Nano-Scale Spin Conversion Science

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Spin conversion science is a generic term for the research field treating a variety of angular momentum transfer phenomena mediated by electronic spins. This can be classified into 4 types such as magnetic, electronic, optical, and thermo kinetic conversions. The magnetic and electronic conversions were initiated by the theoretical and experimental demonstrations of spin transfer torque1, 2) and its reverse effect, i.e. spin pumping3, 4). These two phenomena have separately evolved as means to manipulate magnetic switching and domain wall displacement, or to inject dynamic spin currents into adjacent materials. When the adjacent materials exhibit strong spin-orbit interaction, spin currents can be converted into charge currents and vice versa via the direct (DSHE) and inverse spin Hall effects (ISHE)5). Important to note is that the ISHE enabled us to detect the spin currents and to discover a variety of spin conversion phenomena including the thermo kinetic spin conversion, Spin Seebeck effects in metals6) and insulators7). The same is true for the optical conversion where the optical angular momentum of circularly polarized light can be transferred to the magnetic moment and eventually switch its direction8).

In this symposium we will show our recent experimental and theoretical efforts to understand the spin conversion phenomena in terms of the above mentioned 4 types of conversions. In this talk, the overview of the spin conversion science is given and then some of representative magnetic spin conversion phenomena such as SHEs in random spin systems9) and spin torque ferromagnetic resonance studies are presented.

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Electric Spin Conversion Phenomena

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Introduction

Spin conversion is a concept of transformation between quasi-particles in solids via a spin degree of freedom. It has been so far reported that there is a variety of spin conversion methods, such as magnetic, electric, optical, thermal and dynamical. The spin conversion is revealed in nano-sized materials and can be generated in a hetero-interface. Currently, there is a number of studies on the spin conversion by using various approaches. The purpose of this talk is to introduce electric spin conversion phenomena. An example of the electric spin conversion is spin Hall and inverse spin Hall effects, where conversion of pure spin current from/to charge current is realized, and spin conversion in a heterostructure between inorganic semiconductors and metals provides a new stage of spin-related physics. Here, I introduce the latest topics of the spin conversion in semiconductor and molecular spintronics in this talk.

Electric spin conversion

Spin Hall effect (SHE) is a phenomenon, where pure spin current can be generated by a flow of electric current. The direction of the pure spin current is perpendicular to the direction of the electric current, which is an origin of the name, "spin Hall effect" (it should be noted that the physical origin of the SHE is completely different from that of the Hall effect). The SHE has been theoretically [1] and experimentally [2] investigated. The inverse spin Hall effect (ISHE) is the reciprocal effect of the SHE, which was discovered by using a dynamical spin pumping [3]. The both effects allows electric spin conversion to charge, and now are widely utilized in spintronics. The origin of the effects is a spin-orbit interaction (SOI), and a material with a large SOI is a good material stage for the effects. Thus, the heavy metals, such as Ta, W, Pt and Pd, and semiconductors with a large SOI are good detectors for pure spin current, since electric spin conversion in them can be easily realized.

The electric spin conversion in Pt, GaAs, p-type Si has been reported based on this concept [3-5]. Recently, the electric spin conversion in conductive polymer, PEDOT:PSS was also achieved, although the SOI in organic polymer is quite small [6]. The spin Hall angle, an index of the electric spin conversion, in the polymer is ca. $10^{-7,}$ which is 5-6 orders of magnitude smaller than that of Pt, Ta and so on. This is quite surprising in molecular spintronics. Since sufficient amount of spin accumulation allows the spin conversion, the spin conversion can be also realized in the other molecular materials. One example is the spin conversion in single-layer graphene, where the spin Hall angle was estimated to be ca. 6×10^{-7}, which is comparable to that of PEDOT:PSS [7].

