Strong-coupling phenomena in spintronics

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Traditional spintronic devices control the magnetic order digitally. Magnetic and electric fields, charge, spin, and heat currents, sound, microwaves, light, etc. can write a bit by switching the magnetization of a memory element between the “up” to “down” states. However, new computational classical and quantum architectures require analogue control over the magnetic texture. Ideally, the dynamic magnetization is manipulated coherently to point into any direction on the Bloch sphere, which requires control parameters that strongly couple to the magnetic order, i.e. an interaction strength that exceeds the lifetime broadening. Since magnetic dipoles interact only weakly with the environment, the strong-coupling regime of spintronics can be reached with high-quality materials and devices only.

The material of choice to study the physics and applications of strong coupling is yttrium iron garnet (YIG), an electrically insulating ferrimagnet with a Curie transition far above room temperature. Its record magnetic, acoustic and optical quality led already to the discovery of entirely new phenomena, such as the spin Seebeck effect, which raise the hope for new applications in a sustainable future electronics. Due to a decade of a global research effort, we now quantitatively understand much of YIG’s basic physics, such as the temperature-dependent spin dynamics and the interaction of the magnetic order with photons and phonons.

I will present a selection of our recent progress in the physics of YIG and our search for evidence for strong coupling in YIG devices.

Probabilistic Computing with Stochastic Magnetic Tunnel Junctions

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Digital computing is based on deterministic bits that represent 0 or 1, with stable charges on a capacitor or ferromagnets with a stable magnetic orientation. Quantum computing on the other hand is based on q-bits that represent superpositions of 0 and 1, with coherent quantities such as a single spin or the phase of a superconducting junction. Here, we draw attention to something in between, namely, a probabilistic bit or a p-bit that fluctuates between 0 and 1 that can be represented by unstable entities such as stochastic nanomagnets [1-2].

While probabilistic bits are not substitutes for *coherent* quantum bits, many applications envisioned for Noisy Intermediate Scale Quantum (NISQ) devices are shared by p-bits. Examples include hardware accelerators for combinatorial optimization and sampling problems as well as inference and learning for machine learning applications. Interestingly, a class of quantum algorithms that are used by D-Wave's quantum annealers can be represented by p-bit networks as long as the encoded system belongs to a special subclass of quantum systems that are called "stoquastic". In the absence of extreme limitations brought on by the cryogenic operation to achieve phase coherence and entanglement in quantum computers, probabilistic networks could represent more complicated stoquastic problems with fewer number of p-bits due to the flexibility of their interconnections.

Naturally, probabilistic *emulators* can be built by conventional digital computers as well. As such, it is natural to ask why dedicated hardware for probabilistic computers would be needed. Our estimates indicate that pseudorandom generators implemented in straightforward digital CMOS requires more than 100X more area compared to a mixed-signal p-bit implementation from a slightly modified 1T/1MTJ cell of the commercial STT-MRAM technology. A much lower cell area results in both better *energy-efficiency* as well as *better scaling* to build larger p-bit networks.

Recently, in a tabletop experiment [1], we demonstrated that a network of 8 p-bits that make use of such stochastic MTJs with unstable free layers can be used to solve classical optimization problems in hardware. Fig. 1a shows the 1T/1MTJ building block (p-bit) that uses the stochastic MTJs developed by the Fukami / Ohno laboratory of Tohoku University. An essential feature of this design comes from its *asynchronous* nature, namely, that there is no global clock that synchronizes the dynamical evolution of the system, rather, each p-bit is free to make an update by considering the input it receives from its neighbors. An asynchronous design that satisfies this requirement can achieve a very large number of flips per second due to the possibility of designing *massively parallel* STT-MRAM chips with more than a million 1T/1MTJ cells that operate independently.

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Logic operation using electron spins in silicon

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Logic gates using electron spins in silicon are expected to realize beyond complementary metal-oxide-semiconductor (CMOS) architectures with a superior switching energy, a high logic density, and a nonvolatile function. Here we focus on the semiconductor-based universal magnetologic gate (MLG) where the operand of logic operation is the magnetization direction [1]. The MLG consists of five ferromagnetic (FM) electrodes with parallel easy magnetization axes (Fig. 1(a)). The two collinear easy axes, +*y* and –*y*, are defined as the binary states "1" and "0", respectively. The two outmost FM electrodes are input terminals and the center electrode is the output terminal. The other electrodes are configuration terminals that define the gate operation such as NAND or OR. By applying charge currents, spin accumulation is generated in the semiconductor channel, whose amplitude beneath the output electrode is represented by NAND or OR. Any binary logic operation can be realized by using a finite number of MLGs. Furthermore, the reconfigurable logic gates at a clock frequency provides flexibility in logic circuit design. An MLG consists of two exclusive or (XOR) gates. Therefore, logic operation of one XOR gate using three ferromagnetic electrodes (Fig. 1(b)) is a fundamental technique to realize MLG operation.

Here we present room temperature operation of a spin exclusive or (XOR) gate in lateral spin valve devices with nondegenerate silicon (Si) channels [2, 3]. The device for the spin XOR gate consists of three iron (Fe)/cobalt (Co)/magnesium oxide (MgO) electrodes. The spin drift effect was controlled by a lateral electric field in the Si channel to adjust the spin accumulation voltages detected by FM-M under two different parallel configurations of FM-A and FM-B, corresponding to (1, 1) and (0, 0), so that they exhibit the same value. As a result, the spin accumulation voltage detected by FM-M exhibited three different voltages, represented by an XOR gate in MLG as shown in Fig. 1(c). The one-dimensional spin drift-diffusion model clearly explained the obtained XOR behavior. Charge current detection of the spin XOR gate was also demonstrated. The detected charge current was 1.67 nA. Furthermore, gate voltage modulation of the spin XOR gate was also demonstrated, which enables operation of multiple MLG devices.

