### Instructions for use

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Spin-Filter Device Based on the Rashba Effect Using a Nonmagnetic Resonant Tunneling Diode

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We propose an electronic spin-filter device that uses a nonmagnetic triple barrier resonant tunneling diode (TB-RTD). This device combines the spin-split resonant tunneling levels induced by the Rashba spin-orbit interaction and the spin blockade phenomena between two regions separated by the middle barrier in the TB-RTD. Detailed calculations using the InAlAs/InGaAs material system reveal that a splitting of a peak should be observed in the \( I-V \) curve of this device as a result of the spin-filtering effect. The filtering efficiency exceeds 99.9% at the peak positions in the \( I-V \) curve.

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Experimental realization of a spin-polarized current source and manipulation of electron spin in a semiconductor are among the most important issues in “spintronics” research [1]. In this research area, extra degrees of freedom provided by electron spins, in addition to those provided by electron charges, are expected to play important roles in realizing new functions in future electronic devices, which include spin-FET [2], spin interference devices [3], and a readout device for the qubit information [4]. In order to explore the roles of spin degrees of freedom in a semiconductor, it is essential to realize a spin-polarized current source from which spin-polarized electrons are injected. The properties of electron spins, including their dynamical motions in the pertinent materials are then studied using the injected spin-polarized electrons. Thus far, various magnetic materials, including ferromagnetic metals [5–7] and diluted magnetic semiconductors [8–13], have been used as spin injection sources. Besides the successes in these approaches, it is also important to develop a spin-polarized current source, or a spin filter, that uses only nonmagnetic semiconductors from the viewpoints of both the attainability of high-quality heterostructures and the absence of the stray magnetic field that may cause some undesirable effects on the spin-filtered electrons.

In this Letter, we propose a spin-filter device that uses a triple barrier (TB) resonant tunneling diode (RTD) which can generate a spin-polarized current without using magnetic properties of materials. Instead, we utilize the Rashba spin-orbit coupling effect [14–16] (Rashba effect) to induce spin-split resonant tunneling levels (RTL) in the proposed device even in the absence of magnetic field. So far, the Rashba effect in a double barrier (DB) RTD has been discussed from both theoretical [17] and experimental points of view [18], and is predicted to provide some degrees of spin polarization in the transmitted electrons [17]. However, the utilization of Rashba effect alone in a DB-RTD does not produce a high degree of spin polarization (>90%). To overcome this problem, we propose combining the spin-splitting phenomena caused by the Rashba effect with level-matching between the spin-dependent RTLs, which is accomplished by adjusting the emitter-collector voltage \( V_{EC} \) in the TB-RTD. This level matching procedure is analogous to the recently proposed spin-blockade concept [4,19].

We propose to realize this spin-filter device using a structure illustrated and detailed in Fig. 1(a) and Table I, respectively. A special feature that differentiates the proposed device from other TB-RTDs is the particular mountain-like (triangular) shape in the potential profile as illustrated in Figs. 1(b) and 1(c). This mountain-like potential profile is realized by introducing \( n \)-type impurities in barriers 1 and 3, and the compensating amount of \( p \)-type impurities in barrier 2. The actual amount

FIG. 1. (a) A schematic illustration of the proposed spin-filter device. The \( z \) axis is set vertically, pointing downward. The shaded areas denote the metal electrodes for the \( I-V \) measurement. (b),(c) Conduction band potential profiles for the proposed device to show how the matching of spin-dependent resonant tunneling levels is performed by controlling the emitter-collector bias voltage \( V_{EC} \). The downward and upward arrows in region 1 denote the clockwise and counterclockwise spin states, respectively.

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of these impurities that would cause sufficiently large Rashba spin splittings was determined based on
our previous studies of asymmetric quantum wells [16,20].

The p- and n-type impurities in the barrier layers are
assumed to be completely ionized because the accepter
and donor levels in these layers are, respectively, below
and above the Fermi levels in the emitter and collector
leads. As a result of this particular potential-profile shape,
the direction of electric field that an electron feels in
region 1 of the device [see Fig. 1(a)] is opposite to that in
region 2. Hence, the signs for the corresponding Rashba
constants are also opposite each other. In the present work,
conduction band offset values between the emitter lead and
barrier 1 (denoted as $\Delta E_c^{(1)}$) were set smaller than
that for the lattice-matched In$_{0.53}$GaAs/IIn$_{0.52}$Al$_{0.48}$As
interface for the purpose of reducing the leakage current
in the actual experiment. However, care was taken to
make the position of the lowest RTLs still lie higher than
that of the conduction band edge of the emitter lead so
that electrons can resonantly tunnel through the barriers.
Experimentally, the $\Delta E_c^{(1)}$ value can be adjusted by
varying the Ga composition $x$ in the In$_{1-x}$Ga$_x$As emitter
lead. The value of the Fermi energy in the emitter lead in
the present work ($E_F = 75$ meV relative to the conduction
band edge) is chosen in such a way that only the lowest
RTL can contribute to the total transmission current for
all the three proposed device structures listed in Table I.

