Microwave detection based on magnetoresistance effect in spintronic devices

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***Abstract*—We demonstrate a radio-frequency electromagnetic signal detection in spintronic devices utilizing various magnetoresistance effects. Different device layout is proposed such as tunneling magnetoresistance nano-pillar or giant magnetoresistance stripe, which enable DC voltage generation when a device is supplied with radio-frequency current. Depending on the detection method, sensitivity of up to 80 V/W was achieved in a frequency range between 1 - 10 GHz, depending on the magnetic field.**

***Index Terms*—spintronics, microwave detectors, ferromagnetic resonance**

I. Introduction

Ferromagnetic thin films can emit or absorb electromagnetic signals in a microwave frequency range due to spin waves excitation's. In addition, in such films, resistance is a function of the magnetization vector, arising from magnetoresistance (MR) effect. Magnetization vector can be controlled using external magnetic field, or, more efficiently, by spin polarized current using so called spin transfer torque (STT) effect [1]. Combining all these physical effects, by means of spin-torque diode effect [2] absorption of the radio-frequency (RF) signal can produce a measurable DC voltage due to mixing of the RF current and oscillating resistance of the device. Different magnetoresistance mechanisms are observed in magnetic multilayer thin films, such as anisotropic- (AMR), giant- (GMR) [3] or tunneling-magnetoresistance (TMR) [4]. AMR of a fraction of a per-cent is measured in most of ferromagnetic thin films (Fe, Ni, Co and their alloys) when a magnetization direction changes with respect to the current direction. In more complicated structures, such as ferromagnet / normal-metal / ferromagnet multilayer system, a stronger GMR of a few per-cent is measured. Moreover, changing normal metal to an ultra-thin (1-2 nm thick) insulator enables one to use TMR effect, which reaches a few hundred per-cent, however, at a cost of complicity of the multilayer stack and fabrication method. In case of AMR and GMR device a simple strip is suitable, whereas, in case of TMR a more complicated nanometer-sized pillar is needed. In general, magnetization direction is determined by the magnetic anisotropy and external magnetic field. In ferromagnetic thin films, RF current induces spin-polarized electrons, which in turn drives magnetization into precession, which is particularly efficient at ferromagnetic resonance frequency. In this work we aim to present and compare various spintronic microwave detectors from sensitivity, size and performance point of view, also with respect to existing Schottky-diode devices.

II. Experimental

In this paper we examine three groups of devices: AMR consisting of: W(4) / CoFeB(0.9) / MgO(5) multilayer, GMR: Ta(3) / SAF / CoFe(2.1)/ Cu (2.1) / CoFe(1) / NiFe(5) / Ru(0.5) / Cu(1) / Ta(3) and TMR: Ta(5) / SAF / CoFeB(2.3) / MgO(2) / CoFeB(1.6). Thicknesses in parentheses are given in nm. All devices were deposited using magnetron sputtering method on thermally oxidized Si wafer. Synthetic antiferromagnet (SAF) layer system was used to pin the magnetization of bottom magnetic layer in GMR and TMR devices[5]. After the deposition process multilayers were patterned using electron-beam lithography, ion-beam etching and lift-off processes into rectangular stripes of different width, ranging from 1 to 40 μm^2 and 70 μm^2 long or elliptical nano-pillar of 0.28×0.53 μm^2 with appropriate electrode system. Electron microscope images of fabricated devices are presented in Fig. 1.

Sensitivity of the device is determined using microwave signal generator Agilent E8257D and DC voltmeter connected to the device under test (DUT) using microwave cabling and bias-T from Mini-Circuits. Frequency dependent losses of the measurement setup and DUT (originating mainly from the impedance mismatch) were taken into account [6].

