Thermally-Generated Spin Current in the Topological Insulator Bi_2Se_3

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Abstract:

We present measurements of thermally-generated transverse spin currents in the topological insulator Bi2Se3, thereby completing measurements of interconversions among the full triad of thermal gradients, charge currents, and spin currents. We accomplish this by comparing the spin Nernst magneto-thermopower to the spin Hall magnetosistance for bilayers of Bi_2Se_3/CoFeB. We find that Bi_2Se_3 does generate substantial thermally-driven spin currents. A lower bound for the ratio of spin current density to thermal gradient is shown in Equation (A) at right, and a lower bound for the magnitude of the spin Nernst ratio is -0.61 ± 0.11. The spin Nernst ratio for Bi_2Se_3 is the largest among all materials measured to date, 2-3 times larger compared to previous measurements for the heavy metals Pt and W.

$$\frac{J_s}{\nabla_x T} = (4.9 \pm 0.9) \times 10^6 \left(\frac{\hbar}{2e}\right) \frac{Am^{-2}}{K\mu m^{-1}} \quad \textbf{(A)}$$

$$J_s = \frac{\hbar}{2e}\frac{\theta_{SH}}{\rho_{SS}}E. \quad \textbf{(1)}$$

$$\Delta R(\hat{m}) = (1 - m_y^2)\Delta R_{SMR} = \Delta R_{SMR} cos^2\theta \quad \textbf{(2)}$$

$$J_s = -\frac{\hbar}{2e}\frac{\theta_{SN}}{\rho_{SS}} S_{SS}\nabla_x T. \quad \textbf{(3)}$$

$$\Delta V_{th}^x = -l\nabla_x T(1 - m_y^2)S_{SNT} = -l\nabla_x T S_{SNT} cos^2\theta \quad \textbf{(4)}$$

Equations (A) through (4).

Summary of Research:

By taking advantage of the electron's spin as well as its charge, the field of spin caloritronics has provided new strategies for energy harvesting from thermal gradients, for thermal management within electronics, and for magnetic manipulation [1]. However, the field has been limited by low efficiencies for interconversion between thermal gradients and spin currents within the materials studied to date. Here, we provide measurements of the efficiency of transduction from a thermal gradient to spin current density in a topological insulator. Topological insulators have already been demonstrated to provide very high efficiencies for interconversion between the other two legs of the triad of thermal gradients, charge currents, and spin currents. Topological insulators have achieved record efficiencies for transduction between charge current density and spin current density that are of interest for applications in spin-orbit-torque manipulation of magnetic devices [2], and also highly-efficient transduction of thermal gradients to electric field with potential for thermoelectric applications [3]. We find that the topological insulator Bi_2Se_3 also enables highly-efficient transduction of thermal gradients to spin currents, with by far the largest spin Nernst ratio among materials measured to date.

We measure thermally-generated spin currents using the same physics by which electrically-generated spin currents give rise to the spin Hall magnetoresistance (SMR) effect [4]. In the electrically-generated case, an electric field E applied in the plane of a spin-source/ferromagnet bilayer gives rise to a vertically-flowing spin current density J_s via the spin Hall effect, with an efficiency characterized by the spin Hall ratio, θ_{SH} Equation (1) above, where $\hbar$ is the reduced Planck constant, e is the magnitude of the electron charge, and ϱ_{SS} is the electrical resistivity of the spin-source material. The degree of reflection of this spin current at the magnetic interface depends on the orientation of the magnetization $m\hat{}$ in the magnetic layer. The reflected spin current produces a voltage signal by the inverse spin Hall effect, causing the resistance of the bilayer to depend on the magnetization angle (4), which can be further simplified in geometry studied in this work (Figure 1 (A)), Equation (2).

