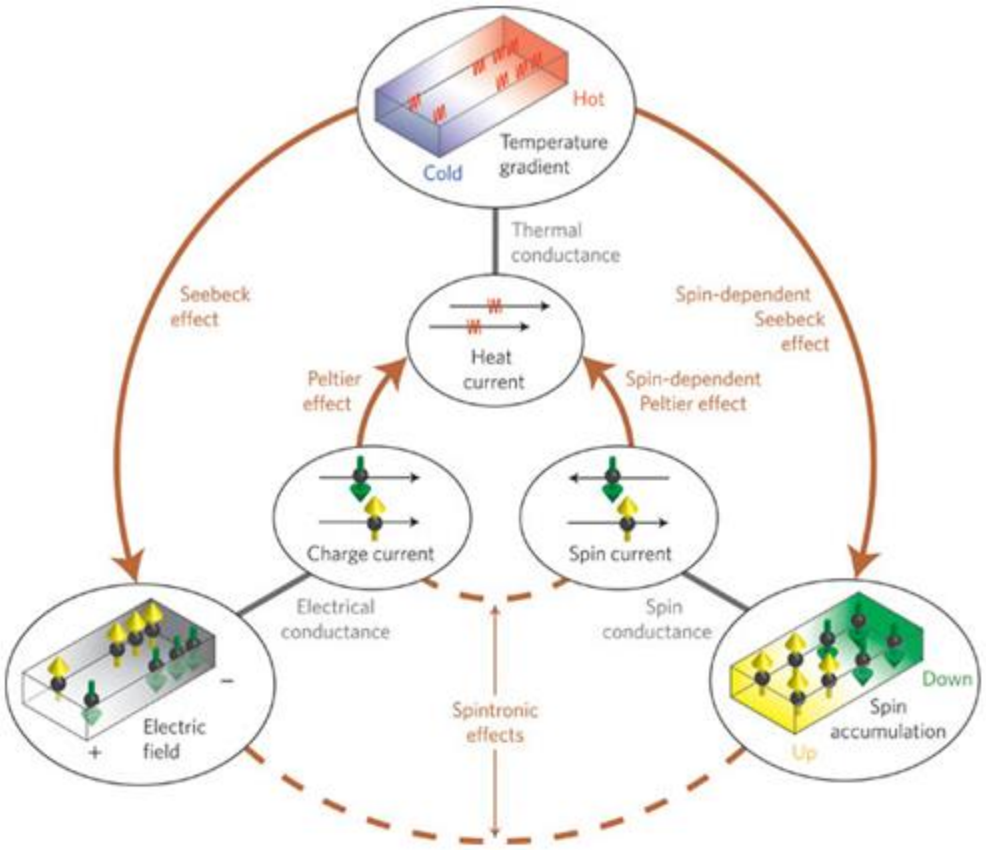
Spin seebeck effect

Presented by: Ning-Xuan Yang

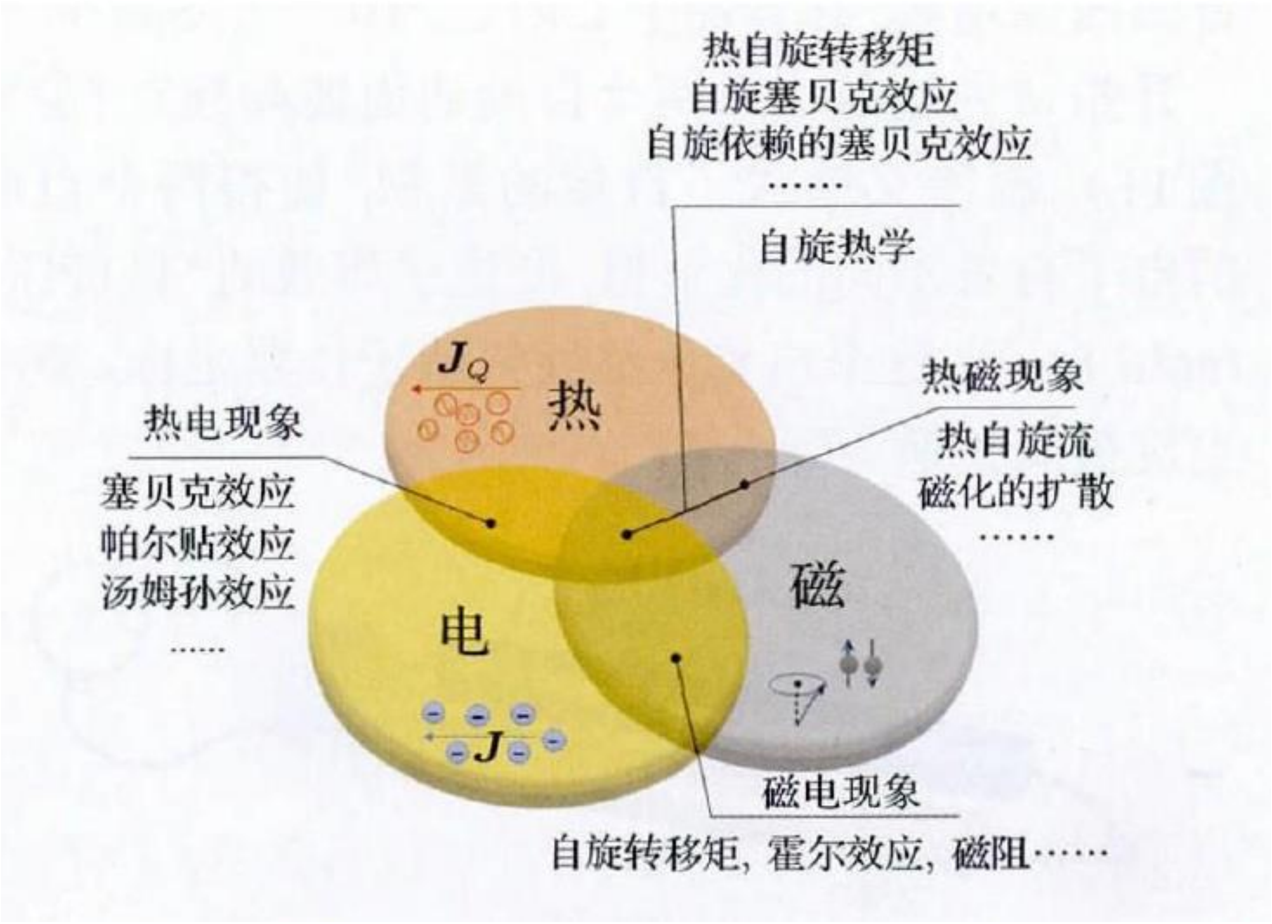
ICQM

2017-12-22

Introduction



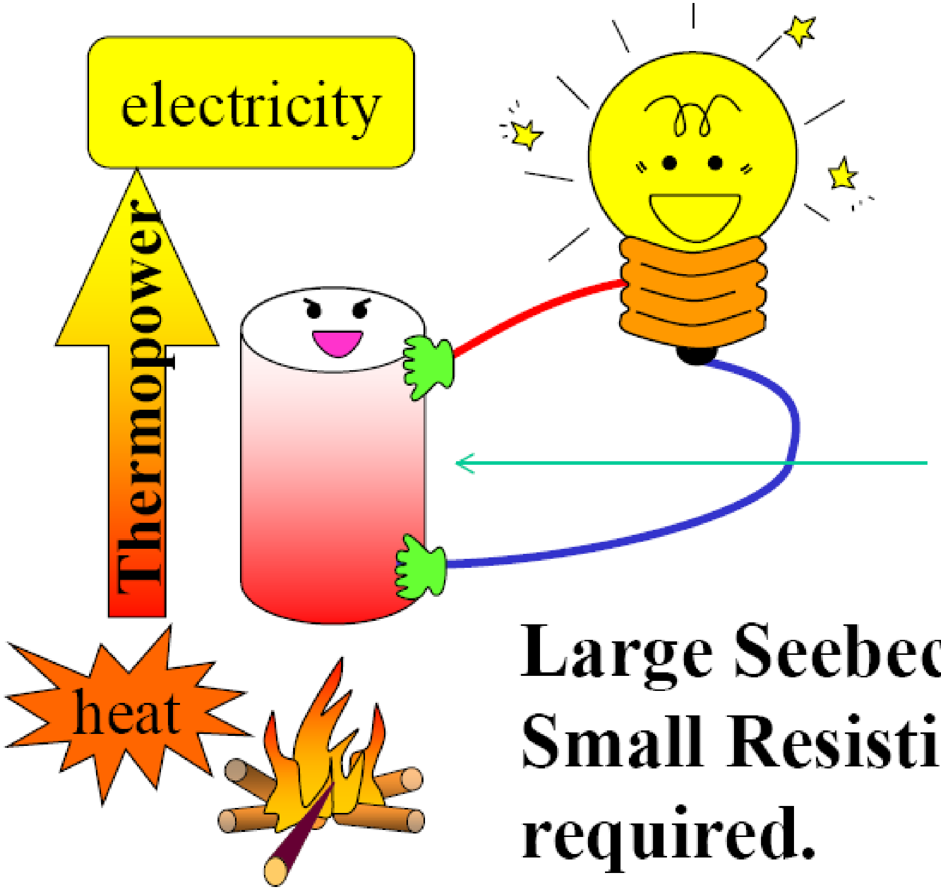
Goennenwein & Bauer, Nature Nanotech. (2012)



Chen Xiao-Bin & Duan Wen-Hui, Acta Phys. Sin. (2015)

Energy conversion from heat to electricity:

•*Seebeck effect :*