In the presentation, we will also report recent progress of the spin logic operation using spins in silicon.

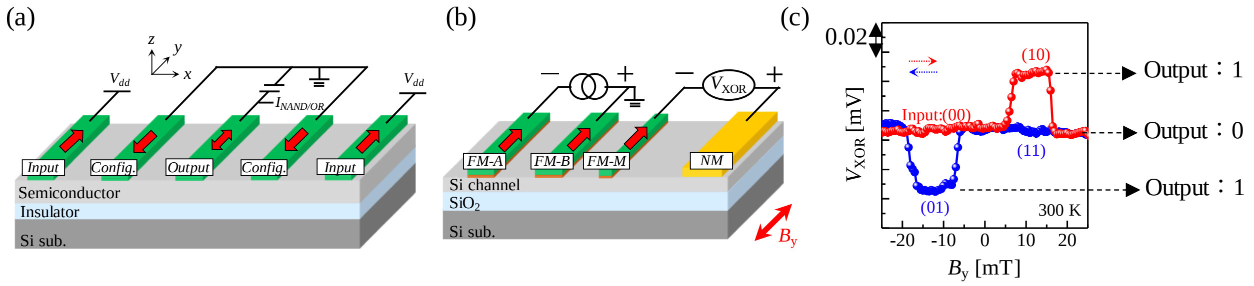

Figure 1 (a) Schematic illustration of the semiconductor-based MLG device proposed by Dery et al. [1]. (b) Schematic illustration of the silicon-based multiterminal lateral spin valves for the XOR operation. (c) A typical V_{XOR}-B_y curve in the XOR operation.

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Reservoir computing using dynamics of magnetic skyrmions

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Artificial neural networks, mimicking human brains, exhibit great abilities in several tasks such as image recognition. Nowadays, most artificial neural networks rely on silicon-based general-purpose electronic circuits such as a central processing unit (CPU) and a graphics processing unit (GPU). However, in these circuits, a large amount of energy is consumed. Moreover, the absence of memory functionality in CPU and GPU is a disadvantage especially for recurrent-type artificial neural networks, in which past data is stored in the network as actual human brains. Therefore, developing devices specialized for brain-inspired computing, namely neuromorphic devices, are highly required. So far various neuromorphic computing models using spintronic devices have been proposed and demonstrated[1)]. Among them, one of the promising models is a physical reservoir computing model. In the physical reservoir computing model, the input data are nonlinearly converted into multi-dimensional outputs by using nonlinear dynamics of spintronic devices. Incidentally, this nonlinear mapping of input data into the high-dimensional space is a key to neuromorphic computing; the mapping enables linearly inseparable data to be linearly separable, like the kernel method.

In this presentation, we demonstrate physical reservoir computing by using a magnetic-field induced nonlinear dynamics of skyrmions. A skyrmion is a particle-like topological spin structure and can be manipulated with low power consumption. Thus, skyrmions are expected to be applied to energy-saving devices. Moreover, skyrmions are theoretically predicted to show high performance in reservoir computing[2)]. We use Pt/Co/Ir film deposited on $LiNbO_3$ substrate in which the formation of disordered skyrmion has been observed[3)]. Our skyrmion-based physical device consists of parallelly connected Hall-bar shaped devices in which various constant magnetic field are applied (Fig. 1). In each Hall-bar device, we input a time-dependent out-of-plane magnetic field [$H_{\mathrm{AC}}(t)$] whose waveform is the same as what we want to compute. The output is anomalous Hall voltage [$V^i(t)$] (Here, i denotes the output from i-th Hall bar); $V^i(t)$ changes in response to $H_{\mathrm{AC}}(t)$ because of $H_{\mathrm{AC}}(t)$-induced change in magnetic structures and is nonlinear with respect to $H_{\mathrm{AC}}(t)$. In this way, the input signal is nonlinearly converted into multi-dimensional data set $\boldsymbol{V}(t) = [V^1(t), \cdots, V^N(t)]$. Then, the final output is calculated by a linear combination of $\boldsymbol{V}(t)$ (i.e. $\sum W_i V^i$), in which the coefficients (W_i) of the linear combination are optimized by using a training data set so that the final output is desirable.

We succeeded in a waveform recognition task, which is a conventional benchmark. Notably, the recognition rate of the skyrmion-based neuromorphic computing device is better than a neuromorphic computing device in which ferromagnetic-domain structures were used instead of skyrmions. This is attributed to a more complex nonlinear mapping and the larger number of the output dimension, both of which originate from the large degree of freedoms of the disordered skyrmion system such as the position and the size of skyrmions. Our results provide a guideline for developing energy-saving and high-performance neuromorphic computing devices with the use of skyrmions.

