$linear spin splitting of their states is small. This, together with the rapid spin relaxation of heavy holes let us assume that the final states 3 and 4 do not contribute to the creation of spin polarization. Therefore, the spin current is carried by released states in the Fermi distribution of electrons in the quantum well ("holes " in the Fermi sea of electrons), which are generated in pairs during each elementary act of CHCC– process of Auger recombination (see Fig.2).

2. Carriers state and Auger recombination rate

In order to describe Auger recombination it is crucial to take into account mixing of the valence and conduction bands states to each other. Since the spin relaxation processes are rapidly accelerated with increasing of temperature we restrict ourselves to the limit of low temperatures $T \to 0$. For sake of simplicity we consider carrier concentration $n$ satisfying the relation

$$ q \leq q_f \ll \frac{\pi}{a} \ll k_g = \sqrt{\frac{3E_g}{P}}, $$

where $q$ is the in-plane wave vector, $a$ is the well width, $q_f = \sqrt{2\pi n}$ is the Fermi wave vector, $E_g$ is the bandgap, $P$ is the Kane matrix element. Thus, electrons and holes occupy only the ground level of size quantization.

To obtain carriers states, first we consider the symmetric well without spin splitting and further modify the obtained functions with respect to Rashba spin-orbit coupling. Heavy holes in symmetric well are described by Luttinger model \cite{5} for infinitely deep well, which gives

$$ \psi_{q,\uparrow \downarrow}^{(3)}(z) = \sqrt{\frac{2}{a}} \begin{pmatrix} \frac{\sqrt{2}}{\pi} E_g q_{\uparrow} + \cos \frac{\pi z}{a} \\ 0 \\ -i \frac{\sqrt{2}}{2} \frac{q_{\uparrow}}{a} \left(-\sin \frac{\pi z}{a} + \frac{2z}{a}\right) \end{pmatrix}, \sqrt{\frac{2}{a}} \begin{pmatrix} 0 \\ -\frac{\sqrt{2}}{\pi} E_g q_{\downarrow} - \cos \frac{\pi z}{a} \\ 0 \end{pmatrix}. \quad (4) $$

Electrons are described by Kane model \cite{4}. Thus, we obtain the following wave functions for electrons in quantum well

$$ \psi_{q,\uparrow \downarrow} = \sqrt{\frac{2}{a}} \begin{pmatrix} \cos \frac{\pi z}{a} \\ -\frac{1}{\sqrt{3} E_g} q_{\downarrow} - \cos \frac{\pi z}{a} \\ \sqrt{\frac{2}{3} E_g} q_{\uparrow} \sin \frac{\pi z}{a} \end{pmatrix}, \sqrt{\frac{2}{a}} \begin{pmatrix} 0 \\ \cos \frac{\pi z}{a} \\ \frac{1}{\sqrt{6} E_g} q_{\uparrow} \cos \frac{\pi z}{a} \end{pmatrix}. \quad (5) $$

where $P$ – Kane matrix element, $q_{\pm} = q_{\pm} \pm iq_{\gamma}$, $z$ is growth direction. We describe spin splitting of electron states in the well by mixing the multi-band functions (5) corresponding to different spins with the coefficients obtained from the single-band model (1).

$$ \psi_{\xi}^{(e)}(z) = \psi_{q,\uparrow}(z) + i\mu e^i\varphi \psi_{q,\downarrow}(z) \frac{1}{\sqrt{2}}. $$

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where \( q = (q \cos \varphi, q \sin \varphi, 0) \), \( \varphi \) – angle of in-plane wave vector with respect to \( x \) axis, \( \xi = \{ q, \mu \} \) is the set of the quantum numbers.

The wave functions (4), (6) are used to calculate the rate of Auger recombination. Auger recombination probability per unit time is calculated by the Fermi golden rule.

\[
P_{1 \rightarrow f} = \frac{2\pi}{\hbar} | M_{fi} |^2 \delta(E_f - E_i) ,
\]

where

\[
M_{fi} = \langle \psi_{e, \xi_3, \xi_4, k_4}^{(f)} (r_1, r_2) \mid \frac{e^2}{\varepsilon |r_1 - r_2|} \mid \psi_{e, \xi_1, \xi_2}^{(i)} (r_1, r_2) \rangle \quad (8)
\]

is the Coulomb matrix element. Antisymmetry requirement of two-particle wave functions describing the initial and final states results in two terms in the matrix element of Auger transition. This leads to contribution containing their interference

\[
|M_{fi}|^2 = |M_I|^2 + |M_{II}|^2 + 2 \text{Re}(M_I^* M_{II})
\]

It can be shown that matrix element of electron-electron interaction under assumptions (3) reduces to product of overlap integrals of the initial and final single particle states

\[
M_{I,II} = \frac{2\pi e^2}{\varepsilon q_{I,II}} \langle \psi_{e, \xi_3, \xi_4, k_4}^{(e)} | \psi_{e, \xi_1, \xi_2}^{(e)} | \psi_{e, \xi_3}^{(3)} \rangle \delta_{q_{1,2} - q_3, q_2 - q_1} ,
\]

here \( q_I = |q_1 - q_3| \), \( q_{II} = |q_2 - q_3| \) – transferred in-plane wave vector.

