Spin-mechanical device for detection and control of spin current by nanomechanical torque

P. Mohanty,[1] G. Zolfagharkhani,[1] S. Kettemann,[2,3] and P. Fulde[3]
[1]*Department of Physics, Boston University, 590 Commonwealth Avenue, Boston, Massachusetts 02215, USA*
[2]*1. Institut für Theoretische Physik, Jungiusstr. 9, Universität Hamburg, Hamburg 20355, Germany*
[3]*Max-Planck Institut für Physik Komplexer Systeme, Nöthnitzer Str. 38, D-01187 Dresden, Germany*
(Received 29 April 2004; published 2 November 2004)

We propose a spin-mechanical device to control and detect spin currents by mechanical torque. Our hybrid nanoelectromechanical device, which contains a nanowire with a ferromagnetic-nonmagnetic interface, is designed to measure or induce spin-polarized currents. Since spin carries angular momentum, a spin-flip or spin-transfer process involves a change in angular momentum and hence, a torque, which enables mechanical measurement of spin flips. Conversely, an applied torque can result in spin polarization and spin current.

DOI: 10.1103/PhysRevB.70.195301 PACS number(s): 72.25.Ba, 71.30.+h, 72.15.−v, 73.20.Fz

I. INTRODUCTION

Electronics and information processing with spins promise to be anything but conventional.[1,2] In spin-based electronics, information is injected, stored, transferred, or manipulated with the spin degree of freedom. The realization of its importance—and the ensuing excitement—stems from the fact that successful incorporation of spins into conventional semiconductor technology will allow to combine both information storage and information manipulation within a single platform. The recent discovery of a number of spin-based phenomena, such as giant magnetoresistance,[3] has also marked the beginning of a new era with spintronics,[1,2] and spin-based quantum information processing.[4] The transport properties of *d* electrons in ferromagnetic transition metals like Fe, Co, Ni, and their contribution to the ferromagnetism are also of important fundamental interest.[5–9]

At the heart of spintronics is detection and control of electron spins moving through a ferromagnetic-metallic or ferromagnetic-semiconductor heterostructure. Towards this end, there have been a large number of important experiments[10] and theoretical works,[11] leading to a whole new dictionary for spin-based electronics, including spin diode, spin transistor, spin pump, spin battery, and spin filter.[1,2] Here, we propose a spin-mechanical device for detection and control of spins in hybrid magnetic-nonmagnetic structures by mechanical torque.

Spin transport and nanomechanics form the underlying basis of the proposed spin-mechanical device, which is capable of detecting, controlling, and creating both spin transport and spin population. The central concept of its function is rather simple: spin carries angular momentum, and a change in the angular momentum due to spin transport creates a torque, which can be detected by a nanomechanical torsion oscillator.

The deceptive simplicity of the idea contrasts its rich history, both in theory and experiment. The original proposal to detect changes in the magnetization by measuring the associated torque dates almost a century back to the work of Richardson,[12] and Einstein and de Haas.[13] The reverse effect, inducing magnetization by rotation, has been suggested and measured soon by Barnett.[14] Another mechanism is the associated Wiedemann effect:[15] a current flowing through a ferromagnet, such as a Ni or Fe wire, in a parallel magnetic field induces a torque on the wire due to magnetoelastic interactions.

Motivated by these historical experiments, it was recently pointed out that a current flowing through a ferromagnetic-nonmagnetic (FM-NM) interface produces a mechanical torque. In a ferromagnet, a current has an associated spin current, which is absent in a nonmagnetic metal. Therefore, there is a sink or source of angular momentum at an FM-NM interface, depending on the current direction, which results in a torque,[16] which can be transferred into a mechanical torque of the device.[17] This is precisely the underlying principle of the classic optical experiment by Beth,[18] in which the change in the angular momentum of circularly polarized photons through an optically active glass is measured; the torque on the glass plate results due to the change in polarization at the interface. This allowed to prove experimentally the quantization of the spin of photons.

