Spintronics applications of gyromagnetic effect

Yukio Nozaki[1,2]
([1]Keio Univ., [2]Keio CSRN)

The gyromagnetic effect was discovered by Einstein, de Haas, and Barnett about a hundred years ago. They found that macroscopic rotation and magnetization of a macroscopic ferromagnet are convertible with each other. Strong gyromagnetic effect appears by increasing rotation frequency, implying that.a rotation frequency is equivalent to a magnetic field. The magnetization is originated from microscopic angular momentum of electrons in solid, i.e. spin angular momentum and orbital angular momentum. Therefore, the macroscopic rotation can give a torque on microscopic angular momentum of electrons via conservation law of angular momentum in a rotationally symmetric system.

From the microscopic point of view, the gyromagnetic effect is understood as an inertial effects of Dirac particles, which appears when a local inertial frame rotates. Hehl and Ni deduced the Hamiltonian in a rotating frame and found the spin rotation coupling (SRC) given by the inner product between spin angular momentum and angular velocity of rotation [1]. It is noted that such a spin rotation coupling remains in the Hamiltonian under a nonrelativistic limit. The mechanical rotation $\boldsymbol{\Omega}$ in the SRC is coupled with spin angular momentum σ similarly to the magnetic field in the Zeeman effect. The amplitude of emergent magnetic field, so called "Barnett field", is given by $\boldsymbol{\Omega}/\gamma$, where γ is the gyromagnetic ratio. Such a Barnett field is very weak so that we can observe the effect only in ferromagnetic materials so far. However, recent state of art technologies enable us to observe the Barnett field in non-magnetic elements [2,3].

In this talk, we provide three topics on the gyromagnetic effect, which can be applied to spintronics devices. First one is an acoustic gyromagnetic effect in ferromagnetic NiFe thin film, where we have observed phenomena based on magnon-phonon coupling via gyromagnetic effect [4,5]. Second topic is associated with another acoustic gyromagnetic effect in nonmagnetic Cu films, whose spin orbit interaction is much weaker than platinum. Here, we will show some experimental results on an alternating spin current generation due to a gradient of acoustic Barnett field in Cu films [6-8]. Third topic is related to the experimental study on current-induced spin torque via spin vorticity coupling in composition gradient interface [9-10].

Reference

1) F. W. Hehl and W.-T. Ni, Phys. Rev. D. **42**, 2045 (1990).
2) H. Chudo et al., Appl. Phys. Express **7**, 063004 (2014).
3) R. Takahashi et al., Nature Phys. **12**, 52 (2016).
4) Y. Kurimune, YN et al., PRL **124**, 217205 (2020).
5) S. Tateno, YN et al., PRB **104**, L020404 (2021).
6) D. Kobayashi, YN et al. PRL **119**, 077202 (2017).
7) S. Tateno, YN et al., PRB **102**, 104406 (2020).
8) Y. Kurimune, YN et al., PRB **102**, 174413 (2020).
9) G. Okano, YN et al., PRL **122**, 217701 (2019).
10) T. Horaguchi, YN et al., PREPRINT (Version 1) available at Research Square [https://doi.org/10.21203/rs.3.rs-955888/v1].
11) H. Nakayama, YN et al., PRB **107**, (2023).

Theory of acoustic gyromagnetic effect

M. Matsuo
Kavli Institute for Theoretical Sciences, University of Chinese Academy of Sciences

The gyromagnetic effect, a phenomenon where magnetic angular momentum and mechanical angular momentum are mutually converted, was discovered approximately a century ago, prior to the establishment of quantum mechanics. Both Barnett and Einstein-de Haas discovered that ferromagnetic bodies could become magnetized when rotated[1], and conversely, these bodies rotate when magnetized[2]. At that time, it was believed that the source of magnetism was the Ampere magnetic field created by the circular current of electrons in a magnetic body, and the orbital angular momentum of the electrons was assumed to carry the magnetic moment. Surprisingly, experiments by Barnett and others showed the gyromagnetic ratio (g-factor) of electrons in magnetic bodies to be about 2, significantly deviating from the expected g=1 predicted by classical electrodynamics. This crucial discovery suggested that the electron inherently possesses a form of angular momentum different from orbital angular momentum, later identified as spin angular momentum with the advent of quantum theory.

