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The Basis of Magnon Transistors

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In the development of spintronics motivated by the concept of spin-current, a number of promising phenomenon for ultralow-power consumption devices were discovered. Among these phenomenon, we review the progress in magnonics research, which manipulates a magnon (spin) current, and discuss present issues and future plans for the development of magnonics research.

INTRODUCTION

A. Spin-wave as a non-charge information carrier

Modern electronics uses the charges of electrons as information carriers, and semiconductor technology allows for the robust control of charge flow. Through electronics, researchers have developed highly integrated systems such as laptop computers and smart phones, and these technologies have created dramatic changes in modern society. The developments of semiconductor technology suggest new classes of devices, such as wearable and IoT (Internet of Things) devices, and can generate enormous amounts of information, up to YB (10^{24}). However, society requires clean energy sources and more energy efficient devices for the data processing. The electronic realm is now facing a dilemma, i.e., the realization of fast processing and low energy loss operation.

In light of this background, the spin of an electron is now considered to be a promising information carrier because the controlling energy of spin is much smaller than the charge flow. Spin flow (spin-current) has now succeeded in building the concept of spin-FET[1], spin-RAM[2], and STT-RAM[3], to reduce the total energy consumption of electron-based devices. Interestingly, the spin-current is the flow of spin-angular momentum and can propagate into not only a conductor but an insulator [4]. Thus a spin-current, especially a spin-wave, is considered to be a promising information carrier. The applied research, including transistor, thermal transport, and thermoelectric conversion [5] by spin-wave, is now developing rapidly.

B. Potential of magnonics

A research field that aims for the creation of ultralow power consumption devices by manipulating spin waves in micro- fabricated devices is now called “magnonics” [6, 7], whereby a spin-wave is treated quantum mechanically and described by a quasi-particle of “magnon”[8]. The crucial difference of magnonics from electronics is that the flow of magnon is a flow of angular momentum and generates no Joule heating. Furthermore, magnons have a potential to transmit information with GHz-THz carrier frequencies. Magnon can be created by electric microwave in general; however, it is also possible to generate magnon by thermal and optical methods. Magnonics now has become a multidisciplinary research field including electronics, magnetics, thermal engineering, and optics, and shows potential in the creation of multi-functional device principles [9]. For example, there is the possibility to create a non-Boolean logic and a neuron-like signal processing with multi-input/output architecture.

CONCEPT OF MAGNON TRANSISTOR

Magnon was recently proved to be a non-charge carrier in signal processing, using a Yttrium-Iron-Garnet (YIG) crystal made by liquid phase epitaxy (LPE) [10]. Figure 4 shows the basic structure of a “magnon transistor”. Mirroring the electron transistor,single source (S), drain (D), and gate (G) electrodes are made on top of a YIG waveguide.

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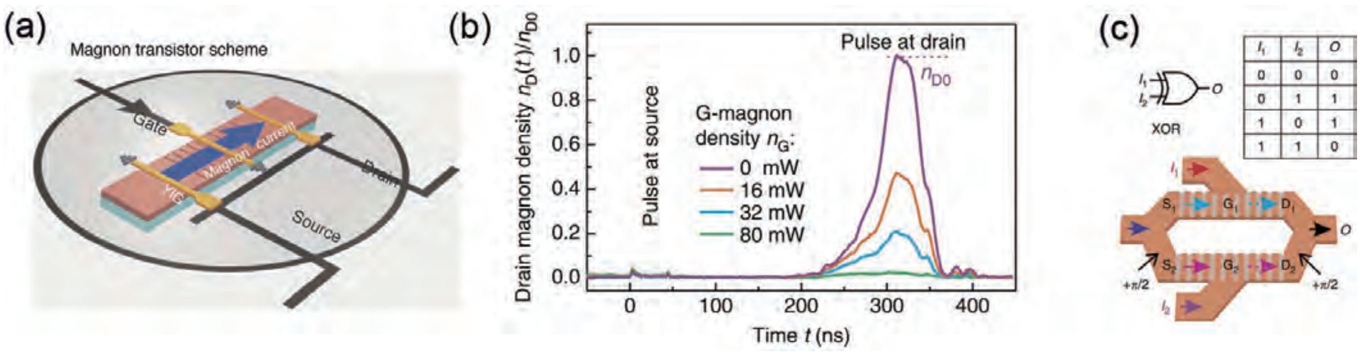

