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Spin Splitter Based on Magnetically Confined Semiconductor Microstructure Modulated by Spin-Orbit Coupling

MAOWANG LU, SAIYAN CHEN, XINHONG HUANG, AND GUILIAN ZHANG

College of Science, Guilin University of Technology, Guilin 541004, China

CORRESPONDING AUTHOR: M. LU (e-mail: maowanglu@126.com)

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ABSTRACT We report a theoretical investigation on Goose–Hänchen (GH) effect for spin electrons across a magnetically confined GaAs/$\mathrm{Al_xGa_{1-x}As}$ microstructure modulated by spin-orbit coupling [(SOC), including Rashba and Dresselhaus types]. An intrinsic symmetry in the device is broken by SOC, which gives rise to a considerable spin polarization effect in GH shifts of electrons. Both magnitude and direction of spin polarization can be manipulated by Rashba or Dresselhaus SOC, i.e., interfacial confining electric field or strain engineering. Based on such a semiconductor microstructure, a controllable spatial spin splitter can be proposed for spintronics applications.

INDEX TERMS Magnetically confined semiconductor microstructure, Goos-Hänchen effect, spin splitter.

I. INTRODUCTION

Due to small size, low dimensionality and quantum confinement, semiconductor microstructure embedded in electronic device possesses abundant quantum effects, such as quantum Hall effect [1], spin polarization effect [2] and giant magnetoresistance effect [3]. It is these effects that drive electronic devices operating, e.g., based on spin polarization effect a new generation of spintronics devices works, in which information is carried by spins [4]. Study on quantum effects, manipulations and device applications have become an important direction in the research field of semiconductor microstructure [5]. In recent years, the spin-dependent Goos-Hänchen (GH) effect [6] has aroused great enthusiasm in magnetically confined semiconductor heterosturcture (MCSH) [7], because such a quantum effect can provide an alternative method to spin-polarize electrons into semiconductors. When an electron is reflected at an interface or traverses a semiconductor microstructure, it will undergo a lateral shift due to its wave's nature. This phenomenon is known as the GH effect. In principle, such a scheme [8] to generate spin current separates spins from spatial domain by means of distinct discrepancy of spatial positions (angle, shift or displace) between spin-up and spin-down electrons across a MCSH, i.e., MCSH serves as spatial spin splitter [9].

A simple proposal for spintronic devices is to exploit a single ferromagnetic (FM) stripe deposited on top of a semiconductor heterosturcture [10]. Horizontally magnetized FM stripe produces anti-symmetric magnetic field and symmetric vector potential—an intrinsic symmetry [11] in this MCSH, which results in electronic transmission independent of its spins [12]. As a result of the intrinsic symmetry, such a MCSH itself cannot serve as a spatial spin splitter. However, if a Schottky-metal (SM) stripe is in parallel configuration deposited in vicinity of FM stripe [13] or on bottom of the heterostructure [14], this intrinsic symmetry will be broken. As a consequence, the single FM stripe device can be designed as a spatial spin splitter [15], [16]. To break the intrinsic symmetry, Lu [17] advised to place another FM stripe on bottom of the heterostructure, and proposed a spatial spin splitter [18]. Very recently, edified by modern materials growth such as molecular beam epitaxy (MBE), Lu *et al.* [19] introduced a δ-doping into this device by atomic layer doping technique [20]. They found that such a doping can break the intrinsic symmetry and

