Gate-voltage-induced switching of the Rashba spin-orbit interaction in a composition-adjusted quantum well

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The coefficient α of the Rashba spin-orbit interaction is calculated in an asymmetric quantum well consisting of $Ga_{0.47}In_{0.53}As$ (well), $Al_{0.48}In_{0.52}As$ (left barrier), and $Al_xGa_{1-x}As_ySb_{1-y}$ (right barrier) as a function of the external electric field perpendicular to the well E_z^{ex} which is controlled by the gate voltage. This coefficient α, which depends on the band offset, can be tuned to be zero by adjusting the Al fraction x in the right barrier layer to the optimum value x_0 in the case where the wave function vanishes at the left heterointerface. Such a composition-adjusted asymmetric quantum well is proposed as a structure in which the magnitude of α can be switched by changing the polarity of E_z^{ex}. The calculation shows that, when $|x - x_0| < 0.01$, the on/off $|\alpha|$ ratio >40 for a large enough $|E_z^{ex}|$ ($|E_z^{ex}| > 10^7$ V/m for a well width of 20 nm), which results in the on/off spin-relaxation-rate ratio exceeding 10^3 in the Dyakonov-Perel mechanism.

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Spintronics [1,2], which explores the application of the spin degree of freedom to electronics, is one of the major subjects in applied physics. As a milestone in spintronics, Datta and Das have proposed a spin field-effect transistor (FET) [3], in which the spin orientation of an electron, in transport through a two-dimensional channel, rotates around the in-plane effective magnetic field ($\boldsymbol{B}_{\rm eff}$) induced by the Rashba spin-orbit interaction [4–7]. The angular frequency of the spin rotation is proportional to $B_{\rm eff}$ ($\equiv|\boldsymbol{B}_{\rm eff}|$). This effective magnetic field switches the current on and off each time the change of $B_{\rm eff}$ increases the angle of the spin rotation in the channel by π. Therefore the action of this spin FET relies on the control of $B_{\rm eff}$ by the gate voltage, that is, by the external electric field perpendicular to the plane E_z^{ex}, which has been confirmed by experiments in quantum wells [8–10].

Another spin FET [11,12], called the spin-lifetime FET, has been proposed by Hall and others in which the spin relaxation switches the current on by changing the electron distribution from fully spin-polarized to unpolarized. The spin-lifetime FET, in contrast to the Datta-Das spin FET, uses only one component of the spin polarization vector. The action of the spin-lifetime FET relies on the switching of the spin relaxation rate by the change of the gate voltage. As a method to vary the spin-relaxation rate, the original paper [11,12] proposed to use the above-mentioned E_z^{ex} dependence of $B_{\rm eff}$ ($\propto|E_z^{ex}|$) in quantum wells [8–10], which makes the spin-relaxation rate in the Dyakonov-Perel mechanism [13–15] [$\propto(B_{\rm eff})^2$] proportional to $(E_z^{ex})^2$. The decrease of E_z^{ex} from a higher value E_z^{H} to a lower one E_z^{L} reduces the current from $I_{on} \propto (E_z^{H})^2$ to $I_{off} \propto (E_z^{L})^2$, leading to the on/off current ratio $I_{on}/I_{off} = (E_z^{H}/E_z^{L})^2$. Unfortunately, this method requires a precise control of the gate voltage to achieve a high on/off current ratio because E_z^{L} must be in the close vicinity of $E_z^{ex} = 0$.

We have recently found [16] that $B_{\rm eff}$ due to the Rashba spin-orbit interaction and the resulting spin-relaxation rate vary in a wide range by changing the band offsets (of conduction, valence, and split-off bands) between the well and barrier semiconductors in a quantum well. In particular, the coefficient α of the Rashba spin-orbit interaction (and of $\boldsymbol{B}_{\rm eff}$) can be tuned to vanish by adjusting the band offsets. For example, in a quantum well consisting of $Ga_{0.47}In_{0.53}As$ (well) and $Al_xGa_{1-x}As_ySb_{1-y}$ (barrier), where the band offsets change with the Al fraction x, α and the associated spin-relaxation rate become zero at an optimum fraction x_0.

