Strain-Induced Coupling of Spin Current to Nanomechanical Oscillations

A. G. Mal'shukov,[1] C. S. Tang,[2] C. S. Chu,[3] and K. A. Chao[4]

[1]*Institute of Spectroscopy, Russian Academy of Science, 142190, Troitsk, Moscow oblast, Russia*
[2]*Physics Division, National Center for Theoretical Sciences, P.O. Box 2-131, Hsinchu 30013, Taiwan, Republic of China*
[3]*Department of Electrophysics, National Chiao Tung University, Hsinchu 30010, Taiwan, Republic of China*
[4]*Solid State Theory Division, Department of Physics, Lund University, S-22362 Lund, Sweden*

(Received 6 May 2005; published 1 September 2005)

We propose a setup which allows us to couple the electron spin degree of freedom to the mechanical motions of a nanomechanical system not involving any of the ferromagnetic components. The proposed method employs the strain-induced spin-orbit interaction of electrons in narrow gap semiconductors. We have shown how this method can be used for detection and manipulation of the spin flow through a suspended rod in a nanomechanical device.

DOI: 10.1103/PhysRevLett.95.107203 PACS numbers: 75.40.Gb, 71.70.Ej, 71.70.Fk, 72.25.−b

An ability to control the spin transport in semiconductors is a key problem to be solved towards implementation of semiconductor spintronics into quantum information processing [1–3]. Many methods have been proposed to achieve control of the electron spin degree of freedom using magnetic materials, external magnetic fields, and optical excitation [for a review see Ref. [3]]. Other promising ideas involve the intrinsic spin-orbit interaction (SOI) in narrow gap semiconductors to manipulate the spin by means of electric fields [4] and electric gates [5–7]. Recently, some of these ideas have been experimentally confirmed [8,9].

In semiconductors the spin-orbit effect appears as an interaction of the electron spin with an effective magnetic field whose direction and magnitude depend on the electron momentum. A specific form of this dependence is determined by the crystal symmetry, as well as by the symmetry of the potential energy profile in heterostructures. In strained semiconductors new components of the effective magnetic field appear due to violation of the local crystal symmetry [10]. The effect of the strain-induced SOI on spin transport was spectacularly demonstrated by Kato *et al.* in their Faraday rotation experiment [9]. An interesting property of the strain-induced SOI is that the strain can be associated with mechanical motion of the solid, in particular, with oscillations in nanomechanical systems (NMS), in such a way making possible the spin-orbit coupling of the electron spin to nanomechanical oscillations. At the same time a big progress in fabricating various NMS [11] allows one to reach the required parameter range to observe subtle effects produced by such a coupling.

In this Letter we will consider NMS in the form of a suspended beam with a doped semiconductor film epitaxially grown on its surface (see Fig. 1). An analysis of the SOI in this system shows that the flexural and torsion vibrational modes couple most efficiently to the electron spin. As a simple example, we will focus on the torsion mode. The strain associated with torsion produces the spin-orbit field which is linear with respect to the electron momentum and is directed perpendicular to it. This field varies in time and space according to respective variations of the torsion strain. Because of the linear dependence on the momentum, the SOI looks precisely as interaction with the spin dependent electromagnetic vector potential. An immediate result of this analogy is that the time-dependent torsion gives rise to a motive force on electrons. Such a force, however, acts in different directions on particles with oppositely oriented spins, inducing thus the spin current in the electron gas. The physics of this phenomenon is very similar to the spin-current generation under time-dependent Rashba SOI, where the time dependence of the SOI coupling parameter is provided by the gate voltage variations [6]. In the present work we will focus, however, on the inverse effect. Because of the SOI coupling, the spin current flowing through the beam is expected to create a mechanical torsion. The torque effect on NMS due to spin flow has been previously predicted by Mohanty *et al.* [12] for a different physical realization, where the torque has

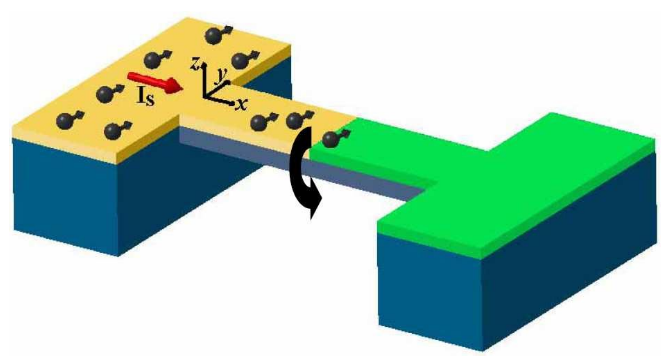

FIG. 1 (color online). Schematic illustration of electromechanical spin-current detector, containing a suspended semiconductor-metal (S-M) rectangular rod atop an insulating substrate (blue). A spin current is injected from the left semiconductor reservoir (yellow) and then diffuses toward the metallic film (green). While passing through the semiconductor film, the spin current induces torque shown by the black arrow.

