Strong-coupling phenomena in spintronics

Gerrit E.W. Bauer
AIMR and IMR, Tohoku University, Sendai, Japan

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

Kerem Camsari[1,7], William A. Borders[2], Ahmed Z. Pervaiz[1], Shunsuke Fukami[2-5], Supriyo Datta[1] and Hideo Ohno[2-6]

[1]School of Electrical and Computer Engineering, Purdue University, USA,

[2]Laboratory for Nanoelectronics and Spintronics, Research Institute of Electrical Communication, Tohoku University, Japan

[3]Center for Spintronics Research Network, Tohoku University, Japan

[4]Center for Innovative Integrated Electronic Systems, Tohoku University, Japan

[5]Center for Science and Innovation in Spintronics, Tohoku University, Japan

[6]WPI-Advanced Institute for Materials Research, Tohoku University, Japan

[7]Department of Electrical and Computer Engineering, University of California, Santa Barbara, USA

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

Yuichiro Ando and Masashi Shiraishi

(Kyoto University)

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.

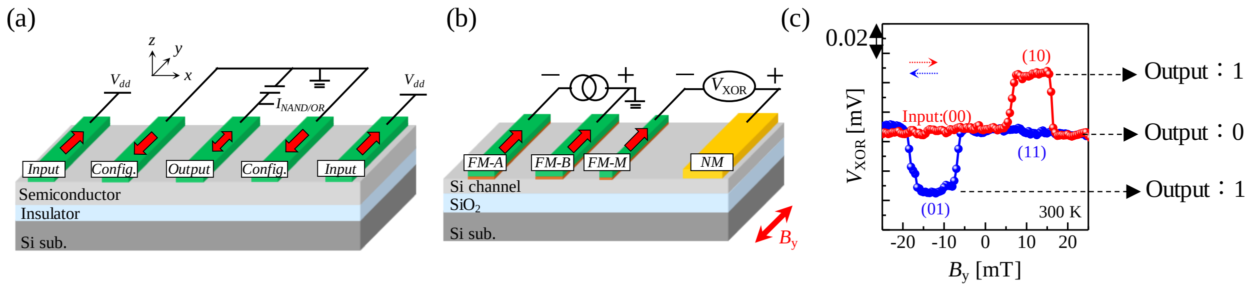

Figure 1 (a) Schematic illustration of the semiconductor-based MLG device proposed by Dery et al. [1]. (b) Schematic illustration of the silicon-based multiterminal lateral spin valves for the XOR operation. (c) A typical V_{XOR}-B_y curve in the XOR operation.

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Reservoir computing using dynamics of magnetic skyrmions

Tomoyuki Yokouchi
RIKEN Center for Emergent Matter Science (CEMS), Wako 351-0198, Japan.
Department of Basic Science, The University of Tokyo, Komaba, Tokyo 153-8902, Japan

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 [$H_{AC}(t)$] 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 $H_{AC}(t)$ because of $H_{AC}(t)$-induced change in magnetic structures and is nonlinear with respect to $H_{AC}(t)$. 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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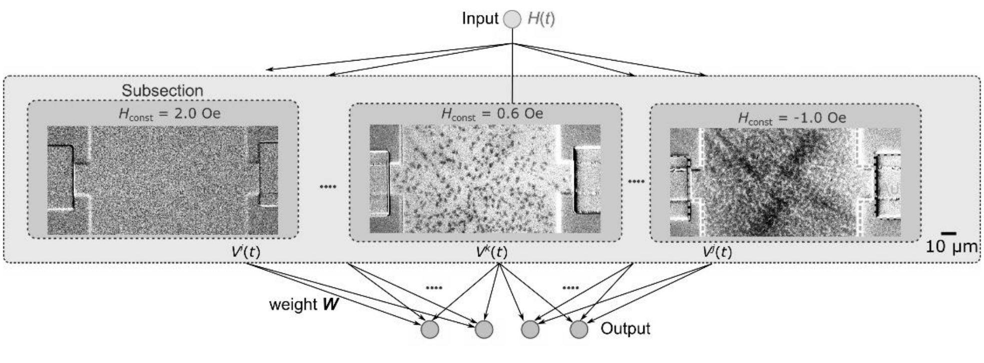

Fig. 1 Schematic illustration of a skyrmion-based neuromorphic computer. Polar Kerr images of Hall bar device with various constant magnetic field (H_{const}) are also presented.

