CASSIOPEE

Spintronics harnesses
the exotic electrons of topological insulators

This study led jointly by researchers of the unité mixte de physique CNRS – Thales and CEA INAC in collaboration with the team of the CASSIOPEE beamline led to the observation of a high level of spin – charge conversion at ambient temperatures achieved because of the particular electronic structure of the topological insulator α-Sn. Angle-resolved photoemission (ARPES) and spin pumping by ferromagnetic resonance measurements have provided evidence of this phenomenon promising for spintronics applications.

The functioning of the majority of existing spintronic devices is based on the manipulation of spin currents that do not carry electrical charges. These currents can be described as equal fluxes of electrons of opposite spin moving in opposite directions.

The essential processes used in spintronics are the creation of such spin currents from charge currents or their detection by transforming them into charge currents. Both cases involve conversion phenomena between charge currents and spin currents. Normally these conversions are made using magnetic materials but now it appears that the spin-orbit interaction phenomenon can likewise be used. Typical examples of spin-orbit coupling effect are the spin Hall effect in heavy metals through which a charge current can be converted into a transverse spin current and the inverse spin Hall effect which enables the inverse conversion. This spin current generation effect based on the spin-orbit interaction can also be exploited for the switching of the magnetisation in magnetic memories. One of the advantages, compared to conventional tunnel junctions, is that the spin current is orthogonal to the charge current, which consequently need not cross the tunnel junction at the risk of its degradation.

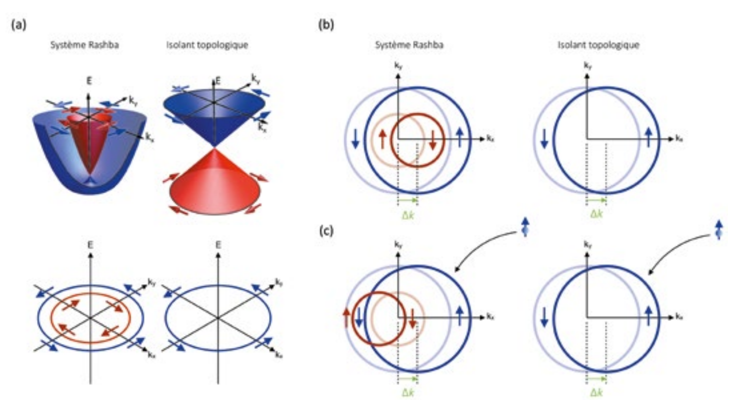

Fig. 1 (a) Distributions *E(k)* of the two-dimensional states of the surface or interface in a Rashba system and in a topological insulator. Rashba systems exhibit circular Fermi contours (set of values of k_x and k_y corresponding to the Fermi energy, i.e. the level of filling of the conduction band in the present case) with tangential spin polarisations in opposite directions for each of the contours (red and blue in the figure). Topological insulators have a single Fermi contour with a tangential spin polarisation. (b) Edelstein effect in a Rashba system and in a topological insulator. An electrical current along k_x corresponds to a surplus in the wavevector Δk for the Fermi level electronic states, that is a shift Δ*k* of the Fermi contours. This shift leads to a increase in spin up along k_y (partially compensated in the case of the Rashba system) and hence in the appearance of a net spin polarisation along y. (c) Inverse Edelstein effect in a Rashba system and in a topological insulator. An spin up polarised current, for example along y, is injected into spin up states of the two-dimensional electron gas, that is in the k_x positive direction. The accumulation of spin up electrons therefore leads to a shift Δ*k* of the Fermi contours which corresponds to an electrical current along k_x.

