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Spin orientation due to longitudinal current and interband tunnelling in narrow-gap heterostructures

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Abstract. The mechanism of spin orientation under the interband tunnelling transport of carriers due to the longitudinal current has been considered. The spin-dependent interband tunnelling probability has been calculated for Kane and Dirac-like models. For lead chalcogenides and InAs/AlGaSb/GaSb heterostructures the degree of spin orientation can be greater than 10% under weak current-induced longitudinal anisotropy of the distribution function.

1. Introduction

The invariant $\sigma[p \times n]$ (where p is the two-dimensional momentum and n is the normal to the plane of a heterostructure) which occurs due to the spin–orbit interaction with the transverse localized potential, describes the connection of the spin orientation with the lateral motion. This invariant appears under the consideration of electron spin relaxation on a non-ideal surface [1] and the spin-splitting of the 2D electron-energy spectrum [2–4]. In the case of the current along this structure, the spin orientation of 2D electrons arises [3, 5, 6]. Investigations of spin-orientation effects in lateral electron transport were carried out for ferromagnetic-metal (or semiconductor) tunnelling structures [7, 8]. Recently, double-barrier heterostructures with magnetic semiconductor barriers have been considered [9]. The spin orientation is obtained due to self-magnetic or induced momentum of magnetic materials.

In this paper the mechanism of spin orientation under the tunnelling transport of the electrons is discussed for heavily doped semiconductor heterostructures due to the lateral current. In this case the spin orientation is connected with above-mentioned spin–orbit term. Such a situation can be realized using narrow-gap semiconductors based on lead chalcogenides and A_3B_5 materials [10–12]. These heterostructures are extensively studied as high-frequency diodes with negative differential resistance (NDR). The spin orientation is caused by the dependence of the particle tunnelling probability upon the spin quantum number. This mechanism was mentioned in [10], but a detailed consideration was not carried out.

2. Theoretical model

We consider single-barrier heterostructures with heavily doped narrow-gap layers (schematic diagrams are shown in figure 1). The first structure (figure 1(a)) is formed by two type-I heterojunctions and can be realized using lead chalcogenides or A_3B_5 materials; the

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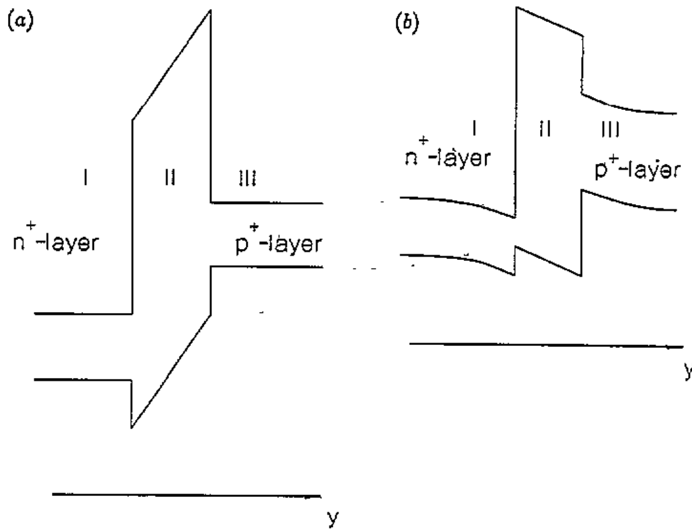

Figure 1. Schematic diagrams of the structures under consideration.

second structure contains type-II heterojunctions (the InAs/AlGaSb/GaSb structure is a diode of this type). The left-side narrow-gap layer (layer I) is heavily doped by donors, the right side by acceptors. Electrons can tunnel from the conduction band of layer I to the valence band of layer III (see figures 1(*a*) and 1(*b*)), if a positive external bias is applied to the structure. The electron states in the conduction band of the n^+ layer can be characterized by a quantum number $\sigma = \pm 1$, which corresponds to various spin orientations. Due to the spin–orbit interaction the tunnelling probability T depends upon this quantum number. However, accounting for the symmetry of the system to time inversion, $T^\sigma(k_\parallel) = T^{-\sigma}(-k_\parallel)$ can be obtained (where $k_\parallel$ is the lateral wavevector). Then $T^\sigma(k_\parallel) - T^{-\sigma}(k_\parallel) = -(T^\sigma(-k_\parallel) - T^{-\sigma}(-k_\parallel))$. For this reason the overall spin-polarization density of flux is equal to zero, if the electron distribution function in the n^+ layer has only a symmetrical part with respect to $k_\parallel$. In this case the occupation probability of the electrons does not depend upon the sign of $k_\parallel$ and the contributions of electrons with opposite values of $k_\parallel$ to this value are opposite. Applying the external bias along layer I (direction x), the spin-polarized electrons can be obtained in this layer due to the existence of an anti-symmetric part in the electron distribution function which is proportional to $v_x = \hbar^{-1}(\partial E/\partial k_x)$ (where E is the energy and k_x is the wavevector component along the lateral current). In this situation the spin-dependent tunnelling current creates the following density of flux of spin-oriented electrons:

$$\delta J = \int \frac{\mathrm{d}^3 k}{(2\pi)^3} v_{1y}[T^\sigma(E, \boldsymbol{k}, \Delta V) f_1^\sigma - T^{-\sigma}(E, \boldsymbol{k}, \Delta V) f_1^{-\sigma}](1 - f_2). \qquad (1)$$

In this expression y is the direction normal to the interfaces, v_{1y} is the velocity component normal to the interfaces, ΔV is the total voltage across the barrier layer, $\boldsymbol{k}$ is the wavevector, $f_1^{\pm\sigma}$ are the distribution functions for electrons with different values of σ in front of the barrier layer, and f_2 is the distribution function in the valence band. We have neglected the reverse tunnelling current. This is possible for the low-temperature case and for a positive external bias. For the sake of simplicity, we do not take into account the spin orientation of holes. This is possible due to the rapid relaxation of the hole spin

polarization in A_3B_5 structures. This relaxation is caused by the transitions between the light-hole and heavy-hole subbands. For lead chalcogenides-type structures the influence of the hole spin polarization on the value of δJ can be neglected, if the conduction band edge of the n^+ layer is higher than the hole Fermi level in the p^+ layer. In this situation all states in the p^+ layer, which are higher than the n^+ layer conduction band edge, are empty and spin-polarized electrons cannot tunnel from the p^+ layer to the conduction band of the n^+ layer. Spin polarization in the p^+ layer in lead chalcogenides-type structures can be calculated in a similar way as in the n^+ layer.

In the time relaxation approximation, the antisymmetric part of the electron distribution function in the n^+ layer can be expressed as

$$f_{\mathrm{as}}^{\pm\sigma} = -eFv_x\tau(E^{\pm\sigma})\frac{\partial f_{1\mathrm{s}}^{\pm\sigma}}{\partial E} = eFv_x\tau(E_{\mathrm{F}}^{\pm\sigma})\delta(E - E_{\mathrm{F}}^{\pm\sigma}). \tag{2}$$

Here F is the electric field parallel to the lateral current, $E_{\mathrm{F}}^{\pm\sigma}$ are Fermi levels for particles with different values of σ, e is the absolute value of the electron charge, $\tau(E_{\mathrm{F}}^{\pm\sigma})$ is the relaxation time, and $f_{1\mathrm{s}}^{\pm\sigma} = \theta(E_{\mathrm{F}}^{\pm\sigma} - E)$ at zero temperature. The difference between the symmetric parts of the electron distribution functions $\delta f = f_{1\mathrm{s}}^{\sigma} - f_{1\mathrm{s}}^{-\sigma}$ can be evaluated in the following way:

$$\delta f = \frac{\delta n(0)}{g(E_{\mathrm{F}})}\delta(E - E_{\mathrm{F}}). \tag{3}$$

Here $\delta n(0)$ is the concentration of spin-oriented electrons in front of the barrier, $E_{\mathrm{F}} \approx E_{\mathrm{F}}^{\sigma} \approx E_{\mathrm{F}}^{-\sigma}$ (we have supposed that $|E_{\mathrm{F}}^{\sigma} - E_{\mathrm{F}}^{-\sigma}| \ll E_{\mathrm{F}}^{\pm\sigma}$). Using (2), (3) and the previous assumptions we can rewrite (1) in the following form:

$$\delta J = \int \frac{\mathrm{d}^3k}{(2\pi)^3} v_{1y}[T^{\sigma}(E, \mathbf{k}, \Delta V) - T^{-\sigma}(E, \mathbf{k}, \Delta V)]f_{\mathrm{as}} - \int \frac{\mathrm{d}^3k}{(2\pi)^3} v_{1y} T \delta f. \tag{4}$$