been created by spin flips at the nonmagnetic-ferromagnetic interface. They also suggested an experimental setup to measure such a small torque. As it will be shown below, the torque due to the strain-induced SOI can be large enough to be measured using the experimental setup proposed in Ref. [12]. Besides this method, other sensitive techniques for displacement measurements can be employed [13].

The system under consideration is a rectangular beam of the total length L_t, width b, and thickness c. The coordinate axes are chosen as shown in Fig. 1. The semiconductor film with the thickness $c/2$ occupies the length L of the beam. The rest part contains a metal film. It can also include some additional elements for detection of the torque, for example, in Ref. [12]. Here we will consider an example when the spin current is created by diffusion of the spin polarization from the left contact in Fig. 1. Therefore, there is no electric current flow through NMS. The spin polarization diffuses towards the metal film which, due to its relatively high conduction, can play an important role as a reservoir for the spin polarization relaxation.

We start from the strain-induced SOI [10] described by the Hamiltonian

$$\begin{aligned} H_{\mathrm{SO1}} = \alpha[&\sigma_x(u_{zx}k_z - u_{xy}k_y) + \sigma_y(u_{xy}k_x - u_{yz}k_z) \\ &+ \sigma_z(u_{yz}k_y - u_{zx}k_x)] + \beta[\sigma_x k_x(u_{yy} - u_{zz}) \\ &+ \sigma_y k_y(u_{zz} - u_{xx}) + \sigma_z k_z(u_{xx} - u_{yy})], \end{aligned} \tag{1}$$

where u_{ij} are elements of the strain tensor, σ_i stand for Pauli matrices, and k_i denote components of the electron wave vector. In the narrow gap semiconductors the parameter β is usually much smaller than α [10]. Therefore, the term proportional to β will be omitted below. Besides the strain-induced H_{SO1}, the total SOI Hamiltonian also includes the strain independent interaction H_{SO2}. Because of submicron cross-section dimensions of the doped semiconductor film, H_{SO2} will be determined by the bulk Dresselhaus term [14].

$$H_{\mathrm{SO2}} = \delta\sum_{ijn}|\epsilon^{ijn}|k_i(k_j^2 - k_n^2). \tag{2}$$

This interaction, in the range of doping concentrations 10^{17} cm^{-3} and higher, provides the main mechanism for spin relaxation in bulk materials [10].

Since the S-M rod with total length $L_t \gg b$ and c, the major contribution to the strain comes from flexural and torsion motions of the rod [15]. Within the isotropic elastic model, the flexural motions are represented by the diagonal elements u_{xx} and u_{yy} [15] which do not enter into the first square brackets of Eq. (1). On the other hand, due to the crystal anisotropy effects, the u_{xy} components are not zero for such sort of motion and could contribute to Eq. (1). We will consider, however, the simplest example of torsion motions of the rod within an isotropic elastic model. In this case the strain can be represented as [15]

$$u_{yx} = \tau(x)\frac{\partial\chi}{\partial z}; \qquad u_{zx} = -\tau(x)\frac{\partial\chi}{\partial y}; \qquad u_{yz} = 0, \tag{3}$$

where $\tau(x) = \partial\theta/\partial x$ stands for the rate of torsion determined by the torsion angle θ. The function χ depends only on z and y and is uniquely determined by the rod cross-section geometry.

