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Spin-polarized electronic current in resonant tunneling heterostructures

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The spin-dependent tunneling phenomenon in symmetric and asymmetric resonant semiconductor heterostructures is employed in a theoretical study to investigate the output tunnel current polarization at zero magnetic field. A simple model of the resonant tunneling structures and a simple one-electron band approximation with spin-orbit interaction are used in this work. It is shown that asymmetry in the electron distribution at the electrode regions provides spin-polarized tunnel current. An approach to optimize this spin-dependent effect is explored theoretically. In asymmetric resonant tunneling structures, we estimate theoretically that the polarization can reach 40% with a moderate applied electric field. © *2000 American Institute of Physics.* [S0021-8979(00)09501-3]

I. INTRODUCTION

Resonant tunneling structures (RTSs) have been extensively investigated since the pioneering work of Tsu and Esaki and others.[1–4] RTSs with a negative differential conductance are widely used in high frequency amplification, oscillation, fast switching, and logic functions. During an almost quarter-century-long history of research and development, the RTS has dealt with ''nonspin'' electrons only. Recently it has become clear that the employment of electron spin in tunneling processes can provide a new degree of freedom in this area.[5–7] The tunneling and resonant tunneling processes involving electron spin show prominent perspectives for new field-spin-dependent fast electronics. There are at least two areas of extensive research in spin-dependent tunneling and its associated phenomena. For example, spin-polarized scanning probe microscopy with an optical orientation of the tunneling electrons and tunneling spin valves is discussed extensively in the literature.[8–10]

In this article, we analyze the spin-dependent tunneling phenomenon in resonant tunneling structures. The spin-polarized electronic current is due to spin splitting of electronic bands in asymmetric heterostructures.[11–14] The asymmetry in quantum well and quantum barrier heterostructures can be achieved technologically when the left and right barriers in the heterostructures are different. The asymmetry can also be obtained dynamically by applying an external electric field to the heterostructures. Spin splitting in the electron conduction band at zero magnetic field is a well-known problem in connection with the fundamental physical characteristics of heterostructures. In asymmetric heterostructures with built-in or external electric fields, spin-orbit interaction provides coupling between spin and the electron's spatial motion in the plane perpendicular to the direction of the structure growth (in-plane motion). An advantage of this approach is that the spin-dependent current can be controlled by an electric field. Theoretical and experimental investigations have demonstrated the existence of the spin-splitting effect in asymmetric quantum well structures. Experimentally the spin-orbit splitting for electrons confined in heterostructures has been studied by Raman scattering[15–17] and Shubnikov-de Haas oscillation.[18,19] Recently we found out that this effect is also strong in tunnel barrier structures and it can lead to the spin-dependent tunneling phenomenon.[7]

Advances in modern epitaxial growth technologies such as molecular-beam epitaxy (MBE) and metalorganic chemical vapor deposition (MOCVD) have provided us with an opportunity to produce semiconductor heterostructures in which the material parameters can be changed over a wide range and controlled within considerable accuracy.[20,21] This level of quality allows the relevant theoretical analysis within the framework of relatively simple approximations for semiconductor band structures.[22,23] So it is worthwhile to investigate how to obtain spin-polarized electronic current using the spin-spliting effect in the RTS.

In this article, the spin-dependent tunnel current in double-barrier heterosturctures is calculated. We show that to obtain the spin-polarized output electronic current we need asymmetry in the in-plane electronic wave vector distribution. The asymmetry can be created by an additional in-plane electric field and we show that a measurable value of spin-polarized output electronic current is attainable. Two types of RTS are discussed: (1) symmetric RTS (sRTS) and (2) asymmetric RTS (aRTS). In aRTS we can obtain a polarization up to 40% with a moderate external electric field.

