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Generation of dc spin current in a narrow channel with Rashba and Dresselhaus spin-orbit interactions

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The authors consider a finite range ac-biased front gate acting on a quantum channel with Rashba and Dresselhaus spin-orbit interaction effects. The ac-biased gate, giving rise to a dynamical Rashba coupling, causes spin-resolved coherent resonant inelastic scattering. A pure dc spin current is subsequently generated without accompanying charge current. In the presence of Dresselhaus effect, the dc spin current is suppressed in the regime but is assisted in the high kinetic energy regime.
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Manipulation of electron spins is achievable with external active control, which is a central requirement of spintronic devices. Of fundamental interest and practical application is the spin current in the emerging field of spintronics.[1] One of the key issues is how to generate spin current in spintronic devices. The standard way is to inject spin polarized current from a ferromagnetic electrode.[2] However, its efficiency is usually limited by the poor quality of the interface, and it is accompanied by the charge current. Narrow gap semiconductor heterostructures offer an efficient control of spins through intrinsic spin-orbit interaction (SOI). Several approaches utilizing spin Hall effects,[3–8] magnetic fields,[9–12] ferromagnetic materials,[13,14] or optical excitations[15–17] were proposed.

The success of dc front-gate control for the measurement[18] of Rashba coupling strength[19] inspired proposals for spin current generation by nonmagnetic means.[20–24] These proposals include adiabatic quantum pumping in a quantum dot with static SOI (Ref. 20) interfaced with a time-dependent barrier and a spatially separated Rashba SOI region[21] and an ac-biased Rashba-type two-dimensional (2D) disorder system[23] or quantum channel.[24] It is known that the translational invariance is broken in the channel direction due to a spatially localized time-dependent potential, thus allowing us to explore coherent resonant inelastic scattering and time-modulated quasibound state features.[25]

In addition to the Rashba SOI,[19] which is caused by the structure inversion asymmetry of the confining potential of the 2D trapping well, there is also a Dresselhaus effect[26] caused by the bulk inversion asymmetry[27] (BIA) and the interface inversion asymmetry (IIA).[28] The contributions associated with BIA and IIA are phenomenologically inseparable. The Rashba effect is usually dominant, but the Dresselhaus effect could be also observable.[29] In this article, we consider a narrow channel formed in a high-mobility electronic quantum well by applying negative bias on the front split gates. When a finger gate is deposited above the split gate separated by an insulating layer, a local time varying Rashba coupling parameter $\alpha(\mathbf{r},t)$ can be induced by ac-biasing the finger gate.[21,24] We shall explore how the interplay among the static Rashba, the static Dresselhaus, and the dynamical Rashba SOI effects influences the efficiency of spin current generation in the absence of source-drain bias. The considered dynamical system for spin pumping is depicted in Fig. 1.

The electron transport in a narrow channel in the presence of SOI can be described by the dimensionless Hamiltonian,[25]

$$\mathcal{H}_0 = k^2 + \mathcal{H}_{\mathrm{SO}}^0 + V_c(y), \tag{1}$$

where the first term $k^2 = k_x^2 + k_y^2$ denotes the kinetic energy and the third term $V_c(y) = \omega_y^2 y^2$ is a potential that confines the electron in the **y** direction. For a narrow quantum well along the [0,0,1] crystallographic direction, the unperturbed SOI term $\mathcal{H}_{\mathrm{SO}}^0$ involving Rashba and Dresselhaus interaction effects can be described in terms of k-linear form,

$$\mathcal{H}_{\mathrm{SO}}^0 = \mathcal{H}_{\mathrm{R}}^0 + \mathcal{H}_{\mathrm{D}}^0 = \alpha_0(\sigma_x k_y - \sigma_y k_x) + \beta_0(\sigma_x k_x - \sigma_y k_y), \tag{2}$$

where σ_i $(i=\{x,y,z\})$ are the Pauli matrices and $\mathbf{k}=(k_x,k_y)$ is the 2D electron wave vector. The unperturbed Rashba coupling strength α_0 is proportional to the electric field along **z** direction perpendicular to the 2D electron gas. Moreover, the Dresselhaus coupling strength β_0 is determined by the semiconductor material and the geometry of the sample.