III. Results

A. AMR

Firstly, we focus on the simplest device consisting of a single CoFeB layer deposited on the W underlayer and covered with a thin insulator capping. The application of electrical current through the W underlayer induces spin accumulation at W/CoFeB interface due to spin Hall effect, which in turn drives magnetization precession. The input power was set to P_{in} = 10 dBm, which results in about P_{AMR} = 0.87 mW effective power in 10 μm-wide stripe. The magnetic field was swept from 0 up to 3 kOe at the angle of 45 degree with respect to the long axis of the stripe. The mixing DC voltage

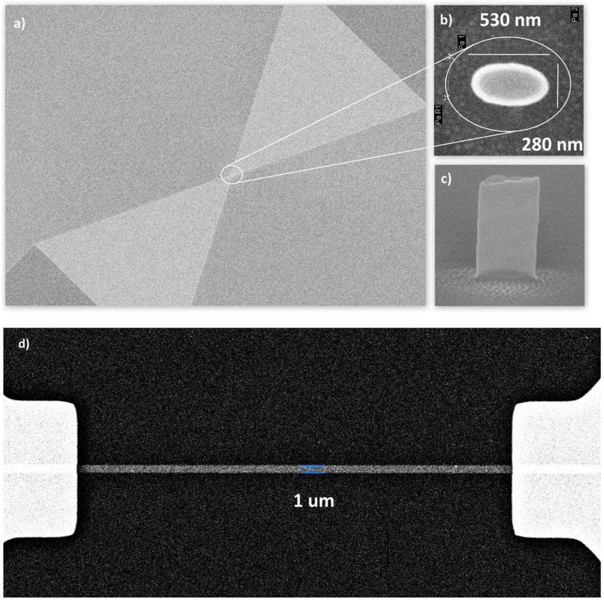

Fig. 1. Example images of fabricated AMR stripe (a) and TMR device (b-d). Typical contact electrodes have 100 × 100 μm^2 size. TMR nano-pillar is placed at the intersection between top and bottom electrode (b), magnified image in (c) and side view on (d).

reaches 0.25 mV at the test frequency of 4 GHz. By taking into account the measurement setup losses, the resulting sensitivity is about 0.3 V/W. DC voltage as a function of the external magnetic field and frequency is plotted in Fig. 2. The optimal conditions for the detection is determined by the effective magnetic anisotropy and external magnetic field [7].

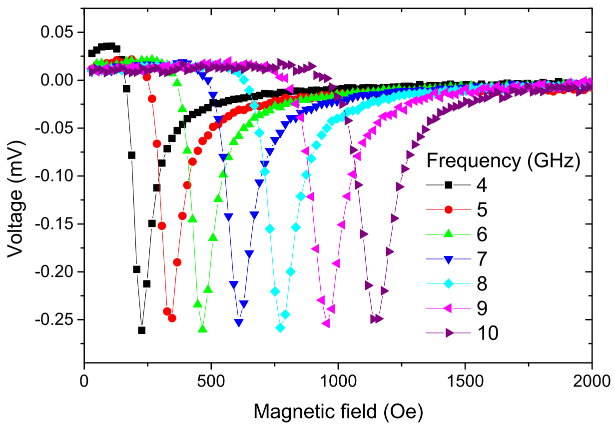

Fig. 2. Mixing DC voltage as a function of the external magnetic field measured for different input frequencies. The power delivered to the stripe was P_{AMR} = 0.87 mW.

B. GMR

Next, we present results from the GMR stack. In this case, the majority of the RF current flow through a low resistive Cu spacer [8], which produces the RF Oersted field. This field induces the precession of the magnetization vector and, thus, the resistance oscillations through the GMR effect. The MR ratio in this device reached 8 %. In this case the power delivered to the device is P_{GMR} = 3 mW. The sensitivity at the resonance reaches 2.5 V/W. Contrary to AMR and TMR (discussed later), where the spin torque effect is responsible for the resistance change through angular precession of the magnetization vector [9], in case of GMR stripe the magnetic Oersted field drives the magnetization angular precession, therefore, the shape of the curve is asymmetric - Fig. 3. The dependence of the maximum output voltage vs. input power is depicted in the inset of Fig. 3.

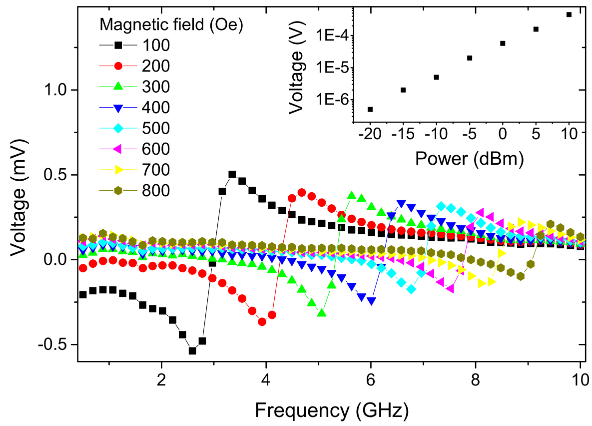

Fig. 3. Voltage vs. input frequency dependence for different magnetic fields. Inset presents the output voltage vs. input power.