The article is organized as follows. In Sec. II some details of the standard calculation of the electron spin-dependent tunneling probability in RTS are described. In Sec. III we propose a way to obtain spin-polarized output tunnel current in RTS and a method to evaluate the polariza-

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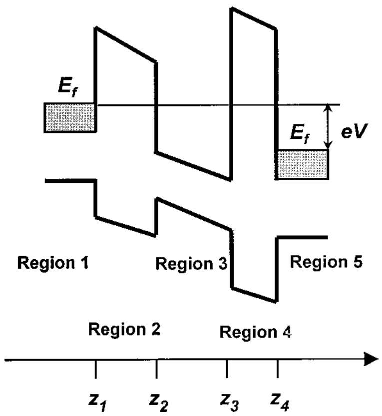

FIG. 1. Variation of the semiconductor band parameters in a RTS under external electric voltage V.

tion. The calculated results of the symmetric and asymmetric RTS are presented in Sec. IV. In Sec. V we summarize possible directions to optimize the effect.

II. SPIN-DEPENDENT TUNNELING PROBABILITY

A RTS with an external electric field F_z applied along the direction of structure growth z is shown in Fig. 1. Layers of the structure are perpendicular to the z axis, and the in-plane electron wave vector is k [if k is put along an arbitrary x direction, the spin polarization is set along the y axis in the layer plane $\rho=(x,y)$]. In the structure there are two sources for the k-vector dependence of the transmission coefficient: (1) through position-dependent energy band parameters (like in Refs. 24–29), and (2) through the coupling between in-plane electron motion and the electron's spin caused by the external electric field. The second one can lead to the spin polarization dependence in sRTS. The former leads to the spin dependent boundary conditions and manifests the spin-splitting effect in aRTS even without the presence of any external electric field.[7,30,31] We use in our calculations the effective quasione-dimensional one-electron-band Hamiltonian[30,32] within the envelope function approximation.[22] The total wave function of the electron $\Phi_\sigma(z,\rho)$ can be written as

$$\Phi_\sigma(z,\rho)=\Psi_{j\sigma}(z)\exp(ik\cdot\rho).$$

The wave function $\Psi_{j\sigma}(z)$ satisfies the z component of the Schrödinger equation in the jth region:

$$H_{j\sigma}\Psi_{j\sigma}(z)=E\Psi_{j\sigma}(z), \tag{1}$$

where

$$H_{1\sigma}=-\frac{\hbar^2}{2m_1(E)}\frac{d^2}{dz^2}+\frac{\hbar^2k^2}{2m_1(E)}+E_{1c},\quad \text{when } j=1;$$

$$H_{j\sigma}=-\frac{\hbar^2}{2m_j(E)}\frac{d^2}{dz^2}+\frac{\hbar^2k^2}{2m_j(E)}+E_{jc}-eF_z(z-z_1)$$
$$-\sigma\alpha_j kF_z,\quad \text{when } j=2-4;$$

$$H_{5\sigma}=-\frac{\hbar^2}{2m_5(E)}\frac{d^2}{dz^2}+\frac{\hbar^2k^2}{2m_5(E)}+E_{5c}-eF_zd,$$
$$\text{when } j=5;$$

$$\frac{1}{m_j(E)}=\frac{P^2}{\hbar^2}\left[\frac{2}{E-E_{jc}+E_{jg}+eF_z(z_j-z_1)}+\frac{1}{E-E_{jc}+E_{jg}+\Delta_j+eF_z(z_j-z_1)}\right] \tag{2}$$

is position-dependent electronic effective mass in nonparabolic approximation, and α_j is the Rashba spin-orbit coupling parameter, the "second" contribution to the Rashba spin-orbit splitting:[30]

$$\alpha_j=\frac{\hbar^2}{2m_j(0)}\frac{\Delta_j}{E_{jg}}\frac{2E_{jg}+\Delta_j}{(E_{jg}+\Delta_j)(3E_{jg}+\Delta_j)}.$$

In Eqs. (2) E denotes the total electron energy in the conduction band, $\sigma=\pm1$ refers to the spin polarization, $d=z_4-z_1$ is total thickness of regions 2–4, and e is the electronic charge. The matrix element P is assumed to be z independent,[22] and E_{jc}, E_{jg}, and Δ_j stand for the conduction-band edge, the main band gap, and the spin-orbit splitting inside the jth region ($E_{1c}=0$, conventionally) respectively. In the calculations, the nonparabolic approximation Eqs. (2), for the electronic dispersion relations was used for all materials of the structures.[7,30] The role of the nonparabolic approximation was discussed in Ref. 7.