Thermo-electric material

Large Seebeck effect (*Q*) & Small Resistivity (ρ) are required.

Seebeck effect was discovered in 1821.

Thomas Johann Seebeck

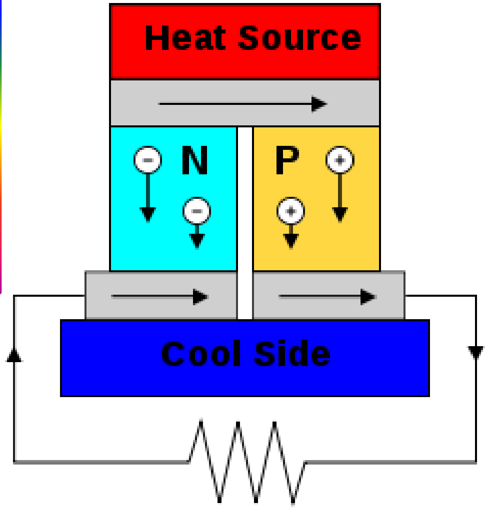
Jean Charles Athanase Peltier

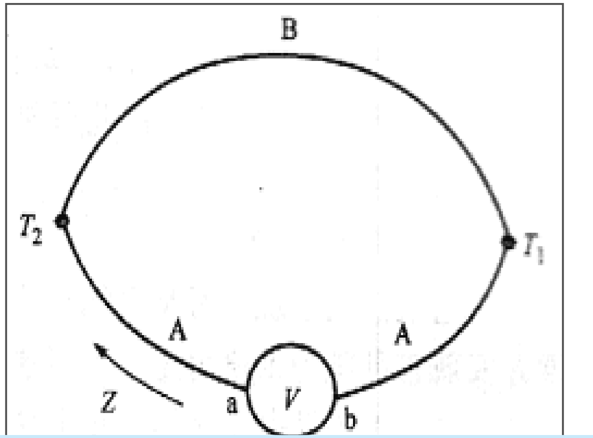
➢The Seebeck effect refers to the production of a longitudinal electromotive force induced by the temperature gradient.