The first term in (4) corresponds to the spin-polarization flux due to the difference between the tunnelling probabilities $T^{\pm\sigma}$, and the second term corresponds to the spin-polarization flux due to the direct tunnelling of spin-oriented electrons to the valence band of the p^+ layer, $T \approx T^{\sigma} \approx T^{-\sigma}$. We have assumed that $|T^{\sigma} - T^{-\sigma}| \ll T^{\pm\sigma}$. In deriving (4) we have taken into account that $f_1^{\pm\sigma} = f_{1\mathrm{s}}^{\pm\sigma} + f_{\mathrm{as}}^{\pm\sigma}$. Only linear terms with respect to $f_{\mathrm{as}}^{\pm\sigma}$, δf are considered for the case of weak longitudinal anisotropy of the distribution function and weak spin-polarization degree.

The relaxation of the spin orientation in the quasi-neutral region of the emitter layer is described by the following equation:

$$-\frac{\delta n}{\tau_{\mathrm{s}}} + \frac{\partial}{\partial y} D \frac{\partial \delta n}{\partial y} = 0 \tag{5}$$

where δn is the concentration of the spin-oriented electrons, τ_{s} is the spin-relaxation time, and D is the diffusion coefficient. We neglect the drift current normal to the interfaces in the quasi-neutral region, because the corresponding electric field is negligible in this region. We also use the fact that the value of δn is independent of x. This is possible if the lateral current and electric field are uniform and constant, and the bias along the structure is negligible. The value of D is approximately independent of the electric field in the quasi-neutral region for small values of F, when this field produces only weak anisotropy of the

distribution function. (This case is considered in the present work.) If the spin relaxation in the space charge region is negligible, then we have the following boundary condition at $y = 0$:

$$-D\frac{\partial \delta n}{\partial y}\bigg|_{y=0} = \delta J \tag{6}$$

where $y = 0$ is considered to coincide with the boundary of the space charge region. This is reasonable if the thickness of the space charge region is much smaller than that of the quasi-neutral region.

3. Spin-dependent tunnelling probability

The tunnelling probability can be calculated using a Dirac-like model for lead chalcogenides structures, which was described in detail in [10]. For A_3B_5 structures we employ the Kane model (see, for example, [12]). In [10, 12] the interband tunnelling probability and the current–voltage characteristics of the interband tunnelling structures were obtained, but the dependence of T upon the spin was not considered. Numerical calculations of the tunnelling probability can be carried out using the transfer matrix method. Suppose that the axis of quantization is normal to the particle wavevector. In this notation, the tunnelling probabilities $T^{\pm}$ corresponding to two solutions of the Schrödinger equation for the energy E and lateral wavevector $k_{\parallel}$ can be written [12]

$$T^{\pm} = \frac{k_{y(N+1)}E_{N+1}k_1}{k_{y1}E_1k_{N+1}^2}|t^{\pm}|^2 \tag{7}$$

where E_i and k_i are the energy and wavevector in the ith layer, in which the conduction band edge is used as the energy reference, $k_{yi}^2 = k_i^2 - k_{\parallel}^2$, E_i and k_i satisfy the dispersion relation in each material, $t^{\pm}$ are the transmitted amplitudes corresponding to two waves with different values of σ, and the subscripts $N + 1$ and 1 refer to the transmitted and incident waves. In (7) the amplitude of the incident envelope function, which is related to the conduction band basis function, is normalized to unity. The transmitted amplitudes $t^{\pm}$ can be determined using the respective transfer matrices $M_i^{\pm}$. The transfer matrices for the Kane model calculated in [12] and the corresponding matrices for the Dirac-like model obtained here are presented in the appendix.