The mass and spin-dependent boundary conditions for $\Psi_{j\sigma}(z)$ in an interface plane $z=z_j$ between j and $j+1$ regions were introduced in Ref. 30,

$$\frac{1}{m_j(E)}\left\{\frac{d}{dz}\ln[\Psi_{j\sigma}(z)]\right\}_{z=z_j}-\frac{1}{m_{j+1}(E)}\times\left\{\frac{d}{dz}\ln[\Psi_{j+1\sigma}(z)]\right\}_{z=z_j}=\frac{2\sigma k[\beta_{j+1}(E)-\beta_j(E)]}{\hbar^2},$$
$$\Psi_{j\sigma}(z_j)-\Psi_{j+1\sigma}(z_j)=0, \tag{3}$$

where

$$\beta_j(E)=\frac{P^2}{2}\left[\frac{1}{E-E_{jc}+E_{jg}+eF_z(z_j-z_1)}-\frac{1}{E-E_{jc}+E_{jg}+\Delta_j+eF_z(z_j-z_1)}\right]$$

is the position- and energy-dependent electronic spin-coupling parameters.

We calculate the spin-dependent transmission probability $T_\sigma(E_z,\mathbf{k})$ of the structure as a function of the longitudinal component of the electron energy E_z and the in-plane wave vector k. The relations among E_z, k, and the total energy in view of the nonparabolicity can be found from the following expression:

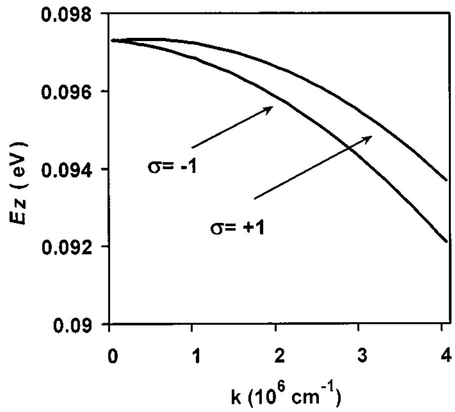

FIG. 2. Positions of the spin-split resonance tunneling probability peaks on the (E_z-k) plane for the symmetric RTS InAs–GaAs–InAs–GaAs–InAs (the parameters are obtained from (Refs. 23 and 35): $E_{2c}=E_{4c}=0.792$ eV, $E_{3c}=E_{5c}=0.0$ eV, $E_{1g}=E_{3g}=E_{5g}=0.418$ eV, $E_{2g}=E_{4g}=1.52$ eV, $\Delta_1=\Delta_3=\Delta_5=0.38$ eV, $\Delta_2=\Delta_4=0.341$ eV, $m_1(0)=m_3(0)=m_5(0)=0.023m_0$, $m_2(0)=m_4(0)=0.067m_0$ (m_0 is the free electron's mass), $z_2-z_1=z_5-z_4=30$ Å, $z_3-z_2=60$ Å.

$$E(E_z,k)=E_z+\frac{\hbar^2k^2}{2m_1(E,k)}.$$

The well-known transfer matrix approach[33] including spin-dependent boundary conditions (3) are used to calculate $T_\sigma(E_z,\mathbf{k})$, as described in Ref. 31.

Before we present calculation of the spin-dependent tunneling current, it is worthwhile to look at the characteristics of $T_\sigma(E_z,\mathbf{k})$. The spin-dependent tunneling probability $T_\sigma(E_z,\mathbf{k})$ shows a spin splitting of the resonant peaks in the (E_z-k) plane.[30–32] Those split up peaks correspond to the quasistationary levels with different electron spin polarization in the RTS well. The splitting appears when there is asymmetry in the z direction in the structure. In *s*RTS the splitting is zero when $F_z=0$, and it increases with electric field. As was found in Ref. 31 the splitting also exists for *a*RTS even without the presence of any external electric field. In Fig. 2 we present the split peak locations on the (E_z-k) plane for a *s*RTS consisting of two identical InAs–GaAs–InAs barriers. Each barrier has a barrier width of $z_2-z_1=z_5-z_4=30$ Å and a corresponding spacing between the barriers, $z_2-z_3=60$ Å under an external electric field of $F_z=5\times10^4$ V cm^{-1}.