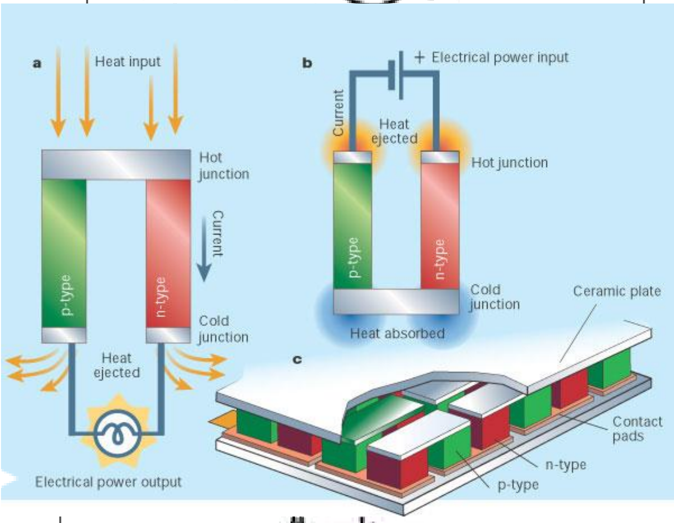
The Seebeck coefficient $S_c = -\frac{\Delta V}{\Delta T}\Big|_{J=0}$

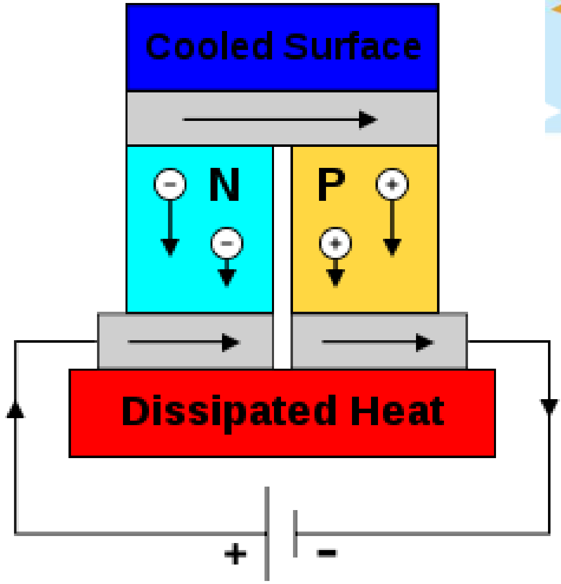
The Peltier coefficient $\Pi_c = \frac{Q}{J}$

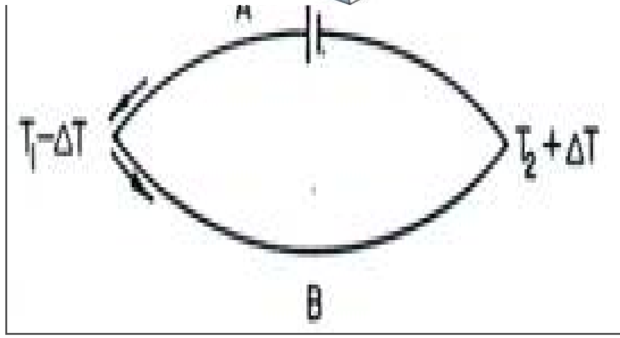
➢The Peltier effect refers to the evolution of the longitudinal heat current ***Q***, which is induced by the electric current ***J*** across an isothermal junction of two terminals.





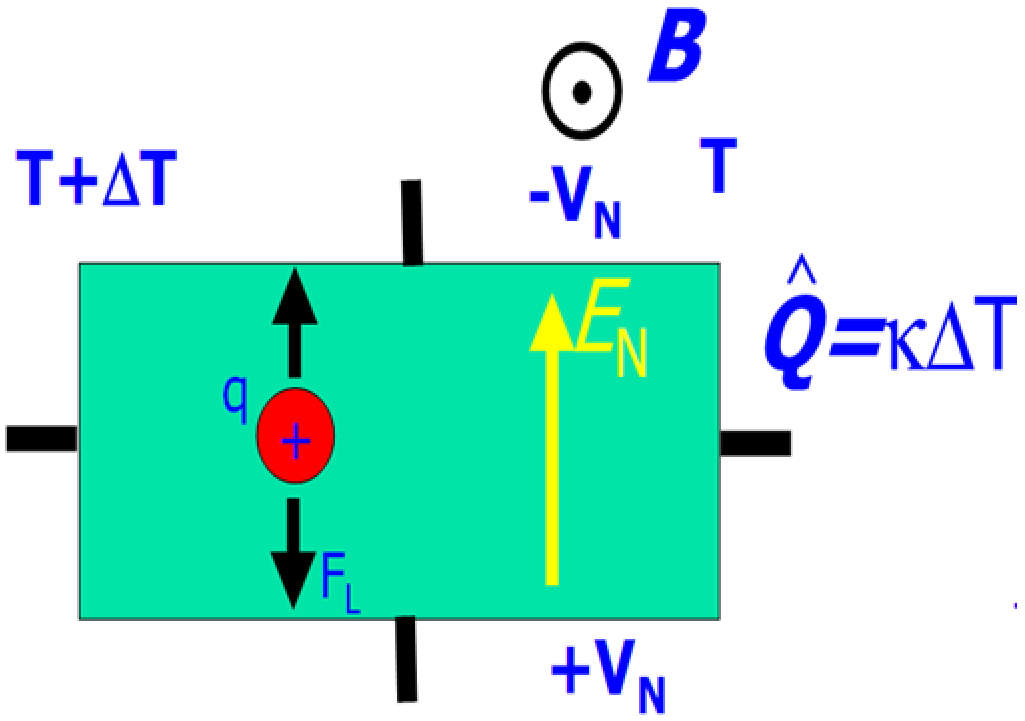






➢The Nernst effect describes the transverse electric force induced by the longitudinal temperature gradient in the multiterminal system in the condition of zero transverse current.