It appears now that a more efficient conversion could be obtained by exploiting the spin polarisation properties of the two-dimensional electron gas which exists at the surface of certain materials. This spin polarisation may result from the spin-orbit interaction generated by the high potential gradient due to the symmetry breaking caused by the surface (Rashba effect) or from the particular electronic structure existing in a class of materials referred to as topological insulators. A spin texture exists in these two material categories that results from the relationship existing between the direction of the spins and the wavevector *k* of the electronic states which are perpendicular. Thus the contours of constant energy are circular and the spin polarisation is tangential to these circles (Fig. 1a).
The particular geometry of these spin textures implies that an electrical current in this type of two-dimensional electron gas is automatically accompanied by the appearance of a spin polarisation, that is of an accumulation of spin in the direction perpendicular to the current. This is the Edelstein effect (Fig. 1b) which can be understood as a charge – spin conversion phenomenon.
The inverse Edelstein effect also exists and corresponds to the inverse spin – charge conversion (Fig. 1c). In this case, the injection of a current having a vertical spin polarisation leads to the appearance of an electric current in the two-dimensional electron gas.

The aim of this work [1] was to study the existence of an inverse Edelstein effect in α-Sn(001) whose topological insulator properties have recently been highlighted [2] and for which a spin – charge conversion efficiency higher than any other attained thus far has been observed. To be able to observe this effect, it is necessary to inject spin polarised electrons into the topological insulator. At a practical level this requires the growth of a thin ferromagnetic film on the topological insulator. To integrate these surfaces states in spintronics devices, it is therefore interesting to observe the change in these states when they are covered by a material. We therefore prepared thin films of 30 atomic layers of α-Sn(001) deposited on InSb(001) which represented the start topological insulator. These thin films were then characterised by angle-resolved photoemission (ARPES) and they were further covered by different thickness films of Fe and Ag. The results obtained are shown in Figure 2. The Dirac cones observed on the bare surfaces of α-Sn(001) are characteristic of a topological surface state. The Dirac point (which corresponds to the intersecting vertexes of the lower and upper cones) is located at approximately 30 meV below the Fermi level. It is noted that this topological state disappears as soon as the α-Sn(001) surface is covered by a fraction of Fe atomic layer, while it remains when the surface is covered by a film of silver, even for a thickness up to 12 Å. Therefore the Ag film does not destroy the topological state that exists at the interface but rather shifts the Dirac point towards a higher binding energy (about 75 meV below the Fermi level).

Measurements of spin pumping by ferromagnetic resonance intended to measure a possible spin – charge conversion were then performed on the different stacks: InSb(001)/Fe/Au (for reference measurements on a film of Fe), InSb(001)/α-Sn(001)/Fe/Au and InSb(001)/α-Sn(001)/Ag/Fe/Au. The principle of these measurements is to apply a static magnetic field in the plane of the thin films so that macroscopic magnetisation is created in the Fe layer, then to apply, in the perpendicular direction, but still in the plane of the films, a radio frequency field of varying frequency which causes the magnetisation to precess. At the frequency of resonance, a spin current is injected into the non-magnetic layers and a possible charge current can be detected by the appearance of a voltage between the ends of the sample (Fig. 3a). Figure 3b shows the results of the ferromagnetic resonance (top) and the charge current signal

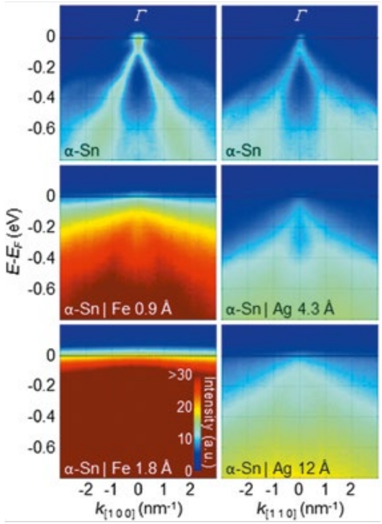

Fig. 2 Surface state of α-Sn measured by ARPES for bare surfaces (top) then covered by Fe (left) and Ag (right) films of different thicknesses.

