Journal Club 2013.06.06 Kazutaka Shoyama

Solution-processed organic spin–charge converter

Ando, K.[*]; Watanabe, S.; Mooser, S.; Saitoh, E.; Sirringhaus, H.

Nature Materials, **2013**, doi:10.1038/nmat3634.

1. Introduction

1.1. Spintronics

- Electron has two types of properties, 1: electric charge, 2:spin (*Figure 1*).
- Utility of spin in addition to electrical charge will opens up new types of low-energy-consuming nanoelectronic devices. (e.g. Magnetic RAM, Spin transistor, High sensitivity magnetic sensor)

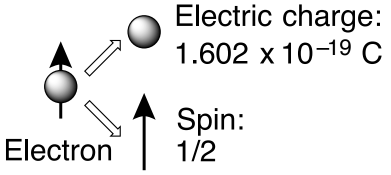


Figure 1. Two properties of electron.

1.2. Organic materials on spintronics

- Organic materials have advantages over inorganic materials such as flexibility, large-area processability and low-cost manufacturing.
- Also, small spin–orbit coupling of organic material causes a long spin lifetime.
- In order to use spin of organic materials, a method to convert spin information to an electric signal is indispensable.

1.3. Conversion between electric charge and spin information

- Electric current is the entity to store electronic information.
- Spin current instead, is the entity to store spin information (*Figure 2*).

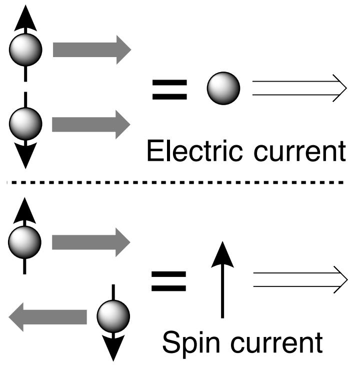
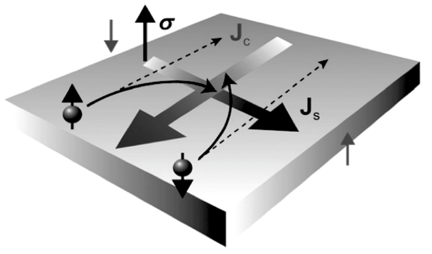


Figure 2. Two types of currents.

- Spin current is generated in following mechanism (*Figure 3a*):
  - When certain voltage is applied, a flow of electrons, J_c, is generated.
  - Due to spin polarization σ, electrons gain force perpendicular to both J_c and σ.
  - When spin polarization σ is aligned in a certain direction due to spin–orbit coupling, spin current J_s is generated. This is called spin Hall effect, SHE.
- In the opposite case, where spin current J_s is generated, electric current J_c is induced (*Figure 3b*). This is called inverse spin Hall effect, ISHE. ($E_{\mathrm{ISHE}} \parallel J_s \times \sigma$)

(a) Electric current (J_c)➡Spin Current (J_s)



(b) Spin Current (J_s)➡Electric current (J_c)

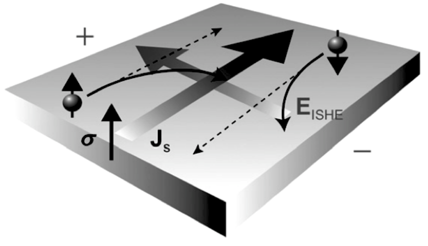


Figure 3. SHE and ISHE.

1.4. Difficulty on detection of ISHE in organic materials

- Detection of ISHE in inorganic materials is relatively easy due to their stronger spin–orbit coupling. (cf. Pt)
- Detection of small voltage difference is required for observation of ISHE in organic materials, since they have smaller spin–orbit coupling.
- Any possible noise that comes from injection of spin current should be avoided.

1.5. Spin pump[1]: a strong method for spin injection in various materials[2]

- In this method, no voltage is applied to active material. Thus, electric noise is small.
- Spin pump from ferromagnetic metal towards non-magnetic material is performed in following procedure (*Figure 4*):
  - Magnetic field ***H*** is applied in ferromagnetic metal.
  - Microwave irradiation causes precession of magnetic moment ***M***(*t*). This situation is similar to NMR, in which magnetic moment of a nucleus is considered instead of magnetization that comes from whole magnetic moment of a material.
  - The precession movement injects spin current $\boldsymbol{J}_s$ into non-magnetic material.