A measurement of the torque at a FM-NM interface would allow for a determination of the relative contributions of different types of electrons to the current, e.g., of *s* and *d* electrons in the case of Fe.[5,6] Those electrons are polarized to a different degree because of their different bandwidths. From an experimental measurement of the tunneling density of states, magnetic polarizations of $\alpha = 0.11$, 0.34, and 0.44 for Ni, Co, and Fe, respectively, have been estimated, while a theoretical calculation for *s* electrons alone would give for Ni, $\alpha_s = 0.01$.[6] Until now, there is no direct measurement available of the relative contribution of the *s* and *d* electrons to the current.

II. SPIN-FLIP TORSION BALANCE

It is the purpose of this paper to show that this spin-flip torsion balance effect can be strongly enhanced in a nanomechanical device when a nanowire containing a FM-NM interface is grown on top of a suspended nanoelectromechanical structure (NEMS). Thereby, the spin transport can be measured by the induced mechanical torque in the NEMS torsion device. The inverse is also true: a torque at the FM-NM interface produces a potential difference between the two metals.[14,19] Accordingly, a spin current can be gen-

1098-0121/2004/70(19)/195301(6)/$22.50

erated by applying an external torque. In this paper, we perform a detailed analysis to show that such a device can be used to detect, control, and induce spin current.

In a nanowire with a ferromagnetic (FM) and a nonmagnetic (NM) part, the ferromagnet is uniformly spin polarized in a direction parallel to the wire. Application of a magnetic field parallel to the wire further elongates the magnetization. When a current I is passed through the wire, a fraction $\alpha/2$ of the electrons passing through the interface between the FM and NM flip their spin. Here, α is the degree of magnetic polarization of the electrons contributing to the current in the ferromagnet.

Each spin flip results in a change in the angular momentum $\Delta L=\hbar$. The number of electrons ΔN passing the interface in a time interval Δt is $\Delta N=I\Delta t/e$, where I is the electrical (charge) current, and e the electron charge. The associated change in angular momentum is $\Delta L/\Delta t=(\hbar\alpha/2)I/e$, which results in a torque,

$$\vec{T}_{\rm spin}=\frac{\hbar}{2}\alpha\frac{I}{e}\hat{x}. \tag{1}$$

Here, $\hat{x}$ is the unit vector along the wire axis. The higher the spin polarization of the conducting electrons, the larger is the resulting torque. Thus, that torque is a direct measure of the spin polarization of the itinerant electrons in the ferromagnet. If the current increases, the resulting torque increases linearly.

There is an additional contribution $T_{\rm W}$ to the net torque because of the Wiedemann effect. This contribution is orders of magnitude smaller than $\vec{T}_{\rm spin}$ in nanomechanical systems as we show below. $T_{\rm W}$ originates from the circular magnetic field $H_c=I/2\pi R$ perpendicular to the magnetization axis of the FM part of the nanowire in the presence of a current I. It leads to small changes in the direction and the absolute value of the magnetization by the magnetoelastic interaction. The resulting torque $T_{\rm W}$ has an associated torsion angle $\theta_{\rm W}=(L\lambda/R)\delta M_c/M_0$. Here, the radius of the wire is R, its length L, and M_0 is the magnetization along the wire axis. $\lambda=\Delta\ell/\ell$ is the magnetostrictive coefficient which characterizes the relative length changes $\Delta\ell/\ell$ due to the changes of the magnetization $|\delta\boldsymbol{M}|$. Here, $\delta M_c=\chi_c H_c$, where H_c is the field generated by the current I and χ_p is the magnetic susceptibility to the magnetic field H_c, pointing circularly around the wire axis, when the single domain ferromagnet is polarized along the wire. The torque is then given by $T_{\rm W}=K\theta_{\rm W}$, where for a wire, $K=(\pi/2)GR^4/L$ and G is the shear modulus of the oscillator. The ratio between $T_{\rm W}$ and $T_{\rm spin}$ is

$$\frac{T_{\rm W}}{T_{\rm spin}}=\frac{R^2Ge\lambda\chi}{2\hbar\alpha M_0}. \tag{2}$$

The magnetostriction coefficient λ is in general quite small (relative to the unpolarized state, it is on the order of 10^{-6}) and both its sign and magnitude depend on the material and the material growth direction. Here, we are interested in the magnetostriction as caused by the reorientation of the magnetization due to the circular field, relative to the state when the wire is fully polarized along the wire. In that case, λ is a function of the magnetization M_0 and applied magnetic field H_c, and it displays strong hysteresis.[20] From magnetoelastic theory one expects $\lambda\approx\Lambda(\delta M/M_0)^2$ (Ref. 20), although the exact functional form may depend on the material and crystal orientation.