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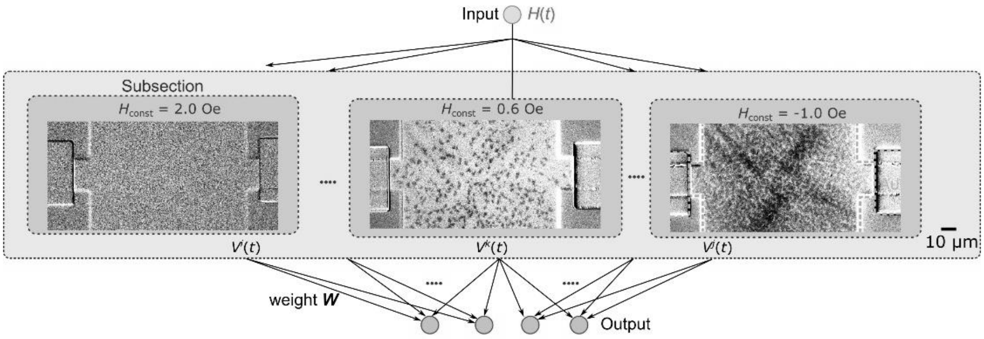

Fig. 1 Schematic illustration of a skyrmion-based neuromorphic computer. Polar Kerr images of Hall bar device with various constant magnetic field (H_{const}) are also presented.

Development of Domain Wall Type Spin Memristor toward Analogue Neuromorphic Computing

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Recent evolution of Artificial Intelligence (AI) is bringing drastic changes to society and industry. On the other hand, the rapid increase of its energy burden has become an urgent issue. From this viewpoint, an analogue neuromorphic computing have attracted much attention due to its extremely low-power and high-performance neural-network (NN) computing ability [1]. Memristors play key roles for realizing neuromorphic devices. It can store a synaptic weight of NN as an analog resistance state. For example, large-scale parallel multiply-accumulate (MAC) operation can be executed by applying an electric current flow to a memristor array. Memories-based spiking neural network devices have also been studied to accelerate the computational processing power with keeping power consumption. Phase change memory (PCM) and Resistive-RAM (ReRAM) are well-known elements in this field. A magnetic domain wall (DW) type memristor (spin-memristor) is another promising candidate for artificial synapses because of its typical conductance change behavior, non-volatility, high speed and high endurance operations. Numerical simulations show potential advantages of the spin-memristor [2]. However, an element-level development has not been well established. The elements have been well studied for a high-speed domain wall (DW) type MRAM, but not so much for memristors. In this presentation, we introduce our recent efforts to develop the spin-memristor for the neuromorphic application. The concept of the spin-memristor was verified by preparing a DW type magnetic tunneling junction (MTJ). Three-terminal top-pinned type MTJs were fabricated on a Si substrate. The stacking layer was Si wafer /buffer /DW layer /CoFeB Free layer /tunnel barrier /CoFeB Reference layer /synthetic antiferromagnetic (SAF) pinned layer. A pulse generator and a source measure unit are used for driving the DW and for measuring the resistance of MTJs. A linear and symmetric conductance response (Fig. 1), which was desirable for the artificial synapse, was experimentally demonstrated in the element level as expected [3]. A good NN computation adaptability was confirmed using a numerical simulation with its simplified element model. In addition, we also developed a 3-terminal element having SAF-type magnetic fixed layer at the one side of DW layer (Fig. 2), and successfully controlled the element initialization process just by applying an external magnetic field [4]. Since this structure allows us to initialize multiple elements by a simple procedure, it becomes helpful to realize an array level system and a mass-production in the future. The prototype element suggested a low power operation potential which may be at least comparable to other memristive elements such as PCM and ReRAM.

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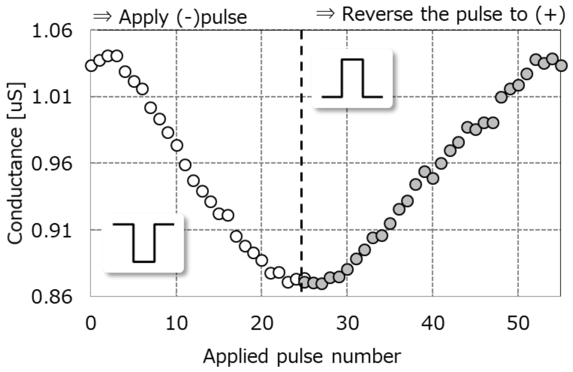

Fig.1 Symmetric conductance response as a function of driving current pulse

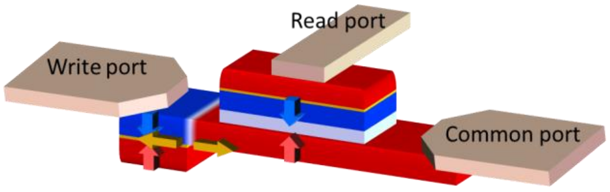

Fig.2 Schematic illustration of the element with SAF-type magnetic fixed layer

Strong magnon-magnon coupling in synthetic antiferromagnets

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Spin waves and their quasiparticles, i.e., magnons, can be used as information carriers and for information processing[1-3]. Hybrid quantum systems based on magnon have been intensively studied in the last decade, because these systems offer a promising platform for novel quantum information technologies[4]. It has been recently reported that an anticrossing gap between two magnetic resonances, so-called a magnon-magnon coupling, can be realized in several kinds of systems[5]-[8], which is analogous to the hybrid quantum system. However, most of experiments focused on magnons with uniform precession ($k = 0.0\ \mu\mathrm{m}^{-1}$, where k is the wave number). In this study we demonstrate the strong magnon-magnon coupling between acoustic and optic modes by utilizing magnons with nonuniform precession ($k \neq 0.0\ \mu\mathrm{m}^{-1}$) in ferromagnetic-metal-based synthetic antiferromagnets (SAFs) of FeCoB/Ru/FeCoB[9].

