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# Enhanced Magnetoresistance in NiFe/GaAs/Fe hybrid Magnon Valve

Long Yang, Nicholas Shipp, Yong Pu, Yequan Chen, Yiyi Chen, Liang He, Xuezhong Ruan, Wenqing Liu and Yongbing Xu

***Abstract*—Magnon valve, which consists of one spacer layer sandwiched between two ferromagnetic layers, is a novel spintronic device. The operation principle of magnon valve depends on magnon current propagating between the two magnetic layers. More specifically, the magnon current is induced in one ferromagnetic layer and then injects magnons into the other ferromagnetic layer through the spacer layer. During this process, the magnetization of the injected ferromagnetic layer is changed, leading to the different relative magnetic orientations of the two magnetic layers. Here, we investigate the electromagnetic property of NiFe/GaAs/Fe magnon valve assisted by microwaves with various frequencies. We find that the magnetoresistance of the magnon valve increases up to 40% when applying an external 3.4 GHz microwave. The increase of the magnetoresistance results from the magnon current propagating between the two ferromagnetic layers. As the magnons induced by the external microwave have the same phase, the magnon current can penetrate 70 µm thick GaAs by coherent propagation.**

***Index Terms*—Magnetoresistance, Microwave, Magnon, Coherent propagating.**

## I. Introduction

Spin valve (SV) [1, 2] is a fundamental spintronic device consisting of one layer of nonmagnetic material sandwiched between two magnetic layers. In the past decades, SV is widely studied for its abundant function in spintronic devices such as magnetic random access memory (MRAM) [3], magnetic reading head [4], and so on. The relative magnetic orientation between the two magnetic layers plays a key role in the performance of SV: The parallel magnetization orientation of the two magnetic layers corresponds to low-resistance state while the antiparallel orientation is high-resistance state. These two different states are well known as giant magnetoresistive effect (GMR) [5, 6]. In order to manipulate the relative magnetic orientation of the two magnetic layers, several methods are used, such as inducing spin-polarized electrons based on spin transfer torque (STT) effect [7, 8], importing pure spin current by spin orbit torque (SOT) [9, 10], and so on.

It is notable that in the above methods, SV exists a lot of energy dissipation to change the relative magnetic orientation of the two magnetic layers. For example, the STT-SV requires the external current flows through SV to transfer magnetic moment, and the critical current density is more than $10^7$ A/cm$^2$ [7], which inevitably induces Joule heating. To avoid Joule heating, magnons are used as the carrier of magnetic moment, because magnons are the collective excitations in magnetic systems like phonon in the crystal, so the dissipation of magnon propagating in magnetic materials is negligible. Recently, Wu et al. [11] came up with a new concept: magnon valve (MV). It works similar to SV but the carrier of spin is different. Comparing with SV, MV works based on the magnon propagating through the spacer layer. During this process, the magnon current changes the relative magnetic orientation of the two magnetic layers. The difference between the SV and MV is that SV requires external field or an external electric current to change the relative magnetic orientation. As for MV, it depends on magnons to achieve such a function, so the MV consumes less energy than SV. In recent years, studies show several ways to induce magnon in the magnetic system [12-18]. The most common one is to apply a thermal gradient on the interface between nonmagnetic metal with strong spin-orbit coupling and ferromagnetic insulator. As a result, the magnon is induced at the edge of the interface, which is called spin Seebeck effect (SSE) [12, 13]. Femtosecond pulse laser is also able to excite the coherent magnon in the ultrafast dynamic process [14, 15]. In addition, by using microwave pumping, one can directly inject the magnon to ferromagnetic insulator and control the density of the magnon during the injection [16-18]. In this work, we designed and fabricated for the first time a ferromagnetic metal-semiconductor hybrid magnon valve. The frequency dependence of the magnetoresistance effect has been studied and large magnetoresistance up to 40% has been observed at room temperature.

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## II. Device Fabrication

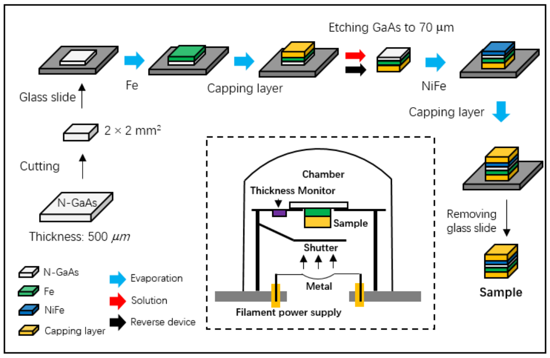


Fig. 1. (Color online) Schematic fabrication process of the hybrid magnon valve. The sandwich structure where the thickness of GaAs is 70 μm.