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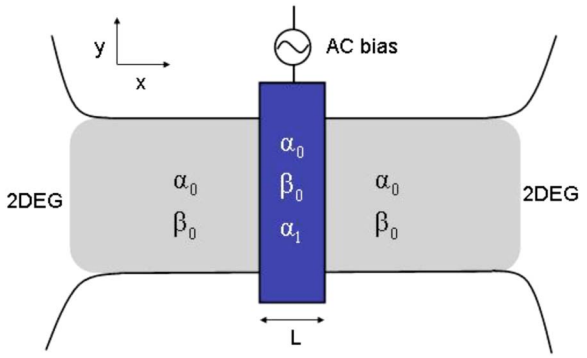

FIG. 1. Schematic illustration of the quantum wire with Rashba and Dresselhaus spin-orbit interaction influenced by an ac-biased finger gate (with length L) across the wire.

For a narrow wire,[30] the spin-orbit coupling contributions can be simplified as $\mathcal{H}_{\mathrm{SO}}^{0} \approx -\alpha_0 \sigma_y k_x + \beta_0 \sigma_x k_x$. The right-going (left-going) eigenfunctions of the unperturbed Hamiltonian in the subband n are given by

$$\psi_{n\mathbf{k}\sigma}^{R(L)}(\mathbf{r}) = \exp[ik_{n\sigma}^{R(L)}(\mu)x]\varphi_n(y)\chi_\sigma, \tag{3}$$

where $\sigma = \pm$ labels the two spin branches, χ_σ is the spinor of branch σ with two components given by $e^{i\theta/2}/\sqrt{2}$, and $\sigma e^{-i\theta/2}/\sqrt{2}$ with $\theta = \arctan(\alpha_0/\beta_0)$. In addition, the wave vectors are defined by $k_{n\sigma}^{R}(\mu) = \sqrt{\mu - \varepsilon_n - \sigma\gamma_0/2}$ and $k_{n\sigma}^{L}(\mu) = -\sqrt{\mu - \varepsilon_n - \sigma\gamma_0/2}$, where μ is the chemical potential, $\gamma_0 = (\alpha_0^2 + \beta_0^2)^{1/2}$, and ε_n is the subband threshold, which is shifted from the bare subband bottom $\varepsilon_n^0 = (2n+1)\omega_y$ by $-\gamma_0^2/4$. The total Hamiltonian $\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{\mathrm{SO}}(t)$ contains a dynamical term, induced by the ac-biased finger gate, which can be written in the form

$$\mathcal{H}_{\mathrm{SO}}(t) = -\frac{\alpha_1}{2}\sigma_y\{k_z, \theta(L/2 - |x|)\}\cos\,\omega t, \tag{4}$$

where $\theta(x)$ is the step function and $\{,\}$ stands for anticommutator.

Below, we assume that the Dresselhaus SOI is weak and neglect the spin-flip mechanism. The scattering wave function of the conduction electron incident from the left reservoir in the spin state σ can be obtained of the form $\Psi_\sigma(\mathbf{r},t) = \Sigma_n \psi_{n\sigma}(x,t)\varphi_n(y)\chi_\sigma$. In the region $x < -L/2$, the time-dependent wave function along the channel direction is given by

$$\psi_{n\sigma}(x,t) = e^{ik_{n\sigma}^{R}(\mu)}e^{-i\mu t} + \sum_m r_{n\sigma}^m e^{ik_{n\sigma}^{L}(\mu_m)x}e^{-i\mu_m t}, \tag{5}$$

where $\mu_m \equiv \mu + m\omega$ and $r_{n\sigma}^m$ denotes the reflection coefficient of the conduction electron in the subband n and photon sideband m. In the region $x > L/2$, the wave function is simply of the form

$$\psi_{n\sigma}(x,t) = \sum_m t_{n\sigma}^m e^{ik_{n\sigma}^{R}(\mu_m)x}e^{-i\mu_m t}, \tag{6}$$

where $t_{n\sigma}^m$ indicates the corresponding transmission coefficient. The longitudinal wave function in the time-modulated region $|x| < L/2$ is given by[25]

$$\psi_{n\sigma}(x,t) = \sum_{m'p}\left\{A_{n\sigma}^{m'}e^{ik_{n\sigma}^{R}(\mu_m)x}J_p\left(k_{n\sigma}^{R}(\mu_{m'})\frac{\alpha_1}{\omega}\right) + B_{n\sigma}^{m'}e^{ik_{n\sigma}^{L}(\mu_m)x}J_p\left(k_{n\sigma}^{L}(\mu_{m'})\frac{\alpha_1}{\omega}\right)\right\} \times \exp[-i\mu_{m'+p}t]\sigma_p, \tag{7}$$