The spin-split resonant tunneling probability provides a difference in resonance conditions for tunneling electrons with different directions of electron spin. We expect that the spin resonant peaks can render different contributions to the total electronic tunneling current in the RTS. Therefore, the spin-polarized output electronic current can be obtained.

III. POLARIZATION OF THE TUNNEL CURRENT

The value of practical interest is the polarization of the output tunnel electron current. We can estimate the polarization of the electron tunnel current under electric field F_z along the z direction for the tunnel structure with heavily doped electrodes shown in Fig. 1 as

$$p=\frac{J_+-J_-}{J_++J_-}, \tag{4}$$

where

$$J_\sigma=\frac{e}{8\pi^3}\int T_\sigma(E_z,\mathbf{k})[f_1(\mathbf{k})-f_5(\mathbf{k})]u_{1z}d\mathbf{k}dk_z$$

is the tunnel current for the electrons with σ polarization, $f_j(\mathbf{k},k_z)$ is the electronic distribution function in three-dimensional $\{\mathbf{k}=(k_x,k_y);k_z\}$ space in the emitter $(j=1)$ and collector $(j=5)$ regions, u_{1z} is the z component of the electron velocity

$$u_1(\mathbf{k})=\frac{1}{\hbar}\frac{\partial E}{\partial\mathbf{k}}$$

in the emitter region.

According to the general features of the spin-orbit interaction, Eqs. (1) and (3), the spin-dependent tunneling probability $T_\sigma(E_z;\mathbf{k})$ satisfies the following relation of symmetry:

$$T_\sigma(E_z;\mathbf{k})=T_{-\sigma}(E_z;-\mathbf{k}). \tag{5}$$

It is easy to find out from Eqs. (4) and (5) that $p=0$ (no polarization in the total output current) if the electric field $V=F_zd$ is applied along the z direction and the distribution $f_0(E)$ for electrons in the electrode regions is assumed to be Fermi like $[f_1(\mathbf{k},k_z)=f_0(E),\ f_2(\mathbf{k},k_z)=f_0(E+\mathrm{eV})]$. We can obtain the polarized output current only when the electron distribution in the emitter region has asymmetry in the (k_x,k_y) in-plane intersection of the $\mathbf{k}$ space.

Let us assume that the total external electric field has an additional in-plane component, F_x. To avoid the influence from this component on the tunneling probability described above we adhere to the condition $F_x/F_z\ll1$. Under an added x component of the electric field the electron distribution becomes asymmetric in the (k_x,k_y) plane. Employing the linear approximation on F_x we can treat the distribution function by[34]

$$f_1(\mathbf{k},k_z)=f(E,k_x)\approx f_0(E)+e\tau(E)\cdot\frac{\partial f_0(E)}{\partial E}\cdot u_{1x}(E)\cdot F_x, \tag{6}$$

where $\tau(E)$ is the relaxation time for electrons and u_{1x} is the x component of the electron velocity $\mathbf{u}_1$ in the emitter region. For a degenerate electron gas with an Fermi energy E_f, $\partial f_0(E)/\partial E\approx-\delta(E-E_f)$. Substituting Eq. (6) into Eq. (4), we get

$$p(F_z,F_x)\approx\xi\cdot\frac{I_-}{I_+}, \tag{7}$$

where

$$\begin{aligned}I_-=&\int_{1-\nu}^{1}(1-\eta)^{1/2}d\eta\\&\times\int_0^{\pi/2}\{T_+[\eta E_f;k_f(1-\eta)^{1/2}\cos\theta]\\&-T_-[\eta E_f;k_f(1-\eta)^{1/2}\cos\theta]\}\cos\theta d\theta,\end{aligned}$$

TABLE I. Allowable additional electric fields for systems with different electronic concentrations n.

n ($\mathrm{cm^{-3}}$)	E_f (eV)	$u_1(E_f)$ ($\mathrm{cm\ s^{-1}}$)	u_1[a] ($\mathrm{cm^2\ V^{-1}\ s^{-1}}$)	$F_x^{\xi=0.1}$ ($\mathrm{V\ cm^{-1}}$)
10^{17}	0.032	6.4×10^7	4×10^4	1.6×10^3
5×10^{17}	0.084	9.1×10^7	4×10^4	2.3×10^3
10^{18}	0.125	1.0×10^8	4×10^4	2.5×10^3