The other notable achievement is the detection of pure spin current propagation in inorganic semiconductors. In the previous studies, the injected pure spin current into nonmagnetic materials was rapidly converted to the electric current, since the spin diffusion length of the materials are quite short in many cases. When we replace the materials to materials with good spin coherence, the long-range propagation of pure spin current can be realized and the propagating spin current can be adsorbed in heavy metals equipped with the spin coherent materials, resulting in the electric conversion. The first success was the detection of transport of pure spin current in p-type Si, where pure spin current was generated by using a dynamical spin pumping method and the pure spin current was detected by a Pd electrode [8]. The similar experimental concept was also utilized in realizing dynamical spin transport in graphene [9], Al [10] and recently in PBTTT [11].

Summary

Electric spin conversion is now applied in various materials, and is recognized as a quite attractive phenomenon in order to investigate various spin-related physics.

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Coupling between single photons and single electron spins via angular momentum transfer in quantum dots

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Spin-selective optical interband excitation, which creates the spin polarization and detects the spin dynamics, has contributed to the considerable progresses for studying spin physics and controlling spins in bulk and structured semiconductors. Though the angular momentum transfer from a single photon to a single electron spin is an elemental process of the spin-selective excitation it has not been fully studied because of the difficulties to detect single photons and single electron spins. Gate-defined lateral quantum dots (QDs) are, however, suitable to detect a single electron spin in a single-shot manner 2) and the coherent manipulation of single electron spins has been extensively studied in such QDs. 3,4) Indeed we have realized the detection of single photoelectrons in a single quantum dot with a charge sensing technique.5) Moreover, the coherent coupling between single electron spin states and photon polarization states would allow us to investigate a quantum correlation between light and spin in solids and would contribute to long distance quantum communications. Here we show that single photoelectron spins can be discriminated by Pauli effect and the angular momentum of circularly polarized single photons can be transferred to single electron spins in lateral GaAs double QDs. These results manifest that photons can be coupled to electron spins in the electrically tunable QDs.

Double QDs with a metal mask were fabricated in $Al_{0.33}Ga_{0.67}As$/GaAs quantum wells (see Fig.1). The light source was a wavelength-tunable pulsed Ti:Sapphire laser. First we show that the interdot tunneling between the two QDs offers a robust detection scheme of the single photoelectrons trapped in the double QD. The interdot tunneling of a trapped single photoelectron can be clearly detected because the amplitude of the interdot tunneling signal obviously exceeds the noise level of the charge sensor current. 6) In two-electron regime, the interdot tunneling timescale of the photoelectrons strongly depends on the relative spin orientation (either parallel or anti-parallel) between two QDs due to Pauli exclusion principle, enabling us to discriminate the single photoelectron spin with a high distinguishability more than 90% (see Fig. 2). Finally by changing the incident photon polarization, the probability of the anti-parallel spin configuration smoothly changes from left-handed to right-handed circularly polarization through liner polarization, indicating distinctly the angular momentum transfer from single photons to single electron spins in double QDs.

We also discuss the feasibility of the coherent transfer from single photons to single electron spins. This can be achieved by designing both electron and hole g-factors appropriate to the theoretical proposal7) and by a spin tomography measurement technique with a rotation of the transferred single electron spin. The coherent transfer provides a route to realize quantum repeaters. Furthermore, introducing an entangled photon pair source would realize the novel experiments of non-local entanglement between a local spin and one of the entangled photons.

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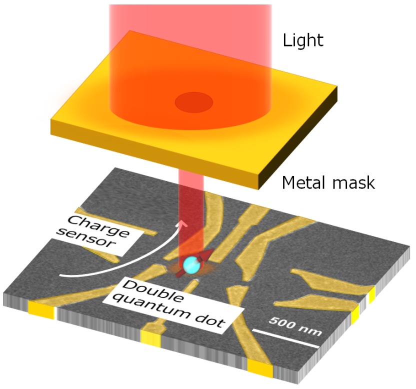

Fig. 1 Schematic of the photon irradiation on to the lateral double quantum dot which is covered with an optical mask with a center aperture.

