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Extrinsic Spin Hall Effect Induced by Iridium Impurities in Copper

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We study the extrinsic spin Hall effect induced by Ir impurities in Cu by injecting a pure spin current into a Cu wire with Ir impurities. The spin Hall angle θ_{SH} is measured by the magnetoresistance without Ir impurity, the spin Hall resistivity of CuB increases linearly with the impurity concentration. The spin Hall angle for CuB (0.1×10^{-3} rad) is about 1% between 1% and 12%, which is practically independent of temperature. These results represent a clear evidence of predominance of new scattering extrinsic contribution to the spin Hall effect in a nonmagnetic alloy.

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The generation of pure spin currents, flows of only spin angular momentum without charge current, should play an important role in future spintronics and quantum computing. The spin Hall effect (SHE) is one of the promising ways to create pure spin currents in nonmagnetic materials. The SHE was first predicted theoretically a long time ago [2] and has been confirmed by the first experimental observation of the SHE in the ferromagnetic metal Mn [3]. The theoretical predictions of SHE in nonmagnetic materials [4,4] and from the first experimental observation of the SHE in Mn [3] have stimulated many theoretical calculations [5]. By flowing the electric current in GaAs samples, spin currents can be observed as magnetoresistive signals at the sites of the samples, which can be seen by scanning Kerr microscopy [6]. The SHE angle is defined as the ratio of the spin Hall angle to the conductance. The yield of the transformation of charge into spin current is called the spin conversion efficiency. One of the most important challenges is to find more efficient materials for this transformation. Larger SHEs have been recently found in the transition metals such as Pt [7–9], Cu [10,11], and this has triggered an important effort of research on the SHE [12].

The SHE relies on spin-orbit (SO) interactions in materials and can be generated by magnetic or electric fields. The large SHE angles of d - and f -transition metals, about 1% in recent measurements, are mainly due to the spin-orbit coupling mechanism based on the degeneracy of orbits by SO coupling [13–15]. The SHE in the transition metals appears to be a universal phenomenon on the basis of spin-orbit coupling in the transition metals [16]. The intrinsic SHE, on the other hand, is expected to be small in nonmagnetic metals, such as presenting strong SO interactions [16–18]. There are two forms of nonmagnetic materials: the skew scattering and the

valley jump [20]. In the former case, the SHE resistivity (ρ_{SHE}) is proportional to the resistivity induced by the spin-orbit coupling, ρ_{SOC} , and the spin Hall angle is given by $\theta_{\text{SHE}} = \rho_{\text{SHE}}/\rho_{\text{SOC}}$, where the impurities are the only source of resistivity or $\rho_{\text{SOC}} = \rho_{\text{SHE}}/\rho_{\text{imp}}$, where ρ_{imp} includes an additional contribution due to the Coulomb interaction between the spins and the impurities [21].

A defining feature of the extrinsic SHE is that one can control the SH angle by changing the concentration of the impurities without changing the impurity concentration. In particular, the relation between the spin Hall angle and the concentration of impurities is given by the following equation [22]:

A series of pioneering works to this end had been performed in the 1980s by a part of the present authors using a spin polarizer and SO impurities such as Li, Ta, and Ir [23]. The spin Hall angle for Li-doped CuB was positive for CuB (2.6%) or negative for CuB (−1.2%), and had been affected to some degree by the concentration. Therefore we put our focus on Li as an exotic SO scatterer. In order to determine the extrinsic nature of the SHE in CuB, we carried out experiments as follows: In DSHE experiments, the spin accumulated on the surface of the sample was measured by the Hall voltage detected with ferromagnetic contacts. In ISHE experiments, spin currents are converted into charge currents and measured by the Hall voltage of the sample as described. ISHE measurements have been intensively carried out by using the spin-polarized current method [24] or spin injection (7.8–10–12.22) or the microwave driven spin pumping method [25]. In the present work, we have adopted the spin-polarized current method to measure the Hall voltage structure to measure the ISHE induced in Cu by Ir impurities. The Hall voltage is proportional to the spin Hall angle if the major contribution to the SHE is the skew scattering by the impurities and what is the magnitude of the SHE angle.



Prof. dr. sc. Amir Hamzić, redoviti profesor Prirodoslovno-matematičkoga fakulteta Sveučilišta u Zagrebu

Prof. dr. sc. Amir Hamzić (Zagreb, 1949.) diplomirao je fiziku na Prirodoslovno-matematičkom fakultetu (PMF) u Zagrebu, a doktorirao na Sveučilištu Paris Orsay. Redoviti je profesor, a sada obnaša dužnost dekana PMF-a. Na Fizičkome odsjeku PMF-a uredio je Laboratorij za niskotemperaturna galvanomagnetska mjerjenja u jakim magnetskim poljima i pri vrlo niskim temperaturama. Za promicanje sveučilišne i znanstvene suradnje Francuske i Hrvatske odlikovan je *Odličjem reda Akademskih palmi Republike Francuske*.

Prof. dr. sc. Amir Hamzić istražuje niskotemperaturna transportna i magnetska svojstva razrijeđenih slitina, sustava s jakim elektronskim korelacijama, slojevitih i lančastih sustava reducirane dimenzionalnosti, koji pokazuju kolektivne pojave te nove spinske efekte koji imaju značajne primjene u spintronici. Među prvima je u Hrvatskoj počeo istraživanja visokotemperaturnih supravodiča, a njegov rad o kvantnom tuneliranju virova magnetskoga toka u supravodiču itrij-barij-kuprata objavljen je u časopisu *Nature*. U novije vrijeme prof. Hamzić se usmjerio na istraživanja u spintronici u suradnji s nobelovcem Albertom Fertom. Aktivno je sudjelovao u prvim eksperimentalnim potvrđdama i kasnijim razradama utjecaja prijenosa spinova na gibanje magnetskih domena u troslojnim magnetskim nanostrukturama, čime je otvorio NOVO POGLAVLJE SPINTRONIKE, tzv. spin-orbitroniku, kao potencijalnu zamjenu poluvodičke elektronike.