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Spin dynamics in magnetic tunnel junctions and related devices

Hitoshi Kubota[1], Akio Fukushima[1], Satoshi Yakata[1], Kay Yakushiji[1], Shinji Yuasa[1], Koji Ando[1], Hiroki Maehara[2], Yoshinori Nagamine[2], Koji Tsunekawa[2], David D. Djayaprawira[2], Naoki Watanabe[2], and Yoshishige Suzuki[1,3]

[1]National Institute of Advanced Industrial Science and Technology (AIST), Nanoelectronics Research Institute, Tsukuba Central 2, 1-1-1, Umezono, Tsukuba Ibaraki 305-8568, Japan
[2]Erectronic Devices Engineering Headquarters, Canon ANELVA Corporation, 2-5-1, Kurigi, Asao-ku, Kawasaki-shi, Kanagawa. Japan
[3]Graduate School of Engineering Science, Osaka University, 1-3 Machikaneyama, Toyonaka, Osaka 560-8531, Japan.

1. Introduction

Spin-transfer related phenomena such as magnetization reversal and microwave emission have been studied extensively in the last decade [1-3]. The new phenomena originate from spin-polarized current flowing through a magnetic multilayer or a magnetic tunnel junction (MTJ). Recently, tunnel magnetoresistance (TMR) effect has revolutionarily increased after the realization of coherent tunneling in MgO-based MTJs [4-6]. Because of the giant TMR, electrical signal due to the spin-transfer induced dynamics become large enough to develop practical devices. In our previous studies, we have demonstrated spin-transfer induced magnetization reversal [7], diode effect [8], microwave emission [9] and negative resistance effect [10] in CoFeB/MgO/CoFeB MTJs exhibiting MR ratios of over 100%. We have also investigated physics of spin-transfer as well as possible applications.

2. Structure of magnetic tunnel junctions

Microstructure of MTJs is illustrated in Fig. 1. The thin Co-Fe-B (2 nm) is a free layer whose magnetization freely switches or precesses by applying magnetic field or spin-polarized current. The thick Co-Fe-B (3 nm) is a pinned layer whose magnetization is fixed by exchange bias through Ru/Co-Fe/Pt-Mn. Tunnel resistance changes depending on the relative orientation of the magnetizations: the resistance is low at parallel configuration and high at anti-parallel configuration. Active junction area was defined in 70 nm x 200 nm using electron beam lithography and ion etching. Thick SiO_2 layer is an insulating layer between the under layer (bottom electrical lead) and Cr/Au layer (top electrical lead). All layers were prepared by magnetron sputtering.

3. Spin-transfer torque induced spin dynamics and rectification

Resistance changes by applying magnetic field (*R-H*) and sequential pulse current (*R-I*) are shown in Figs. 2 (a) and (b), respectively. In the *R-H* loop, the resistance changes abruptly at small magnetic fields due to ordinary magnetization reversal, where MR ratio (= $(R_{\mathrm{High}}-R_{\mathrm{Low}})/R_{\mathrm{Low}}$x100) is about 140%. In the *R-I* loop, resistance jumps at +0.4 mA and -0.3 mA, due to magnetization reversal induced by spin-transfer torque (STT).

The mechanism of STT is schematically shown in Fig. 3. Spin of conduction electrons is polarized in the thick magnetic layer (Polarizer) and reorients along the local spin in the free layer. The change of spin-angular momentum before and after passing the free layer is transferred to local spin in the free layer, producing the STT. Because required current for STT switching decreases with decreasing cell size, STT switching is scalable writing technology for magnetoresistive random access memory (Spin-RAM) with nonvolatility, large capacity, and low energy consumption [11].

STT can also stimulate ferromagnetic resonance (FMR). By applying RF current to the MTJ (experimental setup is shown in Fig. 4), spin precession is enhanced at FMR frequency, where DC voltage peak is observed. Here, the precession angle is still small (<1 degree). Because this rectification effect is a kind of homodyne detection, we named it *spin torque diode* (STD) *effect* [8]. Typical examples of STD spectra are shown in Fig. 5. Diode signal exhibits a peak around 6.6 GHz, which is a resonance frequency of the free Co-Fe-B layer. Peak shape depends on bias current, reflecting bias dependence of STT. Precise STD measurement gives important information for manipulating the STT in actual spin-torque devices [12].

