**Charge, Spin, and Heat transport in the Proximity of Metal Ferromagnet interface**

My research interest has revolved around Spintronics in the area of condensed matter physics. Spintronics is the science and technology of harnessing the spin degree of freedom of electrons with a view to develop energy efficient electronic devices and to endow them with new functionalities. Spin is a purely quantum mechanical entity. The interaction among spin, electron charge and environment offers a unique opportunity to explore the quantum nature of matter. The field is evolving rapidly and there have been many exciting developments in fundamental physics and applications.

Recently, the exploration of spintronics has been advanced towards the manipulation of pure spin current without a charge current. The pure spin current can be realized by compelling electrons of opposite spins to move in opposite directions, or be carried by spin waves (magnons). Pure spin current is beneficial for spintronic operations with the attributes of maximal angular momentum and minimal charge current thus with much reduced Joule heating, circuit capacitance and electromigration. The transverse spin current can be generated via the spin Hall effect (SHE) in nonmagnetic materials by the longitudinal electric field. By analogy with SHE, we now have “spin caloritronics”, where one exploits the interaction between heat transport and the charge/spin degree of freedom. The spin imbalance can also be generated and maintained by a temperature bias. As charge-based logic devices further shrink in size, the Joule heating would soon exceed the tolerance level, generated by charge currents become too high to operate reliably with intolerable levels of Ohmic energy dissipation. The thermal properties of nanostructures have become a fundamental topic owing to the necessity of heat removal in increasingly smaller electronic devices. Spin caloritronics is considered a key solution to relieving the thermodynamic bottleneck with new physics related to spin, charge, entropy and energy transport for future nanodevices.

In this newly developed field of spin caloritronics, one exploits the interaction of charge, spin, and heat. The spin-mediated thermal properties include spin Seebeck effect (SSE), spin-related Hall effects, Nernst effect and other new effects in metals, insulators, and heterostructures. Spin Seebeck effect (SSE) is one of the few phenomena with which one can generate a pure spin current without a charge current therefore is of considerable importance. The observation of SSE has been reported first in the transverse and, subsequently, in the longitudinal geometries with in-plane $\nabla T_x$ and out-of-plane $\nabla T_z$ temperature gradient, respectively. The basic structure for detection includes a spin detection layer on a ferromagnet of interest. The spin current in the ferromagnet diffuses into the spin detection layer, where it is converted by the inverse spin Hall effect (ISHE) into a charge current and measured by an electric voltage. However, since hybrid thin-film structures on substrate are most often employed, the actual temperature gradient must be carefully ascertained. We have demonstrated that thermal spin transport using thin films on substrate suffers the complications of large contribution of substrate and the mixture of other effects, such as the Nernst effect. Our systematic studies show that the ANE signal, which is a sensitive measure of temperature gradient, asymmetric in field has been attained on all cases, regardless of matching thermal conductivity, irrespective of whether the substrates are metallic, semiconducting, or insulating. We have determined the intrinsic spin dependent thermal transport using substrate-free sample and observed intrinsic spin dependent thermal transport, as shown in Fig 1 [Phys. Rev. Lett. 107, 216604 (2011)].
In the longitudinal configuration of SSE, the temperature gradient is applied exclusively out of plane. In the case of ferromagnetic metals, the longitudinal SSE signal will be added to the ANE in ferromagnetic metals. Therefore, pure longitudinal SSE signal can be observable only for ferromagnetic insulators (e.g., YIG). However, one encounters a different issue of magnetic proximity effects (MPEs) when the spin current detector Pt is in contact with YIG. Unexpected magnetoresistance and AHEs are some of the evidences for MPE [Phys. Rev. Lett. 109, 107204 (2012)]. Previously, the proximity-induced ferromagnetism has been predicted by theoretical calculation and extensively demonstrated by experiments in nonmagnetic metals in contact with a ferromagnetic metal. These phenomena present difficulties for the unequivocal establishment of longitudinal SSE in Pt/YIG. Very recently, intrinsic longitudinal SSE in Au/YIG without appreciable MPEs has been demonstrated, as shown in Fig. 2 [Phys. Rev. Lett. 110, 067206 (2013)]. Au is more suitable as a pure spin current detector. These important discoveries allow us to develop a useful method for further investigation, which involves exploring and exploiting materials with giant spin Hall angle, that play essential roles in new spintronic effects.