Under flat-band conditions (or negligible total bias across the barrier layer with respect to the energy gap of this layer divided by e) it is sufficient to take $N = 2$. The precise formula for $T^{\pm}$ in the case of diodes with a thick barrier is listed in the appendix. From the expressions (7), (A1)–(A5) for $T^{\pm}$ it is obvious that $T^{+}(k_{\parallel}) = T^{-}(-k_{\parallel})$ both for the Dirac-like and Kane models. For this reason there is no spin orientation of the electrons in the emitter layer I if $f_{\mathrm{I}}^{\sigma}(E, k_{\parallel}) = f_{\mathrm{I}}^{\sigma}(E, -k_{\parallel})$. For the structure, the band diagram of which is shown in figure 1(a), expressions for $T^{\pm}$ (applying the Dirac-like model and the same assumptions as in [10], which are given below) can be written as

$$T^{\pm} = [16k_{1y}k_{3y}\alpha^{-2}P^2\exp(-2\gamma d)]\{[E_1 + E_g + E_1/\alpha^2 \mp 2k_{\parallel}P/\alpha] \times [E_3 + E_g + E_3/\alpha^2 \pm 2k_{\parallel}P/\alpha]\}^{-1}. \tag{8}$$

Here $E_{g1} = E_{g3} = E_g$, $\alpha = \Delta E_C/\Delta E_V$, ΔE_C and ΔE_V are the conduction and valence band discontinuities for both heterojunctions, P is proportional to the interband momentum

matrix element, d is the barrier thickness, $\gamma = |k_2|$, the energy gaps of narrow-gap materials are equal to each other and are much smaller than that of the barrier layer, $k_\parallel \ll \gamma$, $\gamma d \gg 1$. In this situation $\gamma \approx (\Delta E_C \Delta E_V)^{1/2}/P$, where $P = \hbar(E_g/2m)^{1/2}$, m is the effective mass of an electron and hole in narrow-gap materials. Note that for the symmetric structure ($E_1 = E_3$) the values of $T^\pm$ coincide. If $E_1 \neq E_3$ some difference ΔT between T^+ and T^- exists. Using the linear approximation for ΔT we have the following expression from (8):

$$\Delta T = 2T_0 k_\parallel / k_0 \tag{9}$$

where

$$T_0 \simeq \frac{16 k_1 k_3 P^2 \exp(-2\gamma d)}{E_g^2} \qquad k_0^{-1} = \frac{2P}{E_g}(\alpha + \alpha^{-1}). \tag{10}$$

For the A_3B_5 non-symmetric structures the tunnelling probability also depends upon the quantum number σ. This fact follows from the expressions for $T^\pm$ (A5). Using (A5) and (A3) we obtain the expression (9) for ΔT in the linear approximation in which

$$\begin{aligned} T_0 &\simeq \frac{16E_3k_1/(E_1k_3)\exp(-2\gamma d)}{[1 + E_3k_1/(E_1k_3)]^2 + [E_3\gamma/(E_2k_3) - E_2k_1/(E_1\gamma)]^2} \\ k_0^{-1} &= \frac{E_2/\gamma(E_2/\gamma^2 + E_3/k_3^2)}{(E_3/k_3)^2 + (E_2/\gamma)^2} - \frac{E_2^2/\gamma^3}{(E_1/k_1)^2 + (E_2/\gamma)^2}. \end{aligned} \tag{11}$$

We have assumed in the derivation of (11) that the spin–orbit interaction can be neglected in layer I and is very strong in layers II and III. The first assumption is valid in accordance with Kane's dispersion law if $\Delta_1/3 \ll E_1 + E_{g1} + \Delta_1$, where E_{g1}, Δ_1 are the energy gap and the split-off energy in layer I, respectively. These approximations are reasonable for the electrons tunnelling from the InAs conduction band to the GaSb valence band in the InAs/AlGaSb/GaSb structure (or in any other structure with type-II heterojunctions for which the energy gap is of the order of the split-off energy in each layer). In equations (9)–(11) T_0 is the tunnelling probability for a particle with a wavevector normal to the interfaces. In accordance with (9)–(11) ΔT is equal to zero if $k_\parallel = 0$ and increases with increasing T_0 and $k_\parallel$.

Let us evaluate the wavevector k_0, for example, for lead chalcogenides structures, applying PbS narrow-gap layers and a InAs/AlGaSb/GaSb diode using (10) and (11). Substituting in (10) the values $E_g = 0.28$ eV and $m = 0.08m_0$, where m_0 is the mass of a free electron, and $\alpha = 1$, we obtain $k_0 \sim 10^6$ cm^{-1} for the first situation. For the second diode for electrons tunnelling near the valence band of the barrier layer, suppose that $|E_1/k_1| \ll |E_3/k_3| \leqslant |E_2/\gamma|$. Then k_0 can be of the order of γ. For this structure, with parameters as listed in [12], this value can be of the order of 10^6 cm^{-1}. The difference ΔT can exceed 10% of T, in accordance with (9), if $k_\parallel \ll k_0$.