Figures 1(a)-1(c) shows the spin wave resonance spectra ($k = 1.2\ \mu\mathrm{m}^{-1}$) at $\varphi_k = 0°, 45°,$ and $90°$, where φ_k is the angle between an external magnetic field and the spin wave propagation direction. The anticrossing gap g/π between two modes appears when the spin wave propagates in the direction of $\varphi_k \neq 0°$ and is maximized at approximately $\varphi_k = 45°$. We found that the coupling strength is larger than the dissipation rates for both the resonance modes. Therefore, strong coupling regime is achieved in this study. A theoretical analysis shows quantitative agreements with the experimental results and indicates that the appearance of the anticrossing gap accompanies symmetry breaking with respect to the exchange of magnetizations due to dynamic dipolar interaction generated by the magnetization motion of spin waves. Our study offers a new approach toward tunable magnon-magnon coupling systems for SAF-based magnonic applications.

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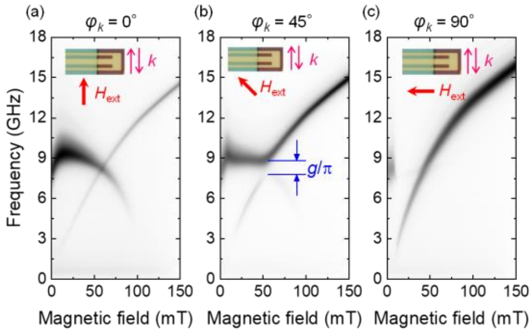

Fig. 1 Contour plots of Re[S_{11}] for spin wave resonance spectra ($k = 1.2\ \mu\mathrm{m}^{-1}$) at (a) $\varphi_k = 0°$, (b) 45°, and (c) 90°.

Measurement and control of spin quantum states utilizing semiconductor quantum dots

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Spin phenomena in semiconductor nanostructures are attractive targets in basic science and important in device applications. Semiconductor quantum dots (QDs) are nanostructures which confine electrons in small regions and work as artificial and controllable quantum states. They can handle single-electron spins. Single-electron spins in QDs are simple spin systems, show quantum mechanical properties, and nowadays are considered as a good candidate for quantum bits in quantum information processing. By utilizing the semiconductor QDs, we can measure and control the single-electron spin states.

To measure the single-electron spins in semiconductor nanostructures, local spin probes which can directly access the spin states are useful. We can realize such probes using semiconductor QDs. We can get the information of the spin states by analyzing the electron tunneling into spin-selective levels formed in the QDs which couple to the target structures. We can also measure the dynamics of the local electronic states by high-speed electric measurements utilizing high-frequency techniques called RF reflectometry. We measure the dynamics of the local single-electron spin and charge states in a semiconductor nanostructure which consists of a QD and an open electronic reservoir. This hybrid system is a simple model of an open quantum system. The change of the local spin and charge states inside of the target QD induced by the interaction between the QD and the reservoir is detected by the local probe. The relaxation times are different between the spin and the charge states. The observed difference is reproduced by a theoretical model treating the tunneling process [1].

Control of single-electron spin states is an essential operation of semiconductor quantum bits utilizing single-electron spins in QDs. The spins have relatively long quantum coherence times in solid-state devices. The control is realized by electron-spin resonances induced by the oscillatory shifts of the QD position by microwave's electric fields and the magnetic field gradient created by micro-magnets. We realize and improve the operation of the single-electron spins by optimizing the device structures and materials. We also fabricate the semiconductor multiple QD devices towards larger quantum bit systems. Scale-up of the quantum bit systems is important to realize larger-scale quantum algorithms. We demonstrate charge state control and single-spin operations in the scaled-up devices [2]. These results are important in the understanding of spin phenomena in semiconductor nanostructures and device applications like semiconductor quantum sensors and qubits.

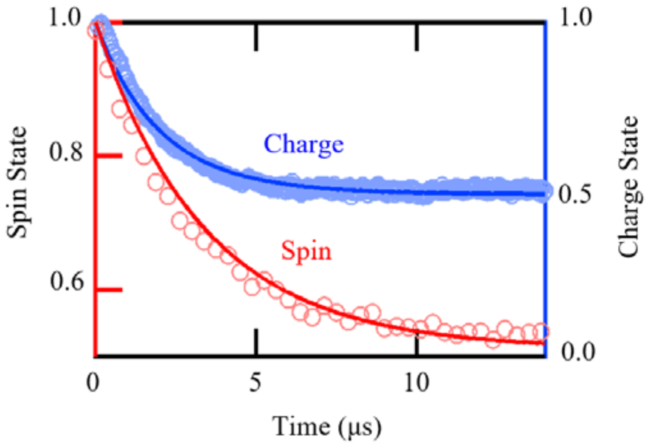

Fig. 1. Measured dynamics of the spin and charge states by a semiconductor quantum dot sensor.

