1. INTRODUCTION

Recently, Ganichev et al. [1] experimentally observed the phenomenon referred to as the spin-galvanic effect (see also references in review [2]). In essence, this effect consists in exciting an electric current in a bulk semiconductor (or a heterostructure) when a nonequilibrium spin orientation of charge carriers is provided, for example, by uniform optical generation [1]. The origin of the current associated with the spin-galvanic effect was explained by the asymmetry of spin-flip scattering of thermalized charge carriers with oppositely directed spins [1]. It should be noted that the spin-galvanic effect caused by spin-dependent scattering processes was previously considered in [3–5]. In particular, Averkiev and D’yakonov [5] discussed the effect (more recently observed experimentally in [6]) governed by the spin diffusion due to a spatially non-uniform optical orientation of spins of charge carriers.

Ganichev and Prettl [2] noted that the spin-galvanic effect can be treated as an inverse (conjugate) effect with respect to the current-induced spin polarization of charge carriers, which would be reasonably termed the galvanospin effect. The galvanospin effect was theoretically considered by Aronov and Lyanda-Geller [7], Edelstein [8], and even earlier by Levitov et al. [9]. In the last work, this effect was called the kinetic magnetoelectric effect. Note that the conjugate effect, i.e., the spin-galvanic effect, was also analyzed in [9]. In all the above works, the appearance of spin polarization was explained by spin-dependent scattering of charge carriers. However, quite recently, Mal’shukov and Chao [10] theoretically described the mechanism of current-induced spin polarization due to the difference between the radiative-recombination rates for electrons with oppositely oriented spins. By analogy with the spin-galvanic and galvanospin effects caused by spin-dependent scattering, the question arises as to whether the spin-galvanic effect can be associated with a similar recombination mechanism.

In the present work, the recombination mechanism of the spin-galvanic effect is considered within a microscopic model. According to this mechanism, the current is generated as a result of the difference between the rates of spontaneous radiative transitions for charge carriers with oppositely directed spins. The difference in the radiative recombination arises when a spatially uniform nonequilibrium spin orientation of electrons (holes) is ensured by any known method. © 2004 MAIK “Nauka/Interperiodica”.

2. MODEL

Let us consider a sample of a semiconductor material whose symmetry allows for the existence of terms linear in the wave vector $\mathbf{k}$ in a Hamiltonian describing the energy spectrum of this sample. For example, these terms can have the form

$$H_{c,v} = \beta_{c,v}^x \sigma_z k_x,$$

where subscripts $c$ and $v$ denote the corresponding crystallographic axes of the sample, $\sigma_z$ is the Pauli matrix, and the quantities $\beta_{c,v}^x$ are related to the spin splitting of the conduction and valence bands due to the spin–orbit interaction. For bulk semiconductors or heterostructures, the symmetry necessary for terms similar to term (1) to exist is well known [11]. A number of simplifying assumptions can be introduced into the model of the recombination mechanism without a loss of generality.

(i) We will consider a $p$-type degenerate semiconductor with allowance made for the spin polarization of only the conduction band electrons, because their spin
relaxation time $\tau^e_r$ is assumed to be considerably longer than the spin relaxation time of holes $\tau^h_s$.

(ii) It is assumed that the states with the angular-momentum projection $m_s = \pm 3/2$ (the subband of heavy holes) are dominant in the vicinity of the valence band top.

(iii) The hierarchy of relaxation times for conduction band electrons is assumed to satisfy the following inequalities: $\tau_p \ll \tau_e \ll \tau_s$ and $\tau^e_r \ll \tau_{nr}$, where $\tau_p$ is the momentum relaxation time, $\tau_e$ is the energy relaxation time, and $\tau_s$ and $\tau_{nr}$ are the radiative and nonradiative recombination times, respectively.

(iv) The spin orientation of conduction band electrons is provided through interband optical transitions induced by circularly polarized (left circularly polarized) light propagating along the $z$ axis.

(v) Optical transitions occur from valence band states lying below the quasi-Fermi level of heavy holes under illumination. It is assumed that the temperatures are sufficiently low.

(vi) We also assume that the degree of spin polarization of electrons, i.e., the relative population of the $s_+$ and $s_-$ spin branches (electrons with $s_z = \pm 1/2$) of the conduction band, is determined primarily by the ratio between $\tau^e_s = \tau_s$ and $\tau_0 = \tau_r \tau_{nr}/(\tau_e + \tau_{nr}) \sim \tau_r$.

A schematic diagram of the band structure satisfying the above conditions is depicted in the figure. The figure also shows the asymmetry in the stationary population of spin-split branches in the conduction band with nonequilibrium electrons ($n_+ - n_-$) upon exposure to light under the above conditions. In order to compare the proposed mechanism of the spin-galvanic effect with the mechanism considered in [1], the spontaneous radiative transitions and the transitions with spin-flip scattering of electrons are represented in the figure. It is assumed that these processes make the determining contributions to spin relaxation.

3. RESULTS AND DISCUSSION

Since the radiative and direct interband transitions obey the same optical selection rules, the radiative recombination and spin-flip scattering are spin-dependent processes. As for the spin-galvanic effect associated with the spin-dependent scattering [1], the recombination contribution to the generation of an electric current is made by electrons of the $s_+$ branch lying above the quasi-Fermi level for electrons of the $s_-$ branch. However, unlike the situation analyzed in [1], there are only three types of radiative transitions. The transitions of the first two types, which occur for both branches (arrows 2, 3 in figure), make mutually compensating contributions to the electric current, because, after the recombination event, electrons with equal but oppositely directed wave vectors are removed from the electron gas. For transitions from the $s_+$ branch (arrow 1 in figure), the corresponding transitions are absent in the $s_-$ branch. Therefore, the processes of radiative recombination from this branch (as well as the corresponding processes of scattering [1]) are accompanied by the generation of a current $j'$. However, the contributions made by scattering and recombination to the spin-galvanic current differ significantly. Let us now turn to the discussion of these differences.

In the case of scattering, the removal of an electron characterized by a parameter $-k_x$ from the region of the $s_+$ branch (this process can be treated as the formation of a positively charged hypothetical “hole” with the same wave vector) is accompanied by the creation of an electron with the vector $k_x$ in the $s_-$ branch. The contributions of the aforementioned hole and electron to the current coincide both in sign and in magnitude [1]. The event of radiative recombination involving the same electron, first, leads to the creation of a similar hole in the electron gas of the conduction band. Second, the real hole with vector $-k_x$ is removed from the hole gas of the valence band due to the recombination. This brings about the generation of an uncompensated hole flux with oppositely directed wave vectors (see figure). Unlike the scattering mechanism, the contributions of the hypothetical and real holes to the recombination