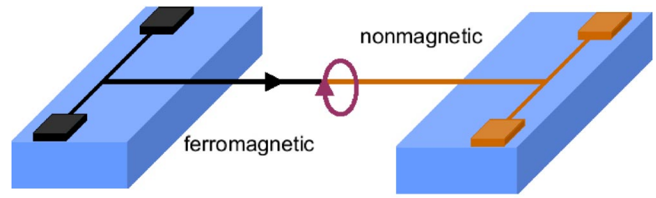

FIG. 1. (Color online) Schematic diagram showing a suspended ferromagnetic-nonmagnetic (FM-NM) wire. The black arrow denotes the direction of the magnetization. A spin-transfer process at or beyond the FM-NM interface torts the wire as indicated.

From magnetostriction measurements on Fe or Ni (Ref. 20) we estimate $\Lambda\approx10^{-5}$, when the ferromagnet is magnetized along the wire with typical magnetization $M_0=(1/4\pi)10^6$ A/m. We find with $G=10^{10}$ N/m^2,

$$\frac{T_{\rm spin}}{T_{\rm W}}=\alpha 8.5\times10^{-5}/(\rho^4\chi_p^3\boldsymbol{j}^2), \tag{3}$$

where $R=\rho$(mm), and $j=\boldsymbol{j}$(A/mm^2) is the current density. In the classical macroscopic experiments[15] with $\rho\approx0.1$ and $\boldsymbol{j}=1$, the Wiedemann effect and the spin-flip torsion effect can be of the same order of magnitude. However, in a nanomechanical torsion oscillator, the wire can be as thin as $\rho=10^{-4}$, while the current density can still be $\boldsymbol{j}=1$, the spin flip torsion balance can exceed the Wiedemann effect by orders of magnitude. When applying the circular magnetic field, the single magnetic domain, magnetized along the wire has some rigidity so that the corresponding magnetic susceptibility χ_c is small. Taking for a ferromagnetic cylinder polarized along its axis a typical value $\chi_c=1$ (Ref. 21) one finds $T_{\rm spin}/T_{\rm W}\approx10^{12}$. Although the circular magnetic susceptibility can depend on the growth direction of the ferromagnetic film, and can change with its dimension, we can conclude that the Wiedemann effect is negligible for any theoretically possible value of the circular magnetic susceptibility, ranging between the Pauli susceptibility $\chi_P\sim10^{-4}$, and values for macroscopic ferromagnets $\chi\sim10^3$.

Spin-mechanical balance. The spin-transfer torque can be measured with a suspended NEMS torsion balance to which the half-ferromagnetic, half-nonmagnetic nanowire is rigidly attached, as shown in Fig. 1. The magnitude of the torque, Eq. (1) along the wire axis is given by

$$T_{\rm spin}=3.3\times10^{-19}\alpha\boldsymbol{I}\ \text{Nm}, \tag{4}$$

where $\boldsymbol{I}$ is the current in units of mA. Thus, the torque is within the sensitivity range of existing NEMS oscillators.[22,23] The torque caused by the finite spin-flip rate, Eq. (1), is in balance with the torque due to the elastic torsion of the wire, as well as a torque due to the finite inertia of the wire, and a friction torque when the torsion angle changes in time. A ferromagnetic wire, on top of the NEMS oscillator, undergoing torsion by an angle θ results in a torque $T_{\rm elastic}=K\theta$. L is the length of the ferromagnetic part of the wire. If the angle

θ changes with time, it will result in an inertial torque T_{inertia} due to the moment of inertia J about the nanowire axis: $T_{\text{inertia}}=J\, d^2\theta/dt^2$. The equation of motion for the torsion angle θ is

$$J\frac{d^2\theta}{dt^2} + \gamma\frac{d\theta}{dt} + K\theta = T_{\text{spin}} + T_{\text{W}} \tag{5}$$

where $\gamma d\theta/dt$ describes frictional damping, and $K=(\pi G/2L)R^4$ for a wire of radius R. Let us first consider the case when I is large and T_{spin} assumes the form Eq. (1). (Since the torque due to the Wiedemann effect T_{W} has been shown to be small above, we will disregard that term in the following.)

