A Nonlocal Spin Hall Magnetoresistance in a Platinum Layer Deposited on a Magnon Junction

As early as 1930, physicist F. Bloch (1905–1983, recipient of 1952 Nobel Prize) put forward the famous concept of spin waves or magnons: the local disturbance of magnetically ordered system spreads in the form of waves in the whole magnetically ordered lattice. Later, its existence was confirmed by physicist B. Brockhouse (1918–2003, recipient of 1994 Nobel Prize) in 1957 with inelastic neutron scattering experiments. Like light waves (photons), spin waves (magnons) also have wave-particle duality, and can be used to propagate spin information directionally over a long distance. However, over the past 90 years, no micro- and nano-scale magnon device with both functional and applicable properties was developed, leaving this a long unresolved challenge on the international frontiers.

From 2012 to 2016, the group headed by Prof. HAN Xiufeng at the State Key Laboratory of Magnetism, Institute of Physics (IOP), Chinese Academy of Sciences (CAS) experimentally fabricated a new type of magnon heterostructure Pt/YIG/Pt, where a thin magnetic insulator (YIG) is sandwiched by two layers of heavy metal Pt (heavy metal/ ferromagnetic insulator/heavy metal sandwich structure, HM/FMI/HM). And they observed the magnon-mediated electric current drag (MECD) effect in this structure which is theoretically proposed by Prof. ZHANG Shufeng *et al*. at University of Arizona: due to the magnon excitation and propagation in YIG, the spin/charge current in one Pt layer drags an opposite spin/charge current in another Pt layer. This phenomenon is called MECD effect. This work demonstrates that the spin information could be carried by magnons in magnetic insulators [H. Wu and X. F. Han, *et al*., *Phys. Rev. B* 93 (2016) 060403(R)]. This experiment fully proves the feasibility of magnons as spin information carriers and the effectiveness of magnetic insulator conducting magnons. The perpendicular magnonic heterostructure HM/FMI/HM has also become a magnon generator via full electrical control.

Then Prof. HAN's group further invented an FMI/HM/FMI magnon valve (YIG/Au/YIG) by taking the advantages of $Y_3Fe_5O_{12}$ (YIG) in magnon transport, which can output magnon currents via the spin Seebeck effect in the parallel and antiparallel states of two layers of YIG. It is like a switch which can regulate magnon flow effectively. This achievement was selected as the editorial recommendation and highlight paper [H. Wu, X. F. Han, *et al. Phys. Rev. Lett*. 120 (2018) 097205, editors' suggestion & featured in physics, https://doi.org/10.1103/physrevlett.120.097205].

Subsequently, in order to avoid the conversion of magnon currents to spin currents in the device and improve the efficiency of magnon production, this research team further developed FMI/AFMI/FMI magnon junction (YIG/NiO/YIG, NiO is a good antiferromagnetic insulator) with magnons as the only information carriers. This kind of magnon junction device can not only realize a 100% switch on-off ratio, but also serve as the basic unit of the magnon transistor (spin transistor) for regulating the pure magnon current (pure spin current) [C. Y. Guo, C. H. Wan, X. F. Han, *et al. Phys. Rev. B* 98 (2018) 134426].

On the basis of the fully insulated magnon junction, in order to achieve the information reading of the magnon devices with lower power consumption, this research team tried to use the magnetoresistance mode (spin Hall magnetoresistance, SMR) instead of the thermoelectric transport mode (spin Seebeck effect, SSE) to read the magnetic structure changes.

They applied a small current in the Pt layer of the YIG/NiO/YIG system and measured the resistance of Pt. It was found that the resistance of Pt depends not only on the direction of the magnetic moment of the top YIG (normal spin Hall magnetoresistance effect) in direct contact with Pt, but also on the direction of the magnetic moment of the bottom YIG layer on the other side of the magnon junction. This is because the different arrangements of the two YIG layers (parallel or antiparallel) lead to the difference of the effective magnon conductance of the magnon junction, thus affecting the spin currents injected from Pt into the magnon junction. This phenomenon is similar to the giant magnetoresistance (GMR) effect or tunneling magnetoresistance (TMR) effect in classical spintronics. The difference is that this effect only uses magnons as information carriers rather than spin polarized electrons.

