**Spin dynamics in $Bi_2Se_3$/ferromagnet heterostructures**

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$Bi_2Se_3$ is a prototypical three dimensional topological insulator (TI), which is expected to exhibit a high spin orbit torque (SOT) efficiency due to the spin-textured topological surface states. However, very few studies have reported the SOT phenomena in ferromagnet/TI by electrical measurements. Here we investigate the SOT efficiency in ferromagnet/ $Bi_2Se_3$ structures at different temperatures by two different techniques such as spin torque ferromagnetic resonance (ST-FMR) and spin pumping.

In the ST-FMR measurements on $Co_{40}Fe_{40}B_{20}$ (5 nm)/ $Bi_2Se_3$ (20 nm), where the charge currents directly flow through devices, we find that the SOTs show a steep increase as the temperature decreases to 50 K, and the SOT efficiency increases abruptly from 0.047 at 300 K to 0.42 below 50 K. Moreover, we observe a significant out-of-plane SOT efficiency in the low temperature range. We exclude the possible mechanisms from the spin Hall effect in $Bi_2Se_3$ bulk and Rashba-split states at the interface. Finally, we conclude that our results clearly demonstrate that the topological surface states are the origin of SOTs in CoFeB/ $Bi_2Se_3$ systems.

We also report the SOT efficiency and spin diffusion length at different temperatures in $Ni_{81}Fe_{19}$/ $Bi_2Se_3$ by the spin pumping technique, where no direct charge current flows thru the device. The SOT efficiency of $Bi_2Se_3$ is found to be ~0.01 at room temperature. In addition, the spin diffusion length in $Bi_2Se_3$ is evaluated to be 6.2 nm at room temperature. Both the SOT efficiency and spin diffusion length in $Bi_2Se_3$ increase at low temperatures. We will discuss possible reasons for the difference between the SOT efficiency from ST-FMR and that from spin pumping measurements.

**BIO:** Hyunsoo Yang is a professor in the Department of Electrical and Computer Engineering, National University of Singapore (NUS). He received his Doctorate and Master from the Stanford University, California. He was a Scientist in the IBM-Stanford Spintronic Science and Applications Center and had previously worked at C&S technology, LG Electronics, and Intelligent Fiber Optic Systems, California. He has won several awards including an Outstanding Dissertation Award for 2006 from the American Physical Society (GMAG). He has authored ~ 350 journal/conference papers and ~10 issued patents.