In this paper we propose and explore the gate-voltage-induced switching of the Rashba coefficient α by using the above-mentioned band-offset dependence of α. The first key factor of the proposed switching is an asymmetric quantum-well structure with two barrier layers formed by different semiconductors, $Al_xGa_{1-x}As_ySb_{1-y}$ ($x \approx x_0$) and $Al_{0.48}In_{0.52}As$. This combination of barrier semiconductors is chosen so that one (the other) interface is that in a symmetric quantum well with a small $|\alpha|$ (a large $|\alpha|$). The second is the wave function deformation due to the external electric field E_z^{ex}, which is produced by the gate voltage. Then the gate voltage switches $|\alpha|$ on and off as the external electric field moves the wave function to the interface with a large $|\alpha|$ and to that with a small $|\alpha|$. We examine the on/off $|\alpha|$ ratio when the Al fraction x in $Al_xGa_{1-x}As_ySb_{1-y}$ deviates from the optimum value x_0 and investigate the required $|E_z^{ex}|$.

We consider an electron in the conduction band of a quantum-well structure which is formed by three different semiconductors with the zinc-blende structure (Fig. 1): S_B^L in the left barrier layer ($z < z_I^L$), S_W in the well layer ($z_I^L < z < z_I^R$), and S_B^R in the right barrier layer ($z_I^R < z$). Due to the translational symmetry along the x and y axes, the associated wave numbers, k_x and k_y, are conserved. The Schrödinger equation for the ground-subband wave function $\varphi_0(z)$ and the corresponding eigenvalue ε_0 is

$$\left[\frac{\hat{p}_z^2}{2m} + V_W(z)\right]\varphi_0(z) = \varepsilon_0\,\varphi_0(z), \tag{1}$$

where $\hat{p}_z = -i\hbar\nabla_z = -i\hbar\partial/\partial z$ and m is the effective mass of the conduction band. The confining potential $V_W(z)$ is

$$V_W(z) = V_{bo}^{c}(z) + V_{es}(z). \tag{2}$$

Here $V_{bo}^{c}(z)$ is the potential due to the conduction-band offset (Fig. 1), the expression of which is given later with those for valence bands. The second term $V_{es}(z)$, which is the

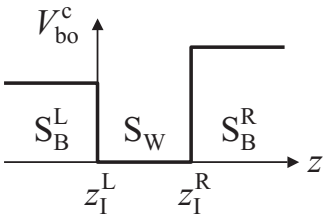

FIG. 1. A quantum-well structure consisting of three different semiconductors with the zinc-blende structure, S_B^L, S_W, and S_B^R. $V_{\rm bo}^{\rm c}(z)$ is the potential due to the conduction-band offset.

electrostatic potential due to the charge distribution in the quantum-well structure, satisfies the Poisson equation

$$\nabla_z^2 V_{\rm es} = -An(z), \tag{3}$$

where

$$A = \frac{4\pi e^2}{\epsilon}, \quad n(z) = N_{\rm s}[\varphi_0(z)]^2, \tag{4}$$

with ϵ the static dielectric constant, $-e$ the electron charge ($e > 0$), and $N_{\rm s}$ the sheet density of electrons. The total electric field is $E_z = \nabla_z V_{\rm es}/e$, while the external electric field $E_z^{\rm ex}$ is that induced by ionized donors and charge induced on the gate electrode. Such charges, which are placed in $z < z_{\rm d}^{\rm L}$ and $z > z_{\rm d}^{\rm R}$, are assumed to be far away from the quantum well so that $E_z^{\rm ex}$ acting on electrons is constant (this assumption can be satisfied by employing the widely used modulation doping where the spacer layer thicker than 10 nm is inserted between the well layer and each doped layer so that the penetration of the wave function into each doped layer is negligible). We introduce the areal external-charge density in the left side of the well ($z < z_{\rm d}^{\rm L}$), $\sigma_{\rm L}$, and that in the right side ($z > z_{\rm d}^{\rm R}$), $\sigma_{\rm R}$. Then the boundary condition for $V_{\rm es}$ at $z = z_{\rm d}^{\rm L}$ becomes

$$\nabla_z V_{\rm es} = A(\sigma_{\rm L}/e) \quad \left(z = z_{\rm d}^{\rm L}\right). \tag{5}$$

The charge neutrality gives $eN_{\rm s} = \sigma_{\rm L} + \sigma_{\rm R}$, while $E_z^{\rm ex} = (2\pi/\epsilon)(\sigma_{\rm L} - \sigma_{\rm R})$.

