Mechanical generation of spin current by spin-rotation coupling

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Spin current, a flow of spins, is a key concept in spintronics [1]. It can be generated by using couplings between an electron spin and other physical quantities such as a magnetic field, magnetization, and orbital degrees of freedom. These conventional methods, however, force us to use magnetic materials or rare metals with strong spin-orbit coupling. In this study, we have presented a new route for spin-current generation by considering the coupling between spin and mechanical rotation. Our method requires neither magnetic moments nor spin-orbit coupling.

First we introduce spin-rotation coupling (SRC):

$$H = -\mathbf{S}\cdot\Omega,$$

where S is the electron spin angular momentum and Ω is the mechanical rotation frequency. If we rewrite the SRC as $H = -\mathbf{S}\cdot\mathbf{B}_\Omega$, where $\mathbf{B}_\Omega = \Omega\gamma^{-1}$ is an effective magnetic field due to mechanical rotation with gyromagnetic ratio γ, the SRC can be regarded as the Zeeman coupling. Historically the SRC is known as a fundamental origin of the Barnett and Einstein-de Haas effects and plays a crucial role in tests of general relativity by use of gyroscopic effect in gravitational fields due to Earth. However, it has not been used for controlling spin currents.

Here we consider rotational motion of the lattice:

$$\Omega = \frac{1}{2}\nabla\times\partial_t\mathbf{u}$$

where $\mathbf{u}$ is the displacement vector of the lattice. When the lattice vibration has transverse modes, Ω does not vanish. In such a case, the mechanical angular momentum of the lattice can be converted into spin angular momentum via SRC. Especially, in the presence of surface acoustic waves (SAWs), rotational deformations that vary in space and time are induced. In this case, the gradient of rotational modes acts on an electron spin as the gradient of a magnetic field. For an electron spin, spin prefers to align to the effective magnetic field and to flow form the bottom to the surface for smaller Zeeman energy [Fig. 1]. Consequently, the stripe pattern of the spin accumulation arises at the surface [Fig. 2].

We developed the spin diffusion equation in the presence of SAWs [2,3] and solved it in the case of the SAW frequency given by

$$\Omega(x,y,t) = \Omega_0 \exp\{-k_t y + i(kx-\omega t)\}$$

where Ω_0 is the amplitude of the SAW, k is the wave number, k_t is the transverse wave number, and ω is the frequency of the mechanical resonator. From the solution, the spin current generated by the SAW is given by

$$J_S = \tau\frac{S}{e}\frac{\omega^2\Omega_0}{c_t}\frac{\sqrt{1-\xi^2}}{\xi}\exp\{-k_t y + i(kx-\omega t+\pi/2)\}$$

where τ is the spin lifetime, c_t is the transverse sound velocity, and ξ is related to the Poisson ratio ν as ξ = (0.875+1.12 ν)/(1+ ν). The result indicates that the spin current J_s is proportional to the spin lifetime. Generally, we have longer spin lifetime in a material with weaker spin-orbit coupling. This implies that larger spin current is obtained in a weaker spin-orbit material such as Al and Cu.

Conventionally, generation of spin current in nonmagnetic materials has required strong spin-orbit coupling because the spin Hall effect has been utilized. In other words, nonmagnetic materials with short spin lifetimes have been used. On the contrary, the mechanism proposed here requires longer spin lifetimes to generate larger spin currents. This means that Al and Cu, which have been considered as good materials for a spin conducting channel, can be favorable for generating spin current. In this sense, our findings offer more options for spin-current generation in nonmagnets than ever before.

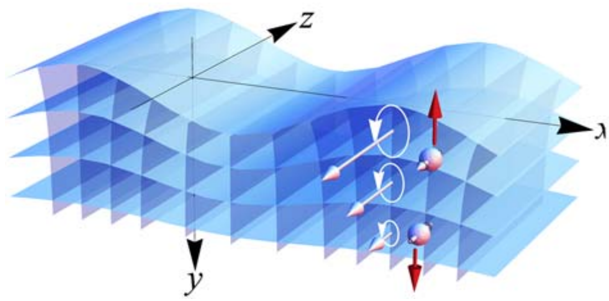

Fig.1 Snapshot of mechanical generation of spin current induced by the SAW. In the presence of a SAW propagating in the *x* direction, a gradient of mechanical rotation around the *z*-axis is generated. The rotation can be regarded as an effective magnetic field. Consequently, spins align to the *z*-axis and the *z*-polarized current flows along to the *y* direction.

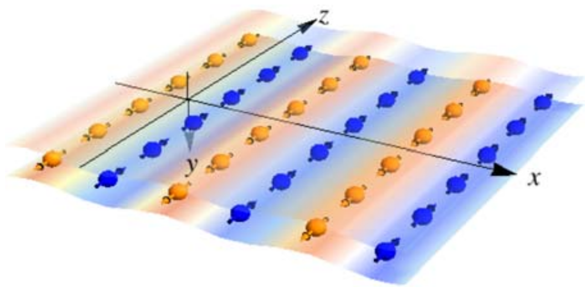

Fig.2 Spin accumulation induced on the surface.

References

[1] S. Maekawa, S. Valenzuela, E. Saitoh, and T. Kimura, ed., Spin Current (Oxford University Press, Oxford, 2012).

[2] M. Matsuo *et al*., Phys. Rev. B **87**, 180402(R) (2013).

[3] J. Ieda *et al*., Solid State Comm. (Available online).