where $\sigma_p = 1$ if p is even and $\sigma_p = -\sigma_y$ if p is odd. Performing the time-dependent mode matching at $x = \pm L/2$,[24] one can obtain the reflection and transmission coefficients, $r_{n\sigma}^m$ and $t_{n\sigma}^m$, at the edges of the time-modulated region. Similarly, it is easy to obtain $\tilde{r}_{n\sigma}^m$ and $\tilde{t}_{n\sigma}^m$ for the conduction electrons incident from the right reservoir.

Summing over all possible scattered propagating modes from both reservoirs, the net right-going dc spin current can be expressed as $I_S = I^{\uparrow} - I^{\downarrow}$, where

$$I^\sigma = \frac{e}{h}\int dE f(E)[T_{RL}^\sigma + T_{LR}^{\bar{\sigma}}], \tag{8}$$

with $f(E)$ being the Fermi function in the reservoirs. In addition, $T_{RL}^\sigma = \Sigma_n \Sigma_m' |t_{n\sigma}^m|^2 v_n^m / v_n^0$ and $T_{LR}^{\bar{\sigma}} = \Sigma_n \Sigma_m' |\tilde{t}_{n\bar{\sigma}}^m|^2 v_n^m / v_n^0$, where $v_n^m \equiv (\mu_m - \varepsilon_n)^{1/2}$. The spin current conservation is maintained due to the suppression of spin-flip subband mixing. Since a symmetric narrow channel configuration gives $T_{LR}^\sigma = T_{RL}^{\bar{\sigma}}$, the net charge current $I_Q = I^{\uparrow} + I^{\downarrow}$ is identically zero, and a pure nonequilibrium spin current is generated. It turns out that the two charge currents for both spin types have identical values but opposite directions. Therefore, the generated pure spin current implies the fully polarized charge current.[31]

The calculations presented below are carried out under the assumption that the electron effective mass $m^* = 0.036 m_0$, which is appropriate to the InGaAs–InAlAs interface. The typical electron density $n_e \sim 10^{12}\ \mathrm{cm}^{-2}$ and $\hbar\alpha_0 \sim 10^{-11}$ eV m.[18] We select $\omega_y = 0.035$ such that the subband level spacing, $\Delta\varepsilon = 2\omega_y$, is 4.13 meV. Accordingly, the length unit $L^* = 4.0$ nm, the energy unit $E^* = 59$ meV, and the spin-orbit coupling parameters are in units of $v_F^*/2 = 1.8 \times 10^5$ m/s.

In Fig. 2, we demonstrate how the Dresselhaus spin-orbit coupling strength influences the dc spin current generated by the ac-biased front gate with driving region $L = 120$ nm. The other parameters are static Rashba parameter $\hbar\alpha_0 = 1.5 \times 10^{-11}$ eV m, $\alpha_1 = 0.38\alpha_0$, and $\hbar\omega = 0.2$ meV. In Fig. 2(a), the sharp dip structure at $K \approx \omega$ is the one-photon quasibound state feature.[25] For electron energies at $1 < K/\omega < 2$, we see clearly $T_{RL}^{\uparrow} < T_{RL}^{\downarrow}$ leading to positive spin current. The change in sign in the transmission difference $\Delta T_{RL} = T_{RL}^{\uparrow} - T_{RL}^{\downarrow}$ comes across the dip structures, that is, $\Delta T_{RL}(K = \omega^-) > 0$, while $\Delta T_{RL}(K = \omega^+) < 0$. Consequently, for electrons with incident energy $K/\omega \approx 1$, the spin current peak is generated within the order of 1 nA, as is shown in Fig. 2(b).