We derive the formula for the spin-orbit interaction induced by the band offsets and the electrostatic potential, which is denoted by $V_{\rm W}^{\rm so}$, as well as the Rashba coefficient α in the case of an asymmetric quantum well consisting of three different semiconductors [17]. In deriving $V_{\rm W}^{\rm so}$ we employ the $\boldsymbol{k}\cdot\boldsymbol{p}$ theory developed for heterostructures [18,19] (it has been shown in a number of papers [9,10,20–24] that the Rashba coefficient α derived by the $\boldsymbol{k}\cdot\boldsymbol{p}$ theory in various heterostructures agrees well with the experimental value and with that calculated in the tight-binding model). Then we obtain, for an electron with wave numbers k_x and k_y in the conduction band,

$$V_{\rm W}^{\rm so} = \frac{P^2}{3} G(z)(\sigma_x k_y - \sigma_y k_x), \tag{6}$$

where σ_x and σ_y are the Pauli spin matrices and P is the Kane matrix element [25]. In this equation,

$$G(z) = \nabla_z \left(\frac{1}{E - \tilde{E}_{\rm v}} - \frac{1}{E - \tilde{E}_{\rm s}} \right), \tag{7}$$

where E is the electron energy measured from the conduction-band bottom of S_W, while $\tilde{E}_{\rm v}$ ($\tilde{E}_{\rm s}$) is the diagonal element of the 8×8 Kane Hamiltonian, corresponding to the heavy-hole plus light-hole bands (the split-off band). They are given by

$$\begin{aligned} \tilde{E}_{\rm v} &= E_{\rm K0} - E_{\rm g} + V_{\rm bo}^{\rm v}(z) + V_{\rm es}(z), \\ \tilde{E}_{\rm s} &= E_{\rm K0} - E_{\rm g}^{\rm s} + V_{\rm bo}^{\rm s}(z) + V_{\rm es}(z). \end{aligned} \tag{8}$$

Here $E_{\rm K0} = (\hbar^2/2m_0)(k_x^2 + k_y^2 + \hat{k}_z^2)$ with m_0 the electron rest mass and $\hat{k}_z = -i\nabla_z$, and $E_{\rm g}^{\rm s} = E_{\rm g} + \Delta_{\rm so}$ with $E_{\rm g}$ ($\Delta_{\rm so}$) the band gap (the spin-orbit splitting) of S_W, while $V_{\rm bo}^{\rm v}(z)$ [$V_{\rm bo}^{\rm s}(z)$] is the potential due to the band offset for an electron in the heavy-hole plus light-hole bands [the split-off band]. These potentials together with that for the conduction band, $V_{\rm bo}^{\rm c}(z)$ in Eq. (2), are expressed by

$$V_{\rm bo}^{i}(z) = V_{\rm bo}^{i{\rm L}}(z) + V_{\rm bo}^{i{\rm R}}(z), \quad V_{\rm bo}^{i\ell}(z) = \Delta E_i^{\ell} h_{\ell}(z), \tag{9}$$

where $i = {\rm c,v,s}$, $\ell = {\rm L,R}$, and

$$h_{\rm L}(z) = \begin{cases} 1 & \left(z < z_{\rm I}^{\rm L}\right), \\ 0 & \left(z > z_{\rm I}^{\rm L}\right), \end{cases} \quad h_{\rm R}(z) = \begin{cases} 0 & \left(z < z_{\rm I}^{\rm R}\right), \\ 1 & \left(z > z_{\rm I}^{\rm R}\right), \end{cases} \tag{10}$$