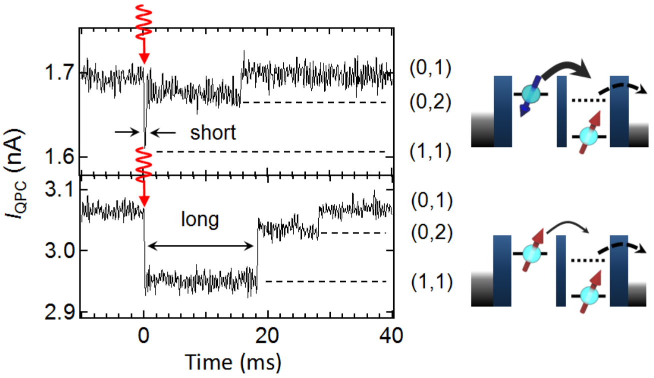

Fig. 2 Example traces of single-shot single photoelectron spin detection measured at 750 mT. Top (bottom) shows the detection of anti-parallel (parallel) photoelectron spin configuration, respectively.

Spin current generation from heat and mechanical motion

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Angular momentum conversion between spins and mechanical rotation is a promising candidate of a mechanism for micro driving devices. Fundamental phenomena of the angular momentum conversion are the Einstein-de Haas effect (body rotation due to its magnetizing) [1], and the Barnett effect (magnetizing by body rotation) [2]. An essential Hamiltonian of both effects is spin-rotation coupling

$$H_\Omega = -\hbar S \cdot \Omega,$$

where S and Ω are a spin and angular velocity of mechanical rotation, respectively. The Hamiltonian is effective for all particles which have angular momentum $\hbar S$ and expected to play a central role for generating spin current from the mechanical rotation. In order to explore the spin-rotation coupling Hamiltonian, we have observed the Barnett effect acting on the nuclei by using nuclear magnetic resonance (NMR) method [3].

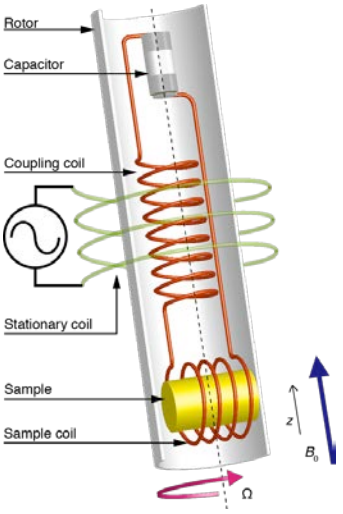

Fig. 1 Illustration of an experimental setup.

The Barnett effect implies that an effective magnetic field arises in a rotating body. The emergent field B_Ω, called Barnett field, can be derived theoretically from quantum relativistic theory [4]. B_Ω acting on a particle is linearly depends on the angular velocity of rotation Ω:

$$B_\Omega = \frac{2m}{gq}\Omega:$$

where m, q, and g are mass, charge and g-factor of the particle. The Barnett field is in proportion to the particle's rest mass. Since nuclei are much more massive than electrons, relatively large Barnett fields are expected to act on nuclei. In addition, the Barnett field acting on the nucleus depends on the nuclear g-factor.

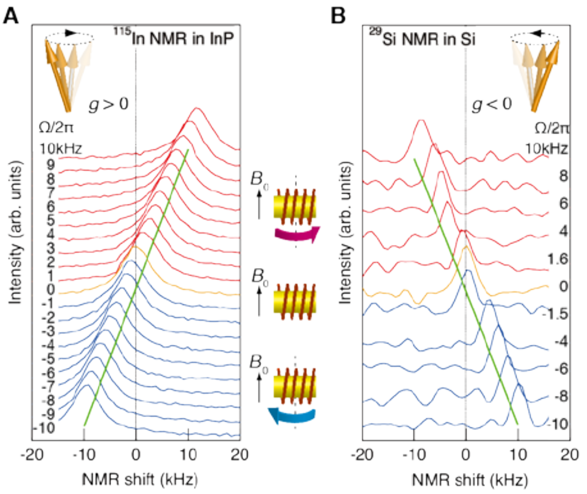

Fig. 2 NMR spectra for positive and negative g-factor. Spectra for (A) ^{115}In and (b) ^{29}Si NMR obtained at various angular velocities. The origin of the transverse axis is difined as the peak position of the NMR spectrum at Ω=0.