[a]Reference 36.

$$I_+=\int_{1-\nu}^{1}d\eta\int_0^{(1-\eta)^{1/2}}\kappa d\kappa \times\int_0^{\pi/2}\{T_+(\eta E_f;\kappa k_f\cos\theta)+T_-(\eta E_f;\kappa k_f\cos\theta)\} \times d\theta,$$

$$k_f=\frac{1}{\hbar}\sqrt{2m_1(E_f)E_f},$$

$\xi=\mu_1F_x/u_1(E_f)$, $\nu=\mathrm{eV}/E_f$, μ_1 is the electron mobility in the emitter region, and $m_1(E_f)$ is the electron effective mass under the nonparabolic approximation (2) at the Fermi energy.

The unitless coefficient ξ in Eq. (7) is used traditionally to verify the linear current theory's [Eq. (6)] applicability.[34] To satisfy the linear theory condition, an appropriate value of the coefficient $\xi=0.1$ is used. In Table I each maximum allowable additional field F_x evaluated at $\xi=0.1$ for InAs electrodes with different electron concentrations is presented. The fields as a whole satisfy the condition mentioned before ($F_x/F_z\ll1$), when $F_z\geqq0.5\times10^4\ \mathrm{eV\,cm^{-1}}$.

IV. RESULTS AND DISCUSSION

First the polarized tunnel current in sRTS is discussed. As we demonstrated previously, the spin-split resonant peaks in the tunneling probability appear only with the presence of an external electric field F_z. The result of our calculation for the tunnel heterostructures with a composition arrangement of InAs–GaAs–InAs–GaAs–InAs and different levels of electron concentration is shown in Fig. 3. The curves present the total output electronic current polarization $p(F_z)$ as a function of the longitudinal electric field when $\xi=0.1$. Two sharp peaks on the plots represent the highest level of the electronic output current polarization. The peaks' appearance and position are clarified in Fig. 4 by the normalized total tunnel current along with the polarization curves for this structure having an electron concentration of $10^{17}\ \mathrm{cm^{-3}}$. We notice that the polarization peaks are situated at the beginning and the end of the tunnel current plot. The first peak appears when the Fermi level crosses the lowest spin-split quasistationary level in the well (see Fig. 2). The second one appears when the highest spin-split level (with another spin polarization) crosses the bottom of the electronic band in the emitter region. This phenomenon allows us to optimize the magnitude of this effect.

To achieve a higher level of polarization, it is desirable to investigate aRTS with a built-in spin splitting of the resonant peaks in the tunneling probability.[31] The external electric field in these structures can amplify the splitting effect. From the description given above we can conclude that the

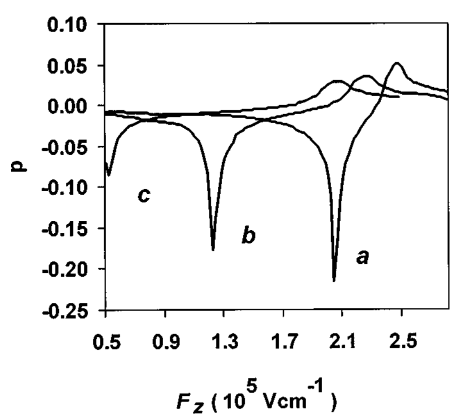

FIG. 3. Polarization of the total output tunnel current for the structure in Fig. 2 with different electron concentrations, n, in the electrodes. Curves (a)–(c) correspond, respectively, to the cases of $n=10^{17}$, 5×10^{17}, and $10^{18}\ \mathrm{cm^{-3}}$.

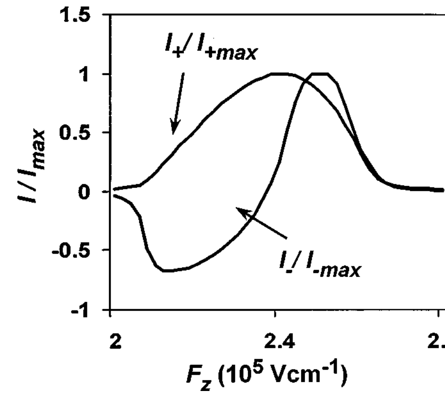

FIG. 4. Normalized to their maximums are the total tunnel current ($I_+/I_{+\max}$) and a polarization difference ($I_-/I_{-\max}$) for the structure illustrated in Fig. 2.