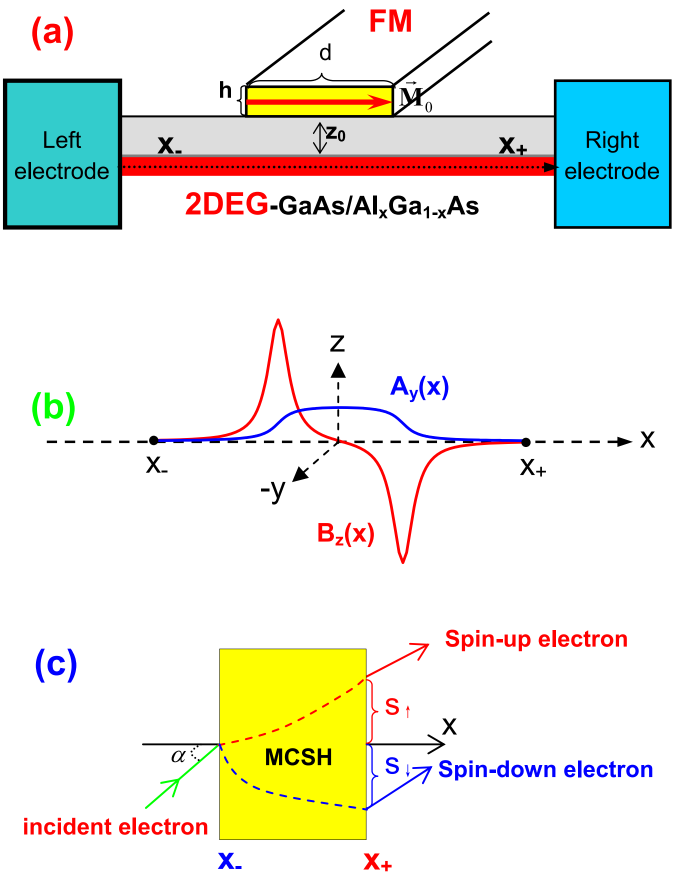

FIGURE 1. **(a) Schematic illustration of single FM stripe device, (b) magnetic profile $B_z(x)$ and magnetic vector potential $A_y(x)$, and (c) GH shifts of spin electrons across this device.**

consequently proposed a structurally controllable spatial spin splitter.

In an III-V based semiconductor heterostructure, there exists spin-orbit coupling (SOC) effect—couples electronic spin and momentum degrees of freedom [21], including two significant SOCs—Rashba and Efros [22] and Schliemann and Loss [23] types. In the Letter, we explore influence of Rashba and Dresselhaus SOCs on GH effect for spin electrons across single FM stripe device, to propose a spin splitter for spintronics applications.

II. THEORY AND METHOD

The MCSH device is shown in Fig. 1(a), where a FM stripe is deposited [24] on top of GaAs/Al$_x$Ga$_{1-x}$As heterostructure. Horizontally magnetized FM stripe induces a magnetic field, $\vec{B} = B_z(x)\hat{z}$, as [25]

$$B_z(x) = B_0\left[\frac{z_0 d}{(x-d/2)^2 + z_0^2} - \frac{z_0 d}{(x+d/2)^2 + z_0^2}\right], \quad (1)$$

where $B_0 = M_0 h/d$, $\vec{M}_0$, h and d stand for magnetization, thickness and width of FM stripe, respectively, and z_0 is vertical distance between the FM stripe and the two-dimensional electron gas (2DEG). In Landau gauge, vector potential $\vec{A} = A_y(x)\hat{y}$ is expressed by [26]

$$A_y(x) = B_0 d\left[\tan^{-1}\left(\frac{x-d/2}{z_0}\right) - \tan^{-1}\left(\frac{x+d/2}{z_0}\right)\right]. \quad (2)$$

Anti-symmetric $B_z(x)$ and symmetric $A_y(x)$ (i.e., an intrinsic symmetry are plotted in Fig. 1(b), while left and right ends of the device are assigned at $x = x_-$ and x_+, respectively. Hamiltonian describing such a 2DEG in the presence of SOCs is then written, within the single particle, effective mass approximation, by [27]

$$\begin{aligned} H = {} & \frac{\hbar^2 k_x^2}{2m^*} + \frac{\left[\hbar k_y + eA_y(x)\right]^2}{2m^*} + \frac{eg^*\hbar}{4m_0}B_z(x)\sigma_z \\ & + \eta_R\left[\left(k_y + A_y\right)\sigma_x - k_x\sigma_y\right] \\ & + \eta_D\left[k_x\sigma_x - \left(k_y + A_y\right)\sigma_y\right], \end{aligned} \quad (3)$$

where m^*, m_0, e, $\vec{k} = (k_x, k_y)$, and g^* are effective mass, free mass, charge, wave vector, and effective Landé factor of electrons, respectively, η_R/η_D is and Rashba/Dresselhaus SOC strength, and $\vec{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ is Pauli vector. Assuming spin quantization axis along z direction, Eq. (3) can be expressed in spinors by a 2×2 matrix equation,

$$\hat{H} = \begin{pmatrix} H_0 + \Lambda & z \\ z^* & H_0 - \Lambda \end{pmatrix} \quad (4)$$

with $H_0 = [(\hbar k_x)^2 + (\hbar k_y + eA_y)^2]//(2m^*)$, $\Lambda = em^*g^*\hbar B_z(x)/(4m_0)$ and $z = [\eta_R(k_y + A_y)] + i[\eta_R k_x + \eta_E(k_y + A_y)] = |z|e^{i\delta}$, whose eigenspinors and eigenvalues are, respectively,

$$\chi^{\uparrow(\downarrow)} = \begin{pmatrix} \pm e^{i\delta} \\ 1 \end{pmatrix} \text{ and } E_{\uparrow(\downarrow)} = H_0 \pm \sqrt{|z|^2 + \Lambda^2} \quad (5)$$