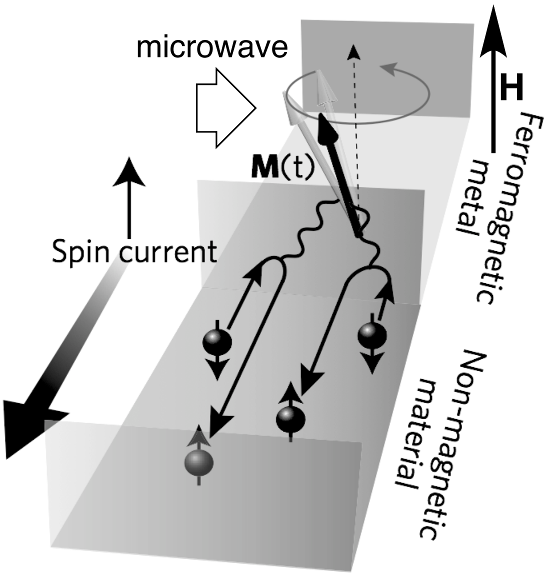


Figure 4. Spin pump method.

1.6. This work

- Detection of ISHE in an organic material for the first time.
- The use of *magnetic insulator*, $Y_3Fe_5O_{12}$,[3] for injection of spin current, instead of conventional ferromagnetic metal, further diminishes noise in the organic material.

2. Methods

2.1 Device configuration

- $Gd_3Ga_5O_{12}$ (substrate)/$Y_3Fe_5O_{12}$ (5 μm)/PEDOT:PSS (80 nm)/Au (*Figure 5a*)
- $Y_3Fe_5O_{12}$ was grown on $Gd_3Ga_5O_{12}$ substrate by liquid-phase epitaxy.

- The authors used PEDOT:PSS, which is a polymer conductor with high in-plane conductivity of around 10^3 S cm^{-1} with large anisotropy (*Figure 5b*).

2.2. Pumping spin current in PEDOT:PSS

- A magnetic field ***H*** was set to the direction of *z* axis.
- Microwave was set to the direction of *x* axis to induce precession of magnetization ***M***(*t*) in $Y_3Fe_5O_{12}$.
- Spin current $\boldsymbol{J_s}$ is injected into PEDOT:PSS to the direction of –*x* axis.

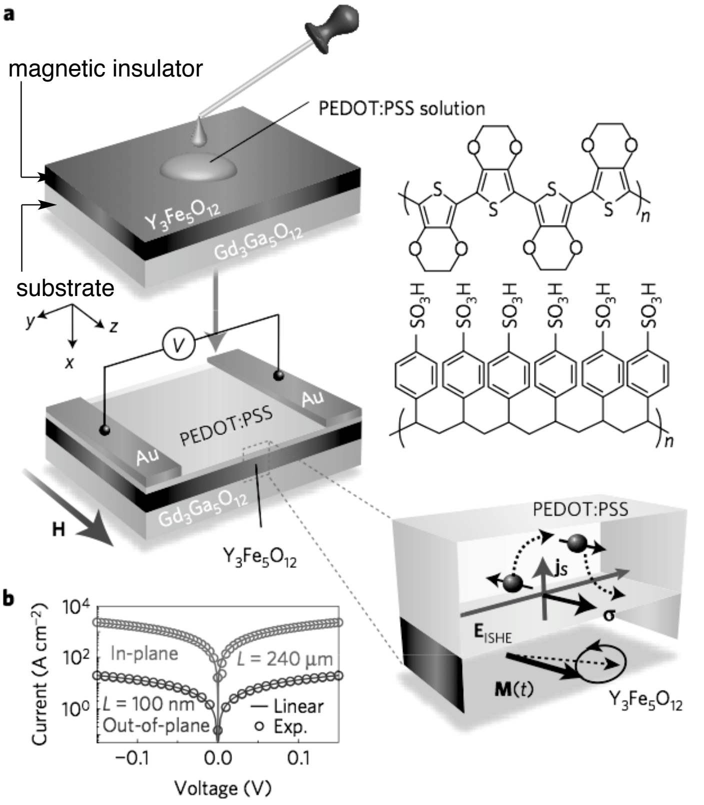


Figure 5. (a) Device configuration for measurement of V_{ISHE}. (b) Conductance anisotropy of PEDOT:PSS.

3. Results and discussion

3.1 Observation of electric voltage difference between two electrodes

- In above conditions, electric voltage difference V_{ISHE} was generated (*Figure 6a*).
- Dependance of V_{ISHE} against θ is consistent with ISHE symmetry (*Figure 6b*).[4]
- This electric field is expected to be induced by ISHE, however, several possible reasons should be excluded, such as ***H***-dependent and/or independent thermoelectric effect by microwave irradiation of PEDOT:PSS.

3.2 Exclusion of other possible reasons

- Absence of ***H***-dependent thermoelectric effect was confirmed by checking voltage difference under various magnetic field ***H*** (*Figure 6c*).
- Reversing magnetic field ***H*** caused inversion of electric field without significant change of $|V_{\mathrm{ISHE}}|$ (*Figure 6d*), indicating no ***H***-independent thermoelectric effect occurred.