Our research endeavors to utilize the gyromagnetic effect for spin and valley transport. Specifically, in this talk, we introduce the "acoustic version of the gyromagnetic effect" using the interaction between vorticity in surface acoustic waves and angular momentum carried by electron.

First, we introduce a mechanism for generating conduction electron spin current in copper (Cu) by exciting surface acoustic waves, a phenomenon caused by the interaction between electron spin and the vorticity in surface acoustic waves. [3,4,5,6] Unlike the traditional spin Hall effect in nonmagnetic metals, our mechanism does not require spin-orbit interaction. Thus, light metals such as Cu, which have been considered unsuitable for generating spin current due to their weak spin-orbit interaction, can now be utilized as spin current generators, potentially significantly expanding the choice of materials for spin devices.

Next, we introduce a theory of spin electromotive force generated by exciting surface acoustic waves in ferromagnetic metals. [7] The vorticity of surface acoustic waves causes time-space nonuniform dynamics between conduction electron spin and magnetization, resulting in the generation of spin electromotive force. In contrast to traditional spin electromotive force, our mechanism can generate continuous electromotive force with a simple device structure, such as a single layer of a ferromagnetic metal, which is a considerable advantage.

Finally, we will also introduce valley transport driven by the vorticity of surface acoustic waves. [8] In materials with broken spatial inversion symmetry, massive Dirac electrons have orbital angular momentum dependent on the valley. We theoretically demonstrate that the interaction between this orbital angular momentum and the vorticity of the surface acoustic waves generates valley currents.

Reference

1) S.J. Barnett, Phys. Rev. 6, 239 (1915).
2) A. Einstein and W.J. de Haas, Verh. Dtsch. Phys. Ges. 17, 152 (1915).
3) Y. Nozaki, JSAP Rev. 230203 (2023).
4) M. Matsuo et al., Phys. Rev. B 87, 180402(R) (2013)
5) M. Matsuo et al., Phys. Rev. B 96, 020401(R) (2017).
6) D. Kobayashi et al., Phys. Rev. Lett. 119,077202 (2017).
7) T. Funato and M. Matsuo, Phys. Rev. Lett. 128, 077202 (2022).
8) Y. Ominato et al., Phys. Rev. B 105, 195409 (2022).

Acoustic phonon induced spin dynamics

Masamitsu Hayashi
The University of Tokyo

Studies have shown that phonons can interact with other degrees of freedoms in solids. For example, the coupling between phonons and photons can lead to Raman scattering, which is often exploited to study the structure/chemical state of materials. Scientifically, the coupling between phonons and other degrees of freedom are attracting significant interest for potential applications in quantum technologies.

Surface acoustic waves, a form of acoustic phonons, can be excited using conventional electronics. The frequency and wavelength of such acoustic phonons are defined by the sound velocity of the substrate and the geometry of the interdigital transducers (IDT) patterned on the substrate. The acoustic phonons excited at one of the IDTs can typically travel a distance significantly larger than its wavelength. If a thin film is placed on the substrate adjacent to an IDT, acoustic phonons can be excited within the film. Such device can therefore be used to study the interaction between acoustic phonons and other degrees of freedoms in solids.

We have studied the coupling between acoustic phonons and electron spins in non-magnetic and magnetic materials. For the former, we have studied the effect of SAW on the electron spin dynamics in non-magnetic metals[1]. We find that transverse spin currents emerge when SAW traverses across the film, only when the spin orbit coupling of the film is sufficiently large. In the presentation, we discuss the origin of the SAW-induced spin current. We have also studied phonon-magnon coupling in magnetic materials using SAW. A particular focus is put on the coupling in synthetic antiferrromagnets[2]. We discuss the strength of phonon-magnon in such systems.