Fig. 1: Basic structure of a magnon transistor. (a) YIG waveguide with grooves (300 μm spatial periodicity) was placed in the center. Single source (S), drain (D), and gate (G) electrodes were fabricated on the top of YIG. (b) The evolution of drain magnon density by changing the power of gate microwave signals. (c) Example of a logical XOR using the magnon transistor. Copyright 2014 Authors. Creative Commons License from Ref. [10].

Magnons generated by the source electrode (source magnons) flow into the drain, passing through the gate electrodes. Here, note that periodic grooves were made on top of YIG waveguide with 300 μm spatial periodicity at the gate region. This is called a magnonic crystal and acts as a frequency filter; magnons fulfill the Braggs condition ($k_a = m \times \pi/a$, where m is an integer and a is a lattice constant) can be strongly localized in the magnonic crystal. The localized magnons (gate magnons) bring about the nonlinear 4-magnon scattering with the source magnons, resulting in the decrease of magnon density at the drain. In Fig. 1(b), the change of drain magnon density is demonstrated by controlling the gate magnon. When increasing the power of the gate signals from 0 to 80 mW, the drain signal becomes weaker due to the 4-magnon scattering and is suppressed significantly.

Figure 1(c) shows an example of the magnonic application that is represented by the True/False table of exclusive OR (XOR) operation. By constructing a Mach-Zehnder interference circuit, the source magnons are split into different arms (S_1 and S_2). By modifying the length of the bottom-side arm, an initial phase of the magnon current S_2 is set to have $\pi/2$ difference from S_1. In this structure, when input magnon currents I_1 and I_2 are 0, the output magnon current (O) becomes 0. If either I_1 or I_2 is 1, the output magnon current becomes 1 showing XOR operation.

The importance of the prototype of the magnon transistor is that we can tentatively estimate power consumption. The current device's dimensions are 5.5 μm $\times$ 1.5 μm $\times$ 6 mm and electric power for the gate input requires 2.5×10^{-9} J, which is much higher than CMOS devices (10^{-16} J). However, if we can reduce the dimensions down to 20 nm $\times$ 100 nm $\times$ 0.5 μm, the electric power is proven to go down to 4.8×10^{-18} J, two orders smaller than CMOS devices. The downsizing of a YIG crystal by introducing the pulse laser deposition (PLD) method is thus one of the main and current experimental issues.

MAGNONIC LOGIC OPERATIONS

A. Logic operation by phase interferences

Metallic magnets allow for the downsizing of magnonic applications due to the micro-fabrication technique, and it has already been possible to execute the logic operation in micro scale devices utilizing magnon phase interferences [11–13].

Figure 2 shows a three-terminal logic device used to perform the 1/0 logic operation by magnons (spin waves). The width and thickness of a FeNi microwire is set to be 2.5 μm and 35 nm, respectively. Spin waves are excited by both the left side and right side electrodes using microwave signals [14]. By changing a phase of the excitation microwave, spin waves emitted excitation antennas show constructive and destructive interferences in the central region. In Fig. 2(b), a spatial distribution of magnon density probed by Brillouin light scattering (BLS) spectroscopy is shown, detecting six distinct peaks. Note that the stronger density shown in the color red enables the "1" output, and that the blue region corresponds to the "0" output. The phase interference shows the possibility to achieve a multiple input/output device principle.

As shown in Fig. 2(b), the magnonic logic operation is demonstrated in the center region of the microwire indicated by an effective width (W_{eff}~1 μm), which is defined by a wave confinement and a demagnetizing field in the microwire. Of note is that the effective width can reduce the effect of stray fields when several magnetic microwires are placed nearby.