Development of Domain Wall Type Spin Memristor toward Analogue Neuromorphic Computing

T. Shibata[1], T. Shinohara[1], T. Ashida[1], M. Ohta[1], K. Ito[1], S. Yamada[1], Y. Terasaki[1], and T. Sasaki[1]
[1]Advanced Products Development Center, TDK Corporation, Chiba 272-8558, Japan

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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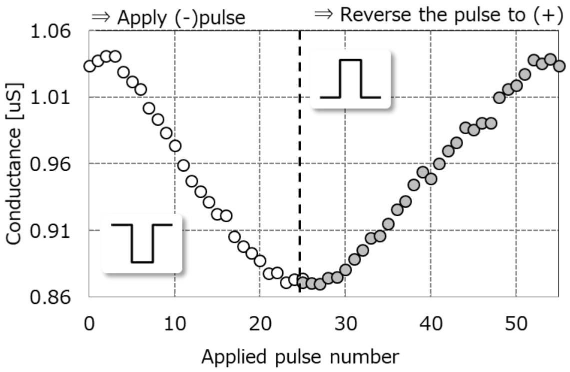

Fig.1 Symmetric conductance response as a function of driving current pulse

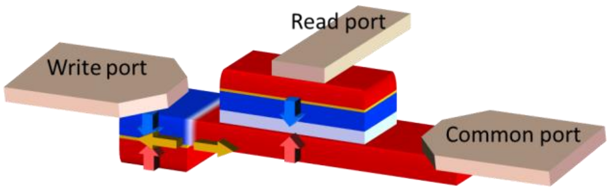

Fig.2 Schematic illustration of the element with SAF-type magnetic fixed layer

Strong magnon-magnon coupling in synthetic antiferromagnets

Yoichi Shiota[1], Tomohiro Taniguchi[2], Mio Ishibashi[1], Takahiro Moriyama[1], and Teruo Ono[1,3]
[1]Institute for Chemical Research, Kyoto University
[2]National Institute of Advanced Industrial Science and Technology (AIST), Spintronic Research Center
[3]Center for Spintronics Research Network, Graduate School of Engineering Science, Osaka University

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 ($k = 0.0\ \mu\text{m}^{-1}$, 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 ($k \neq 0.0\ \mu\text{m}^{-1}$) in ferromagnetic-metal-based synthetic antiferromagnets (SAFs) of FeCoB/Ru/FeCoB[9].
Figures 1(a)-1(c) shows the spin wave resonance spectra ($k = 1.2\ \mu\text{m}^{-1}$) 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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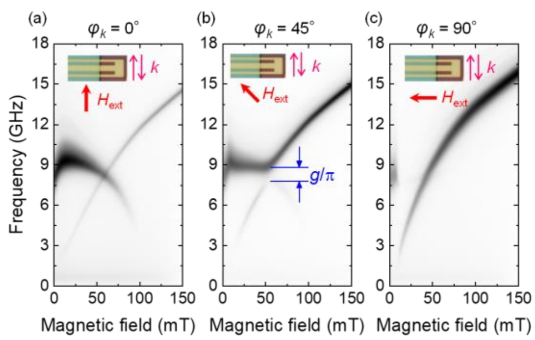

Fig. 1 Contour plots of Re[S_{11}] for spin wave resonance spectra ($k = 1.2\ \mu\text{m}^{-1}$) at (a) $\varphi_k = 0°$, (b) 45°, and (c) 90°.

Measurement and control of spin quantum states utilizing semiconductor quantum dots

T. Otsuka[1,2,3], T. Nakajima[3], M. R. Delbecq[3], P. Stano[3,4], S. Amaha[3], J. Yoneda[3], K. Takeda[3], G. Allison[3], S. Li[3], A. Noiri[3], T. Ito[3], D. Loss[3,5], A. Ludwig[6], A. D. Wieck[6], and S. Tarucha[3]
[1]Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577, Japan
[2]Center for Science and Innovation in Spintronics, Tohoku University, Sendai 980-8577, Japan
[3]Center for Emergent Matter Science, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[4]Institute of Physics, Slovak Academy of Sciences, 845 11 Bratislava, Slovakia
[5]Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel
[6]Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, D-44780 Bochum, Germany

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.

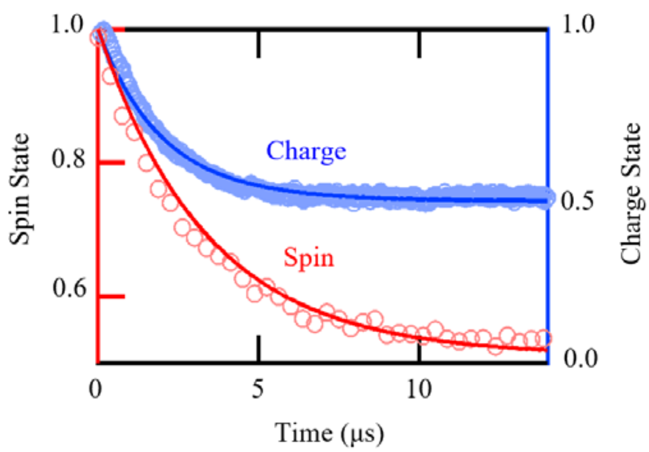

Fig. 1. Measured dynamics of the spin and charge states by a semiconductor quantum dot sensor.

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

Yuichi Kasahara
Department of Physics, Kyoto University, Kyoto 606-8502, Japan

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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