References

[1] T. Kawada *et al.*, Science Advances **7** eabd9697 (2021).
[2] H. Matsumoto *et al.*, Applied Physics Express **15** 063003 (2022).

Hydrodynamic Generation mediated by Spin Current

R. Takahashi[1]
[1]Ochanomizu University, Tokyo 112-8610, Japan

A spin current, a flow of spin angular momentum, has enabled the interconversion among various kinds of physical entities such as electricity, magnetization, heat, and mechanical motion like elastic motion and liquid motion. Such spin-mediated interconversion is realized on a micro or nano scale and has been extensively studied in the field of spintronics. Our study[1)] has revealed that hydrodynamic motion can also act as a constituent of this interconversion framework: spin hydrodynamic generation (SHDG).

SHDG is a method used to generate an electromotive force via a spin current in hydrodynamic motion. The origin of SHDG is the spin-vorticity coupling, that is, the coupling between electron spin and local mechanical rotation of a fluid, the vorticity $\boldsymbol{\omega}$. The spin current whose polarization is directed along $\boldsymbol{\omega}$ is diffusively induced along the spatial vorticity gradient (see a schematic image in Fig. 1). The induced spin current is converted to the electromotive force along the fluid flow direction, caused by the inverse spin Hall effect of the fluid itself. According to this mechanism of SHDG, therefore, the induced spin current should strongly depend on vorticity distribution and SHDG is categorized reflecting the two typical regimes of hydrodynamics, that is, turbulent flow and laminar flow regimes.

In a turbulent flow in a cylindrical channel, the electromotive force should be generated only near the inner wall. Figure 1 shows the results of measurements performed by using Hg turbulent flows in some kinds of cylindrical channels.[1)] There clearly exhibits a nonlinear scaling behavior with respect to velocity v_* dependence of the voltage signal V. This behavior reflects the mechanism mentioned above; in the turbulent flow regime, the vorticity gradient, driving force for the spin current in SHDG scenario, should exist only near the inner wall of a channel.

In a laminar flow, on the other hand, the electromotive force should be generated all over the cross section of a channel. In the results of measurements with Hg "laminar" flows[2)], there does not exhibit the nonlinear scaling behavior, appearing in the turbulent flow regime, but exhibits a linear one. This result reflects the difference in the vorticity distribution between the laminar and the turbulent flow; in the laminar flow, the fluid velocity distribution pervades in a parabolic way, and thus the vorticity gradient is created all over the cross section of a channel. It is noteworthy that the energy conversion efficiency η shown in Fig. 2 is exceedingly enhanced in the laminar flow regime. Here, *Re* is the Reynolds number. This should be because there exists the capability of voltage generation all over the channel cross section in a laminar flow, while that in a turbulent flow is localized near the inner wall and thus the rest area reduces the generation due to short circuit currents, suggesting that SHDG can be much more efficient in a laminar flow than in a turbulent flow. In this presentation, our experimental results mentioned above, its consistency with theoretical studies and recent progress in this spin-hydrodynamic generation phenomenon will be discussed.

Reference
1) R. Takahashi *et al.*, Nat. Phys. **12**, 52 (2016).
2) R. Takahashi *et al.*, Nat. Commun. **11**, 3009 (2020).

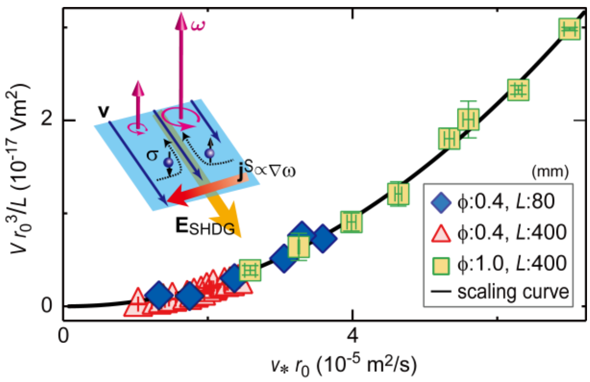

Fig. 1 Scaling behavior with respect to velocity (v_*) dependence of SHDG voltage (V) in turbulent flow.