Here m_y is the component of the magnetization unit vector that is in-plane and perpendicular to the electric field. Similarly, the thermally-generated spin current and voltages takes the form in Equations (3) and (4) where θ_{SN} is the spin Nernst ratio, S_{SS} is the Seebeck coefficeint

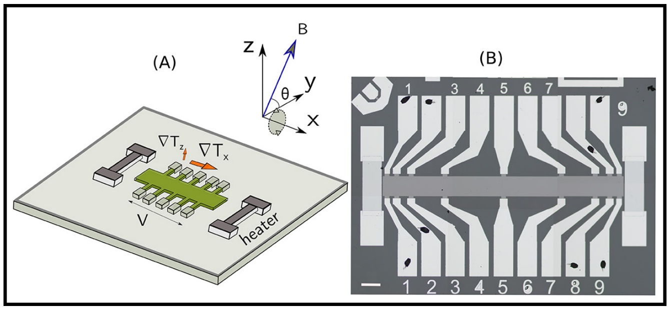

Figure 1: (A) Sample geometry for the spin Nernst magneto-thermopower experiments. (B) Microscope image of the device used for measuring spin Nernst magneto-thermopower. Scale bar is equivalent to 200 μm.

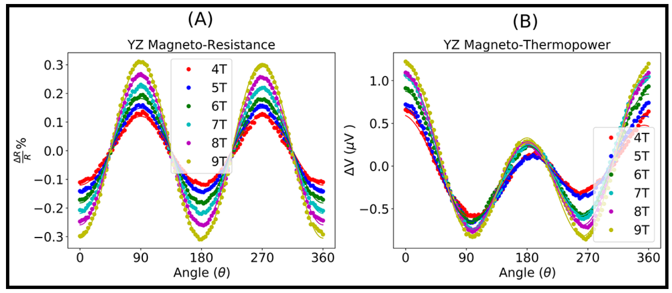

Figure 2: (A) Magnetoresistance percentage ratio ($\frac{\nabla R}{R} \times 100$) as a function of the magnetic field angle and R magnitude for bilayers of Bi_2Se_3 (8 nm)/CoFeB (5 nm) at room temperature, for magnetic field rotated in the YZ plane. The four-point device resistance R = 2.137 kOhms. (B) YZ magneto-thermopower voltage as a function of the magnetic field angle and magnitude for the same sample. The heater power used for these sweeps was fixed at 442 mW (equivalent to a temperature drop of 6.8 K along the l = 1.8 mm length of the device).

of the spin source, S_{SNT} is the coefficient of the spin Nernst magneto-thermopower, which represents voltage arising from thermally generated spin currents, $\nabla_x T$ is the in-plane thermal gradient and l is the length of the device.

The results are plotted in Figure 2 for both electrically and thermally generated voltages. After accounting for field dependent magneto-resistance and magneto-thermopower arising from the Bi_2Se_3 (5) layer, we report, $100 \times \Delta R_{SMR}/R = 0.126 \pm 0.008$ where R is the resistance of the device and $S_{SNT} = 90 \pm 10\ nV/\kappa$. Using these values, we can estimate the ratio $\theta_{SN}/\theta_{SH} = -0.83 \pm 0.15$ and θ_{SN} is approximately -0.61 ± 0.11.

These numbers can be used to estimate the net thermally generated spin currents as $J_s/\ \nabla_x T$ is $(4.9 \pm 0.9) \times 10^6$ $(\hbar/2e)$A m^{-2} / κ μm^{-1}.

Conclusions:

In summary, by comparing measurements of the spin Nernst magneto-thermopower in Bi_2Se_3/CoFeB bilayers to the spin Hall magnetoresistance, we find a lower bound for the magnitude of the spin Nernst ratio for Bi_2Se_3 of -0.61 ± 0.11, roughly three times greater than that of previously measured values for Pt and 2-3 times greater than that of W. Moreover, the net spin current generated per unit thermal gradient $J_s/\Delta T_x$ is higher in Bi_2Se_3 than for W and of a similar magnitude as Pt despite the higher resistivity of Bi_2Se_3.

References:

[1] Bauer, G. E., Saitoh, E., and Van Wees, B. J. Spin caloritronics. Nature Materials 11, 391-399 (2012).
[2] Mellnik, A., et al. Spin-transfer torque generated by a topological insulator. Nature 511, 449-451 (2014).
[3] Hor, Y., et al. p-type Bi_2Se_3 for topological insulator and low-temperature thermoelectric applications. Physical Review B 79, 195208 (2009).
[4] Nakayama, H., et al. Spin Hall magnetoresistance induced by a nonequilibrium proximity effect. Physical Review Letters 110, 206601 (2013).
[5] Jain, R., et al. Thermally-generated spin current in the topological insulator Bi_2Se_3. arXiv preprint arXiv:2210.05636 (2022).