The proposed magnon valve in Fig. 1 consists of three layers: Fe, NiFe and silicon doped n-type GaAs. The GaAs is the spacer layer. At present, the longest spin diffusion length is over 100 μm in semiconductor [19, 20], so we etched the GaAs layer to a thickness of 70 μm to make magnon pass through the spacer layer in our device. We fabricated the device following the process as shown in Fig. 1: a segment of a 500-μm silicon doped n-type GaAs substrate was cut into the square samples with a length of 2 mm at the beginning of the fabrication process. Before deposition, we performed a series of cleaning processes on the substrate to ensure a clean and smooth surface. Firstly, we cleaned the GaAs substrate with acetone, and then washed out the substrate with deionized water. Next, the substrate was blow-dried with dry nitrogen to ensure that no solvent or water remained on the surface. The following preparation step was to place the GaAs in a $H_2O_2$ : $H_2O$ : $4H_2SO_4$ solution for 80 seconds to etch off the surface of the wafer. At last, we washed the substrate with deionized water and dried the substrate with nitrogen as before. The substrate was too small to be fixed in the deposition chamber, so we used wax to join the small square substrate onto a glass slide to continue the deposition. Fe of 21 nm, Cr of 14.7 nm and Al of 228 nm were evaporated onto the substrate, successively. In order to decrease the thickness of GaAs, we removed the glass on the bottom of the simi-manufactured device and then immersed the one-side device in the solution prepared by $8H_2O_2$ : $H_2O$ : $H_2SO_4$ to etch the other side of GaAs. It is noted that the etching rate of GaAs is not a constant, so we monitored the height of the device using a microscope. We measured the distance from the lens to the slide, and then the distance from the lens to the device. The difference between these two distances was thus the height of the GaAs plus the metals already evaporated on the other side of the device. Every 15 minutes the device was taken out of the solution, rinsed with water and dried with nitrogen in order to record the height accurately. Finally, we etched the GaAs layer to the thickness of 70 μm. At the last step, we reversed the one-side device and then evaporated NiFe of 20 nm, Cr of 11.4 nm and Al of 62 nm onto the other side of the 70 μm thick GaAs, successively.

## III. Results and Discussion

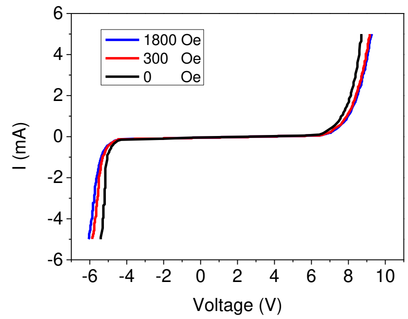


Fig. 2. (Color online) The I-V characteristics of the hybrid magnon valve in the external magnetic field of 0 Oe, 300 Oe, and 1800 Oe, respectively.

First, we measured the I-V property of the device under different magnetic field levels. Two electrodes located on the top and bottom of the device respectively were used to connect the experimental circuit. A Keithley source meter was used to input the DC current and measure the voltage. A specially constructed device holder was used to connect the device to the source meter and hold the device within the magnetic field. The current was applied in a step of 0.049 mA from 0 A to +5 mA, then down to –5 mA and back to 0 A. The voltage across the device was recorded for each current value. Each curve was repeated three times. As shown in Fig. 2, the I-V curve changes when we set the external magnetic field as 0 Oe, 300 Oe and 1800 Oe. It indicates that the resistivity of the device reduces with the external magnetic field increasing. In addition, the I-V curve in Fig. 2. is not symmetric because the turn-on voltage is around -5 V and +7 V for negative and positive voltage respectively. The device consists of Fe/GaAs/NiFe, which exists two metal–semiconductor interfaces, so there are two different Schottky barriers , leading to the asymmetric I-V curve.

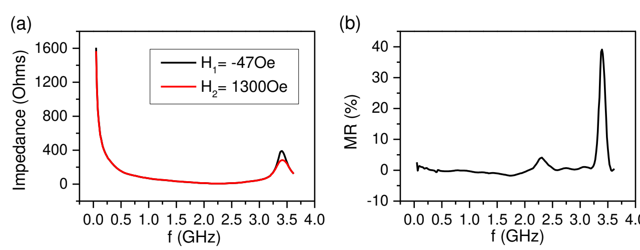


Fig. 3. (Color online) (a) The impedance-frequency response of the device at $H_1$=-47 Oe and $H_2$=1300 Oe. (b) The MR-frequency response.