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Majorana fermions and non-Abelian anyons in a Kitaev quantum spin liquid

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Quantum spin liquid (QSL) is a novel state of matter that lacks long-range magnetic order all the way down to zero temperature while possesses some special patterns of quantum mechanical entanglement. The long-standing experimental challenges associated with the identification of the QSL state is the detection of fractionalized excitations, which are signatures of topological order inherent to the QSL. Recently, the Kitaev spin model of insulating magnets on two-dimensional (2D) honeycomb lattice has attracted interest, as it hosts a QSL where quantum spins are fractionalized into Majorana fermions.1) In magnetic fields, the emergence of Majorana edge current and non-Abelian anyons in the bulk is predicted to manifest itself in the form of thermal quantum Hall effect, a feature discussed in topological superconductors and even-denominator fractional quantum Hall state. Here we report on thermal Hall conductivity κ_{xy} measurements in α-$RuCl_3$, a candidate material for Kitaev QSL on a 2D honeycomb lattice.2,3) In magnetic field perpendicular to the 2D honeycomb planes, positive κ_{xy} develops in a spin-liquid state below the temperature characterized by the Kitaev interaction $J_K/k_B \sim 80$ K, demonstrating the presence of highly unusual itinerant excitations. Although the zero-temperature property is masked by the antiferromagnetic (AFM) ordering at $T_N = 7$ K, the sign, magnitude, and T-dependence of κ_{xy} at $T_N < T < J_K/k_B$ follows the predicted trend of the itinerant Majorana fermion excitations.2) The application of a tilted magnetic field suppresses the AFM order, leading to a field-induced QSL ground state. In this QSL state, the 2D thermal Hall conductance per honeycomb plane κ_{xy}^{2D}/T shows a plateau behavior as a function of applied magnetic field and has a quantization value of $(\pi^2/6)(k_B^2/h)$, which is exactly half of κ_{xy}^{2D}/T in the integer quantum Hall state and conventional odd-denominator fractional quantum Hall state that hosts Abelian anyons.4) We also show that the half-integer thermal Hall plateau is observed even when the magnetic field is applied parallel to the 2D plane. In addition, the topological Chern number determined by the sign of the quantized thermal Hall conductance is consistent with that expected in the Kitaev QSL.5) These results provide strong evidence of topologically protected chiral currents of charge neutral Majorana fermions at the edge and and non-Abelian anyons in the bulk of the crystal.3) Above a critical field, the quantization disappears and κ_{xy}^{2D}/T goes to zero rapidly, indicating a topological phase transition.

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強磁性共鳴による Co-Fe 合金単層膜自己誘起逆スピンホール効果

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Self-induced inverse spin-Hall effect in Co-Fe alloy single-layer films under the ferromagnetic resonance

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はじめに

近年、強磁性共鳴(FMR)の下で強磁性体の単層薄膜に生じる自己誘起逆スピンホール効果による起電力の生成が注目されている 1-3)。Fig. 1 に強磁性薄膜内の局在磁気モーメントの、FMR 下における動的特性の概要を示す。強磁性膜の上面側(空気層側)と下面側(基板側)との間で局在磁気モーメントの減衰特性が異なるため、膜の面直方向に純スピン流が生成され、その純スピン流は逆スピンホール効果(ISHE) 4)によって起電力に変換されると考えられている 2)。これまでに Fe, Co, および Ni$_{80}$Fe$_{20}$ の自己誘起 ISHE による起電力の生成が達成された 1-3)。しかしながら元素により起電力特性が異なった。本研究では FMR 下の Co-Fe 合金の単層膜における自己誘起 ISHE による起電力の生成を達成し、その Co と Fe の組成比依存性を評価した。

実験方法

電子ビーム蒸着法により、熱酸化膜付き Si 基板上に Co$_x$Fe$_{100-x}$ 合金(x = 0, 25, 50, 75, 100)の単層膜(膜厚 25 nm)を作製した。FMR の励起には ESR 装置を用いる方法と、電磁石による静磁界、およびネットワークアナライザによる高周波電流を伝送線路に印加することによって生成される高周波磁界を用いる方法を併用した。起電力の検出にはナノボルトメータを用いた。全ての測定は室温で行った。

実験結果

Fig. 2 に x = 75 の試料における FMR 下の起電力特性を示す。高周波の出力は 200 mW である。共鳴磁界付近において起電力が観測され、起電力の符号は静磁界の方向を逆転することにより、反転した。従来の解析手法 4)により、起電力の起源は主に ISHE であると結論付けた。Fig. 3 に伝送線路を用いて評価した、Co-Fe 合金薄膜における FMR 下の ISHE による起電力の Co 濃度依存性を示す。高周波の出力は 20 mW である。組成の異なる各試料において静磁場に対する反転対称性を示す出力電圧特性が観測された。更に起電力は高周波出力に依存した。以上により ISHE4)によって起電力が発生したと結論付けた。即ち Co-Fe 合金薄膜においても FMR 下で ISHE による起電力の生成を達成した。学会時には以上の詳細を議論する。

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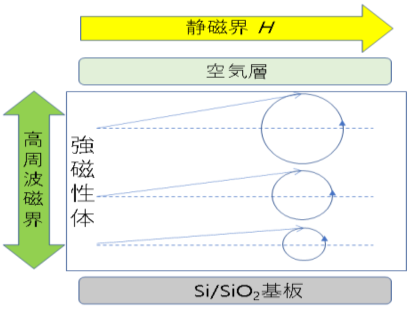

Fig. 1. Spin current generation mechanism in a ferromagnetic metal film under the FMR.