Considering eigenspinors pointing in 2DEG plane, we rotate the Cartesian spin axis such that reference z axis coincides with the new axis along eigenspinors $\chi^{\uparrow(\downarrow)}$, to simply treat wave function matching. Such a spin rotation can be fulfilled by a unitary transformation $U(\theta = \pi/2, \varphi)$ to Eqs. (4) and (5). Note that, this rotation aims only at spin not spatial part of total wave function; however, energy eigenvalues are unchanged under an unitary transformation. In rotated frame, x-dependence of total wave function can be then written by

$$\begin{aligned} \psi(x) = {} & Ae^{ikx}\begin{pmatrix} 1 \\ 0 \end{pmatrix} + Be^{-iqx}\begin{pmatrix} 1 \\ 0 \end{pmatrix} + Ce^{iqx}\begin{pmatrix} 0 \\ 1 \end{pmatrix} \\ & + De^{-ikx}\begin{pmatrix} 0 \\ 1 \end{pmatrix}, \end{aligned} \quad (6)$$

where $(+k, -k, +q, -q)$ are wave vectors for four degenerate eigenfunctions of Eq. (5) and can be obtained from Eq. (5). Because of translational invariance of a MCSH along y axis, total wave function can be expressed by

$$\Psi(x, y) = \psi(x)e^{ik_y y} = e^{ik_y y}\begin{pmatrix} Ae^{ikx} + Be^{-iqx} \\ Ce^{iqx} + Ce^{-ikx} \end{pmatrix}. \quad (7)$$

When the device is contacted between left and right electrodes, wave function for an electron with energy E projects onto the device in an incident angle α [see Fig. 1(c)] can expressed by $\psi_{in}(x) = (e^{ik_lx} + \gamma^{\uparrow}e^{-iq_lx}e^{iq_lx} + \gamma^{\downarrow}e^{-ik_lx})^T, x < x_-$, while outgoing wave function is and $\psi_{out}(x) = (\tau^{\uparrow}e^{ik_rx}\tau^{\downarrow}e^{iq_rx})^T, x > x_-$, respectively, where $k_y = \sqrt{2E}\sin\alpha$, $k_l = k_r = q_l = q_r = \sqrt{2m^*E/\hbar^2 - k_y^2}$, and $\tau^{\uparrow(\downarrow)}/\gamma^{\uparrow(\downarrow)}$ is transmission and reflection amplitudes for spin-up (down) states. According to Eq. (3), velocity operator in x direction can be given by$v_x = -i\frac{\hbar^2}{m^*}\partial_x - \eta_R\sigma_y + \eta_D\sigma_x$. At left and right boundaries of single FM stripe device (x_- and x_+), we can obtain following relationships, from continuity of wave function and conservation of current,

$$\begin{cases} \psi_{in}(x_-) = \psi(x_-), v_x\psi_{in}(x_-) = v_x\psi(x_-); \\ \psi(x_+) = \psi_{out}(x_+), v_x\psi(x_+) = v_x\psi_{out}(x_+). \end{cases} \tag{8}$$

With the help of improved transfer matrix method (ITMM) [28], Eq. (8) can be solved explicitly, and transmission amplitude, $\tau^{\uparrow(\downarrow)} = e^{i\varphi^{\uparrow(\downarrow)}}/\rho^{\uparrow(\downarrow)}$, can be obtained readily. Then, total phase shift is $\varphi^{\uparrow(\downarrow)}$ for transmitted spin-up (down) electrons at $x = x_+$ with respect to incident one at $x = -x_-$. In light of stationary phase method (SPM) [29], GH shift of electrons across the device can be evaluated by $S_{\uparrow(\downarrow)} = d\varphi^{\uparrow(\downarrow)}/dk_y$. Thus, electron-spin polarization can be characterized by considering the relative difference of GH shifts [30], i.e., $P_S = S_{\uparrow} - S_{\downarrow}$.