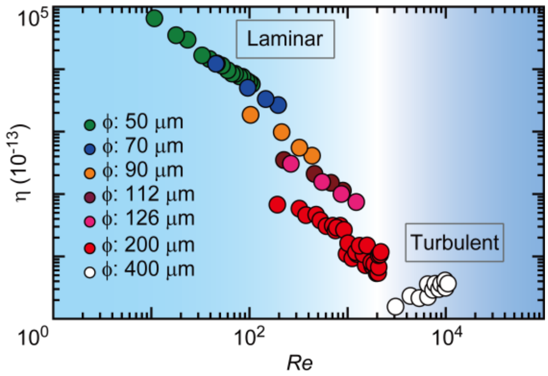

Fig. 2 Dependence of SHDG energy conversion efficiency (η) on the Reynolds number (*Re*).

Magneto-mechanical micro devices

Takahito Ono
Mechanical Systems Engineering, Tohoku University, Sendai 980-8577, Japan
Micro System Integration Center (μSiC), Tohoku University, Sendai 980-8579, Japan

With the recent developments of the information and communication society, sensor and actuator devices are used in cyber-physical systems. Among these, magnetic devices are expected to be used as high-performance actuators and sensors. Our research group has been studying the process technology of magnetostrictive thin-film and its application technology, and in this presentation, we report on its sensor/actuator application and new actuators using spintronics.

Electrodeposition technology for rare-earth using Fe catalyst, etc., has been developed, resulting in the successful deposition of thin films of TbDyFe, TbFeCo, and FeGa, known as giant magnetostrictive materials. Microcantilever structures with the TbDyFe thin film were fabricated, and the actuation performances were evaluated. Magnetostriction of over 1200 ppm was achieved, and an energy density of 1.69×10^5 J/m^3, which is close to the bulk, was achieved. In TbFeCo, the magnetostriction is negative when the amount of Tb is small, and becomes positive when the amount of Tb is increased, thus, the magnetostriction can be controlled positively or negatively. Magnetostrictive materials can also be used as strain sensors by utilizing the inverse magnetostriction effect. FeGa thin films are deposited in microstructures and integrated with strain sensors in which the magnetization change caused by the strain is detected by integrated Si Hall elements.

Magnetostrictive actuators have been limited in miniaturization because they require electromagnets, which are generally difficult to miniaturize. The spin-current volume effect, which utilizes spin currents, generates volume strain due to the spin-lattice coupling by injecting spin-current into magnetic materials and changing the magnetization fluctuations of the magnetic materials. A diaphragm structure composed of the TbFeCo thin film, which exhibits positive volumetric magnetostriction (5.6×10^{-5}/T), was fabricated, and when the diaphragm resonated by the spin-current volume effect, a power density of 1.15×10^6 W/m^3 or higher was experimentally found to be obtained.

In summary, magnetostrictive materials are promising candidates for next-generation micromechanical microdevices, especially through their integration with spintronics.

References
1) H. Shim, et al., Micromachines **11**, 5 (2020) 523.
2) T. Ezura, et. al., Proceeding of Transducers, (2021) 418-421.
3) Y.-T. Huang, et al, J. Mag. Mag. Mater. **577** (2023) 170799.
4) H. Arisawa, et al., Nature Communication **13** (2022) 2400.

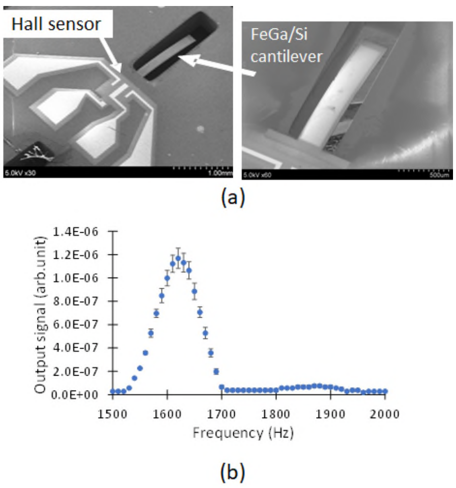

Fig. 1. (a)Cantilevered FeGa strain sensor with an integrated Si Hall sensor. (b) The vibration signal.