This three-terminal device clearly demonstrates that the phase interference has excellent controllability; however, at present, the operated signal is not extracted as a magnon current and is impossible to use for a successive logic operation. For the further development, we should improve the magnonic logic architecture. Another issue is that the phase of spin waves are controlled by an external phase shifter. Fortunately for this issue, another phase control method was discovered. Spin-wave nonreciprocity enabled 1/0 logic operation without an external phase shifter.

B. Logic operation by edge-mode nonreciprocity

As mentioned in the previous section, spin-wave nonreciprocity has the potential to provide 1/0 logic operation. Recently, a different logic unit was proposed using a new type of nonreciprocity discovered in an anisotropic ferromagnetic Fe waveguide [15]. The basic unit of the magnonic gate is depicted in Fig. 3(a), which consists of control line (Y), an input line (Input), an Fe waveguide, a source and detection antennas. By injecting a combination of input and Y signals, we can create a vector local magnetic field around an Fe waveguide. In the remanent state ($H_{ext} = 0$), the magnetization of the Fe waveguide is then controlled to direct easy axis. Since the cubic anisotropy of Fe allows 4 different magnetization directions, a spin-wave generated by the source antenna shows an asymmetric wavefront as shown in Fig. 3(b) and 3(c), according to the magnetization directions; the spin-wave densities of the top and bottom sides of the waveguide, at the detection antenna, exhibit a strong nonreciprocity (edge-mode nonreciprocity).

As shown in Fig. 3(d), in the case that the control Y=0, the direction of H_y is set to be ↑. If the input line is signaled by a negative (positive) current, the direction of H_x is set to be ←(→), resulting in the output "1" ("0") at detection antenna. The unit acts as the NOT gate. In the case that the control Y=1 as shown in Fig. 3(e), the direction of H_y becomes ↓. If the input line is signaled by a negative (positive) current, the direction of H_x is set to be ←(→), resulting in the output "0" ("1"). The unit acts as the PASS gate.

By combining the two units as shown in Fig. 3(f), the XOR [Fig. 3(g)] and XNOR (not shown) gates can be constructed. In this way, the combination of three units provides AND, NAND, OR, and NOR gates. Logic gates using edge-mode nonreciprocity allow a no-field operation and a simple architecture. The current issue is that these prototypes convert the magnon currents many times into electric currents. In the viewpoint of present magnon-electron conversion efficiency, it appears to be difficult to construct an integrated transistor. However, this logic architecture suggests the virtues of spin-wave nonreciprocity: reconfigurable and nonvolatile operations.