III. RESULTS AND DISCUSSION

For convenience, in dimensionless form we express all relevant quantities by using cyclotron frequency $\omega_c = eB_0/m^*$ and magnetic length $\ell_B = \sqrt{\hbar/eB_0}$ with a typical magnetic field B_0, e.g., $A_y \Rightarrow A_yB_0\ell_B$. Moreover, GaAs is taken as 2DEG materials with $m^* = 0.067m_0$ and $g^* = 0.44$. For $B_0 = 0.2T$, $\ell_B = 57.5nm$ and $E_0 = \hbar\omega_c = 0.34meV$. The SOC parameter in GaAs and a 2DEG carrier density are assumed to have a typical values of $0.3E_0\ell_B \approx 5.8meV \cdot nm$ and $\sim 10^{11}cm^{-2}$, respectively. In additions, in order to demonstrate principle of operation of the device, we merely consider incident angle $\alpha = -70°$ and fix $d = 1.0$, $z_0 = 0.1$ and $x_{\pm} = \pm 1.5$.

For single FM stripe deice without SOC, there exists an intrinsic symmetry, i.e., anti-symmetric $B_z(x)$ and symmetric $A_y(x)$. Due to such a symmetry, Hamiltonian is invariant under operator $\hat{T}\hat{R}_x\hat{R}_y$, where $\hat{T} = -i\hat{\sigma}_yK$ with complex conjugation K and reflection operator $\hat{R}_{x(y)}$. This invariance makes states $\Psi(x,y) = e^{ik_yy}\psi(x)$ and $\Psi'(x,y) = \hat{T}\hat{R}_x\hat{R}_u\Psi(x,y)$ have identical eigenenergy, i.e., spin-up state transforms to spin-down state, vice versa. In other words, spin-up and spin-down states with same wave vector k$_y$ are degenerate, or electronic transmission through the MCSH is independent of its spins. As a result, single FM stripe device don't be used as spatial spin splitter in the absence of SOC. However, it can be expected that, the intrinsic symmetry is broken, if the SOC effect is taken into account, i.e., GH shift of electrons will depend on spins.

First of all, we discuss case of Rashba SOC for the moment, which originates from broken inversion symmetry