The next step is to derive from the one-particle interaction Eq. (1) a Hamiltonian which describes a coupling of the spin current to the strain. The electron system carrying the spin current can be described by a density matrix $\hat{\rho}$. In the framework of the perturbation theory the leading correction to the electron energy due to the SOI induced strain can be obtained by averaging H_{SO1} with $\hat{\rho}$. In the semiclassical approximation such a procedure can be represented as averaging over the classical phase space with the Boltzmann distribution function $\hat{F}_{\mathbf{k}}(\mathbf{r})$. This function is a 2×2 matrix in the spinor space. One can also define the spin distribution function $P^i_{\mathbf{k}}(\mathbf{r}) = (1/2)\,\mathrm{Tr}[\hat{F}_{\mathbf{k}}(\mathbf{r})\sigma^i]$. It is normalized in such a way that the local spin polarization $P^i(\mathbf{r}) = \sum_{\mathbf{k}}\mathbf{P}_{\mathbf{k}}(\mathbf{r})$. We notice that, due to electron confinement in y and z directions, the averages of H_{SO1} containing k_y and k_z turn to zero. Assuming that electron distribution is uniform within the cross section of the semiconductor film one thus obtains, from Eqs. (1) and (3), the SOI energy

$$E_{\mathrm{SO}} = 2\alpha\int_0^L dx\frac{\partial\theta}{\partial x}\sum_{\mathbf{k}}k_x\int dydz\left(P^y_{\mathbf{k}}(x)\frac{\partial\chi}{\partial z} + P^z_{\mathbf{k}}(x)\frac{\partial\chi}{\partial y}\right). \tag{4}$$

This expression can be further simplified taking into account that χ turns to zero on a free surface [15]. Hence, in the example under consideration $\chi = 0$ on the top and side surfaces of the doped semiconductor film. Consequently, the second term in Eq. (4) vanishes after integration over y. Now Eq. (4) can be expressed in terms of the spin current $J^y(x)$ which is the flux in x direction of y-polarized spins.

$$J^y(x) = S\sum_{\mathbf{k}}v_x P^y_{\mathbf{k}}(x), \tag{5}$$

where $S = bc/2$ is the semiconductor film cross section and v_x is the electron velocity in x direction [16]. Finally, Eq. (4) can be transformed to

$$E_{\mathrm{SO}} = \gamma\int_0^L dxJ^y(x)\frac{\partial\theta}{\partial x}. \tag{6}$$

Here the coupling constant γ is given by

$$\gamma = \gamma_0\int_{-b/2}^{b/2}\chi(y, z = 0)dy, \tag{7}$$

where $\gamma_0 = 2m^*\alpha/\hbar S$.

From the last equation, it is seen that the spin-polarized flow imposes a distributed torque on the rod. In order to study this effect in detail we will neglect, for simplicity, the difference between elastic constants of semiconductor and metal parts of NMS. As such, the equation of motion for the torsion angle can be then written as

$$I\frac{\partial^2\theta}{\partial t^2} - K\frac{\partial^2\theta}{\partial x^2} - \gamma\frac{\partial}{\partial x}[J^y\eta(L-x)] = 0, \tag{8}$$

where $\eta(x)$ denotes the Heaviside function, K stands for the torsion rigidity, and I is the moment of inertia. It is easy to figure out that the torque imposed by the SOI on NMS can be expressed as

$$\mathcal{T} = \frac{\gamma}{L}\int_0^L dx J^y(x) \equiv \gamma\bar{J}^y, \tag{9}$$

and, for the S-M rod clamped on both ends, the torsion angle at $x = L$

$$\theta_L = \frac{L(L_t - L)}{L_t}\frac{\mathcal{T}}{K}, \tag{10}$$

where L_t is the total length of the rod. From Eq. (8) one can easily see that if the semiconductor film covers the entire length of the beam ($L = L_t$) and the spin current is homogeneous along it, the last term in Eq. (8) turns to 0. Consequently, for a doubly clamped beam the solution of Eq. (8) is $\theta(x) \equiv 0$. In this case, in order to obtain the finite torsion angle, the NMS must include films with different spin-orbit coupling parameters γ, as in Fig. 1 where $\gamma = 0$ in the metal film. On the other hand, if J^y depends on x, as in the example considered below, the metal film is not so necessary. In this example it is shown, however, that such a film can be useful as a reservoir for fast spin relaxation, enhancing thus the diffusive spin-current flow through the beam.

