Electrical Measurements of Spin Hall Effect in Nonmagnetic Metals

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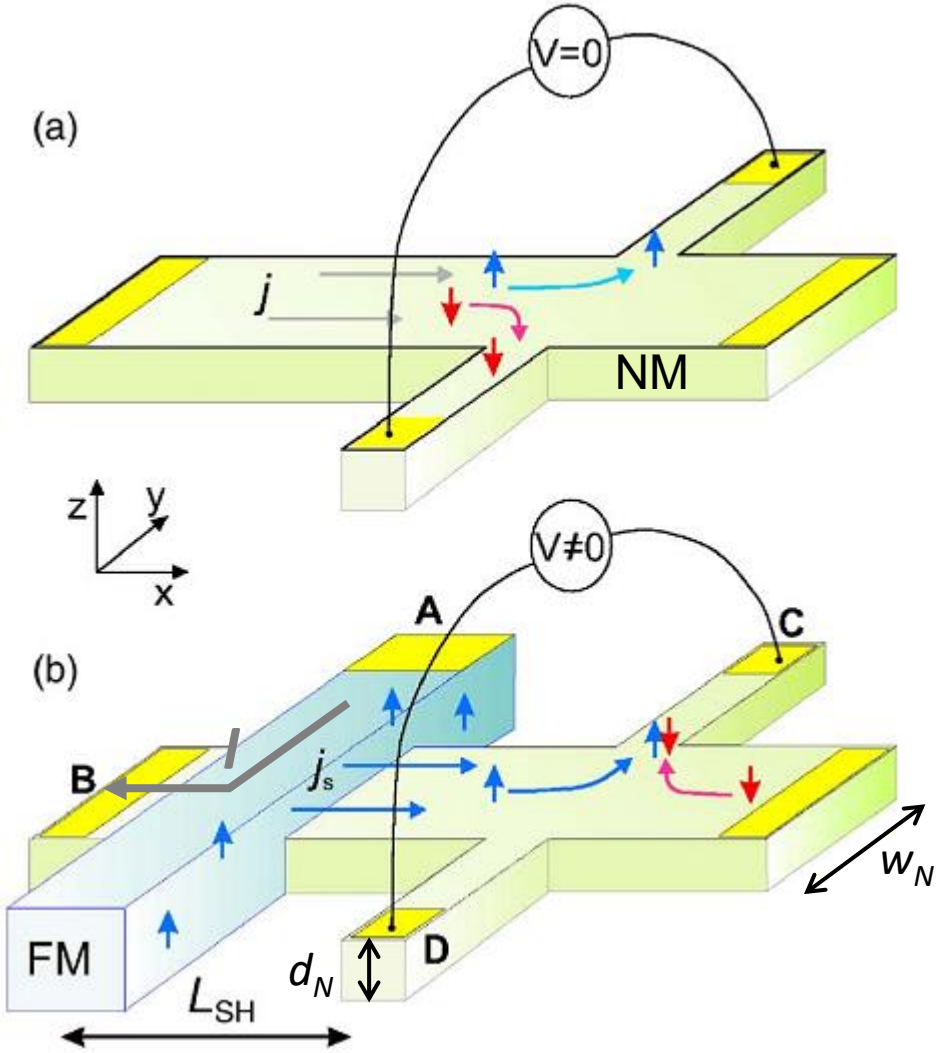
11/15/2019

Schematics of SHE and ISHE



$$\boldsymbol{J}_c = \sigma_N \boldsymbol{E} + \alpha_{SH}(\hat{\boldsymbol{z}} \times \boldsymbol{j}_s)$$

In an open circuit condition, the y-component of $\boldsymbol{J}_c$ vanishes, so $E_y = -\alpha_{SH}\rho_N j_s$.

Integrate over the width w_N to yield the spin Hall voltage $V_{SH} = \alpha_{SH}\rho_N w_N j_s$.