In order to explain the principle of the proposed device,
we consider transmission of an electron with a wave vector $k$
across the device [21]. In the following explanation,
$z$ axis is set perpendicular to the barriers in the RTD. All
the energy levels are measured relative to the conduction
band edge of the emitter lead. Taking advantage of the
circular symmetry of this system about its $z$ axis, we can
represent $x$ and $y$ components of the physical quantities by
a single “parallel” component (denoted by the subscript $||$
hereafter) without the loss of generality. In the absence
of the Rashba effect (or when $k_{||} = 0$), an electron with a
wave vector $k$ can transmit through the device if (1) the
resonant tunneling level in region 1 (denoted as $E_F^{(1)}$
matches that in region 2 (denoted as $E_F^{(2)}$), and (2) the $z$
component of the electron energy in the emitter lead (denoted
by $E_k = \frac{h k_z^2}{2 m^*}$) matches $E_F^{(1)}$ and $E_F^{(2)}$. While
matching between $E_F^{(1)}$ and $E_F^{(2)}$ is performed by controlling
$V_{EC}$, matching between $E_k$ and $E_F^{(1)}$ (or $E_F^{(2)}$) is automatically
made if the resonant levels $E_F^{(1)}$ and $E_F^{(2)}$ lie between
the conduction band edge and the Fermi energy of the
emitter lead. Under these conditions, we should observe a
single sharp peak in the $I - V$ curve of this device, since
condition 1 above can be met only at a certain value of
$V_{EC}$. Now, if the Rashba effect is present and $k_{||} \neq 0$,
the resonant tunneling levels $E_F^{(1)}$ and $E_F^{(2)}$ experience
the level splitting: $E_F^{(X)} \rightarrow E_F^{(X)} \pm \alpha_X k_{||}$ ($X = 1,2$),
where the plus and minus signs correspond to the resonant
levels for different spin states, which we denote as “clockwise”
($l$) and “counterclockwise” ($s$) spins, respectively [22],
and $\alpha_X$ is the Rashba constant in region $X$. Because
of the mirror symmetry in the present device about the
middle barrier, the sign for the value of $\alpha_1$ is opposite to
that of $\alpha_2$, while their absolute values are almost equal.
Therefore, if the Rashba effect is present and $k_{||} \neq 0$,
the value of $V_{EC}$ required to match the resonant levels for
the clockwise spin ($l$) is different from that required for
the counterclockwise spin ($s$) [see Figs. 1(b) and 1(c)].
Hence, we would observe two peaks in the $I-V$ curve.

The values of the actual spin-dependent tunnel current
$I_{\|}$ through the proposed device are calculated by
integrating the spin-dependent transmission coefficient
$T_L^{\|}(E_{k_{||}}, E_k)$ across the device with energy $E_{k_{||}}$
and summing the results over all available $k_{||}$ modes [23,24]:

$$I_{\|} = \frac{|e|}{h} \sum_{|k_{||}| < k_{cF}} \int_{E_F - E_{k_{||}}}^{E_F} T_L^{\|}(E_{k_{||}}, E_k) dE_k. \quad (1)$$

In Eq. (1), $e$ and $h$ are the electron charge and Planck’s
constant ($h = h/2\pi$), respectively, and $T = 0$ is assumed
for temperature, though it turned out that the thermal
smearing effect is minimal at least up to 150 K [25]. It