MAGNONIC MAJORITY GATE

Recent magnonics experiments also succeeded in con-

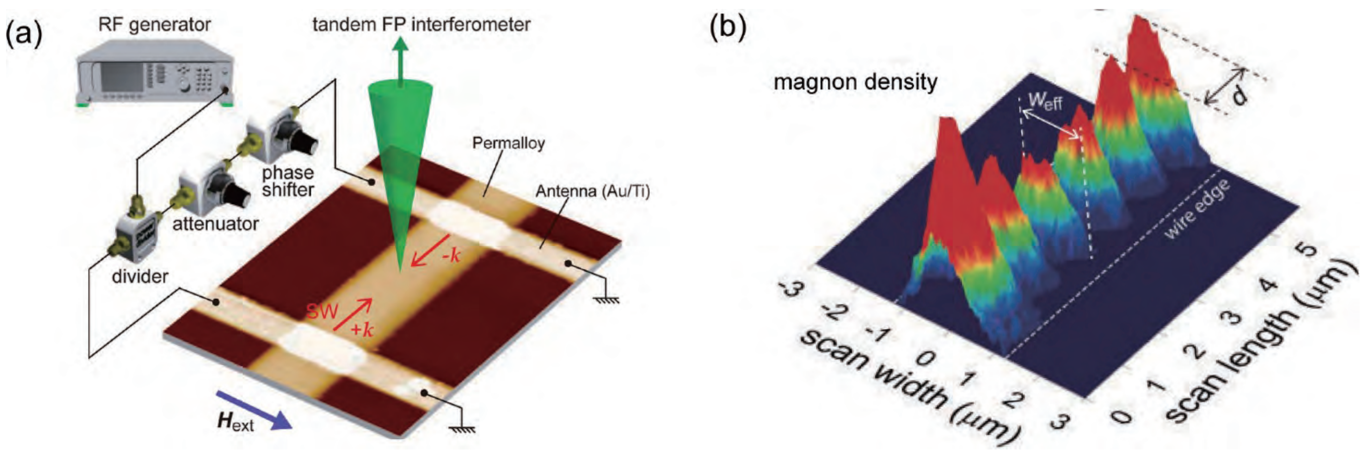

Fig. 2: (a) Schematic of experimental setup to visualize the phase interferences (magnonic logic operation). The center microwire is made by a permalloy that is 2 μm in width and 35 nm in thickness. The left and right side electrodes are excitation antennas. The magnon density is detected by the 532 nm laser. (b) Magnon density at the interface observed by Brillouin light scattering spectroscopy. Copyright 2016 The Japan Society of Applied Physics from Ref. [12].

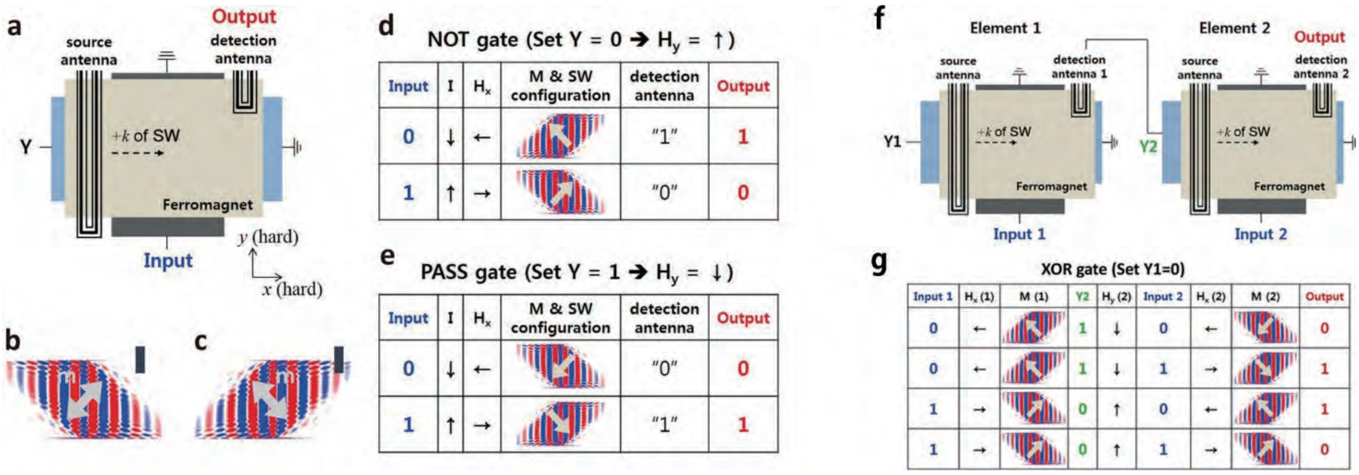

Fig. 3: (a) Schematic of logic gates using edge-mode nonreciprocity. Epitaxial Fe waveguides were located on top of input and Y wires. (b)(c) Wavefront of spin waves in different magnetization directions, showing the edge-mode nonreciprocity. True/False tables for (d) NOT gate and for (e) PASS gate. (f) Schematic architecture for an XOR gate and (g) the XOR gate's True/False table. Copyright (2017) Authors. Creative Commons License from Ref. [15].