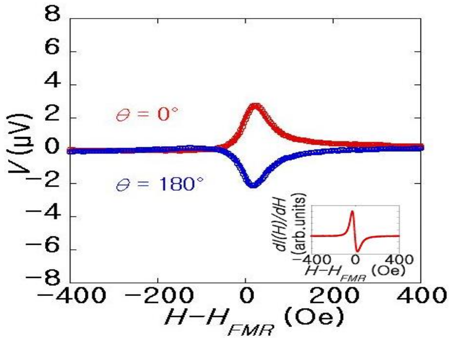

Fig. 2. Output voltage property of Co$_{75}$Fe$_{25}$ under FMR. (Inset) an FMR spectrum.

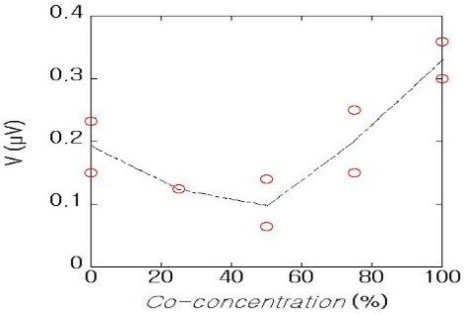

Fig. 3. Co concentration dependence of the output voltage due to the ISHE.

スロット線路を用いたイットリウム鉄ガーネットの磁化ダイナミクス励起とスピン波の検出

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Magnetization dynamics induced by slot line waveguide and detection of spin waves in yttrium iron garnet

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はじめに

我々はイットリウム鉄ガーネット(YIG)の磁化ダイナミクスを励起する高周波伝送線路としてスロット線路に着目し、高周波応答の線路形状依存性を評価した。その結果、スロット線路の間隔に依存する磁化ダイナミクスが励起されることを見出した[1]。マイクロマグネティクスシミュレーションによる解析から線路から発生するスピン波と磁化ダイナミクスの相互作用が存在することが示唆された。そこで、その高周波応答とスロット線路から発生するスピン波の相関を検討したので報告する。

実験方法

試料には(111)ガドリウムガリウムガーネット（GGG）単結晶基板上に液相エピタキシャル法で成長された膜厚 10 µm の YIG(111)単結晶膜を用いた。試料上に高周波伝送線路として、フォトリソグラフィー法で非対称型のコプレーナウェーブ伝送線路、および、スロット伝送線路を形成した。0 dBm の高周波電力をこの伝送線路により YIG 上に入力し、反射電力強度の外部磁界依存性をネットワークアナライザで評価した。また、試料上にスピン波を検出するための非対称型コプレーナウェーブ線路を 1 mm 離した位置に設置し、YIG を伝搬するスピン波をアンテナ法により検出・評価した。

実験結果

図 1 には信号線路幅 10 µm、線路幅間隔 55 µm のスロット線路における測定結果を示す。入力周波数は 7.2 GHz である。反射強度は 1670 Oe および 1730 Oe 付近に吸収ピークが確認される。マイクロマグネティクスによる解析から、スロット線路のそれぞれの線路周辺で局所的に磁化歳差運動が誘起され、スピン波が伝搬することが示唆されている。実際、アンテナ法においてもスピン波に起因する信号が検出されている。1730 Oe 付近の吸収ピークよりも高磁場側においては、アンテナ法で検出されたスピン波の強度と吸収ピーク強度に大きな相関は見られなかった。一方、1700 Oe 近傍の挙動で、高周波電力の吸収強度が少ない磁場領域ではスピン波の検出出力が極小値を示しており、磁化歳差運動とスピン波強度に強い相関を示した。本試料で発生するスピン波は表面静磁波であり、その波長は同一周波数の場合、磁場の低下と共に短くなる。1700 Oe におけるスピン波の波長はおよそ 55 µm と見積もられる。電磁界解析より、伝送線路間の高周波磁場の位相は 180° ずれているため、このスピン波の波長において、スピン波と局所磁化歳差運動が逆位相の関係になり磁化歳差運動のスピン波が抑制されたと考えられる。すなわち、この結果はスピン波が局所磁化歳差運動に影響を及ぼしていることを強く示唆する結果と考えられる。講演では磁化歳差運動とスピン波の相関の素子サイズ依存性を中心に報告する。

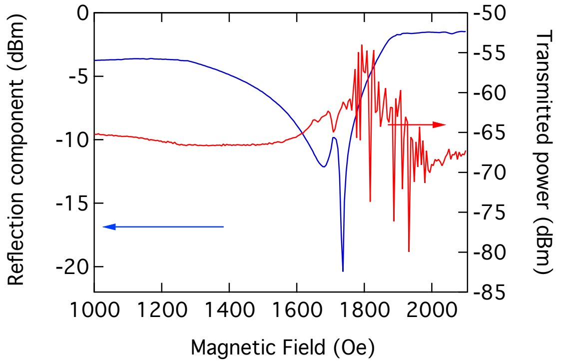

Fig.1. Magnetic field dependence of reflection component of input power and transmitted power for the detection of spin waves.