3. Spin current derivation

Operator of the spin current is given by product of velocity and spin operators

\[
\hat{\mathbf{j}}^{\alpha\beta} = \hat{v}_\alpha \hat{s}_\beta .
\]

In case of Rashba spin splitting there are only off-diagonal non-zero average values of the components of the spin current operator tensor

\[
j^{xy}(\xi) = -\frac{1}{2} \left( \frac{\gamma_R}{\hbar} + \mu \sin^2(\varphi) \frac{\hbar q}{m^*} \right) .
\]

The corresponding components of the macroscopic spin current is calculated in the approximation of the relaxation time

\[
J_R = -\tau_s \sum_{\xi_1, \xi_2} P(\xi_1, \xi_2) f_0(\xi_1) f_0(\xi_2) [j(\xi_1) + j(\xi_2)] ,
\]

where \( \tau_s \) is the spin relaxation time, \( P(\xi_1, \xi_2) \) is the rate of Auger recombination for fixed states of electrons in the well, i.e. spin current carriers generation rate

\[
P(\xi_1, \xi_2) = \sum_{\xi_3, \xi_4, k_4} P(\xi_1, \xi_2, \xi_3, \xi_4, k_4) f_0^h(q_3) .
\]

After summation over in-plane wave vectors and spin indexes, final analytical expression for the spin current in this system can be obtained

\[
J_R = \tau_s \frac{\gamma_R}{\hbar} \frac{8}{3\sqrt{3}} \frac{e^4 \pi^4}{\varepsilon^2 a^3 m^*} F_{qg}^h \frac{I_e}{(2\pi)^3} .
\]
\( I_e \) is the dimensionless integral given by

\[
I_e = - \int_0^1 \frac{d^2 q_3}{(2\pi)^2} \int_0^{2\pi} \frac{d\varphi_1}{(2\pi)^2} \int_0^1 q_1 dq_1 \left\{ \int_0^1 q_2 dq_2 \cos(\text{arg}(\alpha)) - 2 \left[ q_1 \sin^2(\varphi_1) \cos(\text{arg}(\alpha) + \varphi_2 - \varphi_1) + \sin^2(\varphi_2) \cos(\text{arg}(\alpha)) \right]_{q_2=1} \right\}
\]

where \( \text{arg}(\alpha) \) is the argument of complex value \( \alpha = (q_3^+ - q_3^-)(q_3^- - q_3^+) \). This expression makes it clear, that both the Fermi surface and Fermi sea contribute to spin current. Only interference term \( 2\text{Re}(M_I^* M_{II}) \) in the square of the matrix element (8) give contribution to \( I_e \).

4. Discussion and conclusion
In order to analyze results it is more convenient to extract from (15) spin current unit parameter and rewrite analytical expression for spin current in low temperature regime in the form

\[
J_R = \frac{8\pi^4 I_e}{3\sqrt{3}} J_0 \left( \frac{e^2/\hbar}{\tau_s} \right)^2 (n\alpha^2)^3 \gamma_R P^5 E_g^0 a^6,
\]

where \( J_0 = (\tau_s a)^{-1} \) is the "elementary" spin current. The final result strongly depends on band structure parameters as \( P^5 \) and \( E_g^{-6} \) which is consequence of generation via Auger recombination. Since Auger recombination is three-particle process, the value of generated spin current has cubic dependance on carrier concentration.

Estimation of the generated spin current (17) using the following set of parameters– \( E_g = 0.4eV, P = 7 \times 10^{-7}eV \cdot cm, \tau_s = 10^{-9}s, \gamma_R = 10^{-10}eV \cdot cm, a = 10 \text{ nm}, \kappa = 10, n = 10^{11} \text{cm}^{-2} \) gives \( J_R \approx 10^{18} \text{cm}^{-1}s^{-1} \). For comparison, in case of optical excitation with \( I = 1kW/cm^2 \) and the same parameters quantum well photoionization mechanism [6] gives \( J \sim 10^{10} \text{cm}^{-1}s^{-1} \), while interband absorption of light mechanism [7] \( J \sim 10^{16} \text{cm}^{-1}s^{-1} \). Estimations show that typical magnitude of the generated spin current by Auger recombination is much greater than the ones obtained using intraband optical excitation mechanisms and comparable with spin currents driven by interband optical excitation, provided that the quantum well bandgap is narrow enough. Unlike mechanisms using optical excitation, in the considering structure it is sufficient to apply voltage to the junction to create spin currents. This is more convenient for integration into the semiconductor schemes.

Acknowledgments
This work was supported by "Dynasty" Foundation and Russian Federation President support program of leading scientific schools (NSh-5062.2014.2).

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