Direct electronic measurement of the spin Hall effect

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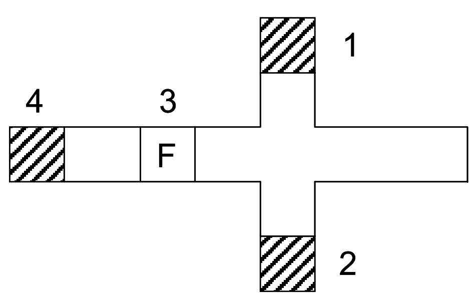
Cond-mat/0605423; to be published in Nature.

Recommended, with commentary, by Bertrand I, Halperin, Harvard University

In the spin Hall effect, an electric current can produce a current of spins, flowing in a transverse direction, due to spin orbit effects, in the absence of a magnetic field or magnetic order. The spin current, in turn, may lead to accumulation of spin, of opposite signs, near the lateral boundaries of the sample. Many theoretical papers have been written on the subject, in part because there are numerous subtleties in predicting the magnitude, and even the sign, of the spin Hall current and associated spin accumulations. However, experimental measurements of the effect have been scarce. Until now, these have involved detection of spin accumulation in semiconductor samples using optical means, such as optical rotation or emission of circularly polarized light by a p-n junction. [1-3]

Since the spin Hall effect has been proposed as a possible source of polarized electrons for electronic applications, one would naturally like to see experimental detection of the accumulated spins by purely electrical means, such as by induced voltage in a ferromagnetic contact. Using a clever geometry, Valenzuela and Tinkham have been able to detect, using purely electrical means, an effect in aluminum, which, though not strictly speaking the spin Hall effect as defined above, is nonetheless equivalent to it according to the Onsager symmetry relations applicable to the system.

A simplified schematic of the geometry used by Valenzuela and Tinkham is shown in the figure below.



Contacts 1, 2, and 4 connect the thin-film aluminum cross to non-magnetic leads, while contact 3 connects the aluminum to a ferromagnetic metal, through a tunnel barrier, which transmits selectively electrons with spin parallel to the ferromagnetic moment. A voltage V_{34} applied between contacts 3 and 4 produces an electrical current I_{34} between the two contacts, and produces spin accumulation under the ferromagnetic contact. A portion of these spins will diffuse through the aluminum in the direction opposite to contact 4, giving a spin current (but no electrical current) through the region between leads 1 and 2. If there are impurities with spin-orbit coupling in this region, and if the orientation of the ferromagnet has a component perpendicular to the plane of the sample, then the Mott skew scattering effect can lead to a voltage difference V_{12} between contacts 1 and 2, which is the signal detected in the experiments of Valenzuela and Tinkham.

What does this have to do with the pin Hall effect as conventionally defined?. Suppose that the voltage observed by Valenzuela and Tinkham is written as $V_{12} = R_{VT}(\mathbf{m})\, I_{34}$, where we have assumed we are operating in the linear current regime, and the coefficient R_{VT} depends on the orientation **m** of the ferromagnet. Then consider an alternate experiment, where an electrical current I'_{12} is passed between leads 1 and 2 and a voltage V'_{34} is measured between leads 3 and 4. This voltage would be non-zero because of the spin-Hall effect: the electrical current would lead to a spin accumulation under contact 3 with a spin perpendicular to the plane, which will lead to a voltage between contacts 3 and 4 if the ferromagnet has a spin component perpendicular to the plane. We may then write $V'_{34}= R_{SH}(\mathbf{m})\, I'_{12}$, where the coefficient .R_{SH} is proportional to the spin Hall coefficient in the active region of the aluminum cross and to the difference in transmission through the barrier of electrons with spins parallel or antiparallel to **m,** reduced by the degree to which electrons may lose their spin polarization in diffusing from the region of the cross to the region under the ferromagnetic contact. Measurement of such a voltage would indeed constitute direct electrical detection of the spin Hall effect in aluminum. As appreciated by Valenzuela and Tinkham, however, Onsager's symmetry relations require that their measured coefficient $R_{VT}(\mathbf{m})$ is identical to $R_{SH}(-\mathbf{m})$.

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The geometry used by Valenzuela and Tinkham is slightly more complicated than that illustrated above, in that they include a second ferromagnetic contact, between contacts 3 and 4,.for purposes of calibration, particularly to measure the efficiency of spin injection from the ferromagnetic contact 3. Also, a magnetic field is applied to control the orientation of the ferromagnetic contact. However, the direct effect of the magnetic field on the aluminum sample should be negligible, and should not contribute to the experimental observations. What is seen in these experiments is thus indeed equivalent, by Onsager symmetry, to an electrical observation of the spin Hall effect.

References:

[1] Y. K. Kato, et al., Science **306**, 1910 (2004).

[2] V. Sih, et al., Nature Physics **1**, 31 (2005).

[3] J. Wunderlich, et al., Phys. Rev. Lett. **94**, 047204 (2005) .