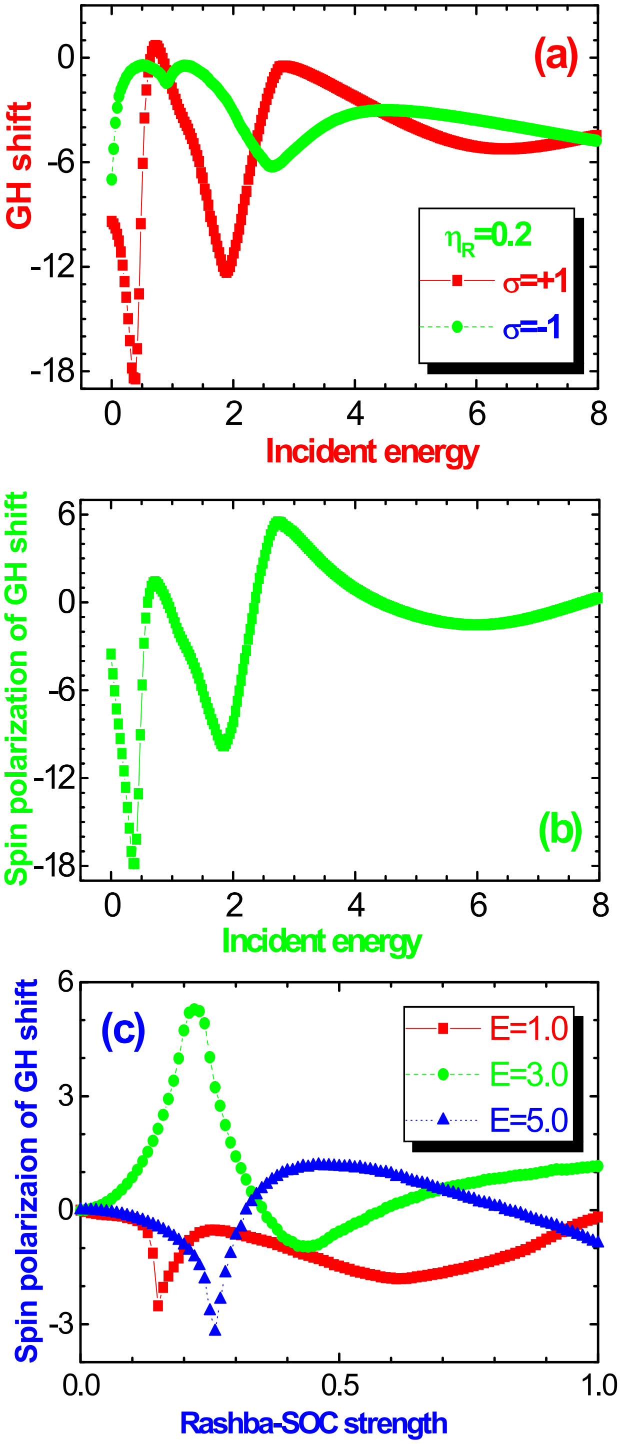

FIGURE 2. **(a) GH shifts of spin electrons, (b) spin polarization of GH shift, and (c) variation of spin-polarized GH shifts with Rashba-SOC under given incident energy.**

at surfaces or interfaces in an III-V based semiconductor heterostructure. In figure 2(a), as a function of incident energy, we plot GH shifts for electrons to traverse this device, where red and green curves correspond to spin-up and spin-down electrons, respectively, while Rashba-SOC is set to be $\eta_R = 0.2$. From this figure, we can see clearly that GH shift depends greatly on electron-spins, namely, GH shift of spin-up electrons differs obviously from that for spin-down electrons. In other words, for single FM stripe device with Rashba SOC, an evident spin splitting effect of GH shift appears, especially in incident-energy range of $E < 4.0$. Such a spin splitting effect can be observed more clearly from Fig. 2(b), where spin polarization versus incident energy is presented. Indeed, a considerable spin polarization effect in the GH shift can be apparently observed for such a Rashba-SOC modulated, single FM stripe device. Moreover, both magnitude and sign of spin-polarized GH shift vary strongly with incident energy, especially in low-energy region.

Because Rashba-SOC strength can be efficiently modulated [31] by an interfacial confining electric field in an III-V based semiconductor heterostructure, one wonders how Rashba SOC impacts on degree of spin polarization of GH shifts in single FM stripe MCSH device. Unquestionably, Rashba SOC will generate a great influence on spin-polarized GH shifts, because of dependence of effective potential experienced by electrons on Rashba SOC effect [see Eq. (3)]. Figure 2(c) gives spin polarization of GH shift directly as a function of Rashba-SOC strength, where incident energy is chosen as $E = 1.0$ (red curve), 3.0 (green curve) and 5.0 (blue curve). From these three curves, we can see evidently modulation of Rashba SOC to spin polarization of GH shifts, including its magnitude and sign. That is to say, degree of spin polarized GH shifts is manipulable by properly adjusting Rashba-SOC strength or interfacial confining electric field. Thus, single FM stripe device can be used as electrically-tunable spatial spin splitter for spintronics. In addition, we can observe apparently from this figure that modulation of Rashba SOC to spin polarized GH shifts is also associated with incident energy of electrons, in particular at $E = 3.0$.