4. Proposals for new STT-based devices

By controlling the magnitude and direction of STT and magnetic field torque independently, we have given three novel functionalities to MTJs. (1) Large-angle precession in FMR frequency can be stabilized under large STT and opposite field torque. This phenomenon attracts a great deal of notice as a new type of *microwave oscillator* [9]. (2) When TMR is very large (>150%), junction resistance can decrease with increasing bias voltage, that is *negative resistance* [10], which is essential to amplification in an electronic circuit. Next step is realization of real amplification (gain > 2) of RF signals. (3) Probabilistic switching is realized when STT switching is thermally assisted. We have applied the probabilistic switching to *random number generator* (we named it *Spin Dice*), which is fast, nonvolatile and easily integrated.

5. Conclusion

Giant TMR in MgO-MTJs with spin-transfer torque opens new fields of physics and application in spintronics. The larger TMR ratio becomes more widely MTJ will be used in various electronic devices [13,14]. We investigated detailed mechanism of STT and proposed various STT-based devices.

Acknowledgements

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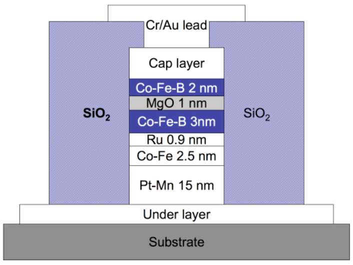

Fig. 1 Schematic illustration of the magnetic tunnel junctions. The thin Co-Fe-B layer is a free layer and the thick Co-Fe-B layer is a pinned layer. MgO is a crystalline tunnel barrier.

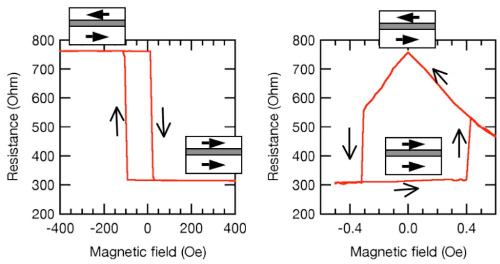

Fig. 2 Resistance change as a function of (a) applied magnetic field and (b) applied pulsed currents. In the anti-parallel magnetization configuration, resistance decreases with current, which is originated in the inelastic tunneling process. Resistance jumps at 0.4 mA and -0.3 mA are due to spin-transfer torque.

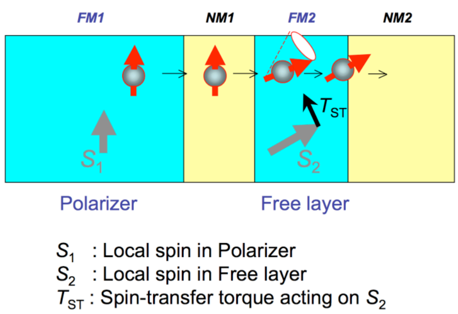

Fig. 3 Electron spin conduction in magnetic layered system and spin-transfer torque. The transverse component of the conduction spin is transferred to local spin in S2, producing the spin-transfer torque.

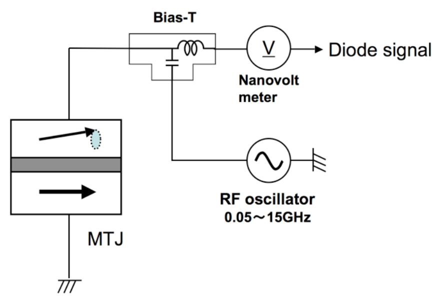

Fig. 4 Measurement setup for spin-torque diode effect. The MTJ rectifies microwave current like a homodyne detector.

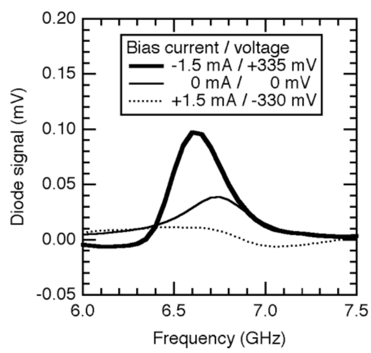

Fig. 5 Spin-torque diode spectra observed the in Co-Fe-B/MgO/CoFe-B MTJ. The spectrum shape reflects magnitude and phase of STT depending on a DC bias.