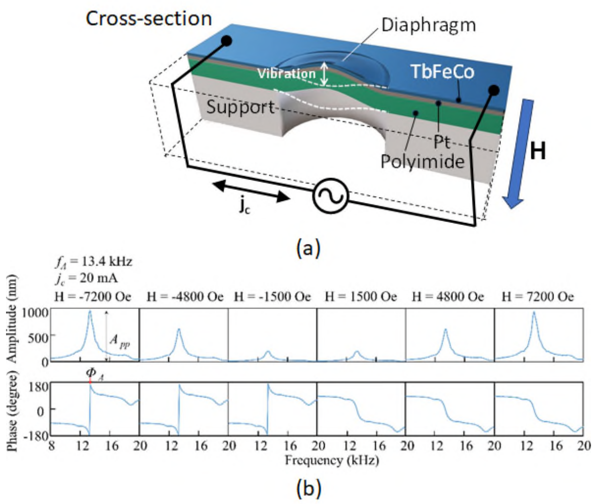

Fig. 2. (a) TbFeCo diaphragm actuator driven at the resonance by spin-current volume effect. (b) Actuated mechanical vibration and phase.

Spin Elastronics -Mechanical sensing using spintronics devices-

D. Chiba
(Osaka Univ., Tohoku Univ.)

Mechanical quantities are the most important sensing targets in physical space. Spin Elastronics is a new area of electronics that can endow mechanical functions to spintronics devices. The magnetization direction of ferromagnetic materials can be altered by the application of strain owing to the magnetoelastic effect. Using a combination of the magnetoelastic effect and the giant magnetoresistive (GMR)[1,2] or tunnel magnetoresistive (TMR) effect[3-5], a strain measurement was experimentally demonstrated. In addition to sensing the strain "magnitude," we achieved strain "direction" sensing using spin valves formed on a flexible substrate.

The stretchability of both the substrate and thin ferromagnetic layers enables strain sensing on a wide range of arbitrary-shaped surfaces, which is not easy when using devices formed on a rigid substrate. These stretchable and miniaturized strain sensors will be of increasing importance for "Trillion Sensors Universe" as well as for wearable devices, from the perspective of structural or human health monitoring, body mechanics, and robotics.

In addition, we are trying to integrate spin devices with organic circuits on a flexible substrate and open up a future in which biomotion or other mechanical motion can be precisely estimated and predicted using a multidimensional vector information carrier (integrated spin / spin network). We expect that this information carrier can become a cyber space as well that has an arithmetic operation function without electric power supply, and a non-volatile recording function.

This work was partly supported by JST CREST (Grant No. JPMJCR20C6), JST A-Step (Grant No. JPMJTR20T7), JSPS KAKENHI (Grant Nos. 25600075, 17J03125, 19H00860, 21K18827, and 23H00183), Murata Manufacturing Co., Ltd., Saginomiya Sseisakusyo, Inc., and Spintronics Research Network of Japan. Part of the work was performed using facilities at the Low Temperature Center, Osaka University.

Reference

1) S. Ota, A. Ando, and D. Chiba, *Nature Electron.* **1**, 124-129 (2018).
2) H. Matsumoto, S. Ota, A. Ando, and D. Chiba, *Appl. Phys. Lett.* **114**, 132401 (2019).
3) S. Ota, M. Ono, H. Matsumoto, A. Ando, T. Sekitani, R. Kohno, S. Iguchi, T. Koyama, and D. Chiba, *Appl. Phys. Express* **12**, 053001 (2019).
4) S. Ota, A. Ando, T. Sekitani, T. Koyama and D. Chiba, *Appl. Phys. Lett.* **115**, 202401 (2019).
5) K. Saito, A. Imai, S. Ota, T. Koyama, A. Ando, and D. Chiba, *Appl. Phys. Lett.* **120**, 072407 (2022).