The spin current at $x = L_{SH}$ is

$$j_S \approx \frac{1}{2} P_{eff} \frac{I}{w_N d_N} e^{-L_{SH}/\lambda_N}$$

Therefore, the nonlocal spin Hall resistance $R_{SH} = V_{SH}/I$ is

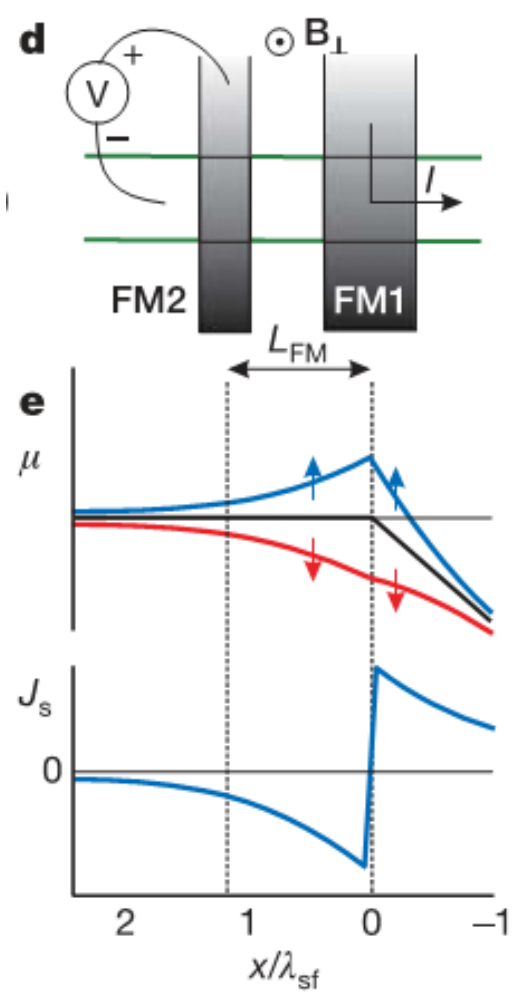
$$R_{SH} \approx \frac{1}{2} \alpha_{SH} P_{eff} \frac{\rho_N}{d_N} e^{-L_{SH}/\lambda_N}$$

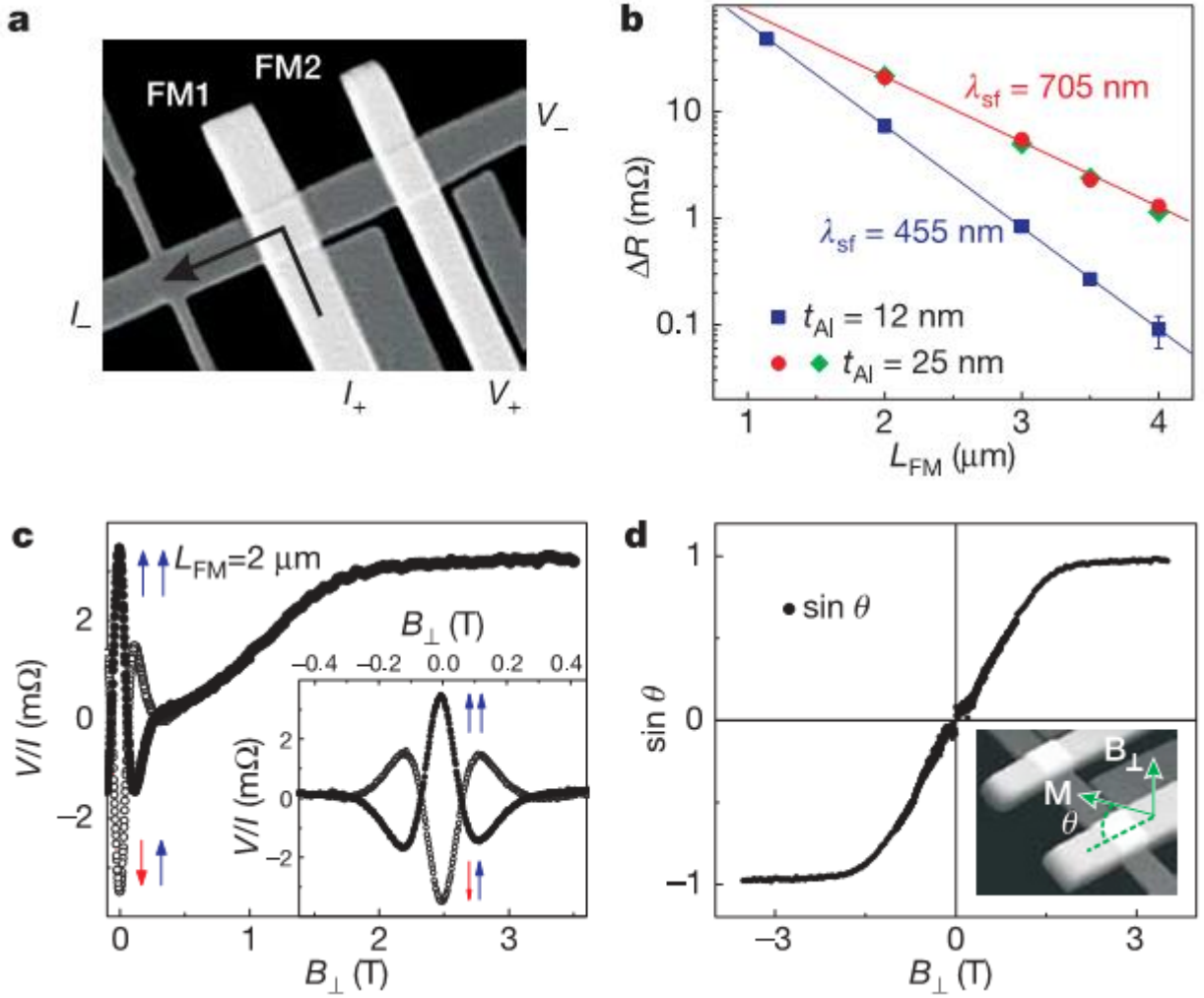
S. O. Valenzuela and M. Tinkham, J. Appl. Phys. 101, 09B103 (2007)