For the cases of zero and weak Dresselhaus SOI such as $\beta_0 = 0.0$ and 0.02, the electrons with energy $K/\omega \approx 2$ exhibit small dip structures which is associated with two-photon quasibound state feature. Since at $K/\omega \approx 2$ the current trans-

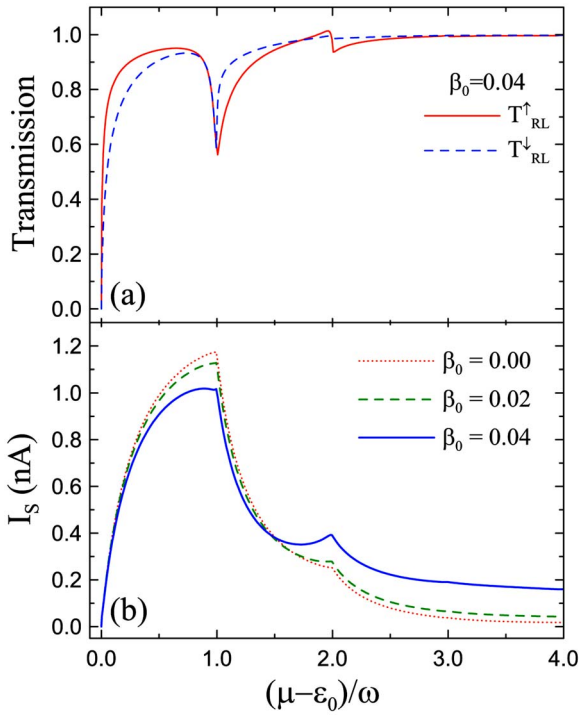

FIG. 2. (a) Spin-resolved current transmission $T^{\uparrow}_{RL}$ (solid red) and $T^{\downarrow}_{RL}$ (dashed blue) as a function of electron energy in units of driving frequency. (b) Generated dc spin current for the cases of β_0=0.0 (dotted red), 0.02 (dashed green), and 0.04 (solid blue). L/L^*=30, α_0=0.13, α_1=0.05, and ω=0.05$\Delta\varepsilon$.

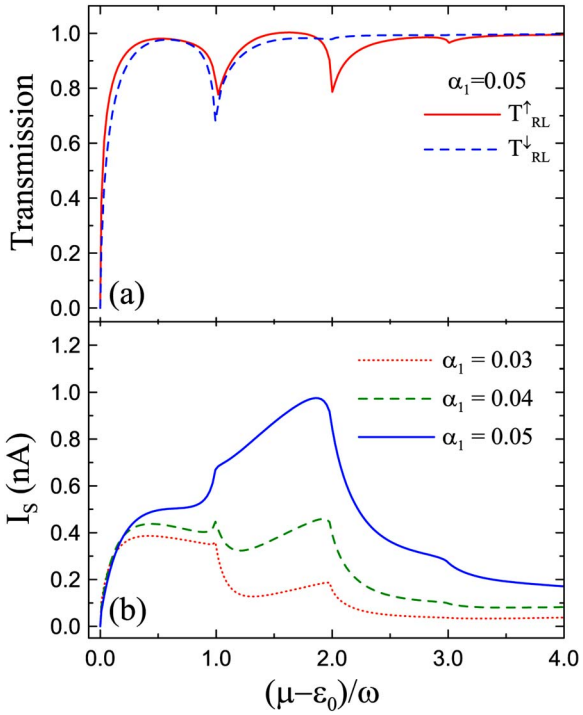

FIG. 3. (a) Spin-resolved current transmission $T^{\uparrow}_{RL}$ (solid red) and $T^{\downarrow}_{RL}$ (dashed blue) as a function of electron energy in units of driving frequency. (b) Generated dc spin current for the cases of α_1=0.03 (dotted red), 0.04 (dashed green), and 0.05 (solid blue). L/L^*=50, α_0=0.13, β_0=0.03, and ω=0.05$\Delta\varepsilon$.

mission $T^{\uparrow}_{RL}$ of spin-↑ electron is still less than $T^{\downarrow}_{RL}$ of the spin-↓ electron, there is no significant contribution to the generation of dc spin current. In Fig. 2(a), we show the current transmission for the case of strong Dresselhaus coupling β_0=0.04. The right-going spin-↑ electron manifests Fano-type peak-and-dip line shape in transmission at $K\approx 2\omega$, which is associated with the two-photon quasibound state feature. This Fano-type feature enhances $T^{\uparrow}_{RL}$ to be greater than $T^{\downarrow}_{RL}$. Consequently, the pumped dc spin current is thus significantly enhanced. We would like to mention in passing that the Fano spin filtering effects may be realized in an open quantum dot[32] or a stub waveguide system.[33]

In the absence of Dresselhaus effect, the electron in the low kinetic energy regime may be multiple scattered by the transverse confining potential, such that the spin orientation is mainly along the wire direction. The Dresselhuas effect plays a role to rotate the spin direction toward the y direction. Consequently, the net spin current is thus enhanced. However, the spin direction of an electron in the high kinetic energy regime is mainly perpendicular to the wire direction, the Dresselhaus effect thus plays a role to enhance the spin current generation.