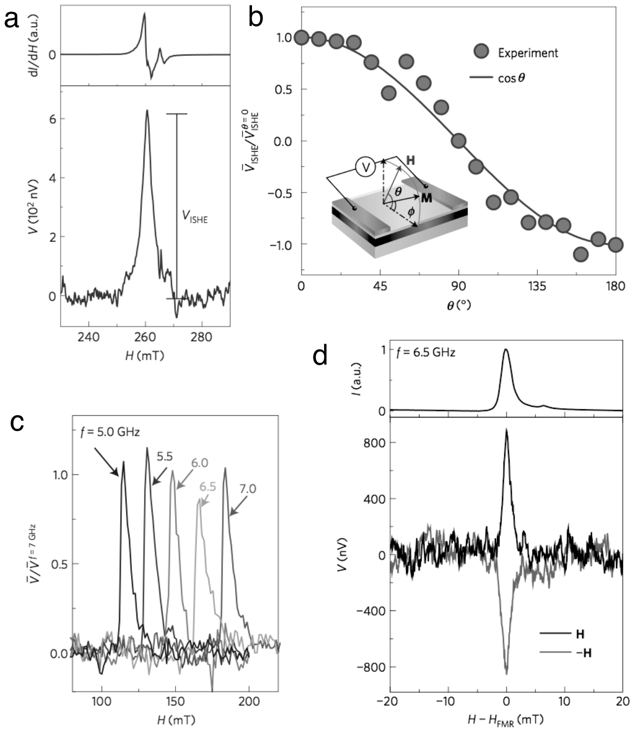


Figure 6. Electric voltage detection at several magnetic resonance conditions.

3.3 Investigation of conversion efficiency

- Spin accumulation at the interface $\delta\mu_0$ was calculated from Bloch equation for carrier spin.[3] PEDOT:PSS had higher $\delta\mu_0$ than Pt due to longer spin lifetime (*Figure 7*).
- Spin Hall angle θ_{SHE} of PEDOT:PSS was smaller than Pt due to weaker spin–orbit coupling.
- The large conductivity anisotropy of PEDOT:PSS ($\sigma_c^y/\sigma_c^x \sim 4 \times 10^5$) enhances J_c/J_s conversion efficiency α_{ISHE} to a comparable value to Pt.

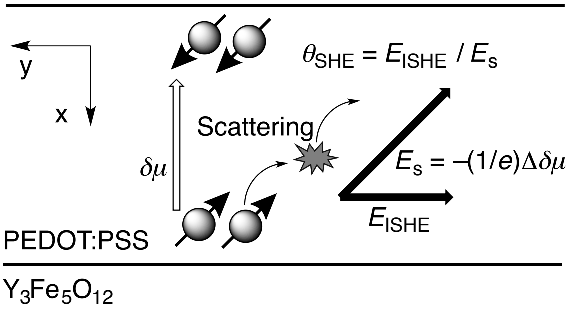


Figure 7. Spin–charge conversion dynamics.

Table 1. Comparison of ISHE parameters.

	$\delta\mu_0$ ($\hbar[\boldsymbol{M}\times\partial_t\boldsymbol{M}]_z$)	θ_{SHE}	α_{ISHE}
PEDOT:PSS	2×10^{-1}	10^{-7}	4×10^{-2}
Pt (ref. 4)	6×10^{-4}	4×10^{-2}	4×10^{-2}
PEDOT:PSS/Pt	$\sim 4 \times 10^{2}$	$\sim 10^{-5}$	~ 1

4. Conclusions

- ISHE of organic materials was observed for the first time using PEDOT:PSS.
- Spin–charge conversion efficiency was comparable to Pt case due to canceling between smaller spin–orbit coupling and large conductivity anisotropy.

5. Perspective

- The microscopic origin of the spin–charge conversion in organic materials is now open for discussion.
- In-depth theoretical studies of the spin–charge conversion in PEDOT:PSS will be stimulated by the results reported in this work.
- The almost-infinite chemical tunability of organic materials paves the way towards molecular-structure engineering of spin–charge conversion in condensed matter.

6. References

(1) Tserkovnyak, Y.; Brataas, A.; Bauer, G. *Phys. Rev. Lett.* **2002**, *88*, 117601. (2) Ando, K.; Takahashi, S.; Ieda, J.; Kurebayashi, H.; Trypiniotis, T.; Barnes, C. H. W.; Maekawa, S.; Saitoh, E. *Nat. Mater.* **2011**, *10*, 655. (3) Kajiwara, Y.; Harii, K.; Takahashi, S.; Ohe, J.; Uchida, K.; Mizuguchi, M.; Umezawa, H.; Kawai, H.; Ando, K.; Takanashi, K.; Maekawa, S.; Saitoh, E. *Nature* **2010**, *464*, 262. (4) Ando, K.; Takahashi, S.; Ieda, J.; Kajiwara, Y.; Nakayama, H.; Yoshino, T.; Harii, K.; Fujikawa, Y.; Matsuo, M.; Maekawa, S.; Saitoh, E. *J. Appl. Phys.* **2011**, *109*, 103913.