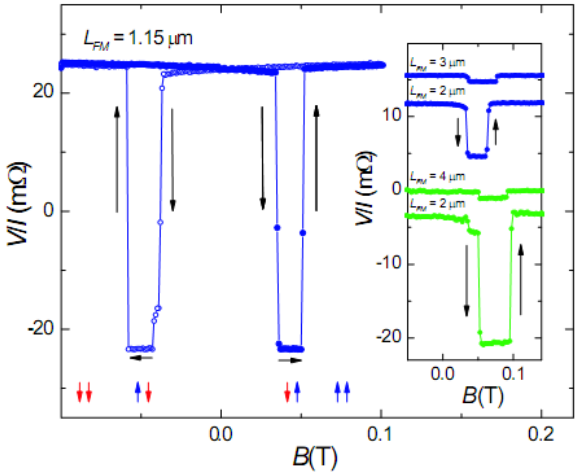
Spin-valve measurements

$$\Delta R = P^2 \frac{\lambda_{sf}}{\sigma_c A} \exp(-L_{FM}/\lambda_{sf})$$

$\vec{B}$ in the device plane







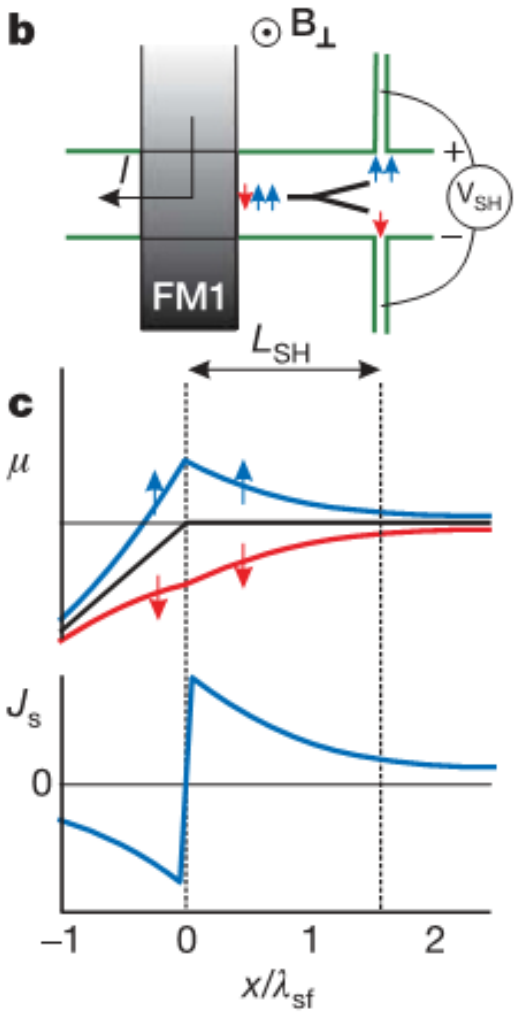
$$V_{\pm}/V_0 = \pm f(B_\perp)\cos^2\theta + \sin^2\theta$$