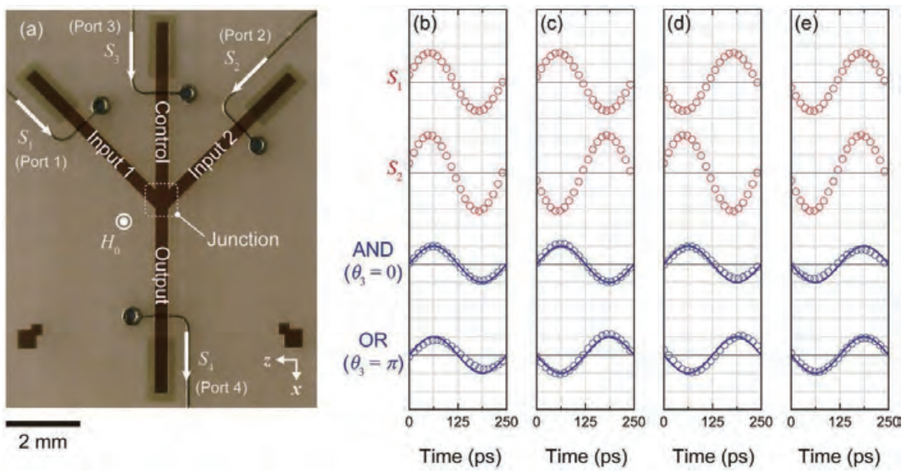

Fig. 4: Magnonic majority gate made by a YIG ψ-shaped device. (a) Image of an optical microscope of the device consisting of the control (S_3), two inputs (S_1, S_2), and output (S_4) terminals. (b)-(e) Waveforms of output signal S_4 for each combination input S_1 and S_2. The control signal S_3 is set to be 0 or π. Copyright (2017) Authors. Creative Commons License from Ref. [16].

structing a magnonic majority gate using the spin-wave interference effect[16, 17]. Figure 4 shows a prototype of a logical AND (OR) device. The ψ-shaped device was made of a YIG single crystal having 350 μm in width and 10 μm in thickness. The ψ-shaped device consists of a control (S_3), two inputs (S_1, S_2), and output (S_4) terminals. A logic operation (interference) will be realized in a center junction. Note that 10-nm thick Au films were evaporated at every end of the terminals in order to increase the signal-to-noise (S/N) ratio. In this device, the forward spin-wave mode (FVSW) was chosen to keep the isotropic propagation.

As shown in Fig. 4(b)-(e), we control two inputs (S_i, i = 1, 2) to have the same (θ_i=0) phase or opposite (θ_i=π) phase (see the upper side of each panel). If we set the initial phase of control S_3 to be θ_3=0, the output phase θ_4 represents the majority of θ_i: MAJ(θ_3, θ_2, θ_1); we have an AND logic operation at the output signal S_4 (bottom of each panel). However, if we set S_3 to be π, we have an OR logic operation at S_4. Furthermore, if we modify the position of excitation input electrodes (thus the initial phase of initial inputs), the logical NAND and NOR gate can be constructed. Surprisingly the logical NAND gate can be realized by a single ψ-device, and we do not need to construct a multi-stage structure like an electric CMOS device. The ψ-device suggests that a wave-based device can simplify a multi-input operation and reduce operation delay.

PRESENT ISSUES AND FUTURE PROSPECTS

As shown in the previous sections, the magnonics research exhibits several promising features. In particular, experiments using YIG crystals developed device prototypes and device principles owing to its ultralow magnetic damping. However, the integrated structure and miniat ualized circuits have not yet been achieved. Experiments with metallic magnets have suggested many magnonic microstructures and functions. However, the stronger magnetic damping of a metallic system appears to prevent implementation in real chip devices. At the present stage, both material systems exhibit advantages and disadvantages. We believe that the spintronics technique, including spin injection, spin Hall effect, and spin torque effect, can make a breakthrough in both material systems.

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