The dependencies of $T^\pm$ upon E_1 are shown in figures 2 and 3 for the different values of ΔV, $d = 5 \times 10^{-7}$ cm and $k_\parallel = 7 \times 10^5$ cm^{-1}. These curves have been calculated using the transfer-matrix method for the InAs/AlGaSb/GaSb diode with parameters as given in [12]. We describe the quasi-particles employing the semiclassical approximation in the heavily doped layers. For this reason the tunnelling probability depends only upon the total voltage ΔV across the barrier layer. The difference ΔT can be about 20% of T and increases with increasing voltage across the AlGaSb layer.

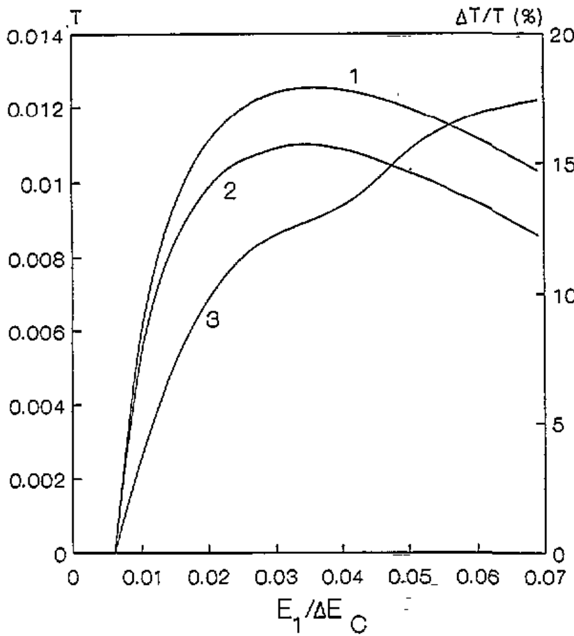

Figure 2. Spin-dependent tunnelling probability for the InAs/AlGaSb/GaSb heterostructure for zero total voltage across the barrier layer. Curve 1 corresponds to T^+, curve 2 to T^-, and curve 3 represents the dependence of $\Delta T/T$ against E_1. ΔE_C is the conduction band discontinuity for the InAs/AlGaSb heterojunction.

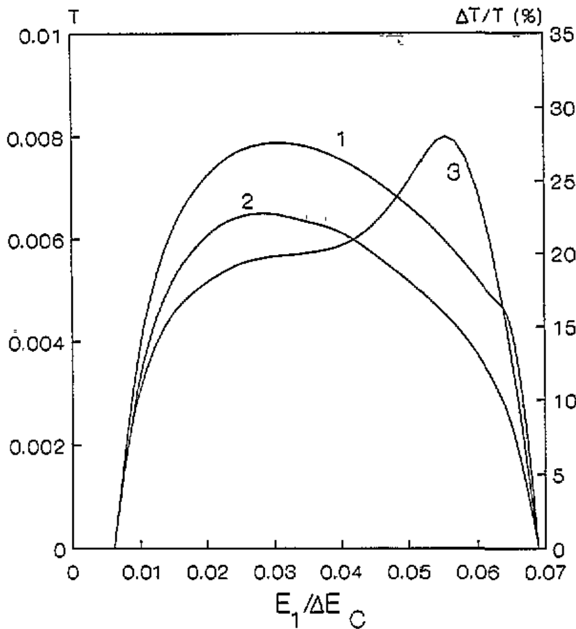

Figure 3. Spin-dependent tunnelling probability for the InAs/AlGaSb/GaSb diode and $\Delta V = 0.06$ V. Curve 1 corresponds to T^+, curve 2 to T^-, and curve 3 represents the dependence of $\Delta T/T$ against E_1. ΔE_C is the conduction band discontinuity for the InAs/AlGaSb heterojunction.