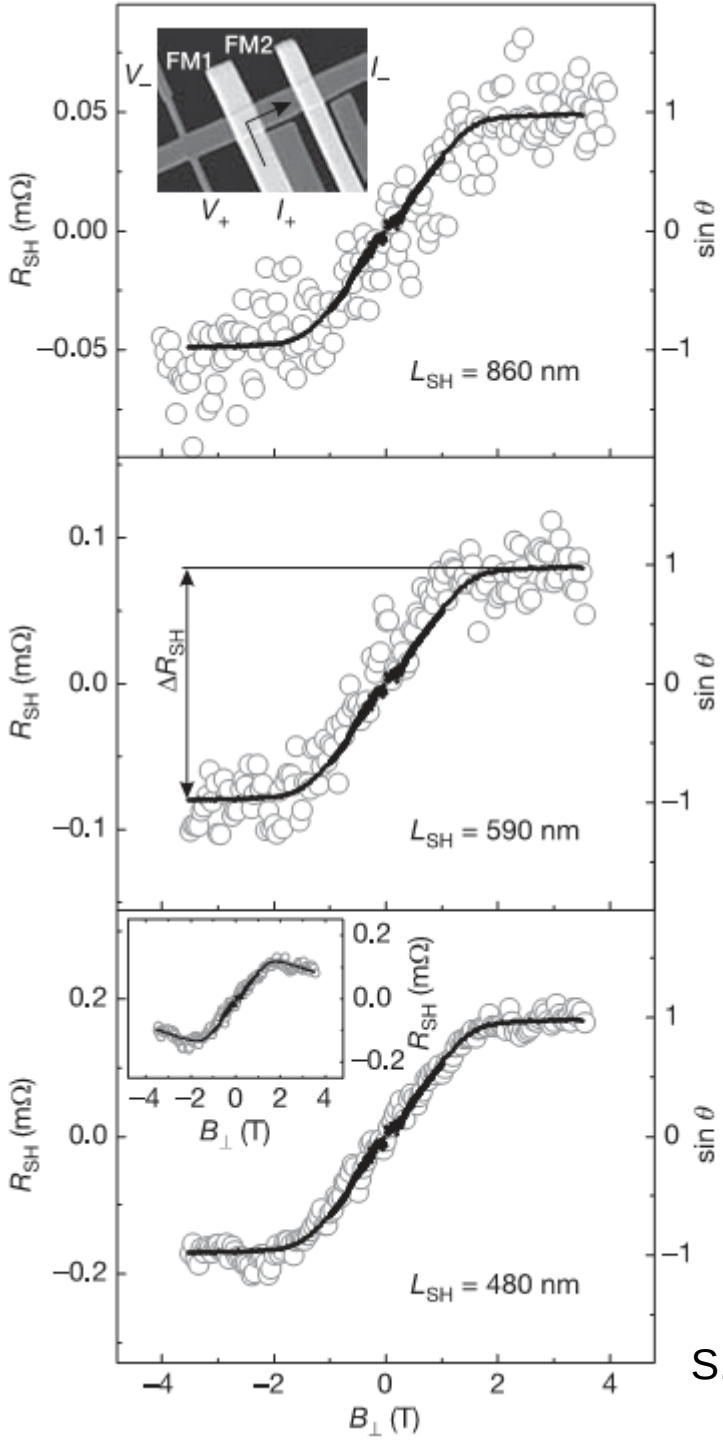
$$(V_+ + V_-)/V_0 = 2\sin^2\theta$$

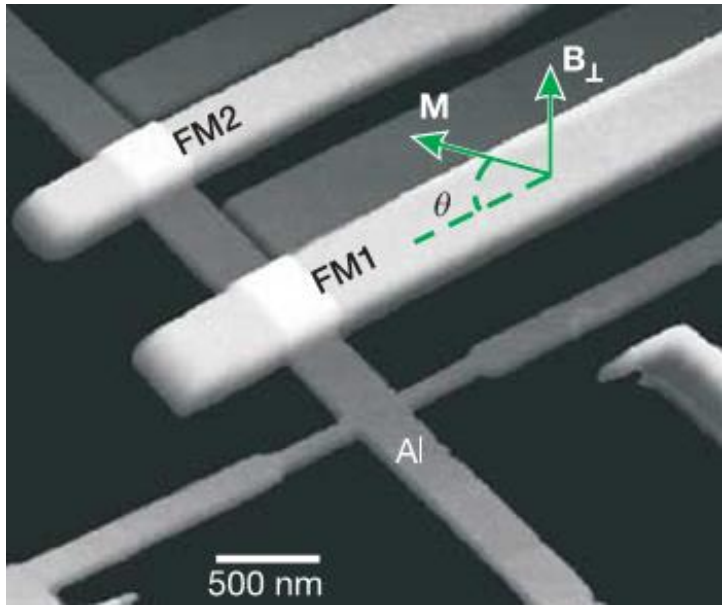
$\vec{B}$ out of the device plane

S. O. Valenzuela and M. Tinkham, Nature 442, 176 (2006)

ISHE measurements