In order to evaluate the torque, let us adopt the following simple model, which is also convenient for an experimental realization. Namely, we assume that the spin current is due to spin diffusion from the left contact. The spin polarization $P^y(0)$ can be created there by various methods ranging from absorption of circularly polarized light to injection from a ferromagnet [3]. One more possibility is the electric spin orientation [9]. For the steady state the diffusion equation reads

$$D_i\frac{d^2P^y}{dx^2} - \frac{P^y}{\tau_i} = 0, \tag{11}$$

where D_i and τ_i are diffusion coefficients and spin relaxation times, with the subscript i indicating the physical quantities in semiconductor ($0 < x < L$) ($i = S$) or metal ($x > L$) ($i = M$) regions. At the semiconductor-metal interface the diffusion current and magnetization $P^y/N_i(0)$ must be continuous, where $N_i(0)$ is the semiconductor or metal density of states at the Fermi energy [17]. We will assume that the length of the metal part of the rod is larger than the spin diffusion length $l_M = \sqrt{D_M\tau_M}$. Therefore, the spin current passes through the semiconductor film and further decays within the metal film. Obviously, in the considered example there is no charge current through the system. Solving the diffusion equation for $l_S \gg L$ and $(\sigma_M L)/(\sigma_S l_M) \gg 1$, where σ_M and σ_S are the 3D conductivities of metal and semiconductor, respectively, we obtain

$$\bar{J}^y = \frac{D_S P^y(0) S}{L}. \tag{12}$$

Since the ratio σ_M/σ_S is very big, Eq. (12) is valid in a broad range of not very small L.

For a numerical evaluation of the spin-orbit torsion effect we take $b = 400$ nm and $c = 200$ nm. The SOI coupling constant $\alpha/\hbar = 4 \times 10^5$ m/sec in GaAs [18]. From Eq. (7) and Ref. [15], it is easy to obtain the spin-current-torsion coupling parameter $\gamma = \gamma_0 k_2 b^3$, where k_2 is a numerical factor depending on the ratio c/b. At $b/c = 2$ the factor $k_2 = 0.03$. For such numerical parameters we find $\gamma = 2.4 \times 10^{-32}$ J sec. It is interesting to compare the torsion effect from the strain-induced SOI with that produced by spin flips at the FM-NM interface [12]. In the latter case $\mathcal{T} = \hbar I_s$, where I_s is of the order of the spin current injected at the FM-NM contact when the electric current passes through it. Comparing this expression with Eq. (9), it is seen that at the *same* spin currents the SOI effect is much stronger, by the factor $\gamma/\hbar \simeq 2.2 \times 10^2$. On the other hand, in [12] the FM-NM contact can be fabricated from all metallic components, while our device must contain the narrow gap semiconductor film. In the former case NMS is able to carry much larger spin current, due to the weaker, by the factor $\sim\sigma_S/\sigma_M$, Joule heating effect. However, the measurement setup suggested by Mohanty *et al.* [12] allows us to measure torsion effects produced by quite weak currents. For example, at $e\bar{J}^y = 10^{-8}$ Amp the torque $\mathcal{T} = 1.5 \times 10^{-21}$ Nm, which is within the sensitivity claimed in [12]. Moreover, the measurement sensitivity can be enhanced [19]. Within our model we can evaluate the spin polarization $P^y(0)$ which can produce a measurable effect on NMS. From Eq. (12), taking $L = 2$ μm, the typical low temperature diffusion constant 300 cm^2/sec, and $n = 10^{17}$ cm^{-3}, one obtains $e\bar{J}^y = 10^4[P^y(0)/n]$ nA. Hence, a measurable 10 nA spin current in NMS can be created by diffusion of spin polarization from an adjacent reservoir containing only 0.1% of spin-polarized carriers. Various methods [3,8,9] are able to provide such and even much larger spin polarization. Higher spin currents are, however, restricted by the heating effects, which depend on the practical design of NMS.

It should be noted that the torsion measurement method of Ref. [12] applies to a time-dependent torque in resonance with a NMS oscillation. For such a measurement the spin current could be modulated in time by a narrow gate between the left contact and the rod, or by varying the spin polarization in the left reservoir, for example, if it is created by absorption of circularly polarized light with modulated intensity.

The static torsion angle at $x = L$ can be found from Eq. (10). On the other hand, the maximum torsion effect is obtained for the time-dependent spin current in resonance with the NMS fundamental oscillation. In this case, the torsion angle θ_L in Eq. (10) must be multiplied by $Q/2$, where Q is the resonance quality factor, which can be quite large in NMS. To observe this torsion angle it must be much larger than the mean amplitude of its thermal fluctuations $\sqrt{\overline{\delta\theta_L^2}}$. For a doubly clamped rod

$$\overline{\delta\theta_L^2} = \frac{k_B T L_t}{\pi^2 K} \sum_{n \geq 1} \frac{1}{n^2} \sin^2\left(\frac{\pi n L}{L_t}\right). \quad (13)$$

For a rectangular cross section with $b/c = 2$, the torsion rigidity $K = 0.057 \mu b^3 c$ [15], where $\mu \simeq 3.3 \times 10^{10}$ N/m^2 in GaAs material. Taking $L_t = 5$ μm and all other parameters the same as in the previous paragraph, $Q = 10^4$ and $T = 100$ mK, we obtain the ratio $\delta\theta_L/\theta_L \simeq 4 \times 10^{-2}$ at $e\bar{J}^y = 10$ nA.