while $\Delta E_{\rm c}^{\ell}$, $\Delta E_{\rm v}^{\ell}$, and $\Delta E_{\rm s}^{\ell}$ are the band offsets of the semiconductor S_B^{ℓ} relative to S_W: $\Delta E_{\rm c}^{\ell} = E_{\rm c}^{\ell} - E_{\rm c}$, $\Delta E_{\rm v}^{\ell} = E_{\rm v}^{\ell} - E_{\rm v}$, and $\Delta E_{\rm s}^{\ell} = E_{\rm s}^{\ell} - E_{\rm s}$ with $E_{\rm c}$ ($E_{\rm c}^{\ell}$) the energy of the conduction-band bottom, $E_{\rm v}$ ($E_{\rm v}^{\ell}$) that of the valance-band top, $E_{\rm s}$ ($E_{\rm s}^{\ell}$) that of the split-off-band top in S_W (in S_B^{ℓ}). We can also express $E_{\rm g}$ and $\Delta_{\rm so}$ as $E_{\rm g} = E_{\rm c} - E_{\rm v}$ and $\Delta_{\rm so} = E_{\rm v} - E_{\rm s}$.

Here we neglect E, $E_{\rm K0}$, and $V_{\rm es}(z)$ in $G(z)$, compared to $E_{\rm g}$ and $E_{\rm g}^{\rm s}$, while we take into account the contribution from $\nabla_z V_{\rm es}(z)$ to $G(z)$, that is, $[(E_{\rm g} - V_{\rm bo}^{\rm v})^{-2} - (E_{\rm g}^{\rm s} - V_{\rm bo}^{\rm s})^{-2}]\nabla_z V_{\rm es}$, in which we neglect $V_{\rm bo}^{\rm v}$ and $V_{\rm bo}^{\rm s}$ since they are nonzero only in the barrier layers where the squared wave function is small (we have confirmed by the numerical calculation that the correction due to $V_{\rm bo}^{\rm v}$ and $V_{\rm bo}^{\rm s}$ in this contribution is less than 6 percent in the cases we considered in this paper). We finally obtain the expression for $V_{\rm W}^{\rm so}$:

$$V_{\rm W}^{\rm so} = a(z)(\sigma_x k_y - \sigma_y k_x), \tag{11}$$

with

$$a(z) = \eta\left[\nabla_z\left(b_{\rm off}^{\rm L} V_{\rm bo}^{\rm cL} + b_{\rm off}^{\rm R} V_{\rm bo}^{\rm cR} + V_{\rm es}\right)\right]. \tag{12}$$

Here η is the effective coupling constant of the spin-orbit interaction for an electron in the conduction band of the semiconductor S_W, given by

$$\eta = \frac{P^2}{3}\left[\frac{1}{(E_{\rm g})^2} - \frac{1}{\left(E_{\rm g}^{\rm s}\right)^2}\right], \tag{13}$$

and $b_{\rm off}^{\ell}$ ($\ell = {\rm L,R}$) is defined by [16]

$$b_{\rm off}^{\ell} = \frac{\Delta E_{\rm v}^{\ell}/\left[E_{\rm g}\left(E_{\rm g} - \Delta E_{\rm v}^{\ell}\right)\right] - \Delta E_{\rm s}^{\ell}/\left[E_{\rm g}^{\rm s}\left(E_{\rm g}^{\rm s} - \Delta E_{\rm s}^{\ell}\right)\right]}{\Delta E_{\rm c}^{\ell}\left\{1/(E_{\rm g})^2 - 1/\left(E_{\rm g}^{\rm s}\right)^2\right\}}. \tag{14}$$

Equation (11) with (12) shows that the spin-orbit interaction $V_{\rm W}^{\rm so}$ for an electron in the conduction band, due to the band offsets and the electrostatic potential, is not proportional to $\nabla_z V_{\rm W}$ except the case where $b_{\rm off}^{\rm L} = 1$ and $b_{\rm off}^{\rm R} = 1$.

The Rashba coefficient α is defined by the expectation value of $a(z)$ with respect to $\varphi_0(z) = \langle z|0\rangle$,