Next, we used a vector network analyzer to measure the character of the device responding to microwave. The frequency response of the device was measured from 40 MHz to 3.6 GHz with the device orientated in its hard axis. We applied two different magnetic fields of $H_1$=-47 Oe and $H_2$=1300 Oe to the device. As shown in the supporting information, the magnetizations of the two magnetic layers of the device are in anti-parallel and parallel configurations, respectively, for these two magnetic fields. Impedance represents the absolute value including dephasing of the resonance. In Fig. 3(a), we can clearly see that the impedance remains high at lower frequencies but drops immediately at higher frequencies, which suggests a series resonance. Due to the different coercivities of Fe layer and NiFe layer, when the external field is $H_1$, the initial magnetization direction of these two layers is in antiparallel (AP) state. When the external field is $H_2$, the original magnetization direction of the two magnetic layers points to the same direction, which is parallel (P) state. In Fig. 3 (a), for both value of magnetic field $H_1$ and $H_2$, a clear enhancement of impedance is observed around 3.4 GHz yet the range of the enhancement is different. It is noted that when external microwave flows through the device, the relative magnetization direction of two magnetic layers could change. Therefore, we define state 1 (S1) and state 2 (S2) to represent the states after applying microwave. S1 means the device is placed in $H_1$ with applying microwave. Similarly, S2 means the device is placed in $H_2$ with applying microwave. Then, we calculate the magnetoresistance (MR) by $MR = (S1 - S2)/S2 \times 100\%$. In Fig. 3 (b), the MR increases up to 40% when the frequency of microwave is around 3.4 GHz. In addition, there is also a small peak around 2.3 GHz in Fig. 3. (b). To get more details, we analyze the differential impedance (S1-S2) versus frequency. The result shows that the resonance frequency 3.4 GHz is still strong but the peak of 2.3 GHz disappears. Therefore, the peak corresponding to 2.3 GHz is pseudo due to mathematical calculation because the value of S2 state is very small as denominator in our MR formula.

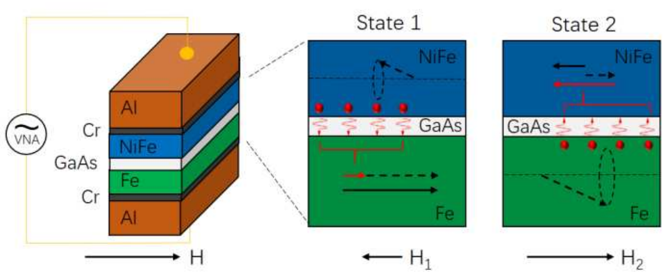


Fig. 4. (Color online) Illustration of the magnon valve device. State 1 and state 2 represent the device state when the external microwave frequency is 3.4 GHz. The dotted black arrow is the original magnetization direction of each magnetic layer decided by $H_1$ or $H_2$. The red arrow is the magnetization transferred by the magnons. When one of the magnetic layers absorbs microwave, the induced magnons (red solid circles) penetrate into GaAs and interact with the other magnetic layer. The solid black arrow represents the final magnetization state influend by both the original magnetization and the transferred magnetization from the magnons.

To explain the significant enhancement of the magnetoresistance, we deduce that when external microwave passes through the device, one magnetic layer absorbs the microwave and thus magnons are induced into this magnetic layer with the same phase. Then the magnons are able to go through the GaAs layer coherently. It is different from the magnon propagation described in Wu et al. [16]. In their work, the magnons are induced by thermal gradient so the phase of each magnon is random. In this way, the propagating process is just the displacement of the magnon. However, in our device the magnon are excited by an external microwave with a stable frequency, so the induced magnons share the same phase and are able to propagate coherently. As shown in Fig. 4, the red solid circles represent magnons. For state 1, The device is AP state under the magnetic field of -47 Oe. When microwave of 3.4 GHz flows through the device, the NiFe layer precesses by absorbing the microwave, resulting in the magnon generation in the NiFe layer. Then the induced magnon current flows through the thin semiconductor layer and interacts with Fe layer. Therefore, the magnetization of the Fe increases. As for State 2, the device is under P state at first when the external field is 1300 Oe. After applying microwave of 3.4 GHz, the resonant frequency of Fe layer is also around 3.4 GHz due to the interfacial effect between GaAs and Fe. Finally, the magnetization direction of NiFe layer is reversed by magnons propagating from Fe layer. For both value of magnetic field $H_1$ and $H_2$, the final state of the device is in AP state. However, these two AP states are different, leading to an increase of magnetoresistance. For S1, the induced magnons from NiFe layer increase the magnetization of the Fe layer. For S2, the induced magnons from Fe layer make the magnetization of NiFe layer reverse.

## IV. CONCLUSION

In this work, a novel hybrid magnon valve was designed and manufactured. The MV consists of a semiconductor layer sandwiched between two ferromagnetic layers. A large increase of magnetoresistance has been observed when applying an external 3.4 GHz microwave. This large increase of the magnetoresistance is attributed to the coherent propagation of the magnon through the semiconductor layer. However, this device is not a pure MV, because the spacer layer is GaAs, which is non-magnetic material. To achieve pure MV, magnetic spacer layer with long magnon decay length could be a good choice, such as YIG. The hybrid magnon valve demonstrated in this work may contribute to the development of the MRAM and spin-FET in the future.

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