The new effect is named as the magnonic nonlocal spin Hall magnetoresistance (MNSMR) effect to reflect the nature of magnon transport. Because there is no charge transport in the magnon junction, Joule heat is not generated, greatly improving the energy efficiency of the magnon junction. The discovery of MNSMR effect provides a new way for the development of magnonic devices without Joule heat. The related work has been published in *Nature Electronics* titled "A nonlocal spin Hall magnetoresistance in a platform layer deposited on a magnon junction". [NATELECTRON-3 (2020) 304].

The discoveries of the magnon generator, magneton valve, magneton junction and MNSMR effect have provided new ways for systematic construction of magnon devices and magnon circuits without Joule heat in the future.

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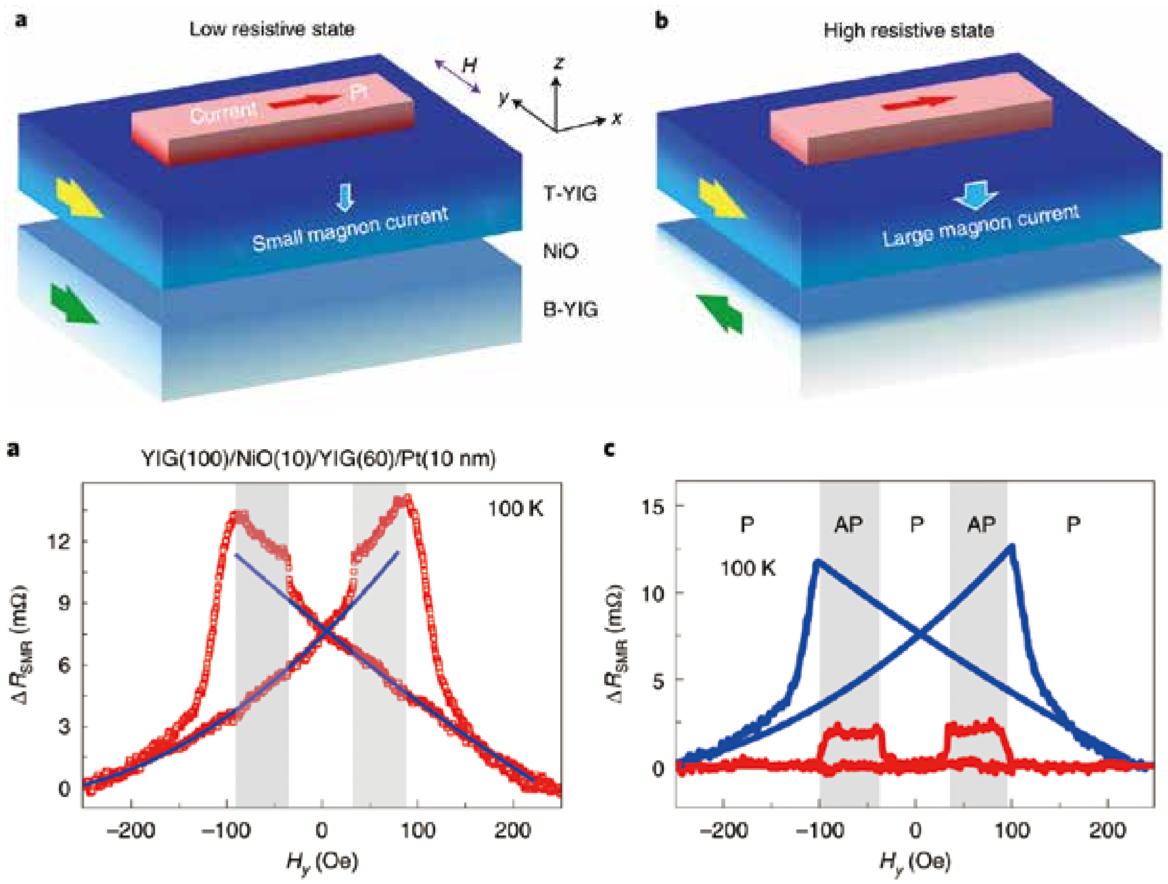

Magnonic nonlocal spin Hall magnetoresistance (MNSMR). a and b, magnon transport across a magnon junction at the parallel (P) and antiparallel (AP) states. The AP state leads to a higher effective magnon conductance across the Pt/top-YIG interface. c and d, SMR measured at a Pt film on the top of a magnon junction and the decomposition of the SMR into the local and spin Hall magnetoresistance.

Professor WAN Caihua contributed equally to this work (Both are from IOP), and Prof. HAN Xiufeng is the corresponding author. This work was performed in collaboration with Prof. ZHANG Shufeng from University of Arizona and Prof. LIU Yaowen from the Tongji University (China).

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