In addition, the RF signal detection in case of GMR can be realized also at the frequencies below the resonance, i.e., in a much broader range, at the cost of the sensitivity. In such case, the operation of the detector is less dependent on the magnetic field [6].

C. TMR

In case of the magnetic tunnel junction exhibiting the TMR effect, the current has to flow perpendicular to the multilayer structure, therefore, the fabrication technique includes three-step process with separate bottom and top contact. In such device, the electrons passing one ferromagnetic layer are spin polarized and tunnel through 1.6 nm-thick MgO insulating tunnel barrier. Depending on the relative orientation between magnetization vectors of the top and bottom layer, spin polarized carriers exert torque on the top ferromagnet, which leads to the resistance change. Because the TMR effect measured in the fabricated device reached 100%, a higher sensitivity is also expected [10]. In case of TMR device, the maximum voltage applied to the tunneling barrier cannot exceed 1.5 V, because of a possibility of the electrical breakdown [11]. The input power in this case was, therefore, limited to P_{in} = -10 dBm, which resulted in P_{TMR} = 1.1 μW. At resonance condition (test frequency 1.6 GHz and external magnetic field H = 600 Oe) the output power reached 45 μW and sensitivity was calculated to 86 V/W. We note that for smaller input power and in the electric bias condition even higher sensitivity of up to 12000 V/W was measured [12], which are competing with existing semiconductor detectors.

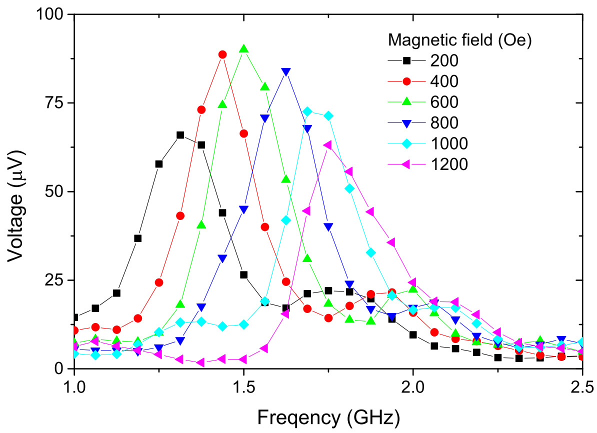

Fig. 4. Output voltage vs. input frequency dependence for different magnetic fields measured in TMR device. In this case the power delivered to the device is P_{TMR} = 1.1 μW.

IV. Discussion

Table I contains comparison of different aspects of spintronics microwave detectors design and operation. Clearly, with higher MR ratio the sensitivity increases. In case of TMR device, the sensitivity reaches tens of V/W, however, if properly biased, it can be comparable or even greater than a typical silicon Shottky Diode detector [13]. The main difference between operation of the spintronic magnetoresistive detectors and semiconductor diodes is that they need external magnetic field for the operation. This requirement can be easily fulfilled by integration of the bias coils on the device chip. In addition, spintronic devices typically have a narrow detection band, which can be used as a frequency-sensitive detectors in a real applications. Moreover, the build-in magnetic bias can be used to tune the frequency-range. Nevertheless, further work is needed to increase the sensitivity.

TABLE I
Comparision between different spintronics detectors. HMIC stands for hybrid microwave integrated circuit.

type	**lithography**	**MR ratio (%)**	**sensitivity (V/W)**
AMR	1-2 step	0.5	0.4
GMR	1-2 step	8	2.5
TMR	3 step	100	86 (up to 12000 [12])
Schottky	HMIC	-	up to 3800

V. Conclusion

In conclusion we fabricated various spintronic devices for the microwave detection comparison. Metallic AMR and GMR device show relatively low MR ratio, which coincides with low microwave sensitivity. On the other hand, TMR device with MR ratio of about 100 % can reach sensitivity range typical for Schottky diodes. Detectors based on spintronic elements need external magnetic field for operation, which limits the detection frequency. However, the need for this additional field can be used to tune the frequency range, in which the device is the most sensitive.

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