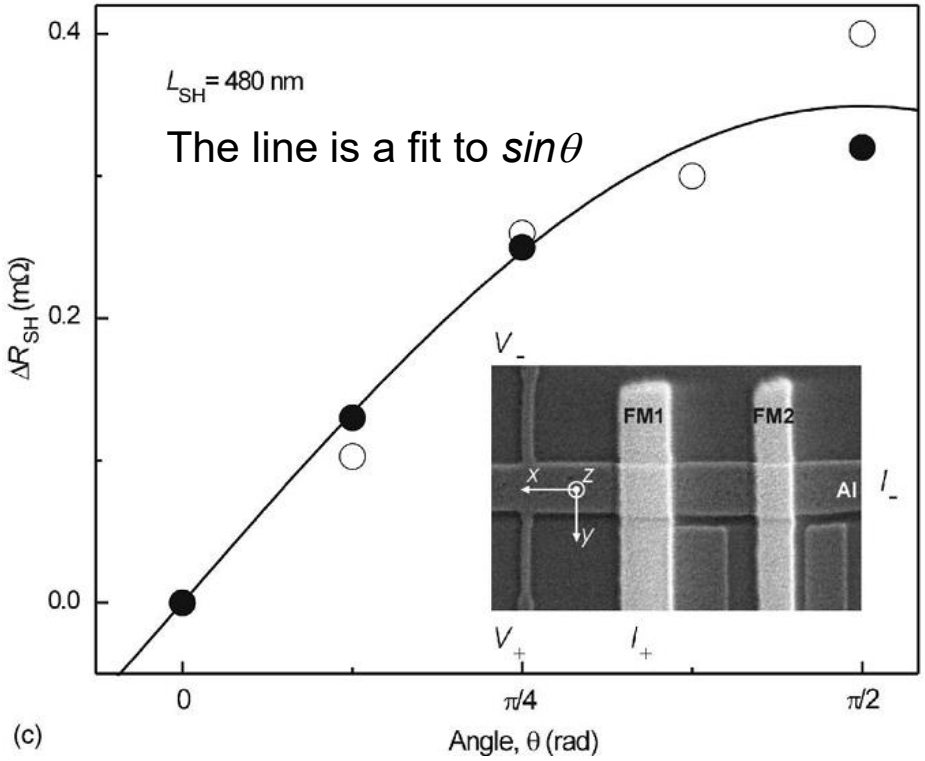
$$R_{SH} = \frac{\Delta R_{SH}}{2} \sin\theta$$

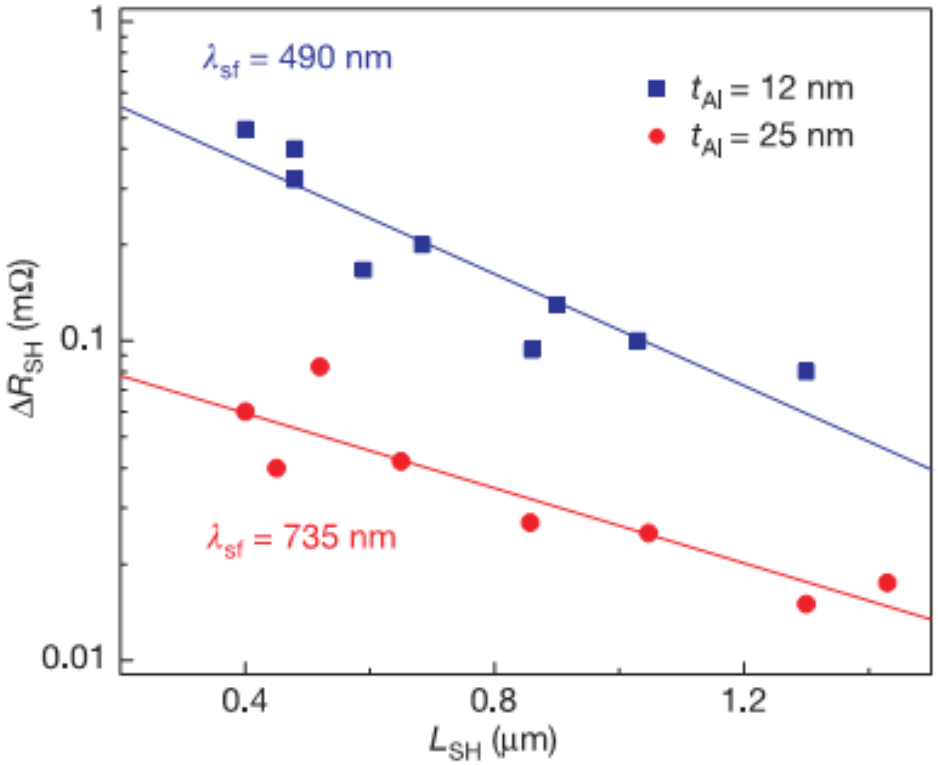
$$\Delta R_{SH} = \frac{P}{t_{Al}} \frac{\sigma_{SH}}{\sigma_c^2} \exp(-L_{SH}/\lambda_{sf})$$