The Nernst coefficient $N_c = \left.\frac{\Delta V_y}{\Delta T_x}\right|_{J_y=0}$



➢The Ettingshausen effect is the reciprocal version of the Nernst effect. It describes the transverse heat current induced by the longitudinal electric current, in the condition of zero transverse electric current.

The Ettingshausen coefficient $\mathrm{E}_c = \left.\frac{Q_y}{J_x}\right|_{J_y=0}$

The efficiency of thermoelectrical materials is measured by the dimensionless-thermoelectrical figure of merit ***ZT.***

Electric conductivity

Seebeck coefficient

$$ZT = \frac{\sigma S^2}{\kappa} T$$

Temperature

Total thermal conductivity

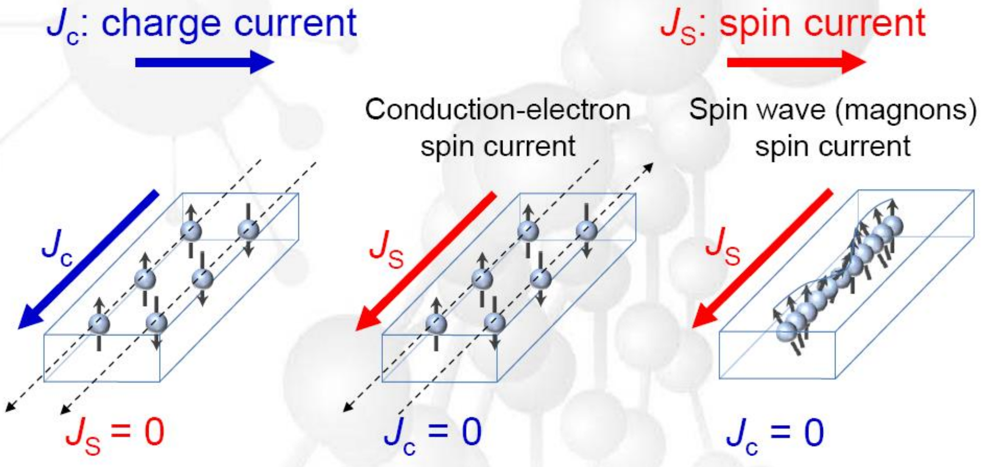
$$\kappa = \kappa_e + \kappa_l$$

Electric thermal conductivity

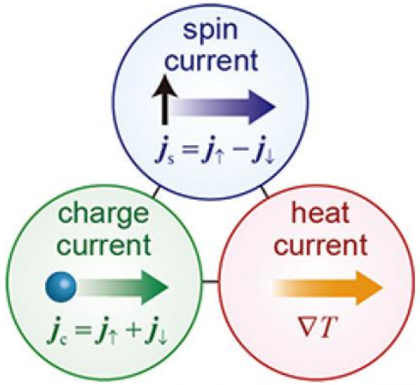
Lattice-thermal conductivity

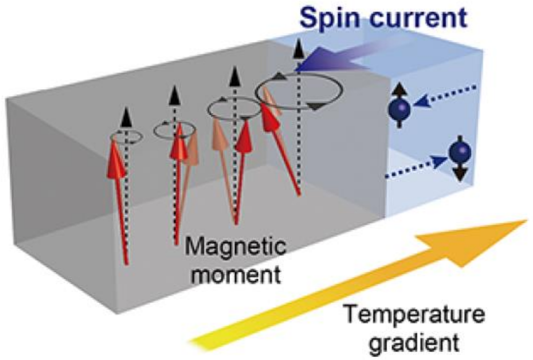
For a material to be a good thermoelectric material, it must have a large ZT, which means in order to achieve a large ZT, one must increase the Seebeck coefficient and electric conductivity and decrease the thermal conductivity.

Charge and spin currents



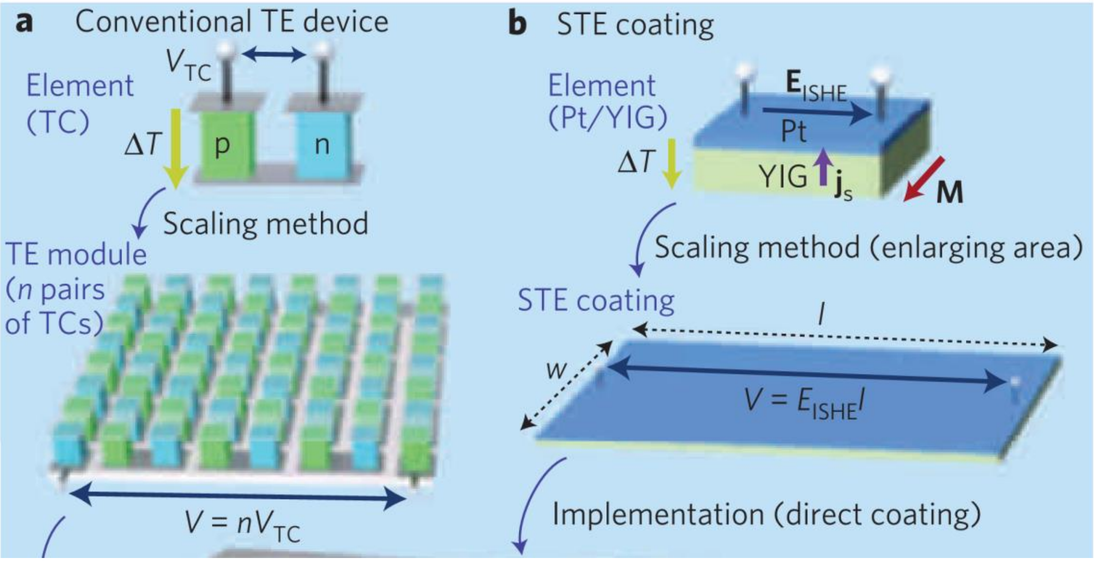
Spin current: no Joule heating!