### Table I. Layer information for the proposed spin-filter device.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>$m^*/m_0$</th>
<th>$E_g$ [eV]</th>
<th>$\epsilon_s/\epsilon_0$</th>
<th>$\Delta d$</th>
<th>Thickness [Å]</th>
<th>Structure 1</th>
<th>Structure 2</th>
<th>Structure 3</th>
</tr>
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<tr>
<td>Emitter</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>Variable</td>
<td>Variable</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>7.74 x 10$^{17}$</td>
<td>7.74 x 10$^{17}$</td>
<td>7.74 x 10$^{17}$</td>
</tr>
<tr>
<td>Barrier 1,3</td>
<td>In$<em>{0.52}$Al$</em>{0.48}$As</td>
<td>0.075</td>
<td>1.66</td>
<td>12.46</td>
<td>0.309</td>
<td>60</td>
<td>4 x 10$^{18}$</td>
<td>2 x 10$^{18}$</td>
<td>0</td>
</tr>
<tr>
<td>Well 1,2</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>0.041</td>
<td>0.783</td>
<td>13.1</td>
<td>0.328</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Barrier 2</td>
<td>In$<em>{0.52}$Al$</em>{0.48}$As</td>
<td>0.075</td>
<td>1.66</td>
<td>12.46</td>
<td>0.309</td>
<td>35</td>
<td>1.37 x 10$^{19}$</td>
<td>6.85 x 10$^{18}$</td>
<td>0</td>
</tr>
<tr>
<td>Collector</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>0.041</td>
<td>0.783</td>
<td>13.1</td>
<td>0.328</td>
<td>N.A.</td>
<td>$\sim 1 \times 10^{17}$</td>
<td>$\sim 1 \times 10^{17}$</td>
<td>$\sim 1 \times 10^{17}$</td>
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$\Delta E_r^{(1)}$ [eV] | 0.270 | 0.165 | 0.030 |
| $|\alpha_1|^2$ [eV m] | 7.23 x 10$^{12}$ | 3.25 x 10$^{-12}$ | 0 |

$^a$Electron effective mass. $m^*/m_0 = 0.041 m_0$ is used for the emitter lead in the present work for simplicity.
$^b$Energy band gap. $\Delta E_c^{(1)}/\Delta E_s = 0.7$ is used to determine the conduction band offset value.
$^c$Static dielectric constant ($\epsilon_s$) and spin split-off energy in the valence band ($\Delta$).
$^d$Barriers 1 and 3 are doped n-type, while barrier 2 is doped p-type. The emitter and collector leads are doped n-type.
$^e$Conduction band offset value between the emitter lead and barrier 1.
$^f$Calculated value for the Rashba constant $\alpha_1$ at the middle of region 1. $E = 0.04$ eV is used for the electron energy.
is noted that the energies $E_{k\|}$ and $E_{k\perp}$ are calculated in the emitter lead ($E_{k\|} = \frac{\hbar^2 k^2}{2m^*}$ and $E_{k\perp} = \frac{\pi^2 k^2}{2m^*}$), where $m^*$ is the electron effective mass. What we are really interested in here is the current injected towards the right ($+k\|$ in Fig. 1) in the collector layer which will be detected by our contact and show spin polarization. The current injected towards the left ($-k\|$) will have exactly the opposite spin polarization since the Rashba field is opposite between $+k\|$ and $-k\|$ states. However, this current flows away from our contact and will not be detected.

We use the transfer matrix method to calculate $T^{\uparrow \downarrow}_{LL}(E_{k\|}, E_{k\perp})$, assuming the conservation of $k\|$ across the device [23,24]. We consider the following effectively one-dimensional Hamiltonian that describes an electronic state in an in-plane mode $k\|$ with energy $E_{k\|}$:

$$\frac{\hbar^2 k^2}{2m^*(z)} + U_{r11}^{\uparrow \downarrow}(k\|, z) = E_{\uparrow \downarrow},$$  \hspace{1cm} (2)

where $U_{r11}^{\uparrow \downarrow}(k\|, z)$ is the effective potential energy for clockwise ($\uparrow$) and counterclockwise ($\downarrow$) spins, respectively:

$$U_{r11}^{\uparrow \downarrow}(k\|, z) = \frac{\hbar^2 k^2_{\|}}{2m^*(z)} \pm \alpha(z)k\| + U_0(z) - E_{k\|.}$$  \hspace{1cm} (3)

In Eq. (3), the second term in the right-hand side corresponds to the energy due to the Rashba effect and the third term corresponds to the conduction band profile in the semiconducting heterostructure. The value of $\alpha(z)$ in Eq. (3) is given by the following equation based on the $k \cdot p$-type formalism [15]:

$$\alpha(z) = \frac{\hbar^2 E_p}{6m_0} \frac{d}{dz} \left( \frac{1}{\Delta E_{\uparrow \downarrow}(z)} - \frac{1}{\Delta E_{\uparrow \downarrow}(z)} \right),$$  \hspace{1cm} (4)

where $m_0$ is the free electron mass, $E_p$ is the $k \cdot p$ interaction parameter ($E_p = 22$ eV is used here [15]), and $\Delta E_{\uparrow \downarrow}(z)$ and $\Delta E_{\uparrow \downarrow}(z)$ are, respectively, the differences between the electron’s total energy $E = E_{k\|} + E_{k\perp}$, which is measured from the conduction band edge in the emitter lead, and the energies of the $\Gamma_7$ (spin split-off band) and $\Gamma_8$ (the highest valence band) valence band edges (denoted as $E_{\Gamma_7}$ and $E_{\Gamma_8}$, respectively) at position $z$. It is also noted that the difference between $E_{\Gamma_7}$ and $E_{\Gamma_8}$ ($E_{\Gamma_7} > E_{\Gamma_8}$) is known as the spin split-off energy $\Delta$ in Table I.