To measure the Barnett field by nuclear magnetic resonance (NMR) method, the detection has to be done on the rotating frame same as the body. The reason for this is that, if there are relative velocity between the signal detector and the body (signal emitter), an extrinsic NMR frequency shift arises from the relative velocity (rotational Doppler effect). To overcome the difficulty, we developed a new detection method in NMR, and directly measured the Barnett field. The detection on the rotating frame was realized by the newly developed tuning circuit that consists of a sample and detection coil both installed in the same rotor.

Figure 1 shows the schematic illustration of the experimental assembly. The assembly comprises two components: the stationary coil placed along external field B_0 and connected to an NMR spectrometer, and a high-speed rotor consisting of a cylindrical capsule in which a specially arranged tuning circuit is installed.

This circuit is composed of two small coils placed perpendicularly and connected in series, and a small capacitor. One of the two coils is arranged parallel to the stationary coil to establish a coupling by a mutual inductance between the tuning circuit and the stationary coil (coupling coil). The other, the sample coil, holds a sample inside. The RF field in the coupling coil is transmitted to the sample coil and generates an oscillating RF field to induce an NMR signal. Under this configuration, the sample coil rotates at exactly the same angular velocity as the sample. The rotor is put inside the stationary coil and, during measurements, it is rotated up to $|\Omega/2\pi|$=10 kHz.

In Fig. 2A, we plot the ^{115}In NMR spectra at various values of the angular velocity Ω. Clearly, the NMR frequency increases linearly with Ω. Furthermore, by reversing the rotation direction, the direction of the NMR shift is also reversed; thus, the sign of B_Ω is reversed. The sign of the g-factor of ^{115}In is known to be positive; that is, the nuclear magnetic moment is parallel to its angular momentum. Next we measured the shifts for nuclei with negative g-factors. From the NMR spectra for ^{29}Si having negative g-factor, the direction of the NMR shift is clearly opposite to that for ^{115}In, indicating that the emergent Barnett field is opposite in direction to that for ^{115}In (Fig. 2B). We collected the NMR shifts for various nuclei as a function of rotation speed in Fig. 3. In each sample, the NMR shift exhibits linear dependence on Ω. The g-factor for ^{7}Li, ^{19}F, ^{23}Na, and ^{115}In are known to be positive, while those for ^{29}Si and ^{119}Sn are negative. All the nuclei with positive g-factor display positive slopes, while all the nuclei with negative g-factors display a negative slope. These results mean that the nuclei feel additional magnetic field to the external field. It is a direct evidence for the existence of Barnett field.

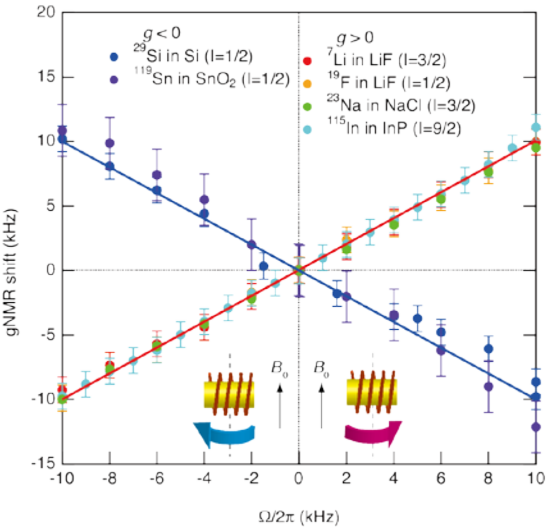

Fig. 3 Universal behavior of NMR shifts as a function of the angular velocity W. Vertical axis represents NMR shifts; its origin is determined by the center frequency at Ω=0.

