Observation of breaking of Onsager's reciprocal relation in a high spin Hall angle ferromagnetic Weyl semimetal at room temperature

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The spin Hall effect (SHE) and the inverse spin Hall effect (ISHE) enable the conversion of a charge current into a transversal spin current and vice versa, and are used to generate and detect spin currents in spintronic devices.[1] These effects have been successfully observed in non-magnetic heavy metals (HMs)[2], but very few measurements on ferromagnetic materials have been reported. However, replacing the HM with a ferromagnet (FM) offer potential advantages such as a precise control of the spin current through the magnetization direction[3]. On the other hand, the ferromagnetic Heusler alloy Co_2MnGa has been exhibiting properties of a Weyl semimetal, among them the manifestation of a large anomalous Hall effect (AHE)[4], which originates from the large Berry curvature distribution around the Fermi energy, associated with the nodal lines or Weyl points.[5] Since it is thought that the AHE and the SHE share a common origin,[6] strong spin Hall phenomena are expected in this promising material for topologically-driven spintronic applications.

In this work, all-metallic lateral spin valve devices using monocrystalline Co_2MnGa as ferromagnetic electrodes and Cu as non-magnetic channel were fabricated to investigate the SHE and ISHE using electrical spin injection. It was systematically observed that SHE and ISHE resistances are different when Co_2MnGa is used as detector electrode, meanwhile in control samples with Pt and Py detectors the resistances were the same. This behavior evidences a breaking of Onsager's reciprocal relation, observed for the first time in this kind of transport phenomena. An explanation in terms of spin-dependent spin Hall conductivities is introduced. In addition, the spin Hall angle θ_{SH} of Co_2MnGa was found to be (-0.19±0.04) at room temperature, which is among the highest reported for a FM to date. Although θ_{SH} is in the same order of magnitude of known HMs, the significantly higher resistivity of Co_2MnGa implies larger detection voltages. This result introduces an efficient material for spin-to-charge interconversion that is still expected to reveal more novel phenomena related to its Weyl nature.

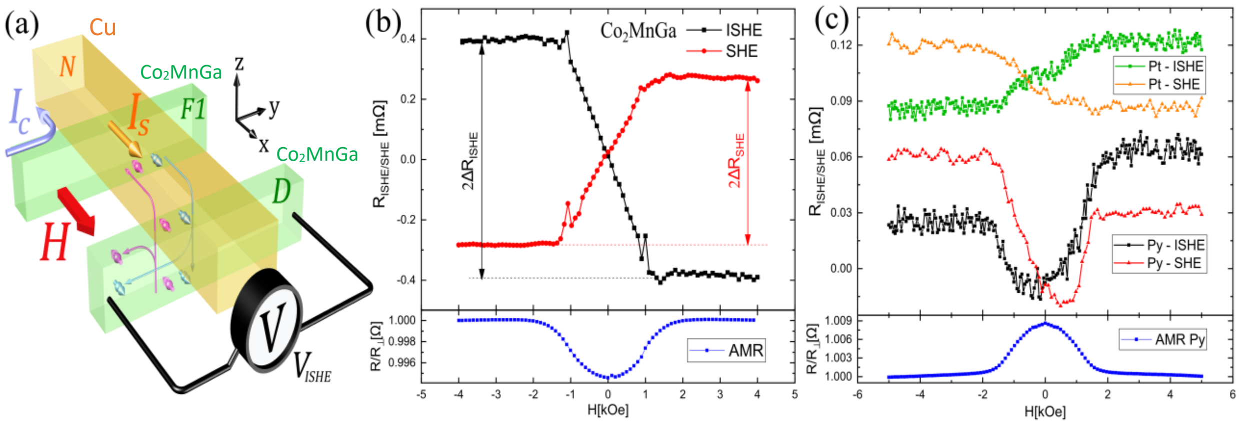

Figure 1: (a) Schematics of the nonlocal ISHE measurement. A charge current *Ic* is injected from *F1* to *N*, producing spin accumulation at the *F1/N* interface and a consequent spin current *Is* diffuses along *N*. Part of this spin current is absorbed by the detector *D* in negative *z* direction. Then, a charge current in positive *y* direction is induced in *D* due to the inverse spin Hall effect, and a voltage can be measured in equilibrium open circuit condition. (b) Nonlocal resistance for the ISHE setup and its reciprocal (direct) SHE setup for a Co_2MnGa detector, measured as a function of in-plane external magnetic field *H* at room temperature. (c) Equivalent nonlocal ISHE and SHE resistances measured for Pt and Py detector control samples at room temperature.

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