4. Spin orientation of electrons in the emitter

We can solve (5) with the boundary conditions (6) to obtain the degree of spin orientation of the electrons $\delta n_0/n_0$ at the boundary of the emitter quasi-neutral region and the space charge region:

$$\delta n_0/n_0 = \delta J/n_0 v_s \tag{12}$$

where $v_s = \sqrt{D/\tau_s}$ and n_0 is the donor concentration in the n^+ region, which is supposed to be approximately equal to the electron concentration in the quasi-neutral region. Assuming that the electron Fermi levels corresponding to the different values of σ are constant in the space charge region and the difference between them is negligible, we derive the expression for the concentration of spin-oriented electrons near the barrier $\delta n(0)$ at zero temperature:

$$\delta n(0) = \delta n_0 g(E_F)/g(E_{F0}). \tag{13}$$

Here $g(E)$ is the density of states, $E_{F0} \approx E_{F0}^{\pm\sigma}$ is electron Fermi level at the boundary of the quasi-neutral and space charge regions, and $E_F \approx E_F^{\pm\sigma}$ corresponds to the interface of the n^+ layer, if the conduction band edge is the energy reference at each point. The latter value and the value of total voltage across the barrier are determined by solving Poisson's equation using the corresponding dispersion laws (see [12]).

The difference between the tunnelling probabilities corresponding to the different values of σ $T^{\pm\sigma}$ can be expressed as $[T^+(E, k_\parallel, \Delta V) - T^-(E, k_\parallel, \Delta V)]\cos\varphi$, where φ is the angle between the x axis and the vector $\boldsymbol{p}$, and the electron wavefunction is approximately considered as a two-component spinor near the conduction band edge. Then, using (3), (4), (12) and (13), we obtain the equation for $\delta n_0/n_0$:

$$\delta n_0/n_0 = -\frac{v_d(E_F)}{8\pi^2 n_0(v_s + v^*)} \int_0^{k_F} dk_\parallel\, k_\parallel^2 [T^+(E_F, k_\parallel, \Delta V) - T^-(E_F, k_\parallel, \Delta V)] \tag{14}$$

where

$$v^* = [4\pi\hbar g(E_{F0})]^{-1} \int_0^{k_F} dk_\parallel\, k_\parallel T(E_F, k_\parallel, \Delta V). \tag{15}$$

Here $v_d(E_F)$ is the electron drift velocity with energy E_F and v^* is the velocity that characterizes the leaving of spin-oriented electrons from the n^+ layer by means of tunnelling through the barrier. The value of v^* depends upon the electron tunnelling probability and the density of states at the Fermi level in the bulk emitter layer, and is of order $v_F T$ where v_F is the Fermi velocity.

Let us evaluate $\delta n_0/n_0$ by substituting into (14) ΔT and $T \sim T_0$ from (9)–(11). Suppose that $E_{F0} \approx E_F$. Then

$$\delta n_0/n_0 \sim -\frac{v_d k_F^3 m}{2\pi^3 k_0 \hbar}. \tag{16}$$

Here m is the effective mass of an electron in the emitter and $k_F \approx \sqrt{2E_F m}/\hbar$. If $k_0 \sim 10^6$ cm, $E_F \sim 0.1$ eV, $m \approx 0.02 m_0$, $v_d \approx 2 \times 10^7$ cm s^{-1} and $n_0 \approx 5 \times 10^{17}$ cm^{-3}, then $|\delta n_0/n_0| \sim 0.1$. The values used are reasonable for the InAs/AlGaSb/GaSb structure.

Figure 4 shows the dependencies of $\delta n_0/n_0$ upon the applied voltage for the InAs/AlGaSb/GaSb diode. We employ the same parameters for the structure (the values of energy gap and split-off energy in the different layers, the conduction and valence band discontinuities for the heterojunctions) as in [11, 12]. The tunnelling probability has been calculated numerically using the transfer-matrix (A2), the formulae (A3) and the Kane dispersion law in each material. The value of total voltage across the barrier layer ΔV and electron Fermi energy has been determined in a similar way as in [12], using the numerical solution of Poisson's equation. All curves have been calculated using (14) and (15) for various values of donor concentration in the n^+ layer and the barrier thickness. The