S. O. Valenzuela and M. Tinkham, Nature 442, 176 (2006)

Angle and distance dependence

$$R_{SH} \approx \frac{1}{2}\alpha_{SH}P_{eff}\frac{\rho_N}{d_N}e^{-x/\lambda_N}$$



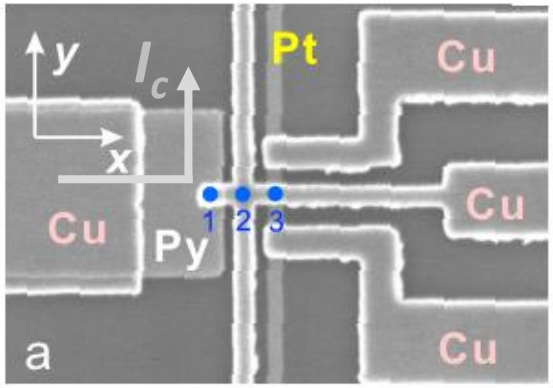


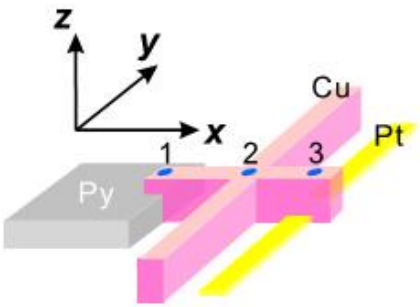
$$\sigma_{SH}/\sigma_c \approx (1\text{–}3) \times 10^{-4}$$

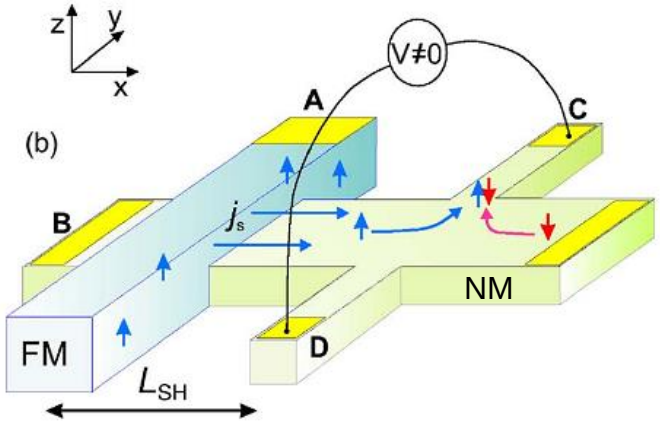
S. O. Valenzuela and M. Tinkham, Nature 442, 176 (2006)