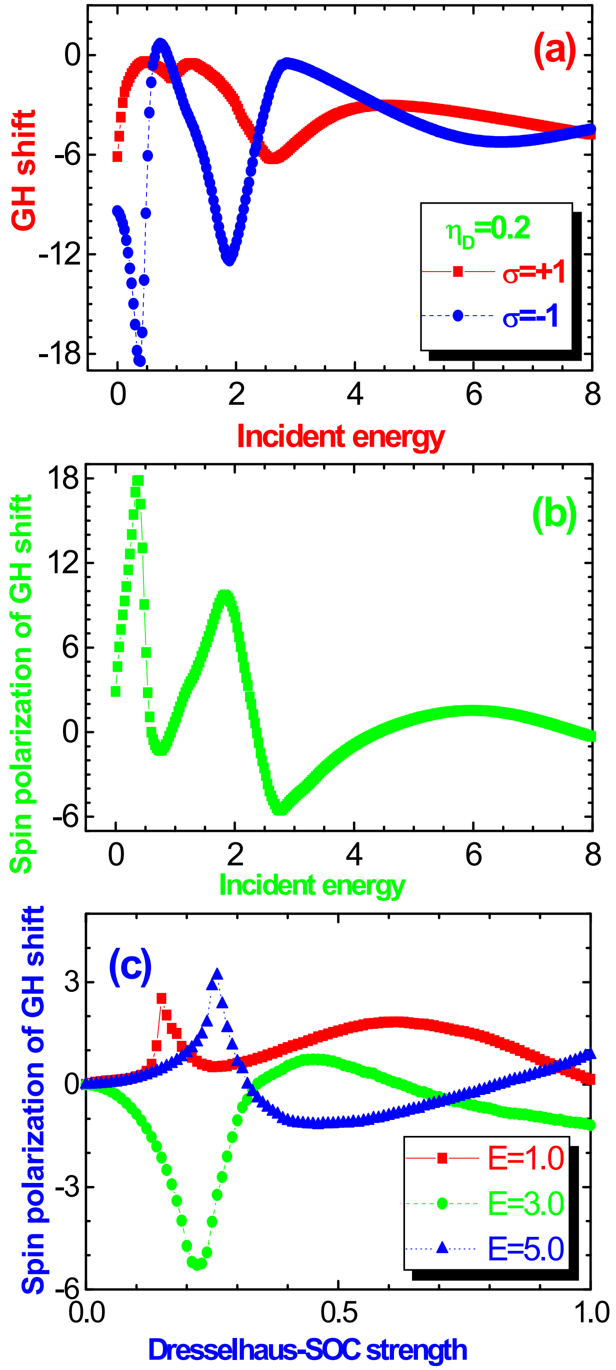

FIGURE 3. **(a) GH shifts versus incident energy, (b) spin polarization of GH shift, and (c) dependence of spin-polarized GH shifts on Dresselhaus SOC for fixed incident energy.**

In an III-V based semiconductor heterostructure, there exists another kind of SOCs, called Dresselhaus SOC, except for Rashba SOC effect. Next, we explore GH shifts for spin electrons across single FM stripe device in the presence of Dresselhaus SOC effect. In Fig. 3(a), we calculate GH shifts versus incident energy for spin-up (red line) and spin-down (blue line) electrons to traverse the device, where Dresselhaus-SOC is chosen as $\eta_D = 0.2$. A distinct difference of GH shifts between spin-up and spin-down electrons, especially in low-energy region, can be observed from this figure, which can be understood from broken intrinsic symmetry by Dresselhaus SOC in single FM stripe device. This means that such a device possesses an appreciable spin polarization effect of GH shifts in the presence of Dresselhaus SOC, as confirmed in figure 3(b). Considering Dresselhaus SOC tunable [32] by strain engineering in an III-V based semiconductor heterostructure, variation of spin polarization effect with Dresselhaus-SOC strength is given in Fig. 3(c), where incident energy is set to be $E = 1.0$ (red curve), 3.0 (green curve) and 5.0 (blue curve). Strong modulation of Dresselhaus SOC to spin-polarized GH shifts of electrons across the device, can be clearly seen from these three curves in this figure. Moreover, this modulation role shows up an evident dependence on incident energy, especially at $E = 3.0$; see green curve. Importantly, this modulation implies that, not only we can manipulate spin-polarized GH shifts in single FM stripe device by changing Dresselhaus-SOC, but also such a device can serve as a strain-tunable spatial spin splitter as a controllable spin polarized source [33].

So far, all results are presented independently for Rashba and Dresselhaus SOCs, respectively, which goes ill with