Active and selective temperature control using mechanical strain

T. Hirai[1]
[1] National Institute for Materials Science, Tsukuba 305-0047, Japan

The importance of thermal management technologies is rapidly growing with the increase in the performance, density, and variety of electronic devices. The vapor compression is the most widespread method for controlling ambient temperature (e.g., installed in a refrigerator and air-conditioning system), but this method could have detrimental impacts on the environment due to the use of greenhouse gas. The use of vapor compressor also limits the miniaturization of systems, which hinders its integration into devices for pinpoint temperature control. For the precise temperature control of integrated electronic devices, solid-state and selective cooling/heating technologies should be developed. In this talk, I show that the mechanical strain is a useful tool for active control of cooling/heating generated by two different thermal effects in solids: thermoelectric effect in magnetic materials, named magneto-thermoelectric effect, and elastocaloric effect as followings. Our demonstration would pave the way for realizing the active and versatile thermal management for next-generation electronic devices.

1. Strain-induced cooling/heating switching of magneto-thermoelectric effect
   The anisotropic magneto-Peltier effect (AMPE), one of the magneto-thermoelectric effect, refers to the phenomenon that the Peltier coefficient depends on the relative angle between the input charge current and magnetization, which enables thermoelectric cooling/heating in a single material without junctions.[1)]
   In the first half of my talk, I show that the application of uniaxial strain actively switches the sign of AMPE-induced temperature change via magneto-elastic coupling (Fig. 1), which cannot be realized when the conventional Peltier effect is used.[2)]

2. Elastocaloric kirigami temperature modulator
   The elastocaloric effect refers to a cooling/heating generation associated to the isothermal entropy change induced by applying a mechanical uniaxial strain to solids, whose fundamental mechanism is similar to the magnetocaloric effect arising from the change in spin ordering by applying a magnetic field.
   In the second half of my talk, I introduce a new way to modify the performance and spatial distribution of elastocaloric temperature modulation by the inspiration of *kirigami*, a traditional Japanese paper craft (Fig. 2).[3)]
   Here, the second half is irrelevant to magnetism and spintronics. Thus, in addition to experimental results, I will explain the basic introduction of elastocaloric effect.

Reference

1) K. Uchida *et al.*, *Nature* **558**, 95 (2018).
2) T. Hirai *et al.*, *Appl. Phys. Lett.* **118**, 022403 (2021).
3) T. Hirai *et al.*, *Adv. Funct. Mater.* **32**, 2201116 (2022).

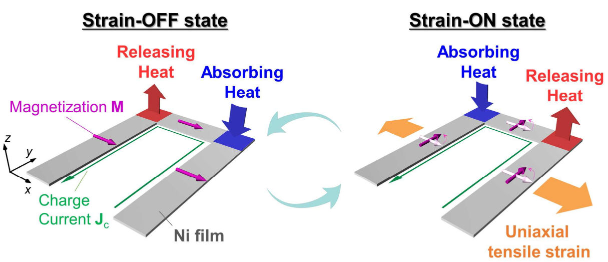

Fig. 1 Schematics of strain-induced active cooling-heating switching of anisotropic magneto-Peltier effect.

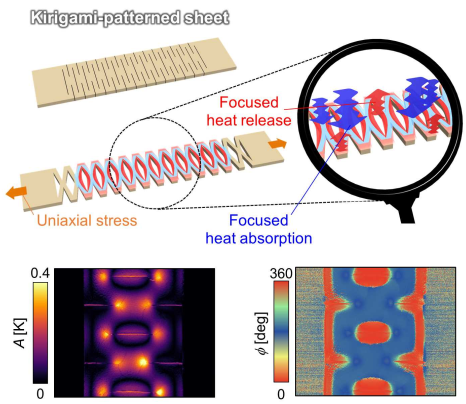

Fig. 2. Schematics of elastocaloric kirigami temperature modulator.