$$\alpha = \langle 0|a(z)|0\rangle. \tag{15}$$

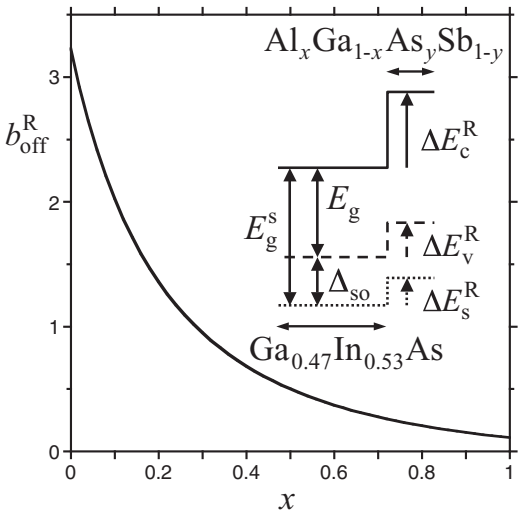

FIG. 2. The factor b^R_{off} [Eq. (14)] for $S_W = Ga_{0.47}In_{0.53}As$ and $S^R_B = Al_xGa_{1-x}As_ySb_{1-y}$ as a function of the Al fraction x in S^R_B [16]. We have used band parameters in Ref. [30] and employed the linear interpolation of band offsets between $x = 0$ and $x = 1$ to obtain $\Delta E^R_c[\text{eV}] = 0.436 + 1.43x$, $\Delta E^R_v[\text{eV}] = 0.444 - 0.354x$, and $\Delta E^R_s[\text{eV}] = 0.373 - 0.371x$, corresponding to $Ga_{0.47}In_{0.53}As$, $E_g[\text{eV}] = 0.816$, and $\Delta_{so}[\text{eV}] = 0.330$.

Here we use the equality $\langle 0|(\nabla_z V_W)|0\rangle = 0$, which means that forces on an electron in a bound eigenstate are balanced [26,27] (the equality is derived according to [28] in [29]). Then we obtain the expression of α using values of the wave function at interfaces:

$$\begin{aligned}\alpha &= \eta\left(b^L_{off}-1\right)\langle 0|\left(\nabla_z V^{cL}_{bo}\right)|0\rangle + \eta\left(b^R_{off}-1\right)\langle 0|\left(\nabla_z V^{cR}_{bo}\right)|0\rangle \\ &= \eta\left(b^L_{off}-1\right)\left[\varphi_0\left(z^L_I\right)\right]^2\left(-\Delta E^L_c\right) + \eta\left(b^R_{off}-1\right)\left[\varphi_0\left(z^R_I\right)\right]^2 \\ &\quad \times\ \Delta E^R_c. \end{aligned} \tag{16}$$

First we assume, for simplicity, that the wave function vanishes at the left heterointerface, that is, $\varphi_0(z^L_I) = 0$ [the numerically calculated wave function, shown in Fig. 3(b), is reduced considerably at the left heterointerface by applying a large negative E^{ex}_z although it does not vanish completely]. In this case, from Eq. (16), we have $\alpha = \eta(b^R_{off} - 1)\langle 0|(\nabla_z V^{cR}_{bo})|0\rangle$, which vanishes at $b^R_{off} = 1$. In Fig. 2, we plot b^R_{off} for $S_W = Ga_{0.47}In_{0.53}As$ and $S^R_B = Al_xGa_{1-x}As_ySb_{1-y}$ as a function of the Al fraction x in S^R_B where y is determined so that S^R_B is lattice-matched to S_W [16]. This figure shows that $b^R_{off} = 1$ at a value x_0 which is close to $x = 0.3$ for the values of band parameters from Ref. [30]. Therefore, an asymmetric quantum well consisting of $S_W = Ga_{0.47}In_{0.53}As$, $S^L_B = Al_{0.48}In_{0.52}As$ ($b^L_{off} = -0.32$), and $S^R_B = Al_xGa_{1-x}As_ySb_{1-y}$ with $x = x_0$ ($b^R_{off} = 1$) has $|\alpha| \approx 0$ for a large negative E^{ex}_z where $\varphi_0(z^L_I)$ is considerably reduced, while it acquires a substantial value of $|\alpha|$ for a large positive E^{ex}_z where $\varphi_0(z^L_I)$ is increased. This means that $|\alpha|$ is switched on and off by changing the polarity of E^{ex}_z.