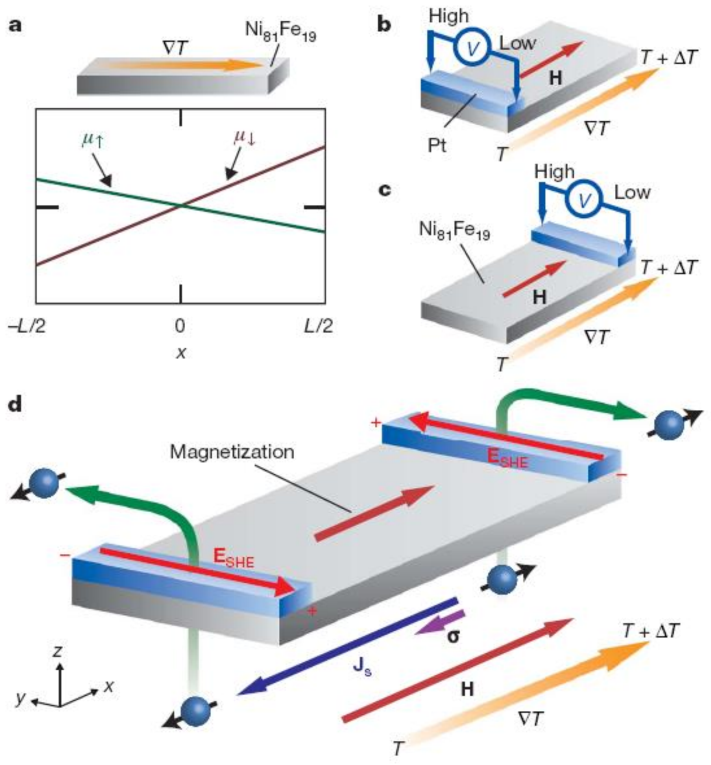
$$\boxed{I_S = -G_S \frac{k_B}{\hbar}(T_F - T_N)}$$

J. Xiao et al. PRB **81**, 214418 (2010)
H. Adachi et al. PRB **83**, 094410 (2011)
Rep. Prog. Phys. **76**, 036501 (2013)



Kirihara, et al, *Nature Materials* (2012)

Spin current generation by heat

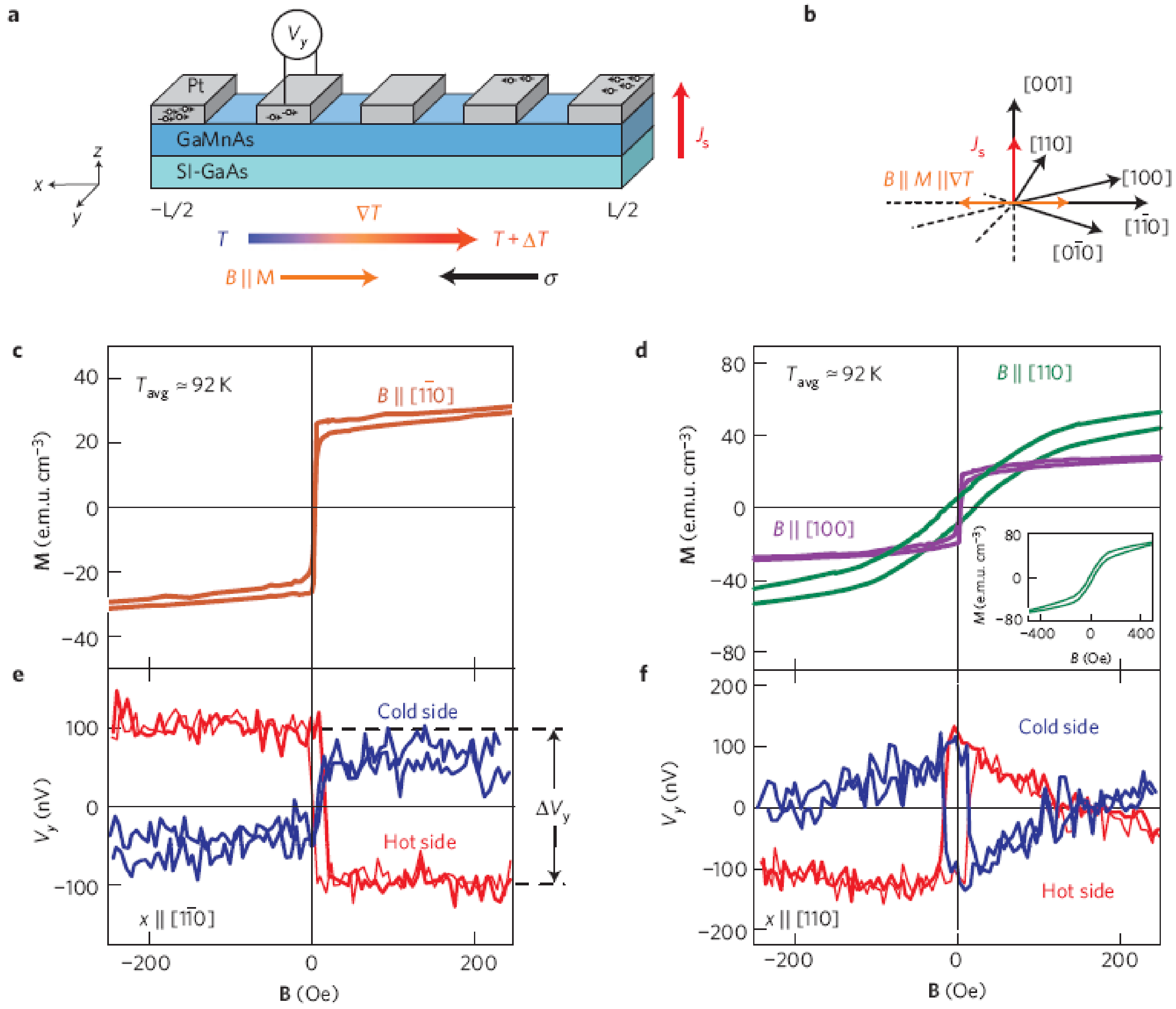


Uchida, et al, Nature (2008)

In 2008, Uchida et al demonstrated that when a ferromagnetic film is placed under the influence of a temperature gradient, a spin current is injected from the ferromagnetic film into the attached nonmagnetic metals with the signal observed over a macroscopic scale of several millimeters.