Case I: Constant spin current (equilibrium torsion). If the spin-polarizing current through the nanowire is time independent, then $T_{\text{spin}}=\text{const}$, which will result in an equilibrium torsion angle θ_0,

$$\theta_0 = \frac{\hbar}{2K}\frac{I_0}{e}\alpha. \tag{6}$$

This simple expression shows that θ_0 is linearly proportional to the current I_0, and the spin polarization α. We note that the torsion angle can be strongly enhanced by reducing the radius of the wire R, since $K\sim R^4$.

Case II: Spin current at a finite frequency ω. A finite-frequency driving current $I_0\cos\omega t$ results in a torque, $T_{\text{spin}}=(\hbar\alpha/2e)I_0\cos\omega t$. With this expression on the right-hand side of Eq. (5), the analysis is that of a driven damped oscillator. The solution for the torsion angle is

$$\theta(\omega,t) = \frac{\hbar I_0\alpha/2e}{J[(\omega_0^2-\omega^2)^2+4\omega^4/Q^2]^{1/2}}\cos(\omega t+\phi),$$

$$\phi = \arccos\Big[(\omega_0^2-\omega^2)/\sqrt{(\omega_0^2-\omega^2)^2+4\omega_0^2\omega^2/Q^2}\Big]. \tag{7}$$

The quality factor of the structure Q is defined through the characteristic exponential decay of the torsion angle in the absence of driving torque, $\theta=\theta_0\cos(\omega t+\phi)e^{-\Gamma t}$ so that $Q=\omega_0/\Gamma=2J\omega/\gamma$.

On resonance $\omega=\omega_0$, the resulting torsion angle from the spin-transfer torque reaches its maximum value,

$$\theta_{\max} = \hbar\frac{Q}{4J\omega_0^2}\frac{I_0}{e}\alpha. \tag{8}$$

It is clear from this expression that the signal is maximized for optimal mechanical parameters: high quality factor Q and low resonance frequency ω_0. In order to be measurable, this torsion angle has to be larger than the thermal fluctuations, $\delta\theta$. By setting the elastic energy $E(\delta\theta)$ equal to $k_BT/2$ (equipartition), one obtains

$$E(\delta\alpha) = \int_0^{\delta\theta} d\theta\, D_{\text{elastic}}(\theta) = \frac{\pi}{4}(\delta\theta)^2 G\frac{R^4}{L}, \tag{9}$$

so the torsion angle may maximally fluctuate by

$$\delta\theta = \sqrt{\frac{2}{\pi}\frac{1}{R^2}}\sqrt{\frac{k_BTL}{G}}. \tag{10}$$

Up to this point, the torsion angle is found not to depend on the spin-flip rate $1/\tau_s$ explicitly. Let us consider the situation when the current is reduced, such that the transfer rate I/q becomes smaller than $1/\tau_s$, and the spin flips occur one by one.

III. RANDOM SPIN FLIP

For low, but constant driving currents, the electron transfer rate at the interface can be smaller than the spin-flip scattering rate $1/\tau_s$. In this case, the spin-transfer torque can be considered to occur randomly at times, t_l, with the average amplitude,

$$T_{\text{R}} = \hbar\frac{\alpha}{2}\frac{1}{\tau_s} = \frac{\alpha}{2}1.1\times 10^{-25}\ \text{N m}\frac{1}{\tau_s}, \tag{11}$$

where $\tau_s=\tau_s(\text{ns})$. Thus, the time-dependent driving torque can be modeled by

$$T_{\text{spin}}(t) = T_{\text{R}}\sum_l [\Theta(t-t_l)-\Theta(t-\tau_s-t_l)], \tag{12}$$

where $\Theta(x)$ is the step function, $\Theta(x)=1$ for $x>1$, and $\Theta(x)=0$, otherwise. The equation of motion Eq. (5) with the right-hand side, $T_s(t)$, can be solved by Fourier transform,