Figure 3 shows the spin-resolved transmission with dynamical Rashba coefficient α_1=0.05 and the generated dc spin current for cases of α_1=0.03, 0.04, and 0.05. The other parameters are ac-driven region L=200 nm, Rashba strength $\hbar\alpha_0=1.5\times10^{-11}$ eV m, Dresselhaus strength $\beta_0=0.23\alpha_0$, and driving frequency $f=\omega/2\pi$=50 GHz. There are common transport features for the three different dynamical coupling strengths. The overlap of I_S curves for the incident electron energies $K/\omega\leqslant 0.2$ implies that the transport properties are insensitive to the driving strength in the very low kinetic energy regime. The similar plateau features in I_S at $K/\omega<1.0$ are caused by the competition of the current transmission of spin-↑ and spin-↓ electrons.

At incident electron energy $(\mu-\varepsilon_0)/\omega\approx 1.0$, there are kink structure in I_S for α_1=0.03, peak structure for α_1=0.04, and shoulder structure for α_1=0.05. For the case of α_1=0.03, the current transmissions of the two spin states are almost the same at $K=\omega^-$, exhibiting plateau feature, while the transmission of the spin-↑ electron is smaller than the spin-↓ at $K=\omega^+$, exhibiting strong drop feature in I_S. For the case of α_1=0.04, the crossover in the transmission for two spin states leads to the peak structure at $K\approx\omega$. However, for the case of α_1=0.05, we see that $T^{\uparrow}_{RL}$ is greater than $T^{\downarrow}_{RL}$ until the crossover at K/ω=1.87 leading to the shoulder behavior in I_S. This feature in combination with the broad dip structure, associated with electrons emitting two photons to the subband threshold forming a quasibound state, results in the broad spin current peak I_S=0.98 nA at K/ω=1.87. Small hill in I_S at $K/\omega\approx 3.0$ is barely recognized. At K/ω=4.0, the spin currents are nearly saturated to I_S=0.04, 0.08, and 0.17 nA for α_1=0.03, 0.04, and 0.05, respectively.

In this article, we have investigated nonadiabatically how the dc spin current is generated under the mechanism of SOI using a dynamical all electrical control on a split-gate-

confined narrow channel. We have demonstrated nontrivial features concerning the spin current generation mechanism caused by different strength of Dresselhaus spin-orbit coupling. These results provide a robust manner of generating spin current without accompanying charge current.

The spin current generating features have been demonstrated and illustrated in detail. It has been found that the Dresselhaus spin-orbit coupling intends to suppress the efficiency of spin current generation in the low kinetic energy regime, while the Dresselhaus effect can enhance the pumped spin current in the high kinetic energy regime. Unlike the parametric quantum pumping, in which two pumping potentials with a phase difference are needed.[9] Our proposed spin current generating device is achievable using a single ac-biased gate and should be achievable within recent fabrication capability.