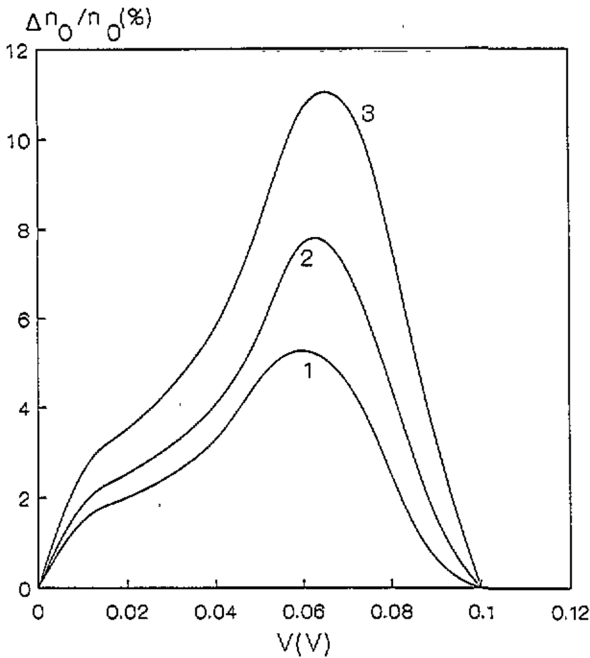

Figure 4. Dependencies of the degree of spin orientation upon the voltage applied to the InAs/AlGaSb/GaSb structure for $v_d(E_F) = 2 \times 10^7 \mathrm{cm\,c^{-1}}$, $v_s = 10^5 \mathrm{cm\,s^{-1}}$. Curve 1 corresponds to $n_0 = 5 \times 10^{17} \mathrm{cm^{-3}}$, $d = 5 \times 10^{-7}$cm; curve 2 corresponds to $n_0 = 2.5 \times 10^{17} \mathrm{cm^{-3}}$, $d = 5 \times 10^{-7}$cm; curve 3 corresponds to $n_0 = 2.5 \times 10^{17} \mathrm{cm^{-3}}$, $d = 3.5 \times 10^{-7}$cm.

acceptor concentration in p^+-GaSb is supposed to be $3 \times 10^{19}\,\mathrm{cm^{-3}}$. The degree of spin-oriented electrons at first increases with increasing voltage applied to the structure external bias, reaches a peak value, and then decreases to zero when the electron Fermi level in the n^+ layer becomes higher than the valence band edge of the p^+ layer. In the latter situation the distribution function of electrons that can tunnel through the barrier layer has only a symmetric part, because $f_{as} \neq 0$ only for $E = E_F$ at zero temperature. The value of $\delta n_0/n_0$ can exceed 10% of δn_0 at the maximum. The electrons can tunnel from the InAs layer to the conduction band of the p^+-GaSb layer if the external voltage is higher than the energy gap of GaSb. In this case the spin orientation of electrons exists in the n^+ layer and in the p^+ layer. This spin polarization can be found by polarized radiation due to electron–hole recombination in the p^+ layer.

5. Conclusion

The considerations given above show that there is considerable spin orientation due to interband tunnelling. Here we indicate some assumptions in our calculations and the possibility of experimentally detecting the spin orientation. In the case of a two-band Dirac-like model for lead chalcogenides materials we suppose that the spectrum of quasi-particles is an isotropic one. This approximation is reasonable, for example, for the PbS/EuS/PbS structure. Computing the tunnelling probability for electrons in the InAs/AlGaSb/GaSb diode, the assumption of an infinite heavy hole mass was used. This assumption was discussed in [12]. We have also neglected the intervalley mechanism of the tunnelling current in all structures under consideration, and have supposed that the interband momentum matrix element differs slightly for all materials of the structures. In the calculations of the degree of spin orientation, the assumptions of weak anisotropy of the electron distribution function and a weak degree of the electron spin orientation were applied. The consideration of the spin diffusion was carried out by employing the

standard expressions [5–8]. The change in degree of spin orientation with respect to the $\sqrt{D\tau_s}$ space charge region is connected with the variation of electron concentration due to a corresponding variation of Fermi energy if the conduction band edge is the energy reference at each point.

A more convenient method of detecting the degree of spin orientation is the investigation of circular polarized band-to-band luminescence or the observation of the oriented nuclear spins caused by their interaction with the electron spins. The first method can be used for $n^+/i/p^+$ structures with an intraband mechanism for the tunnelling current, when electrons from the n^+ layer can tunnel to the conduction band of the p^+ layer (or holes from the p^+ layer can tunnel to the valence band of the n^+ layer) and for structures with the same doping type of narrow-gap materials with the interband mechanism of tunnelling current. In this situation the non-equilibrium electron–hole pairs are generated in narrow-gap materials. The degree of spin polarization of about 10% can be detected by circular polarized infrared radiation [13] (the structures under consideration correspond to this spectrum range). In structures with various doping types of narrow-gap materials and interband mechanisms for the tunnelling current, the orientation of nuclear spins can be detected (in this case the electron–hole radiative recombination cannot occur). It turns out that this nuclear spin polarization is considerable, because the overall electron spin concentration per unit area can be about $10^{13}\,\mathrm{cm}^{-2}$ if the degree of spin orientation is about several per cent, $n_0 \sim 10^{18}\,\mathrm{cm}^{-3}$, $\sqrt{D\tau_s} \sim 10^{-3}$ cm. This leads to a significant nuclear spin orientation [13, 14]. We believe that the increase in the lateral electric field is the simplest way to enhance the spin polarization, because the value of δn_0 is proportional to the drift velocity v_d.