$$\theta(t) = \int\frac{d\omega}{2\pi}\frac{T_{\text{R}}}{\delta+i\omega}\frac{1}{K-\omega^2J+i\gamma\omega}\times\sum_l\{\exp[i\omega(t-t_l)] - \exp[i\omega(t-\tau_s-t_l)]\}, \tag{13}$$

where $\delta\to 0^+$. Performing the residuum integral, we obtain, for $\omega_0<1/\tau_s$; the time dependence of the torsion angle reduces to a sum of sinusoidal oscillators with phase shifts at random times t_l, when a single spin flip occurs,

$$\theta(t) = \frac{\hbar\alpha}{2J\omega_0\sqrt{1-1/Q^2}}\sum_{l,t_l<t}\exp\left(-(t-t_l)\frac{\omega_0}{Q}\right)\times\sin[(t-t_l)\omega_0\sqrt{1-1/Q^2}]. \tag{14}$$

While the amplitude of the torque does depend on the spin-flip rate $1/\tau_s$, the torsion angle does not, and is strictly a function of the current I. For $I/e\gg\omega_0$ it can be shown that Eq. (14) reduces to Eq. (6).

When the resonance frequency of the oscillator exceeds the spin-flip rate, $\omega_0>1/\tau_s$, one obtains for large quality factor $Q\gg 1$, the simplified expression,

$$\theta(t) = \theta_0 + \theta_{\text{R}}\sum_{t_l<t}\cos[(t-t_l)\omega_0] - \theta_{\text{R}}\sum_{t_l+\tau_s<t}\cos[(t-t_l-\tau_s)\omega_0]. \tag{15}$$

Here $\theta_{\text{R}}=T_{\text{R}}/K$. Thus, when $\omega_0>1/\tau_s$, both the torque and the amplitude of the time-dependent torsion angle θ_{R} do depend directly on the spin-flip rate $1/\tau_s$.

The nature of the random spin-flip torque is not known *a priori*. It depends on the microscopic physical mechanism of spin relaxation via a number of channels, such as coupling to local magnetic moments, nuclear magnetic moments, and dominantly, via spin-orbit interaction to phonons by the

Elliot-Yafet mechanism.[24–26] The spin-orbit interaction modified by phonons can break momentum conservation in a periodic crystal,[27,28] and hence, result in relaxation. Furthermore, as shown by D'yanokov and Perel,[29] in crystals lacking momentum-inversion symmetry, the lifting of spin degeneracy by spin-orbit scattering[30] operates as a momentum-dependent internal magnetic field, and contributes to spin relaxation. Temperature dependence of the spin-relaxation rate $1/T_1$ in the Elliot-Yafet mechanism is the same as the temperature dependence of resistivity: (i) $1/T_1 \sim T$ for $T > T_{\rm Debye}$, (ii) $1/T_1 \sim T^5$ (at low temperature). D'yanokov-Perel mechanism results in a spin-relaxation rate proportional to the momentum relaxation time.

In the nonlinear regime, the resonance of the oscillator in the presence of random torques can be enhanced by nonlinear self-excited oscillations. This effect is due to the nonlinear dependence of the torque on the angle θ.[31] In fact, Eq. (5) becomes nonlinear with the magnetization dynamics.

IV. SPIN CURRENT GENERATION

Applying a torque, a potential difference along the wire axis is created,[19] as given by $eV(t) = -(2m/eg)\mathrm{Vol}.M_z d\theta/dt$. With proper design of the device this potential can be used to drive a time-dependent current with density

$$j_B(t) = -\sigma\pi R^2 \frac{2m}{e^2 g} M_z \frac{d\theta}{dt}, \qquad (16)$$

where σ is the conductivity and g is the gyromagnetic coefficient. Writing $M_z = \boldsymbol{M_z}(10^6/4\pi)$ A/m, where the dimensionless $\boldsymbol{M_z}$ is typically on the order of one, and $R = \rho\ \mu$m, we obtain inserting as the typical metallic conductivity $\sigma = 10^7/\Omega\ \mathrm{m}, j_B \sim -10^4 \rho^2 \boldsymbol{M_z}(d\theta/dt)$ s A/cm^2.