The results of the calculation for $I_{\uparrow \downarrow}$ are shown in Figs. 2(a)–2(c) as a function of $\Delta V_{EC}$ ($\equiv V_{EC} - V_{EC}^0$) for the three device structures listed in Table I, where, at $V_{EC} = V_{EC}^0$, the potential profile in region 2 becomes exactly the mirror image of that in region 1 about the center barrier. Shown in the insets to Figs. 2(a)–2(c) are the conduction band profiles for device structures 1, 2, and 3, respectively, at $V_{EC} = V_{EC}^0$. In Fig. 2(a), we see a clear separation in the $I$-$V$ curve peak between the two spin states due to the spin-filtering effect. Since the separation of these two peaks is about 13 mV, such a splitting of the $I$-$V$ curve peak should be observable in a real experiment. In Fig. 2(a), we also find that the spin polarization of the transmitted current ($|I_{\uparrow} - I_{\downarrow}|/|I_{\uparrow} + I_{\downarrow}|$) exceeds 99.9% at the peak positions of the $I$-$V$ curve, showing the excellent spin-filtering property of the proposed device. A notable feature in Fig. 2(a) is the particular triangular-like asymmetric shape of the $I$-$V$ curve peak for each spin state. The reason that the $I$-$V$ curves of the proposed device have this particular shape is the following: As we discussed above, the spin splitting of RTLSs for an electron with a wave vector $k$ is proportional to the value of $k\|$. Therefore, denoting by $V_{EC}^{\uparrow}$ and $V_{EC}^{\downarrow}$ the values of $V_{CE}$ at which the conditions are satisfied for transmitting $\uparrow$ and $\downarrow$ spin electrons with a wave vector $k$, respectively, we can see that the difference between these voltages $V_{EC}^{\uparrow} - V_{EC}^{\downarrow}$ increases as the value of $k\|$ increases. In addition, the values of the tunnel current are proportional to the number of $k\|$ modes available for electron transmission. Since the number of these available modes increases proportionally to the value of $k\|$, the value of $I_{\uparrow}$ also increases with increasing $\Delta V_{EC}$ for $\Delta V_{EC} > -1.5$ meV in Fig. 2(a), for...
example. For $\Delta V_{EC} > 4.5$ meV in Fig. 2(a), the value of $I_1$ decreases rapidly to zero. This is because the total energy of an electron with the corresponding $k_\parallel$ values ($E_{k_1} + E_{k_2}$) exceeds the Fermi energy in the emitter lead in this regime. The behavior of $I_1$ as a function of $\Delta V_{EC}$ in the corresponding regime is also explained in the same way. Shown in Figs. 2(b) and 2(c) are the results of the calculation for device structures 2 and 3, respectively, where the absolute values of the Rashba constant $|\alpha|$ in regions 1 and 2 are reduced from that in device structure 1 due to the reduced impurity densities in barriers 1, 2, and 3. The results show that the separation of the peaks in the $I-V$ curve reduces as the value of $|\alpha|$ decreases and the splitting of the peak disappears as $|\alpha|$ goes to zero.

A few words about the possible detrimental effects to spin filtering in the proposed device. The charge accumulation in the wells leading to band bending would shift the positions of the RTLs. This effect, if it is so strong that the level matching cannot be made by merely varying the $V_{EC}$ value, can be circumvented by thickening the emitter-side barrier (reducing the amount of total tunneling current). Ionized impurity scattering in the barrier layers may also lead to the broadening of the RTLs. One can avoid this problem by utilizing composition grading in the wells [26], instead of $p$ and $n$ doping in the barrier layers. This approach would also produce the "mountainlike" potential shape, which is the key configuration for the operation of the proposed device.

In summary, we have proposed a novel spin-filter device that uses a nonmagnetic triple barrier resonant tunneling diode. In this device, the Rashba spin-orbit coupling effect is combined with the spin blockade phenomena to enhance the spin-filtering efficiency, where the values higher than 99.9% are predicted for the spin-filtering efficiency at the peak positions of the $I-V$ curves. Thus, the excellent spin-filtering properties of this device should play important roles in the future spintronics research.

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[22] The particular spin configuration in a system with the Rashba effect is discussed in Ref. [15]. In short, electron spins are oriented perpendicular to both the in-plane wave vector $k_\parallel$ and the electric field created by the potential profile of the heterostructure.