自旋塞贝克效应指的是温度梯度在铁磁体中产生自旋压，使得自旋流可以在宏观尺度毫米量级的范围内从铁磁体注入到临近的非磁材料中的这样一种效应。

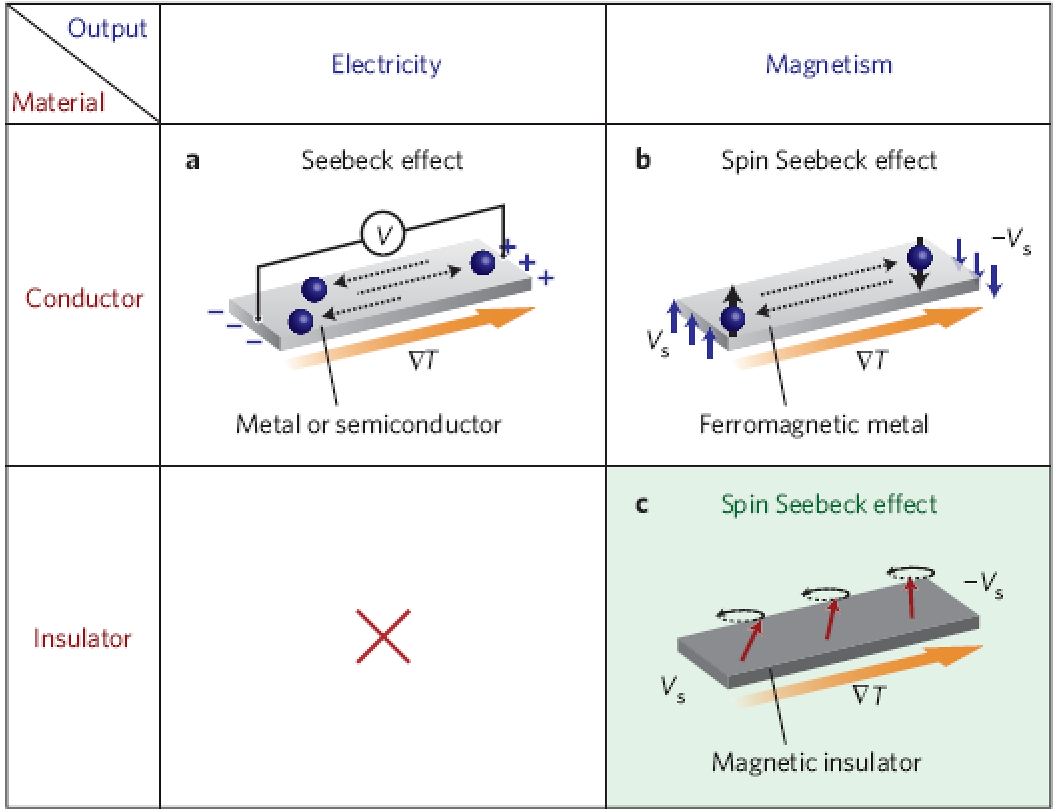
测量机制如下：将样品置于300K的环境温度中，对其施加一个沿x方向的温度梯度，同时外加平行于x方向的磁场。300K时，$Ni_{81}Fe_{19}$的矫顽力在15Oe左右，并且在磁场大于矫顽力时，磁化排列是沿着外磁场方向。在$Ni_{81}Fe_{19}$层中，由于温度梯度产生了自旋电压因而在Pt层中会导致自旋电流(穿过$Ni_{81}Fe_{19}$和Pt的界面)。在Pt层中，自旋压沿z方向减小。由于自旋极化，自旋电流的矢量将沿着磁场方向分布，故在磁场大于矫顽力时，自旋电流会由于Pt层中的逆自旋Hall效应产生一个沿y方向的电动势。