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準周期マグノニック結晶を用いたMSSWの非相反性制御

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Propagation properties of spin waves in magnonic crystal with quasi periodic structure

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はじめに　近年、強磁性体導波路中に周期的な構造を導入したマグノニック結晶(MC)を用いて、スピン波の伝搬特性を制御しようとする研究が精力的に行われている。これまでに我々は、強磁性体金属のパーマロイ(Py)に周期的な溝を導入したMCを作製し、アンテナを用いた電気的手法により特定の周波数帯でスピン波が伝搬できないマグノニックバンドギャップの観測に成功した[1]。長期的な周期性を持たない準周期構造のMCは通常のMCにはない伝搬特性を示すことが期待されるものの、その調査はほとんど行われていない。本研究ではマイクロマグネティックシミュレーションを用い、準周期構造をもつ1次元のPy MC中を伝搬する静磁表面波(MSSW)の伝搬特性を調査した。

計算方法　スピン波の伝搬特性の計算は、Object Oriented Micromagnetic Framework(OOMMF)により行った。縦×横×膜厚が102.4 μm × 6 μm × 75 nmであるPy導波路を仮定し、深さが25 nmで溝の幅 d が0.8 μmの溝と凸の幅が$\frac{1+\sqrt{5}}{2}$ dの凸を、漸化式　$A_{n+2} = A_{n+1} + A_n$　で表されるフィボナッチ数列に従い、Pyの長辺方向に導入した(Fig.1)。+y方向の印加静磁場に対して、右側に伝搬する方向をForward、それと逆方向をReverseと定義した。スピン波励起用のシグナル(S)とグラウンド(G)アンテナの磁場分布はMATLABで行った。S及びGアンテナ幅は、それぞれ1.0及び50 μmで、SG間距離は1.0 μm、それらの厚みは205 nmとした。この磁場分布をOOMMFに取り込み、パルス幅が50 psのガウシアンパルスを印可することにより、スピン波を励起した。静磁場の印可方向はPyの短辺方向(20 mT)としているため、伝搬するスピン波はMSSWモードとなる。

実験結果　Figure 2は、励起アンテナからの距離が 40 μmのときのスピン波のスペクトルである。赤と青はそれぞれ、+y方向の印加静磁場に対して、右側に伝搬する方向(Forward)と、それと逆向き(Reverse)のスペクトルを示している。構造のないPy膜において+y方向に磁化が向いている場合、アンテナ法で励起されたMSSWは、−x方向に比べ、+x方向の強度が大きくなる非相反性を示すことがよく知られている。4 ～ 8 GHz付近では、赤(+x方向)のスペクトル強度が青(−x方向)の強度より大きく、典型的なMSSWモードの非相反性が現れているが、8 ～ 10 GHz付近では、赤と青のスペクトル強度が逆転しており、非相反性が逆転する現象が観測された。これは準周期構造によりMSSWモードの非相反性が変化したことを示している。

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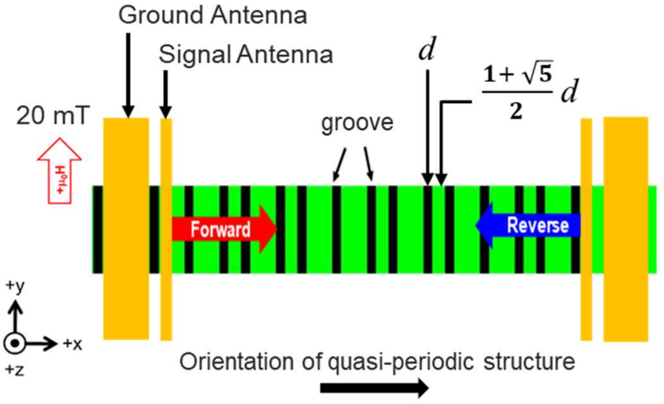

Fig.1 Schematic illustration of a quasi-periodic Py MC.

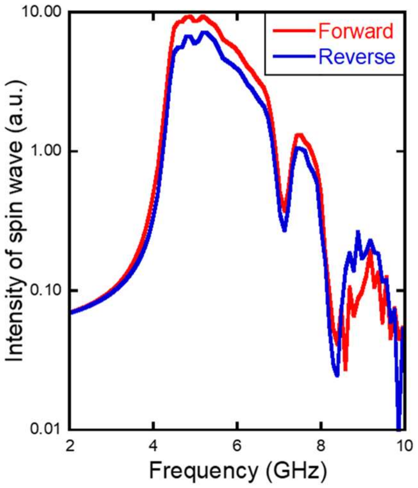

Fig.2 Spin wave spectra for forward and reverse direction of a quasi-periodic Py MC.

Spin Wave Resonance in Perpendicularly Magnetized Synthetic Antiferromagnets

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Spin wave polarization, i.e. the rotation direction of magnetic moments around an applied magnetic field, has been attracted much attention for a new freedom degree of spin waves in addition to spin wave amplitude and phase. Unlike ferromagnetic spin waves, antiferromagnetic spin waves in colinear antiferromagnets have both right and left-handed polarizations [1,2]. However, spin waves in crystal antiferromagnets have high resonance frequency of THz regime due to strong exchange coupling, which can cause difficulties in excitation or manipulation of spin waves. In this study, we experimentally demonstrate spin wave resonance in perpendicularly magnetized synthetic antiferromagnets by spectroscopy using a vector network analyzer.

Films of Ta(3.0)/Pt(2.0)/[Co(0.2)/Ni(0.7)]$_5$/Co(0.2)/Ru(0.5)/Co(0.2)/[Co(0.2)/Ni(0.7)]$_5$/Ru(3.0) (thickness in nm) were deposited using dc magnetron sputtering on thermally oxidized Si substrates. The films were fabricated to devices for spin-wave-spectroscopy as shown in Fig. 1 (a). Figure 1 (b) shows a contour plot of spin wave resonance spectra (k = 1.2 μm) generated from Re[S_{11}] spectra measured at a given out-of-plane bias magnetic field. The applied magnetic field swept from +250 mT to –250 mT with a step of 10 mT. Two resonance modes were observed from 130 mT to - 190 mT, where the two magnetic moments were antiferromagnetically aligned. These two resonance frequencies increase and decrease linearly with the bias magnetic field, which indicates excitation of right and left-handed polarized spin waves. In the presentation, we will discuss more details with theoretical analysis based on the equation of motion.