Another source of potential difference is from magnetostriction: when the magnetized wire is torted, it results in a circular component. This so-called Matteucci effect induces a potential difference, and, hence, in a closed circuit a current density,[32]

$$j_M = -2\sigma \frac{R^2}{L} \lambda G \frac{\chi}{M_z} \frac{d\theta}{dt}. \qquad (17)$$

Inserting the typical values of G, λ, and σ, as given above, we obtain $j_M \sim -10^{-3} \rho^2/\boldsymbol{L}(d\theta/dt)$ s A/cm^2, where $L = \boldsymbol{L}\ \mu$m, which is thus negligible compared to the current due to the Barnett effect, Eq. (16).

V. EXPERIMENTAL REALIZATION

Sensitive measurement of nanomechanical torque generated due to spin transfer in the FM-NM nanowire can be done in a number of configurations. We discuss a specific device which allows ultrahigh detection sensitivity. Figure 2 shows the schematic diagram of such a hybrid device, which contains the ferromagnetic-nonmagnetic nanowire on top of a suspended two-element torsion oscillator. Since the nanowire is fabricated on top of the torsion oscillator, the torque generated in the nanowire will translate to a torque in the entire structure, including the torsion oscillator, modifying accordingly the mechanical parameters, the inertia J, the bulk modulus G, and the resonance frequencies of the device entering Eq. (5).

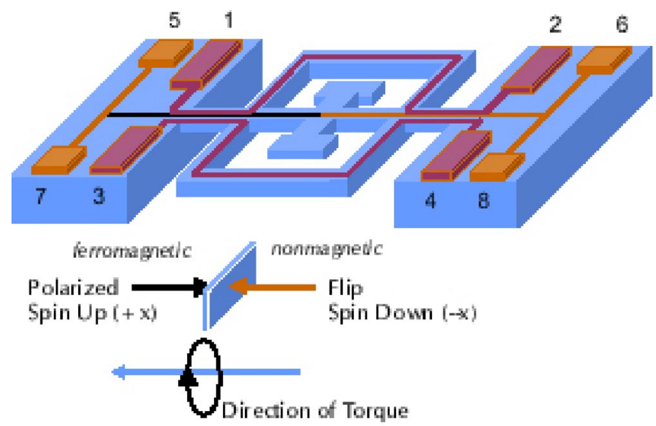

FIG. 2. (Color online) Schematic diagram of the proposed device. It contains a ferromagnetic-nonmagnetic (FM-NM) wire on top of a suspended two-element torsion oscillator. A spin-transfer process at or beyond the FM-NM interface causes a mechanical torque, which twists the suspended structure since the FM-NM wire is rigidly attached to the torsion oscillator. Because of small size, this device has extremely high torque sensitivity at low temperatures. Conversely, a spin polarization can be induced by applying a torque to the outer paddle, which will result in an imbalance in the spin states. The polarity of the spin population along the nanowire is governed by the conservation of angular momentum, which enables the device to operate as a spin battery.

The hybrid structure contains three sets of electrical components. The first one (5-6-7-8) is the central FM-NM nanowire with a typical thickness of 40–100 nm and a lithographically defined width of 60–100 nm. The other two electrical components (1-2 and 3-4), the two electrodes symmetrically placed on both sides of the large outer paddles, are designed to allow both detection and control of the torque,[23] and hence, of the spin transfer. In the presence of a magnetic field, applied in such a way that the torsion of the outer paddles will enclose a finite area, the torsion of the structure will induce an electromotive voltage on the electrode (1-2) by the Faraday effect. Likewise, an applied current through the other electrode (3-4) can generate a control force $F_{drive} = I_{control} LB$ or torque on the structure. This control torque can be used, for example, to induce spin polarization in the structure.

Measurement of the spin-induced torque and application of the control torque in the proposed device can be performed by the magnetomotive technique.[23] Elsewhere, we have discussed in detail low-temperature measurements with torsion oscillators similar to the one schematically shown in Fig. 2.[23] Because of low temperature and small size, the proposed device can operate with unprecedented force sensitivity of 10^{-16} N/$\sqrt{\mathrm{Hz}}$ or a corresponding torque sensitivity of 10^{-21} N m/$\sqrt{\mathrm{Hz}}$, as recent experiments on similar devices have demonstrated.[33] Correspondingly, the minimum detectable force or torque can be obtained by using the intrinsic bandwidth of the device $\omega/2\pi Q$. For a similar control device, we have already obtained a minimum detectable force of 48×10^{-18} N or a minimum detectable torque of 48×10^{-23} N m for a moment arm of $\sim10\ \mu$m at a temperature of 4 K.[33] Elsewhere,[23] we have extensively characterized a set of control torsion devices and their dependence on temperature, field, size, and frequency.