In conclusion, we develop a new coil spinning NMR method of detecting the Barnett field. The Barnett field is observed as an NMR shift proportional to the rotation speed. The sign of the Barnett field depends on the both the sign of the nuclear magnetic moment and the rotation direction against the external magnetic field. These features can be used to determine the unknown sign of the nuclear magnetic moment. Our findings provide direct evidence of the coupling between the nuclear magnetic moment and mechanical rotation, and will produce new technology in which mechanical motion manipulates the nuclear spin angular momentum as well as the electron spin angular momentum.

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Theory on Spin Conversion Function: Topological Engineering of Magnons

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Recent advances in spintronics have revealed various kinds of conversion of electron spins into other degrees of freedom such as heat, electromagnetic wave, spin wave, and so forth. Theoretically there are several approaches for investigations of new kinds of spin conversion phenomena: (a) new theoretical framework, (b) new materials, (c) nanostructures such as interfaces and thin films.

As an example of exploration of new spin conversion phenomena, we studied magnons in ferromagnet from the viewpoint of Berry curvature in momentum space. The Berry curvature in momentum space is represented by the derivatives of the Bloch wavefunctions in terms of the wavevector. As has been studied in the context of spin Hall effect of electrons in semiconductors1), the Berry curvature is closely related to the band structure. We find that the Berry curvature of magnons causes various physical phenomena such as thermal Hall effect2,3). For example, for the magnetostatic forward volume-wave modes in a ferromagnetic slab, where the magnetic field is out-of-plane, we calculate the Berry curvature and resulting magnon thermal Hall conductivity. Furthermore, at the edge of a magnet this Berry curvature gives rise to the shift of the wavepacket, i.e. the Goos-Hänchen shift, known in optics (Fig.1). We discuss possible measurement of this shift in a magnet with a step, used for the observation of the Snell's law for spin waves in Ref.4).

Furthermore, if one introduces an artificial periodicity into a ferromagnet and makes a magnonic crystal, the band structure is modified accordingly. As a result the Berry curvature changes and in some cases the Chern number, i.e. the integral of the Berry curvature over the Brillouin zone, becomes nonzero, implying that the some magnon band gaps have topological nature. It results in an existence of chiral magnonic edge states within the gap (Fig.2)5,6).

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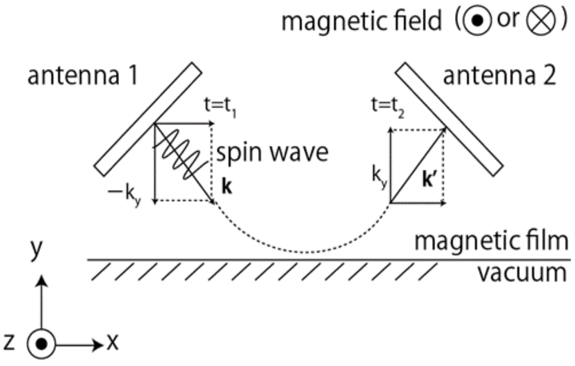

Fig. 1 Schematic illustration of Goos-Hänchen shift of magnons at the edge

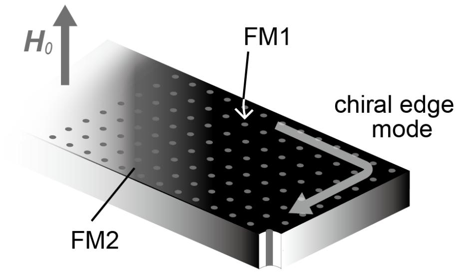

Fig. 2 Topological magnonic crystal and chiral edge mode