# MRAM, CRAM and Magnetic Logic – New Physics and Materials

**Jian-Ping WANG[1-3], Jun-Yang Chen[1], Mahendra DC[2], Yang Lv[1], Zhengyang ZHAO[1], Pro Sahu[3]**

1) Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN 55455
2) Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, MN 55455
3) Physics Department, University of Minnesota, Minneapolis, MN 55455

## I. INTRODUCTION

The manipulation of the intrinsic properties of ferromagnetic materials offer abundant functionalities for developing novel memory and computing systems. [1] The first candidate is magnetic random-access memory (MRAM), where the information is stored in a magnetic tunnel junction (MTJ) with different magnetization orientations. A recently proposed and demonstrated candidate is the computational random-access memory (CRAM), where the computing is carried out using a standard MRAM array [2,3]. The third candidate is magnetic logic devices including but not limited to recently proposed MESO [4] and CoMET devices [5]. A new magnetization switching mechanism, spin orbit torque (SOT) generated from an in-plane charge current through orbit-to-spin momentum transfer in a heavy metal/ferromagnet (FM) bilayer system, provides new means for MRAM, CRAM and magnetic logic devices with write and read separation. [6] It could solve the reliability issue and realize energy-efficient and fast switching. Recently, it has been found the charge-to-spin conversion efficiency can be greater than one in crystallized topological insulator (TI) due to spin-momentum locking. [7] In this talk, first, we will report our recent discovery on the giant SOT efficiency in polycrystalline topological insulator bismuth selenide prepared by a sputtering process [8]. The related new physics based on the quantum confinement effect will be discussed. [9] Second, we will report the unidirectional spin Hall magnetoresistance (USMR) observed in TI/FM bilayer system and its implication for 3D MRAM and CRAM applications. [10] USMR will provide a highly desirable two-terminal reading scheme for SOT devices.

## II. EXPERIMENTAL DETAILS

To characterize SOT arising from sputtered bismuth selenide films, thin films with the multilayer structure Si/$SiO_2$/MgO 2/$Bi_xSe_{(1-x)}$ (Bi-Se) ($t_{BS}$)/CoFeB 5/MgO 2 /Ta 5 (in nm) are prepared in an ultra-high vacuum Shamrock magnetron sputtering tool, with $t_{BS}$=4, 8, 16, and 40 nm. Giant charge-to-spin conversion in sputtered bismuth selenide has also been investigated by growing and switching perpendicular CoFeB multilayers. Hall bar devices were fabricated by standard photolithography processes. Finished devices were then loaded into a Quantum Design PPMS system and tested electrically with standard harmonic measurement setups.

## III. RESULTSI AND DISCUSSION

The spin torque efficiency of 4 nm-thick Bi-Se estimated by dc planar Hall and spin-torque ferromagnetic resonance methods are 18.62 ± 0.13 and 8.67 ± 1.08, respectively. The power dissipation for the magnetization switching via SOT of Bi-Se is an order of magnitude smaller than that compared to the platinum Fig. 1 (a). The sputtered polycrystalline Bi-Se thin films have nanometer scale grains Fig. 1 (b). The size of grains decreases with the decrease in the thickness of the films. As the grain size decreases the non-equilibrium spin accumulation is enhanced due to the quantum confinement. Figure 2 a and c depict the two USRMR states that are determined by the relative direction between spin polarization and magnetization. If a strong current pulse is applied, as shown in fig. 2b, the magnetization could be switched. With the aid of USRMR, such a switching device can operate with only two terminals. As shown in fig. 2 d, the USRMR before and after a successful 'write' should change, and whenever a read is needed, USRMR is used to tell the magnetization state stored in magnetic layer. As shown in fig. 2 e, the first harmonic resistance, $R_\omega$, measured at 300 K exhibits anisotropic magnetoresistance-like angular dependency, when an external field of 3 T is applied and rotated in $xy$ plane. The second harmonic resistance, $R_{2\omega}$, shows the signature of USRMR, which is sensitive to the magnetization projection along $y$-direction. Note that further measurement and analysis is needed to extract thermoelectric effects to confirm and estimation USRMR amplitude.

Jian-Ping Wang
E-mail: jpwang@umn.edu
Tel: +1-612-625-9509

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Fig. 1 (a) A comparative chart displaying the magnetization switching power dissipation. The switching power dissipation due to granular bismuth selenide is an order of magnitude less than that of Pt. (b) The cross-section TEM image of the stack structure used for characterization of spin-torque efficiency. The cross-sectional TEM image shows that the sputtered bismuth selenide thin film is polycrystalline. (c) The switching of perpendicular CoFeB multilayers via SOT from sputtered bismuth selenide.

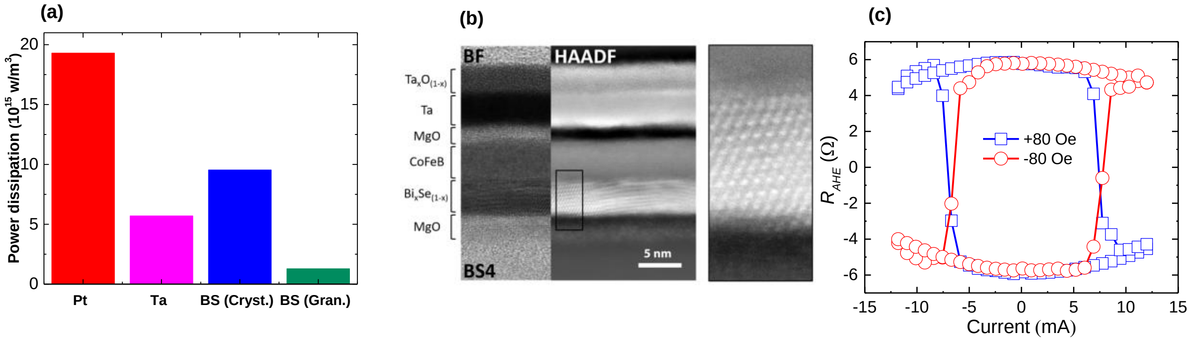

Figure 2. Illustrations of (**a**) high resistance state of USRMR, (**b**) current induced magnetization switching of magnetic layer, (**c**) low resistance state of USRMR, and (**d**) USRMR level change after a 'write' operation of the device. (**e**) The first and second harmonic longitudinal resistance versus external field angle. The applied external field is 3 T and rotates from x+ to y+ direction. The sample was $Bi_2Se_3$ (10 nm)/CoFeB (5 nm)/MgO (2 nm)/Ta (2 nm) and was tested at 300 K.