Now we evaluate the on/off ratio of $|\alpha|$, denoted by R_α, when x slightly deviates from x_0. We start from the expression of α in the case of $\varphi_0(z^L_I) = 0$, $\alpha = \eta(b^R_{off} - 1)\langle 0|(\nabla_z V^{cR}_{bo})|0\rangle$. By using $\varphi_0(z^L_I) = 0$ as well as $\langle 0|(\nabla_z V_W)|0\rangle = 0$ and $\langle 0|(\nabla_z V_{es})|0\rangle = eE^{ex}_z$, we have $\langle 0|(\nabla_z V^{cR}_{bo})|0\rangle = \langle 0|(\nabla_z V^{c}_{bo})|0\rangle = \langle 0|(-\nabla_z V_{es})|0\rangle = -eE^{ex}_z$ and then obtain $\alpha = \eta(b^R_{off} - 1)(-eE^{ex}_z)$. Similarly we obtain $\alpha = \eta(b^L_{off} - 1)(-eE^{ex}_z)$ in the case of $\varphi_0(z^R_I) = 0$. Then the on/off ratio R_α, when the polarity of E^{ex}_z is changed with a large enough $|E^{ex}_z|$, becomes

$$R_\alpha \equiv \frac{|\alpha|_{on}}{|\alpha|_{off}} = \frac{\left|b^L_{off}-1\right|}{\left|b^R_{off}-1\right|}. \tag{17}$$

For a deviation of $|x - x_0| = 0.01$, we have $|b^R_{off} - 1| \approx 1/30$ from Fig. 2. Therefore we obtain $R_\alpha \approx 40$, which leads to the on/off ratio of the spin-relaxation rate (R_{sr}) exceeding 10^3 in the Dyakonov-Perel mechanism where $R_{sr} = (R_\alpha)^2$.

In order to examine how large $|E^{ex}_z|$ is necessary to realize the on/off $|\alpha|$ ratio R_α in Eq. (17), we perform a numerical calculation for $\varphi_0(z)$ by solving the Schrödinger equation Eq. (1) and the Poisson equation Eq. (3) self-consistently, in which we discretize the z coordinate. The obtained $\varphi_0(z)$ as well as $V_W(z)$ in $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As/Al_xGa_{1-x}As_ySb_{1-y}$ ($x = 0.3$) are plotted in Fig. 3 for five different values of the external force $F_z = -eE^{ex}_z$ (the energy separation between the ground subband and the first-excited subband increases with $|E^{ex}_z|$ and the excited subbands are not occupied by electrons in the cases we considered in this paper), while the value of α as a function of F_z is presented in Fig. 4 for three different quantum wells. All of the three quantum wells have a common material in the well layer, $Ga_{0.47}In_{0.53}As$. The difference of the three is in the combination of interfaces, LL, SS, and LS, where L {S} is the interface which gives a large {small} $|b_{off} - 1|$, $Ga_{0.47}In_{0.53}As$(well)/$Al_{0.48}In_{0.52}As$(barrier) with $b_{off} - 1 = -1.32$ {$Ga_{0.47}In_{0.53}As$(well)/$Al_xGa_{1-x}As_ySb_{1-y}$(barrier) ($x = 0.3$) with $b_{off} - 1 = -0.05$}.