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[1] *Semiconductor Spintronics and Quantum Computation*, edited by D. D. Awschalom, N. Samarth, and D. Loss (Springer-Verlag, Berlin, 2002).
[2] S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. von Molna'r, L. Roukes, A. Y. Chtchelkanova, and D. M. Treger, Science **294**, 1488 (2001).
[3] S. Murakami, N. Nagaosa, and S. C. Zhang, Science **301**, 1348 (2003).
[4] Y. K. Kato, R. C. Myers, A. C. Gossard, and D. D. Awschalom, Science **306**, 1910 (2004).
[5] J. Sinova, D. Culcer, Q. Niu, N. A. Sinitsyn, T. Jungwirth, and A. H. MacDonald, Phys. Rev. Lett. **92**, 126603 (2004); J. Wunderlich, B. Kaestner, J. Sinova, and T. Jungwirth, *ibid.* **94**, 047204 (2005).
[6] B. A. Bernevig and S. C. Zhang, Phys. Rev. Lett. **96**, 106802 (2006).
[7] S. O. Valenzuela and M. Timkham, Nature (London) **442**, 176 (2006).
[8] V. Sih, W. H. Lau, R. C. Myers, V. R. Horowitz, A. C. Gossard, and D. D. Awschalom, Phys. Rev. Lett. **97**, 096605 (2006); N. P. Stern, S. Ghosh, G. Xiang, M. Zhu, N. Smarth, D. D. Awschalom, *ibid.* **97**, 126603 (2006).
[9] E. R. Mucciolo, C. Chamon, and C. M. Marcus, Phys. Rev. Lett. **89**, 146802 (2002); S. K. Watson, R. M. Potok, C. M. Marcus, and V. Umansky, *ibid.* **91**, 258301 (2003).
[10] A. Brataas, Y. Tserkovnyak, G. E. W. Bauer, and B. I. Halperin, Phys. Rev. B **66**, 060404 (2002).
[11] P. Zhang, Q. K. Xue, and X. C. Xie, Phys. Rev. Lett. **91**, 196602 (2003).
[12] B. G. Wang, J. Wang, and H. Guo, Phys. Rev. B **67**, 092408 (2003).
[13] Q. F. Sun, H. Guo, and J. Wang, Phys. Rev. Lett. **90**, 258301 (2003).
[14] W. Zeng, J. L. Wu, B. G. Wang, J. Wang, Q. F. Sun, and H. Guo, Phys. Rev. B **68**, 113306 (2003).
[15] R. D. R. Bhat and J. E. Sipe, Phys. Rev. Lett. **85**, 5432 (2000).
[16] J. Hubner, W. W. Ruhle, M. Klude, D. Hommel, R. D. R. Bhat, J. E. Sipe, and H. M. van Driel, Phys. Rev. Lett. **90**, 216601 (2003).
[17] M. J. Stevens, A. L. Smirl, R. D. R. Bhat, A. Najmaie, J. E. Sipe, and H. M. van Driel, Phys. Rev. Lett. **90**, 136603 (2003).
[18] J. Nitta, T. Akazaki, H. Takayanagi, and T. Enoki, Phys. Rev. Lett. **78**, 1335 (1997); D. Grundler, *ibid.* **84**, 6074 (2000).
[19] E. I. Rashba, Sov. Phys. Solid State **2**, 1109 (1960); Y. A. Bychkov and E. I. Rashba, J. Phys. C **17**, 6039 (1984).
[20] P. Sharma and P. W. Brouwer, Phys. Rev. Lett. **91**, 166801 (2003).
[21] M. Governale, F. Taddei, and R. Fazio, Phys. Rev. B **68**, 155324 (2003).
[22] A. G. Mal'shukov, C. S. Tang, C. S. Chu, and K. A. Chao, Phys. Rev. B **68**, 233307 (2003).
[23] C. S. Tang, A. G. Mal'shukov, and K. A. Chao, Phys. Rev. B **71**, 195314 (2005); For a brief review, see C. S. Tang, Int. J. Mod. Phys. A **20**, 869 (2006).
[24] L. Y. Wang, C. S. Tang, and C. S. Chu, Phys. Rev. B **73**, 085304 (2006).
[25] C. S. Tang and C. S. Chu, Phys. Rev. B **53**, 4838 (1996); **60**, 1830 (1999); C. S. Tang, Y. H. Tan, and C. S. Chu, *ibid.* **67**, 205324 (2003).
[26] G. Dresselhaus, Phys. Rev. **100**, 580 (1955).
[27] M. I. D'yakonov, and V. Yu. Kachorovskii, Fiz. Tekh. Poluprovodn. (S.-Peterburg) **20**, 178 (1986); [Sov. Phys. Semicond. **20**, 110 (1986)].
[28] L. Vervoort and P. Voisin, Phys. Rev. B **56**, 012744 (1997).
[29] S. D. Ganichev, V. V. Bel'kov, L. E. Golub, E. L. Ivchenko, P. Schneider, S. Giglberger, J. Eroms, J. DeBoeck, G. Borghs, W. Wegscheider, D. Weiss, and W. Prettl, Phys. Rev. Lett. **92**, 256601 (2004).
[30] R. G. Pereira and E. Miranda, Phys. Rev. B **71**, 085318 (2005).
[31] J. Wang, K. S. Chan, and D. Y. Xing, Phys. Rev. B **72**, 115311 (2005).
[32] J.-F. Song, Y. Ochiai, and J. P. Bird, Appl. Phys. Lett. **82**, 4561 (2003).
[33] Feng Zhai and H. Q. Xu, Phys. Rev. B **76**, 035306 (2007).