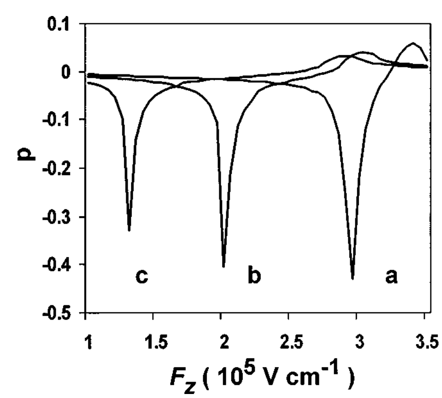

FIG. 5. Polarization of the total output tunnel current for the asymmetric structure InAs–GaAs–InAs–AlAs–InAs (the parameters are obtained from Refs. 23 and 35): $E_{2c}=0.792$ eV, $E_{4c}=1.86$ eV, $E_{3c}=E_{5c}=0.0$ eV, $E_{1g}=E_{3g}=E_{5g}=0.418$ eV, $E_{2g}=1.52$ eV, $E_{4g}=3.13$ eV, $\Delta_1=\Delta_3=\Delta_5=0.38$ eV, $\Delta_2=0.341$ eV, $\Delta_4=0.28$ eV, $m_1(0)=m_3(0)=m_5(0)=0.023m_0$, $m_2(0)=0.067m_0$, $m_4(0)=0.15m_0$, $z_2-z_1=30$ Å, $z_3-z_2=50$ Å, $z_4-z_3=15$ Å. Curves (a)–(c) correspond, respectively, to the different electron concentrations in the electrode regions: $n=10^{17}$, 5×10^{17}, and $10^{18}\ \mathrm{cm^{-3}}$.

resonant levels in the structure have to be situated in higher positions to employ the higher electric field in the beginning of the resonant current appearance. The same circumstance allows us to prefer systems with lower electron concentrations in the electrode regions. Based on those reasons we calculated the polarization in the asymmetric structures with configurations of InAs–GaAs–InAs–AlAs–InAs when $z_2 - z_1 = 30$ Å, $z_2 - z_3 = 50$ Å, and $z_5 - z_4 = 15$ Å. The calculation results are shown in Fig. 5. The curves demonstrate an agreement with the general description of the spin-dependent effect presented above. The highest polarization is reached in a structure with an electron concentration of 10^{17} cm^{-3} and is above 40%. The sign of the polarization can be changed obviously by changing the direction of the additional in-plane electric field.

V. CONCLUSION

Research and applications of spin-dependent transport in semiconductor heterostructures often require spin-polarized electronic current.[6] From this perspective, an active search for new opportunities to obtain spin-polarized output current in quantum heterostructures is essential. Semiconductor quantum heterostructures based on III–V semiconductors are well developed. An approach to control the spin-dependent transport in the structures without additional magnetic fields can be a potential advantage and it is worth investigating.

In this article, the spin-polarized tunneling current in resonant tunneling heterostructures at zero magnetic field was studied. We have theoretically demonstrated that asymmetry of the electron distribution in the electrode regions in RTS with spin-dependent tunneling probability can provide output tunnel current polarization. The polarization can be quite high for optimized structures. The effect is stronger for asymmetric RTSs with built-in spin splitting of the tunneling probability.

Finally, we want to point out that the calculation presented uses a simple model of the resonant tunneling structures and a simple one-electron-band approximation with spin-orbit interaction. The structures have realistic parameters, but the proposed estimate of the total polarized current is only a starting point for the investigation of this new effect. Further experimental investigations of the effects are really needed. Spin-dependent electronic transport that takes into consideration all accompanying de-polarization processes (elastic and inelastic) is the subject of special theoretical and experimental investigation.[10] The development history of RTS indicates that the implementation and optimization procedures require more complicated investigations.[3]

ACKNOWLEDGMENTS

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