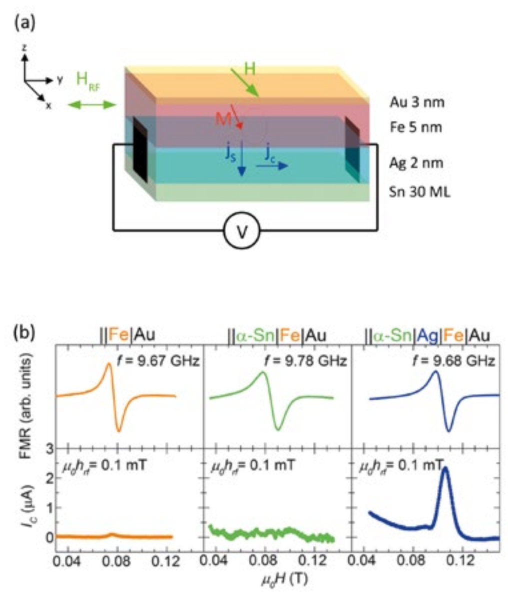

Fig. 3 (a) Schematic diagram of the experimental set-up enabling spin pumping experiments. The magnetic field H applied along the x direction aligns the macroscopic magnetisation *M* of the Fe which precesses under the effect of the radio frequency field H_{RF} applied along the y direction. This precession causes the injection into the non-magnetic layers along the z direction of a spin current j_s which is ultimately converted into a charge current j_c along the y direction and which is detected here by the potential difference present between the ends of the sample. (b) Results of the ferromagnetic resonance (top) and charge current measurements for the 3 investigated stacks (bottom).

for the 3 stacks (bottom). It is noted that only the sample where an Ag film is inserted between the Fe ferromagnetic layer and the topological insulator α-Sn(001) (that is when the Dirac cone is observed by ARPES) presents a clear charge current signal resulting from a spin – charge conversion phenomenon. The efficiency of this conversion can be quantified by the coefficient λ_{IEE} which is the ratio of the injected spin current to the charge current generated. A value of λ_{IEE} = 2.1 nm is found for this system which is much greater than the values obtained up until now, for example at the interface Bi/Ag or with other Rashba systems.

These results draws a promising avenue for room temperature spintronic devices even though the theoretical picture of α-Sn properties is not completely clear yet, opening the road to further experiments and better understanding of this new topological insulator.

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References:
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[2] Y. Ohtsubo *et al.* Phys. Rev. Lett. 111, 216401 (2013).

Spintronics

Spintronics, or spin electronics, is a new electronics, which in addition to the electron's charge, makes use of its spin. The basic idea is to integrate ferromagnetic materials into devices and then to exploit the influence of the spin of the electrons on their mobility. For example, it is possible to design non-volatile magnetic random access memory (MRAM) the basic building blocks of which are magnetic tunnel junctions in which the bit of information 0 or 1 corresponds to the parallel or anti-parallel orientation of the magnetisations of two thin ferromagnetic layers separated by an insulating barrier. Reading of information is by means of the tunnel magnetoresistance effect (the electrical resistance depends on the relative orientation of the two magnetisations) while writing of information takes place by injecting spin currents capable of switching a magnetisation given a sufficiently high current density.

Topological insulators

Amongst its many other properties, a material can be either a conductor or an insulator. The fundamental difference at the origin of one or other of these states is the band structure, that is the way in which the electron binding energies are distributed. In a conductor there are both occupied and unoccupied states at the Fermi level and the electrons can acquire a small amount of surplus energy to be set in motion to create an electrical current. In an insulator there is a forbidden band of energy (the energy gap) between the occupied and unoccupied states and the electrons cannot easily be promoted into unoccupied states because the energy difference is too great. Therefore an electric current cannot be established.
In 2005 and 2007, a new type of insulator was theoretically predicted before being observed experimentally for the first time in 2007. In these materials, a property of the band structure (its topology) combined with the spin-orbit interaction causes the existence of electronic states in the gap, but solely at the surface of a 3D material (or at the edges of a 2D material). These surface states exist in the form of Dirac cones and simultaneously possess occupied and unoccupied states at the Fermi level, the condition for being a conductor. Therefore a topological insulator is a material that behaves as an insulator within its volume but as a conductor at its surface.
Moreover the particular topology of the electronic states of these materials ensures that the conducting surface states cannot be destroyed by faults or non magnetic impurities, in contrast to conventional surface states.