Experimental realization of the proposed device relies on the nanofabrication of a multilayer nanomechanical structure. Recently, we have fabricated a set of suspended devices of single-crystal silicon with a half-gold, half-cobalt nanowire designed to resonate in the range of 1–10 MHz. For device parameters of $L=10\ \mu\mathrm{m}, R=100\ \mathrm{nm}, \omega_0/2\pi \simeq 1$ MHz, and $Q\simeq10^4$ (at 300 mK), the maximum torsion angle due to the spin torque is $\simeq4.0\times10^{-2}$ rad for a drive current of 10 nA. For comparison, the rms value of the fluctuations in the torsion angle due to thermal noise, Eq. (10), in the same device is $\sim2\times10^{-5}$rad at 300 mK. To observe the maximal torsion, the magnetization of the cobalt nanowire is required to be oriented parallel to the wire axis. Indeed, it has been shown experimentally, with the magneto-optical Kerr effect, that the easy axis of cobalt thin films is in plane for a film thickness exceeding $d=1$ nm. Below that, a reorientation perpendicular to the film has been observed[34] and explained, due to the crystal and interface anisotropy, which overcomes the shape anisotropy when the film contains only a few monolayers.[35] Ideally, one should have a single domain along the wire, which is in the chosen wire geometry the one favored by the shape anisotropy. If one has domains with alternating magnetization along the wire, there will be excitation of torsional modes with wavelengths on the order of the domain size, in addition to the zero mode, considered above. In order to maximize the torsion signal, one can obtain a single domain by applying a weak magnetic field of not more than 100 G along the wire.[34]

VI. CONCLUSIONS

In summary, we propose a nanomechanical device: a sensor of spin dynamics at the ferromagnetic-nonmagnetic interface of a wire fabricated on top of a suspended torsion oscillator. We explicitly derive closed-form expressions for the torque created by spin currents and other physical mechanisms. This elementary device can be used to detect, control, and induce spin currents by selectively applying and measuring the torque in the nanomechanical resonator. The basic structure can be further modified to create devices for eventual use in spintronics and spin information processing.

ACKNOWLEDGMENTS

We acknowledge helpful discussions with G. Bergmann, C. Chamon, D. Loss, K. H. Müller, and E. Vedmedenko. The work in Boston University is supported by the National Science Foundation (DMR-0346707 and ECS-0210752) and the Sloan Foundation. S. K. acknowledges the hospitality of Boston University and of the MPI for Physics of Complex Systems in Dresden, and support by DFG, SFB 508, A9.