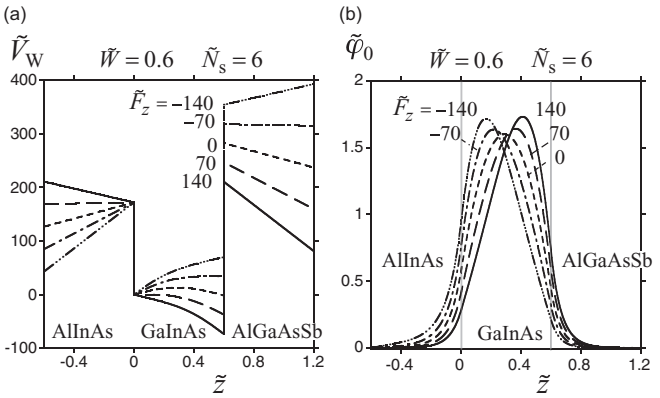

FIG. 3. Calculated results of (a) $V_W(z)$ and (b) $\varphi_0(z)$ for different values of the external force $F_z = -eE^{ex}_z$ in $Al_{0.48}In_{0.52}As/Ga_{0.47}In_{0.53}As/Al_xGa_{1-x}As_ySb_{1-y}$ ($x = 0.3$). The parameter W ($=z^R_I - z^L_I$) is the well width. The dimensionless quantities are defined by $\tilde{V}_W = V_W/\text{Ry}^*$, $\tilde{\varphi}_0 = \varphi_0(a^*_B)^{1/2}$, $\tilde{z} = z/a^*_B$, $\tilde{F}_z = F_z/(\text{Ry}^*/a^*_B)$, $\tilde{W} = W/a^*_B$, and $\tilde{N}_s = N_s(a^*_B)^2$ with $a^*_B = \hbar^2\epsilon/(me^2)$ and $\text{Ry}^* = \hbar^2(a^*_B)^{-2}/(2m)$. For $Ga_{0.47}In_{0.53}As$, $a^*_B = 17.1$ nm and $\text{Ry}^* = 3.04$ meV. Therefore $\tilde{W} = 0.6$ and $\tilde{N}_s = 6$ correspond to $W = 10.3$ nm and $N_s = 2.05 \times 10^{16}$ m^{-2}.

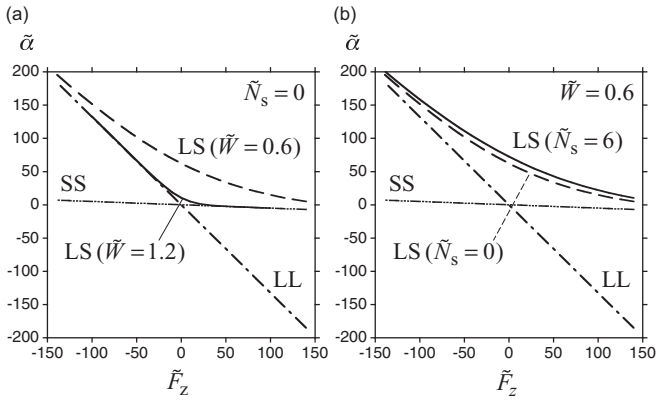

FIG. 4. Rashba coefficient α as a function of the external force $F_z = -eE_z^{\rm ex}$ for three combinations of interfaces: LL, SS, and LS (see text). (a) The well-width (W) dependence for LS. (b) The electron-sheet-density (N_s) dependence for LS. The dimensionless Rashba coefficient is defined by $\tilde{\alpha} = (\alpha/\eta)/({\rm Ry}^*/a_B^*)$. For the definition of other quantities, see the caption of Fig. 3.

In the case of $b_{\rm off}^{\rm L} = b_{\rm off}^{\rm R}$ $(=b_{\rm off})$ as in LL and SS, Eq. (16) becomes $\alpha = \eta(b_{\rm off} - 1)\langle 0|(\nabla_z V_{\rm bo}^{\rm c})|0\rangle = -\eta(b_{\rm off} - 1)\langle 0|(\nabla_z V_{\rm es})|0\rangle = \eta(b_{\rm off} - 1)F_z$, where we have used the equalities $\langle 0|(\nabla_z V_{\rm W})|0\rangle = 0$ and $\langle 0|(\nabla_z V_{\rm es})|0\rangle = eE_z^{\rm ex} = -F_z$. Therefore α of LL and that of SS are independent of the well width W and N_s. They are plotted in Fig. 4 as straight lines with different gradients.

