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**Extrinsic Spin Hall Effect Induced by Iridium Impurities in Copper**

Y. Nishi,<sup>1,2</sup> M. Morita,<sup>3</sup> D.-H. Wu,<sup>4</sup> C. Denisov,<sup>5</sup> M. Batacic,<sup>6</sup> A. Hamzić,<sup>7</sup> A. Fert,<sup>8</sup> and Y. Okada<sup>1,2</sup>

<sup>1</sup>Graduate School of Materials Science, Nagoya University, 1-3-1 Kita-ku, Showa-cho, Chikusa-ku, Nagoya 466-8773, Japan  
<sup>2</sup>Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russian Federation  
<sup>3</sup>CEA, IRFU, Service de Physique des Particules, 91191 Gif-sur-Yvette Cedex, France  
<sup>4</sup>Department of Physics, Faculty of Science, University of Ryukyu, P.O. Box 131, 900-10027 Naha, Okinawa, Japan  
<sup>5</sup>RIKEN-ASL, 2-2 Wako-shi, Saitama 351-0198, Japan  
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We study the extrinsic spin Hall effect induced by Ir impurities in Cu by applying a pure spin current into a Cu wire from a lateral spin valve structure. While no spin Hall effect is observed without Ir impurity, the spin Hall resistivity of Cu increases linearly with the impurity concentration. The spin Hall angle of Cu is 2.1–3.64%–degrees at the impurity concentration range between 1% and 12%, which is precisely identical to that of In. These results reveal a clear analogy of phenomena due to scattering-induced contribution to the spin Hall effect in a nonmagnetic alloy.

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The generation of pure spin currents, flows of only spin momenta without charge current, should play an important role in the next generation spintronics devices [1]. The spin Hall effect (SHE) is one of the promising ways to create pure spin currents in nonmagnetic materials by utilizing external magnetic fields or ferromagnets. The SHE was first predicted by Dresselhaus [2] and has recently received renewed interest which came from several theoretical predictions of SHE in nonmagnetic materials [3,4] and from the first experimental observation of the SHE in semiconductor systems using an optical method [5]. By flowing the electric current into GaAs samples, spin-up and down electrons are accumulated on the opposite sides of the sample, which can be detected by the Kerr rotation microscopy. This is referred to as the direct spin Hall effect (DSHE). However, the spin Hall (SH) angle, which is defined as the ratio of the SH conductivity to the charge conductivity and represents the maximum yield of the transformation of charge into spin current density, is extremely small in semiconductors. Therefore an important challenge is to find the efficient materials for the SHE. Larger SHEs have been reported mainly in noble metals such as Pt [6–10] and Au [11,12] and this has triggered an impetus of research on the SHE in metallic materials.

The SHE arises on spin-orbit (SO) interactions in materials and can be generated by intrinsic or extrinsic mechanisms. Recent theoretical works predict that the large SH angles of 4d and 5d transition metals, about 10 times larger than Pt, for example [13,14], come from the strong mechanism of the destruction of  $\sigma$  orbits by SO coupling [13–15]. This scenario has been supported by recent systematic experiments on the SHEs in 4d and 5d transition metals [10]. The extrinsic SHE, on the other hand, relies on scattering by impurities (or other defects) presenting strong SO interactions [16–18]. There are two types of mechanisms: namely, the skew scattering (SS) and the side-pump (SP). In the former case, the SH resistivity ( $\rho_{\text{SH}}$ ) is proportional to the resistivity induced by the impurities ( $\rho_{\text{imp}}$ ), while, for side-pump effects,  $\rho_{\text{SH}} = \rho_{\text{imp}} + \rho_{\text{imp,ext}}$ , where  $\rho_{\text{imp,ext}}$  includes an additional contribution from scattering potentials with weak SO interactions. A definite source of the extrinsic SHE is that one can induce the DSHE by changing the spin-orbit interaction strength and impurity metal as well as by tuning the impurity concentration. In particular, the relation between the SHE and the resistivity can be realized not only by varying the temperature but also, in a much wider range, by changing the concentration of impurities.

A series of pioneering works to this end had been performed in the 1990s by a part of the present authors using a spin valve structure with a lateral spin current driven by a side-pump and 4d impurities such as Fe, Ta, and Ir [21]. Large SHE angles had been obtained, positive for CuIr (2.6%) or negative for CuTa (-3.2%), and had been ascribed to resonant scattering on SO impurity states split into 5/2 and 3/2 levels by SO interaction. Therefore we put our focus on it for testing DSHE activities. In order to determine the SH angle in further details, the DSHE (DSHE) is measured at 40 K. In DSHE experiments, the effect of the spin-orbit scattering of materials with strong SO interactions are detected with ferromagnetic contacts. In DSHE experiments, spin currents are converted into charge currents and then the potential drop along the current direction is detected. DSHE measurements have been extensively carried out in the literature by one of the present authors (Y. Okada) [17,18,20–22,22] on the spin-orbit-driven spin-pumping techniques [6,9]. In the present study we have adopted the spin absorption method using a lateral spin-valve structure to measure the DSHE induced in Cu by Ir impurities. The final goal of the present study is to identify if the major contribution to the SHE is the skew scattering by the impurities and what is the mechanism 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 mjerena 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 kvantnome 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.