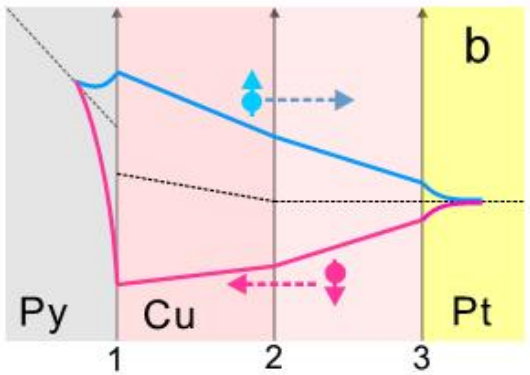
Device schematics

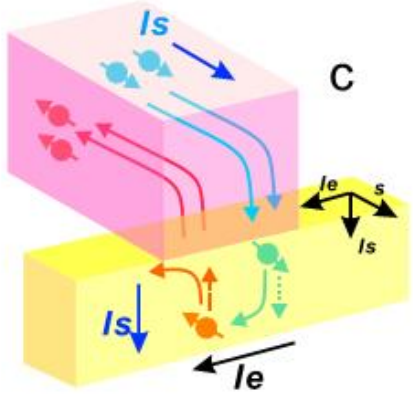
Pt: large SOC, small λ_{sf}



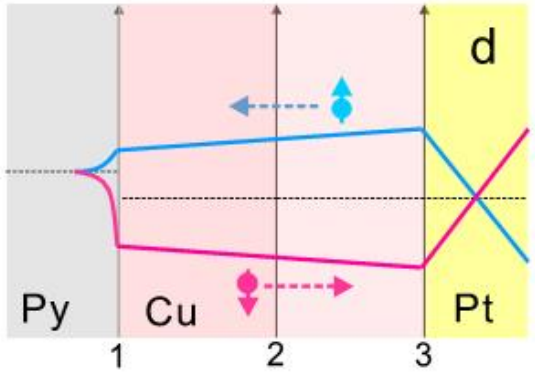


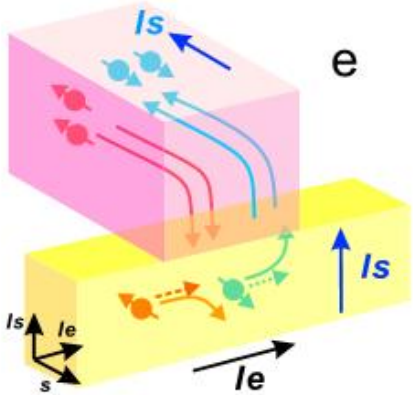