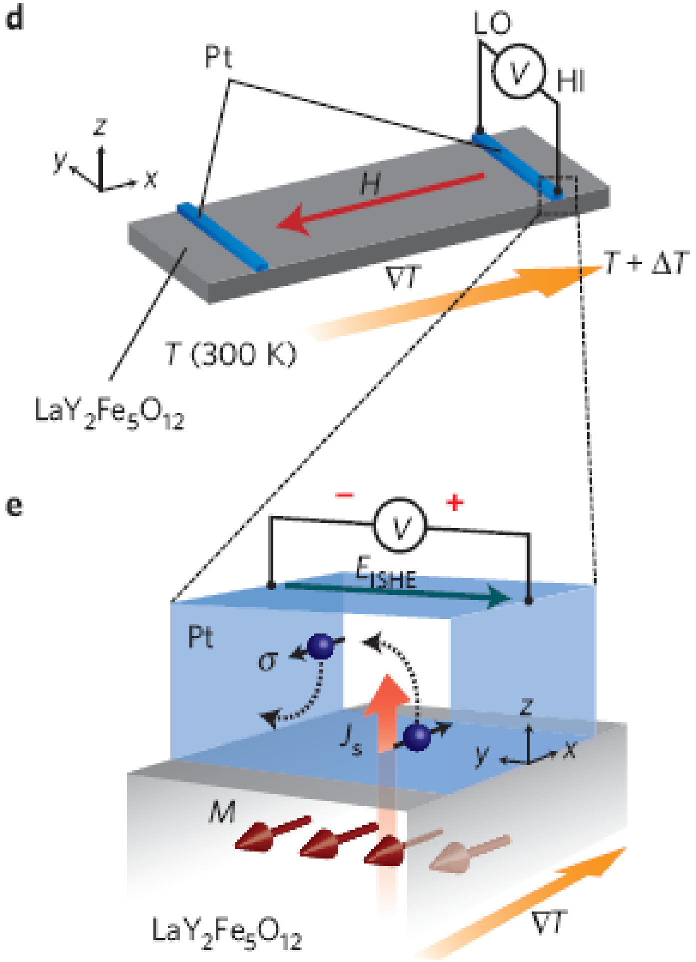


2010年，Jaworski等人在铁磁半导体GaMnAs中观测了不同温度下的自旋Seebeck效应。利用在铁磁体表面不同位置制作多个条形Pt层的方法，在x的方向上测得的E_{ISHE}分布与$Ni_{81}Fe_{19}$的结果不同。 E_{ISHE}不再呈线性分布，而是呈sinh(x)形式分布，并且冷热两端温差相同时整块GaMnAs的平均温度越低，在相同位置所测量到的值越大。

Jaworski C M, et al, Nat. Mater (2010)

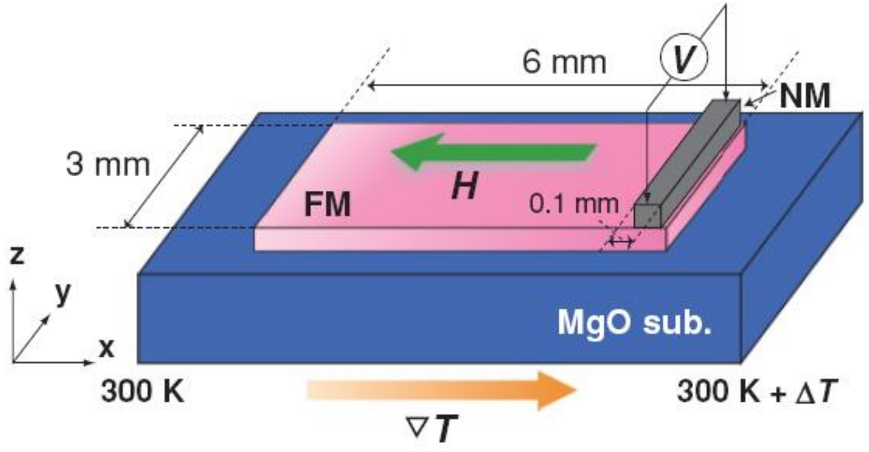
Chen Xiao-Bin & Duan Wen-Hui, Acta Phys. Sin. (2015)



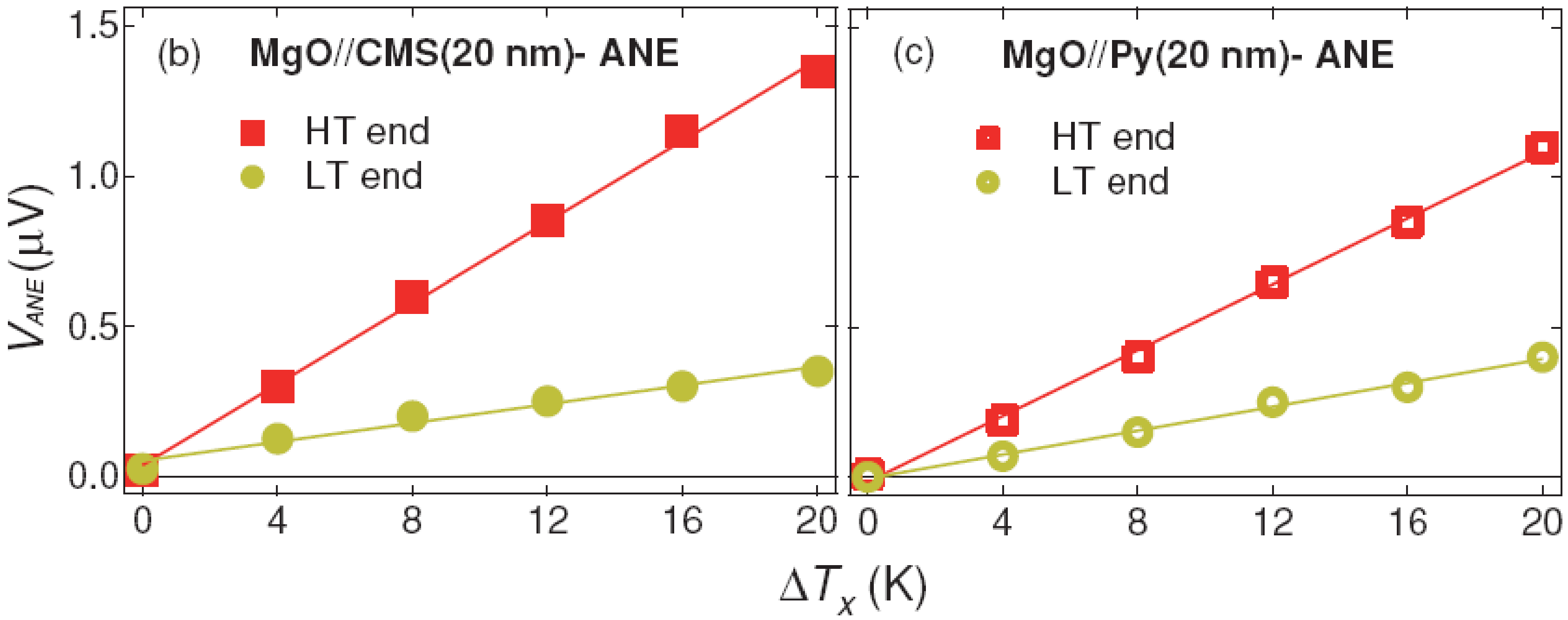


Uchida, et al, Nat. Mater (2010)