1. *Semiconductor Spintronics and Quantum Computation*, edited by D. D. Awschalom, D. Loss, and N. Samarth (Springer, New York, 2002).
2. S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. von Molnar, M. L. Roukes, A. Y. Chtchelkanova, and D. M. Treger, Science **294**, 1488 (2001).
3. G. Prinz, Science **282**, 1660 (1998); M. N. Baibich, J. M. Broto, A. Fert, F. N. Van Dau, F. Petroff, P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988); J. Barnas, A. Fuss, R. E. Camley, P. Grünberg, and W. Zinn, Phys. Rev. B **42**, 8110 (1990).
4. D. Loss and D. DiVincenzo, Phys. Rev. A **57**, 120 (1998).
5. A. Aharoni, *Introduction to the Theory of Ferromagnetism* (Clarendon, Oxford, 1996).
6. P. Fulde, Adv. Phys. **22**, 667 (1973).
7. N. Manyala, Y. Sidis, J. F. DiTusa, G. Aeppli, D. P. Young, and Z. Fisk, Nature (London) **404**, 581 (2000).
8. S. S. Saxena, P. Agarwal, K. Ahilan, F. M. Grosche, R. K. W. Haselwimmer, M. J. Steiner, E. Pugh, I. R. Walker, S. R. Julian, P. Monthoux, G. G. Lonzarich, A. Huxley, I. Sheikin, D. Braithwaite, and J. Flouquet, Nature (London) **406**, 587 (2000).
9. T. Moriya, in *Spin Fluctuations in Itinerant Electron Magnetism*, edited by P. Fulde (Springer, Berlin, 1985).
10. See Ref. 1 for a recent review.
11. S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990).
12. O. W. Richardson, Phys. Rev. **26**, 248 (1908).
13. A. Einstein and W. J. de Haas, Verh. Dtsch. Phys. Ges. **17**, 152 (1915).
14. S. J. Barnett, Phys. Rev. **6**, 239 (1915); **66**, 224 (1944).
15. W. Wiedemann, *Lehre von der Elektrizität* (Vieweg, Braunschweig, 1883), Vol. 3, p. 680; H. A. Pigeon, Phys. Rev. **13**, 209 (1919); R. Skorski, J. Appl. Phys. **35**, 1213 (1964); M. Vazquez, J. Gonzalez, J. M. Blanco, J. M. Barandiaran, G. Rivero, and A. Hernando, J. Magn. Magn. Mater. **96**, 321 (1991).
16. L. Berger, Phys. Rev. B **54**, 9353 (1996); J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996); M. D. Stiles and A. Zangwill, J. Appl. Phys. **91**, 6812 (2002); Phys. Rev. B **66**, 014407 (2002).
17. P. Fulde and S. Kettemann, Ann. Phys. (Leipzig) **7**, 214 (1998).
18. R. A. Beth, Phys. Rev. **50**, 115 (1936).
19. L. D. Landau and E. M. Lifshitz, *Electrodynamics of the Continua* (Pergamon, Oxford, England, 1960), Vol. 8, p. 144.
20. E. W. Lee, Rep. Prog. Phys. **18**, 184 (1955).
21. D.-X. Chen, A. Hernando, and L. Pascual, Meas. Sci. Technol. **15**, 365 (2004).
22. A. N. Cleland, *Foundations of Nanomechanics, from Solid-State Theory to Device Applications* (Springer, Berlin, 2003).
23. P. Mohanty, D. A. Harrington, K. L. Ekinci, Y. T. Yang, M. J. Murphy, and M. L. Roukes, Phys. Rev. B **66**, 085416 (2002).
24. R. J. Elliot, Phys. Rev. **96**, 266 (1954).
25. Y. Yafet, in *Solid State Physics*, edited by F. Seitz and D. Turnbull (Academic, New York, 1964), Vol. 14.
26. J. Fabian and S. Das Darma, Phys. Rev. Lett. **83**, 1211 (1999); **81**, 5624 (1998); J. Vac. Sci. Technol. B **17**, 1708 (1999).

[27] A. W. Overhauser, Phys. Rev. **89**, 689 (1953).
[28] C. Grimaldi and P. Fulde, Phys. Rev. B **55**, 15523 (1997); Phys. Rev. Lett. **77**, 2550 (1996).
[29] M. I. D'yakonov and V. I. Perel, Sov. Phys. JETP **33**, 1053 (1971).
[30] C. Kittel, *Quantum Theory of Solids*, 2nd ed. (Wiley, New York, 1967).
[31] Known examples include excitation of harmonic sounds in a violin by the friction between the bow and the string.
[32] C. Matteucci, Ann. Chim. Phys. **53**, 385 (1858); D. V. Malyugin, J. Magn. Magn. Mater. **97**, 193 (1991).
[33] P. Mohanty, D. A. Harrington, and M. L. Roukes, Physica B **284**, 2143 (2000).
[34] H. F. Ding, S. Pütter, H. P. Oepen, and J. Kirschner, J. Magn. Magn. Mater. **212**, L5 (2000); Phys. Rev. B **63**, 134425 (2001).
[35] E. Vedmedenko, H. P. Oepen, A. Ghazali, J.-C. S. Levy, and J. Kirschner, Phys. Rev. Lett. **84**, 5884 (2000); M. Wellhöefer, M. Weißenborn, R. Anton, S. Pütter, and H. P. Oepen (unpublished).