The lateral current thus causes the spin orientation of particles tunnelling through the barrier layer in narrow-gap heterostructures, and this orientation can be detected using the above-mentioned methods.

Appendix

Here we present the transfer matrices and common expressions for the particle tunnelling probability in structures under flat-band conditions for the Kane and Dirac-like models, which were used in the previous calculations of the spin-dependent tunnelling probability and degree of electron spin orientation. We employ the matrix Hamiltonians and the basis wavefunctions in a similar form as in [10, 12] for Dirac-like and Kane models, respectively. The values $T^{\pm\sigma}$ have been calculated by applying (7), where the transmitted $t^{\pm}$ and reflected $r^{\pm}$ amplitudes of the envelope function, corresponding to the conduction band basis function, are related in the following way:

$$\begin{pmatrix} 1 \\ r^{\pm} \end{pmatrix} = \prod_{j=1}^{N} M_j^{\pm} \begin{pmatrix} t^{\pm} \\ 0 \end{pmatrix}. \tag{A1}$$

Here N is the number of considered layers and the matrices $M_j^{\pm}$ are defined in a similar way as in [12]:

$$M_j^{\pm} = (c_j^{\pm} + c_j^{\mp})^{-1} \begin{pmatrix} (c_j^{\mp} + c_{j+1}^{\pm}) \exp(-\mathrm{i}\varphi_j) & (c_j^{\mp} - c_{j+1}^{\mp}) \exp(-\mathrm{i}\psi_j) \\ (c_j^{\pm} - c_{j+1}^{\pm}) \exp(\mathrm{i}\psi_j) & (c_j^{\pm} + c_{j+1}^{\mp}) \exp(\mathrm{i}\varphi_j) \end{pmatrix} \tag{A2}$$

where the values φ_j and ψ_j are expressed by the coordinate y_j and the normal component of the wavevector k_{y_j} in the jth layer:

$$\varphi_j = (k_{y_j} - k_{y_{j+1}})y_j \qquad \psi_j = (k_{y_j} + k_{y_{j+1}})y_j.$$

The coefficients $c_j^{\pm}$ are obtained from the boundary conditions for the envelope wavefunctions and can be expressed in the following way:

$$c_j^{\pm} = \frac{k_{y_j}(E_j + E_{gj} + 2\Delta_j/3) \pm ik_{\parallel}\Delta_j/3}{(E_j + E_{gj})(E_j + E_{gj} + \Delta_j)} \tag{A3}$$

for the Kane model and

$$c_j^{\pm} = \frac{k_{y_j} \pm ik_{\parallel}}{E_j + E_{gj}} \tag{A4}$$

for the two-band Dirac-like model. In (A3) and (A4) E_j is the energy of a particle in the jth layer if the conduction band edge is the energy reference, and E_{gj} and Δ_j are the energy gap and the split-off energy in the layer j.

Under flat-band conditions when $N = 2$ in (A1), the tunnelling probability $T^{\pm}$ can be expressed using the coefficients $c_j^{\pm}$ in the following way:

$$T^{\pm} = \frac{E_3 k_1^2 k_{y3}}{E_1 k_3^2 k_{y1}} \frac{|c_2^{\pm} + c_2^{\mp}|^2 |c_1^{\pm} + c_1^{\mp}|^2}{|c_2^{\mp} - c_1^{\mp}|^2 |c_3^{\pm} - c_1^{\pm}|^2} \exp(-2\gamma d) \tag{A5}$$

where γ determines the scale of the under-barrier variation of the wavefunction, and is defined by the dispersion law in the barrier layer for the structures under consideration.

Accounting for the band-bending in the structure, we use a constant approximation for the potential in each layer j; the number of parts into which the structure is split is determined by the needed accuracy of the calculations.

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