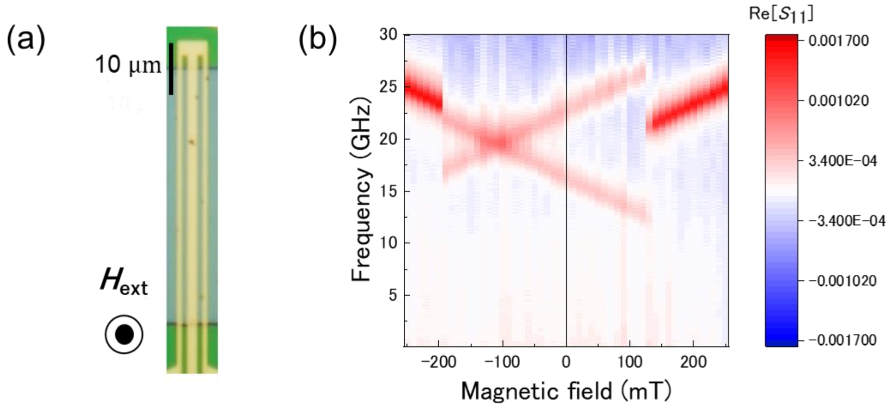

Fig.1 (a) Optical micrograph of the device. (b) Contour plot of Re[S_{11}] spectra.

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Co/Pt 多層膜のコプラナー導波路強磁性共鳴

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Co-planar waveguide ferromagnetic resonance of Co/Pt multilayers

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はじめに

Co/Pt 多層膜は垂直磁気異方性を持つことから、これまで記録媒体やメモリの観点から精力的に研究されてきた 1)。一方で人工磁性体という点からは、Co 膜厚と Pt 膜厚というふたつの自由度を持つため、これらを変化させることで多層膜の磁気特性が制御できることが興味深い。例えば多層膜の g 値が制御できた暁には人工フェリ磁性構造での角運動量補償が可能となり 2)、スピン波デバイスなど新たな応用への可能性が広がると期待される 3)。しかしながらこれらの自由度が具体的に多層膜の g 値やダンピングにどのような影響を与えるかは明らかではない。そこで今回我々は Co 膜厚を変化させた Co/Pt 多層膜を作製し、コプラナー導波路（CPW）を用いた強磁性共鳴（FMR）を測定し、g 値やダンピングを調べる。

実験方法

多層膜はマルチターゲット DC スパッタリング法で作製する。基板は石英基板を用いる。まず下地層として Ta を 1nm、更に Pt を 2nm 成膜する。その上に Co（膜厚 Xnm）と Pt（膜厚 0.3nm）を 10 周期積層して Co/Pt 多層膜とし、最後に 1.7nm の Pt でキャップする。Co 膜厚の X が 0.3、0.6、0.9、1.2、1.5 の 5 種類の試料を作製した。

CPW を作製する前に、多層膜をフォトリソグラフィと Ar イオンエッチングで幅 10μm、長さ 1.5mm の短冊状に加工し、厚さ 100nm の SiO_2 スペーサーを堆積する。Co/Pt 多層膜の短冊の上に CPW の信号線が載るようフォトリソグラフィを行い、Cr を 5nm、Au を 200nm、Cr を 5nm スパッタ成膜し、リフトオフを経て CPW を作製する。CPW の信号線の幅は 10μm である。

CPW を高周波プローブと同軸ケーブルを介してベクトルネットワークアナライザに接続する。マイクロ波の透過率に対応する S パラメータの S_{21} を測定し、絶対値$|S_{21}|^2$ を得る。外部直流磁場は面直方向に印加する。特定の磁場で測定する直前に 1.5T でバックグラウンドスペクトルを測定して差し引く。すると差分の$|S_{21}|^2$ スペクトルに FMR 信号が吸収（ディップ）として現れる。

結果と考察

図に X=0.9 の試料の CPW-FMR スペクトルを示す。面直方向の外部直流磁場を 0.1T から 1.0T まで変化させている。図のスペクトルに現れるディップは、磁場の大きさを増加させると高周波にシフトすることから、FMR 信号であると考えられる。これらスペクトルのディップをローレンツ関数でピーク分離し、外部磁場に対する共鳴周波数のプロットから g 値が、共鳴周波数に対する半値幅のプロットからダンピング定数が得られる。講演では g 値やダンピング定数の、Co 膜厚（X）依存性について解析した結果を報告する。本研究は科研費（20H01911）により支援された。

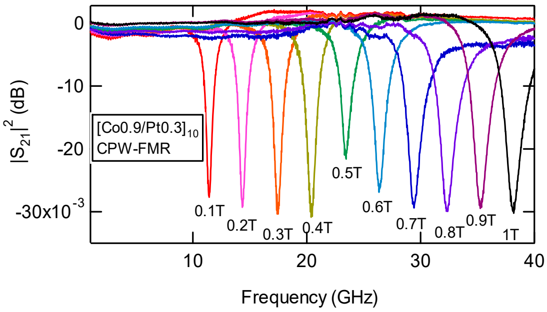

Fig. CPW-FMR spectra of a $[Co0.9/Pt0.3]_{10}$ multilayer sample at various magnetic fields.

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