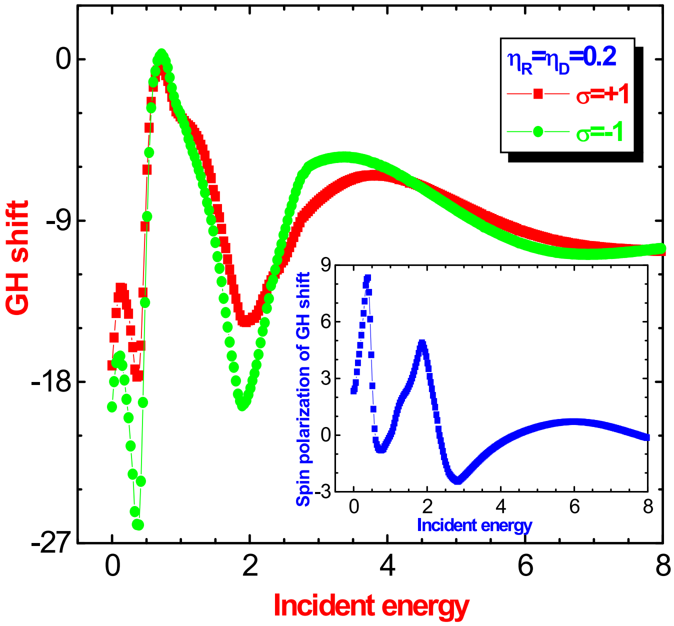

FIGURE 4. **(a) GH shift and (b) spin polarization in the inset, where both Rashba and Dresselhaus are taken into account.**

enriching this paper. Therefore, on the one hand, we make a comparison between Rashba and Dresselhaus SOCs. Contrasting figure 2 to figure 3, one can observe obviously that, these two kinds of SOCs have similar contribution in magnitude to GH shift and its spin polarization, but different effects in the direction of GH shift and its spin polarization. Such a phenomenon originates from the dependence of the effective potential felt by electrons in the device on Rashba or Dresselhaus SOC; see Eq. (3). On the other hand, we also have examined combined effects caused by both Rashba SOC and Dresselhaus SOC. Figure 4 gives GH shifts S_σ and the spin polarization P_s in the inset versus the incident energy for electrons tunneling through the device as shown in Fig. 1, where both Rashba and Dresselhaus SOCs are taken into account: $\eta_R = \eta_D = 0.2$. From this figure, we can observe that the total GH shift and its spin polarization are not the sum of contributions of two kinds of SOCs, since they are not the simple linear relationship in the Hamiltonian [see Eq. (3)]. In addition, in this work we merely consider an incident angle of electrons $\alpha = -70°$ to demonstrate the principle of operation of the spatial spin splitter more clearly, because the spin-dependent GH effect in a MCSH is associated closely with the incident angle and is more apparent for a large negative angle. Of course, the results will vary greatly with the incident angle of the electrons.

IV. CONCLUSION

In summary, we have theoretically investigated GH effect of spin electrons in single FM stripe device modulated by SOCs, which can be experimentally fabricated by depositing a horizontally magnetized FM stripe on top of GaAs/Al$_x$Ga$_{1-x}$As microstructure. GH effect of electrons is independent of spins, due to an intrinsic symmetry in the device in the absence of SOCs. However, either Rashba or Dresselhaus SOC can break such an intrinsic symmetry. As a result, GH shift becomes spin-polarized for electron across the device in the presence of Rashba and/or Dresselhaus SOC. Moreover, spin-polarized GH shifts can be tuned by changing Rashba/Dresselhaus SOC or interfacial confining electric field/strain engineering in the device. These interesting properties may provide an alternative scheme to separate electron-spins from spatial domain in MCSHs, and this single FM stripe MCSH device can serve as an electrically or strain controllable spin spatial splitter for spintronics applications.

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MAOWANG LU received the B.S. degree in physics and the M.S. degree in astrophysics from Hunan Normal University, Changsha, China, in 1987 and 1997, respectively, and the Ph.D. degree in condensed matter physics from the Institute of Solid State Physics, Chinese Academy of Sciences, Beijing, China, in 2003.

Since 2010, he has been a Research Professor with the PlaceTypeCollege of PlaceNameScience, Guilin University of Technology, CityplaceGuilin, country-regionChina.

SAIYAN CHEN received the B.S. degree in physics from Jishou University in 2007 and the M.S. degree in condensed matter physics from Xiangtan University in 2010.

Since 2015, she has been a Teacher with the College of Science, Guilin University of Technology, Guilin, China.

XINHONG HUANG received the B.S. degree in physics from the Hunan University of Science and Technology in 1999 and the M.S. degree in condensed matter physics from Hunan Normal University in 2012.

Since 2010, she has been a Teacher with the College of Science, Guilin University of Technology, Guilin, China.

GUILIAN ZHANG received the B.S. degree in physics from the Hunan University of Science and Engineering in 2006 and the M.S. degree in condensed matter physics from Xiangtan University in 2009.

Since 2016, she has been a Teacher with the College of Science, Guilin University of Technology, Guilin, China.