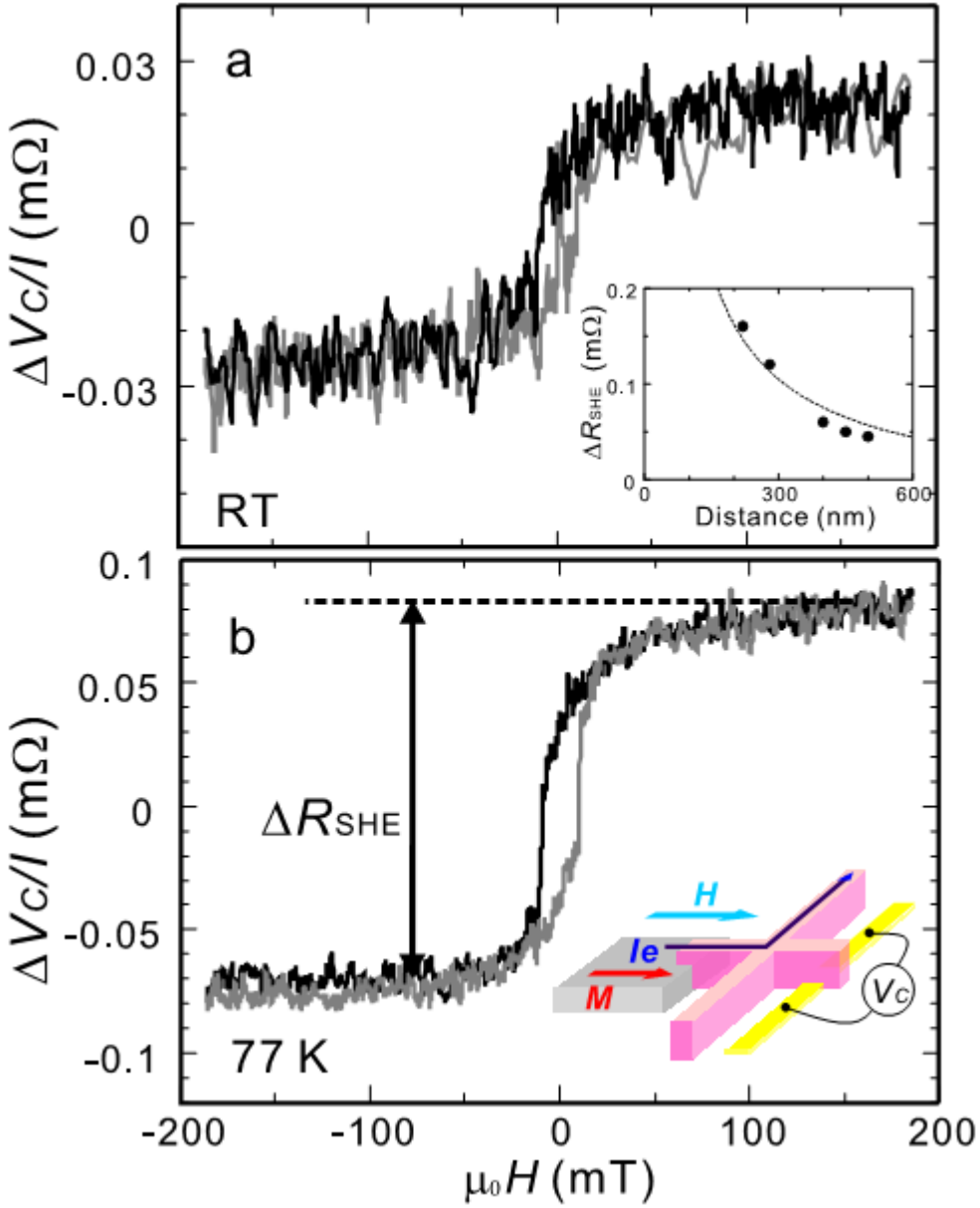
Spin current absorption

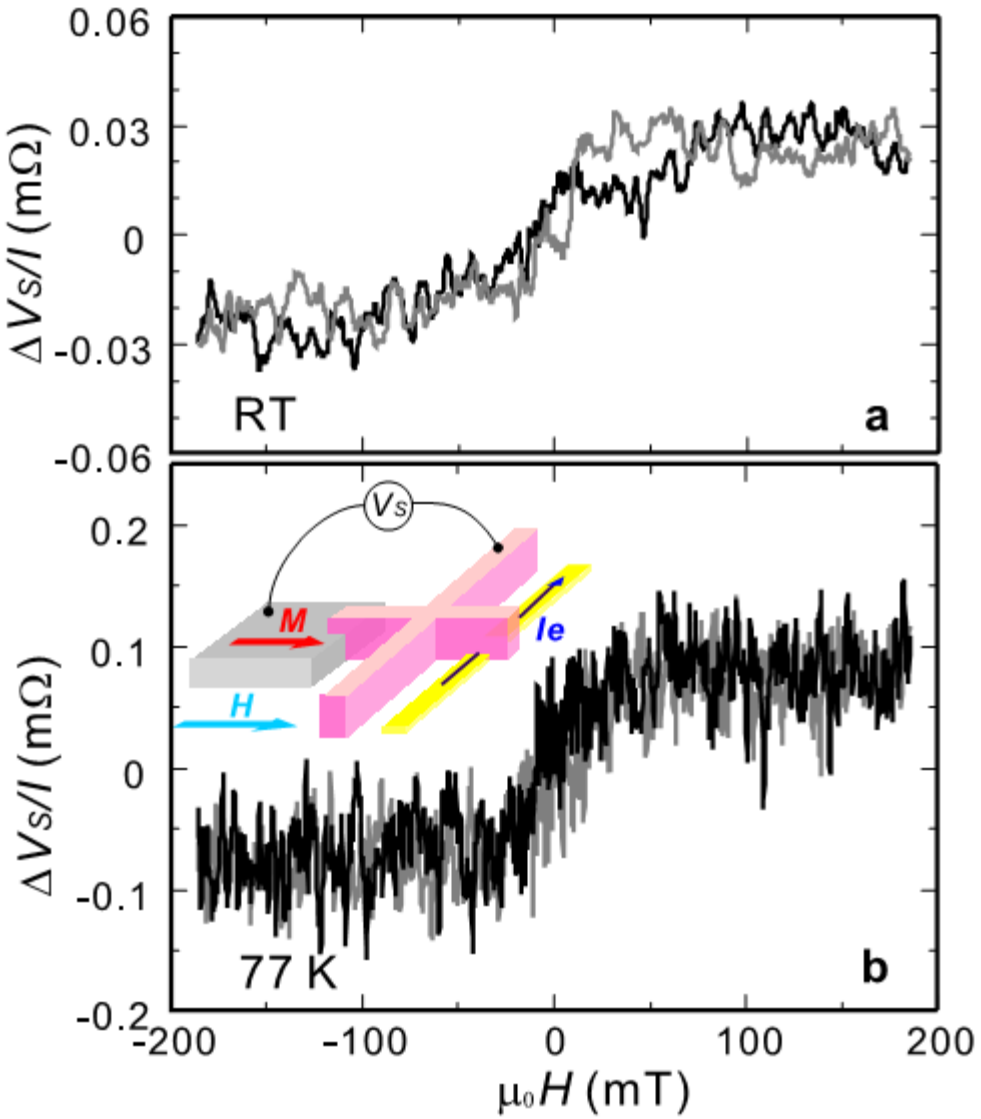




T. Kimura et al, Phys. Rev. Lett. 98, 156601 (2007)

ISHE and SHE measurements





T. Kimura et al, Phys. Rev. Lett. 98, 156601 (2007)