We have considered a simple example of the spin-orbit torque effect produced by spin flux in a diffusive 3D semiconductor film. It would be interesting to study other systems, for example, a superlattice of remotely doped high mobility quantum wells in the ballistic regime (L is less than the elastic mean free path). In such a system energy dissipation within the semiconductor film is reduced and, apparently, larger spin currents are allowable.

In summary, we propose a nanomechanical system where due to the strain-induced spin-orbit interaction the electron spin degree of freedom can couple to NMS mechanical motions. We have shown that this coupling is strong enough to induce the measurable torsion in NMS when the spin polarization flows through the suspended nanobeam. Besides a potential for other possible applications, such NMS can be employed as a sensitive detector of spin currents and spin polarizations. The basic structure can be further modified to create devices for eventual use in spintronics as well as spin information processing.

This work was partly funded by the Taiwan National Science Council and RFBR Grant No. 03-02-17452.

[1] *Semiconductor Spintronics and Quantum Computation*, edited by D. D. Awschalom, N. Samarth, and D. Loss (Springer-Verlag, Berlin, 2002).

[2] S. A. Wolf *et al.*, Science **294**, 1488 (2001).

[3] I. Žutić, J. Fabian, and S. Das Sarma, Rev. Mod. Phys. **76**, 323 (2004).

[4] J. Sinova *et al.*, Phys. Rev. Lett. **92**, 126603 (2004); S. Murakami, N. Nagaosa, and S. Zhang, Science **301**, 1348 (2003); V. M. Edelstein, Solid State Commun. **73**, 233 (1990); A. Voskoboynikov, S. S. Liu, and C. P. Lee, Phys. Rev. B **59**, 12514 (1999); L. S. Levitov and E. I. Rashba, Phys. Rev. B **67**, 115324 (2003).

[5] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990); P. Sharma and P. W. Brouwer, Phys. Rev. Lett. **91**, 166801 (2003); M. Governale, F. Taddei, and R. Fazio, Phys. Rev. B **68**, 155324 (2003).

[6] A. G. Mal'shukov, C. S. Tang, C. S. Chu, and K. A. Chao, Phys. Rev. B **68**, 233307 (2003).

[7] C. S. Tang, A. G. Mal'shukov, and K. A. Chao, Phys. Rev. B **71**, 195314 (2005).

[8] J. Wunderlich, B. Käestner, J. Sinova, and T. Jungwirth, Phys. Rev. Lett. **94**, 047204 (2005).

[9] Y. K. Kato *et al.*, cond-mat/0502627.

[10] G. E. Pikus and A. N. Titkov, in *Optical Orientation*, edited by F. Meier and B. P. Zakharchenya (North-Holland, Amsterdam, 1984).

[11] M. L. Roukes, Phys. World **14**, 25 (2001); H. G. Craighead, Science **290**, 1532 (2000); A. N. Cleland, *Foundations of Nanomechanics* (Springer, New York, 2003).

[12] P. Mohanty, G. Zolfagharkhani, S. Kettemann, and P. Fulde, Phys. Rev. B **70**, 195301 (2004).

[13] R. G. Knobel and A. N. Cleland, Nature (London) **424**, 291 (2003).

[14] G. Dresselhaus, Phys. Rev. **100**, 580 (1955).

[15] L. Landau and E. Lifshitz, *Course of Theoretical Physics* (Pergamon, New York, 1986), 3rd ed., Vol. 7.

[16] We neglected the small correction to the spin current associated with Dresselhaus's term $\frac{\partial H_{SO2}}{\partial \mathbf{k}}$ in the velocity operator, as well as the corresponding correction due to H_{SO1}, within the linear perturbation theory on the strain-induced SOI.

[17] M. Johnson and R. H. Silsbee, Phys. Rev. B **35**, 4959 (1987); **37**, 5312 (1988).

[18] M. I. D'yakonov, V. A. Marushchak, V. I. Perel', and A. N. Titkov, Sov. Phys. JETP **63**, 655 (1986) [Zh. Eksp. Teor. Fiz. **90**, 1123 (1986)].

[19] P. Mohanty (private communication).