The calculated $\alpha(F_z)$ of LS, presented in Fig. 4, approaches the steep-slope $\alpha(F_z)$ of LL in $F_z < 0$ and the gentle-slope $\alpha(F_z)$ of SS in $F_z > 0$ as $|F_z|$ increases, which demonstrates the switching of $|\alpha|$ by changing the sign of F_z (α of LS deviates from zero at $F_z = 0$, which is derived in [31]). A rough estimate for the value of $|F_z|$, at which $\alpha(F_z)$ of LS merges with that of LL or SS, denoted by F_z^c, is given by the potential difference between two interfaces $e|E_z^{\rm ex}|W = |F_z|W$ equal to the energy difference between the ground subband and the first excited subband at $N_s = 0$ and $E_z^{\rm ex} = 0$ in the infinite-barrier model $\varepsilon_1 - \varepsilon_0 = 3\hbar^2\pi^2/(2mW^2)$. This estimate shows a strong W dependence of F_z^c: $F_z^c \propto W^{-3}$, which explains the W dependence (at $N_s = 0$) presented in Fig. 4(a). Using dimensionless variables, $\tilde{F}_z^c = F_z^c/({\rm Ry}^*/a_B^*)$ and $\tilde{W} = W/a_B^*$ with $a_B^* = \hbar^2\epsilon/(me^2)$ and ${\rm Ry}^* = \hbar^2(a_B^*)^{-2}/(2m)$, such an estimate is expressed as $\tilde{F}_z^c = 3\pi^2\tilde{W}^{-3}$, which gives $\tilde{F}_z^c = 137$ for $\tilde{W} = 0.6$ and $\tilde{F}_z^c = 17.1$ for $\tilde{W} = 1.2$. This estimate for $\tilde{F}_z^c$ is consistent with that extracted from Fig. 4(a). The corresponding value of $|E_z^{\rm ex}|$, denoted by E_z^c, becomes $E_z^c = 2.4 \times 10^7$ V/m ($W = 10.3$ nm) and $E_z^c = 3.0 \times 10^6$ V/m ($W = 20.5$ nm) when $a_B^* = 17.1$ nm and ${\rm Ry}^* = 3.04$ meV for $Ga_{0.47}In_{0.53}As$ is used. On the other hand, the dependence of α on the electron sheet density N_s is weak as shown in Fig. 4(b). We therefore find that $|E_z^{\rm ex}|$ above $E_z^c = 3\pi^2\tilde{W}^{-3}{\rm Ry}^*/(ea_B^*)$ is required to realize the on/off $|\alpha|$ ratio R_α given by Eq. (17). From the numerical result in Fig. 4(a) showing that α of LS for $\tilde{W} = 1.2$ is well approximated by α of LL ($F_z < 0$) and α of SS ($F_z > 0$) at $|\tilde{F}_z| > 50$, it is derived that R_α reaches the value in Eq. (17) at $|E_z^{\rm ex}| > 10^7$ V/m for $W = 20.5$ nm ($|E_z^{\rm ex}| = 3 \times 10^7$ V/m has been experimentally attained [32]).

In conclusion, we have calculated the coefficient of the Rashba spin-orbit interaction, α, as a function of the external electric field perpendicular to the well, $E_z^{\rm ex}$, in an asymmetric quantum well consisting of $Ga_{0.47}In_{0.53}As$ (well), $Al_{0.48}In_{0.52}As$ (left barrier), and $Al_{0.3}Ga_{0.7}As_ySb_{1-y}$ (right barrier). We have found that $|\alpha|$ and the resulting spin-relaxation rate in the Dyakonov-Perel mechanism can be switched on and off by changing the polarity of $E_z^{\rm ex}$ when $|E_z^{\rm ex}|$ is large enough. The required $|E_z^{\rm ex}|$ is proportional to W^{-3} with W the well width, and weakly depends on the electron sheet density.

The Dresselhaus spin-orbit interaction [33] also contributes to the spin relaxation in the Dyakonov-Perel mechanism in addition to the Rashba spin-orbit interaction which has been considered in this paper. However, in a quantum well parallel to the (110) plane of the zinc-blende structure, the effective magnetic field induced by the Dresselhaus spin-orbit interaction is perpendicular to the well layer and does not give the spin relaxation in the Dyakonov-Perel mechanism for the spin component perpendicular to the well layer. This has been shown theoretically in [15] and the resulting reduction in the spin relaxation rate has been demonstrated experimentally in [34–37]. Therefore the estimate of the spin relaxation rate, given in this paper, does not change in (110) quantum wells for the perpendicular spin component even when the Dresselhaus spin-orbit interaction is considered in addition to the Rashba spin-orbit interaction.

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$$\alpha = \eta\left(b_{off}^{av} - 1\right)F_z + \eta\left(b_{off}^{L} - b_{off}^{R}\right)\langle 0|\left(\nabla_z \frac{V_{bo}^{cL} - V_{bo}^{cR}}{2}\right)|0\rangle,$$

with $b_{off}^{av} = (b_{off}^L + b_{off}^R)/2$. At $F_z = 0$ the first term is zero, while the second term is nonzero in an asymmetric quantum well with $b_{off}^L \neq b_{off}^R$.
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