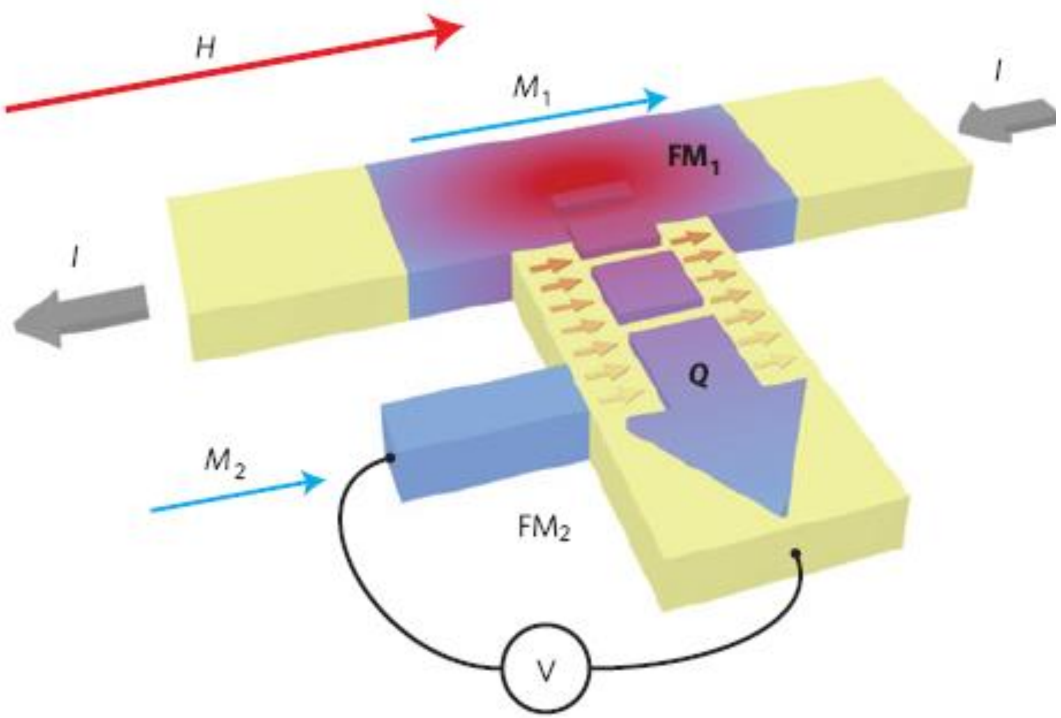
2010年，Saitoh研究组在铁磁绝缘体$LaY_2Fe_5O_{12}$，也发现了自旋seebeck效应。

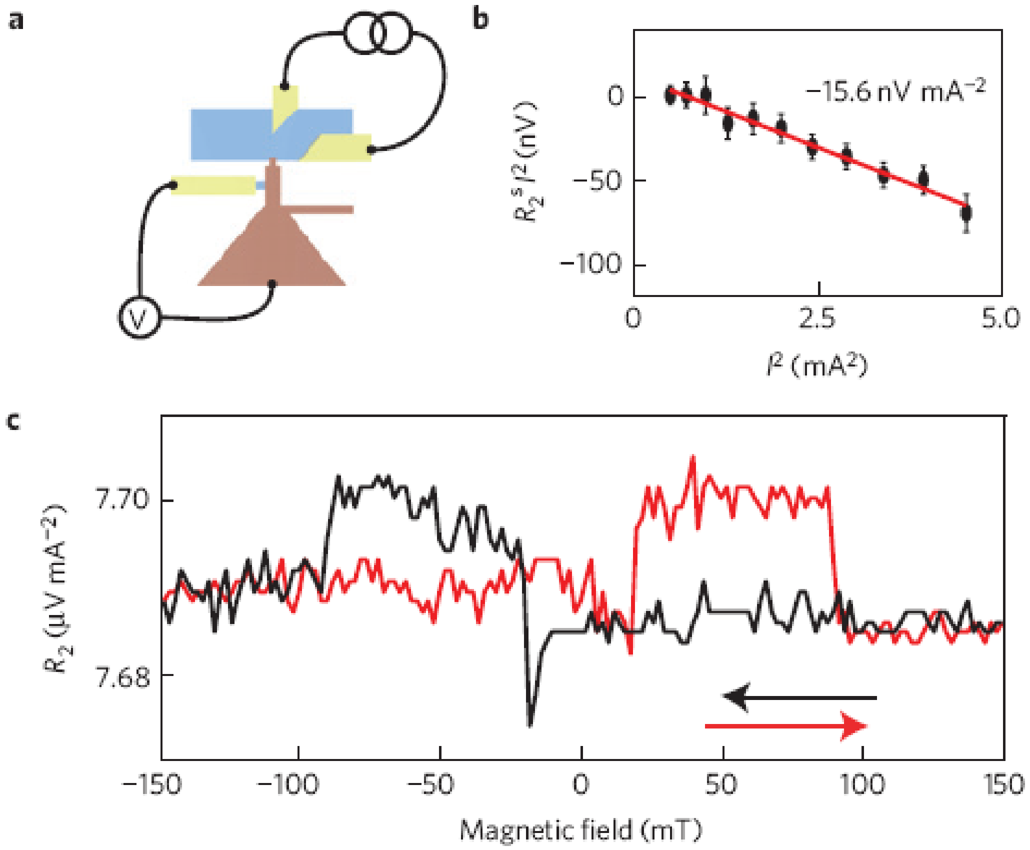


2011年，Takanashi研究组在半金属性的霍伊斯勒化合物Co_2MnSi/Pt薄膜中发现由磁振子引起的自旋Seebeck效应。



Bosu, et al, Phys. Rev. B (2011)





Slachter, et al, Nat. Phys. (2011)

2011年，Slachter研究组报道了他们的实验，由温度梯度驱动的自旋流。电流I通过铁磁体FM1产生焦耳热；热流JQ从FM1流向普通金属NM的过程中造成界面自旋累积，从而产生自旋注入。

Temperature dependence of the spin Seebeck effect in $[Fe_3O_4/Pt]_n$ multilayers

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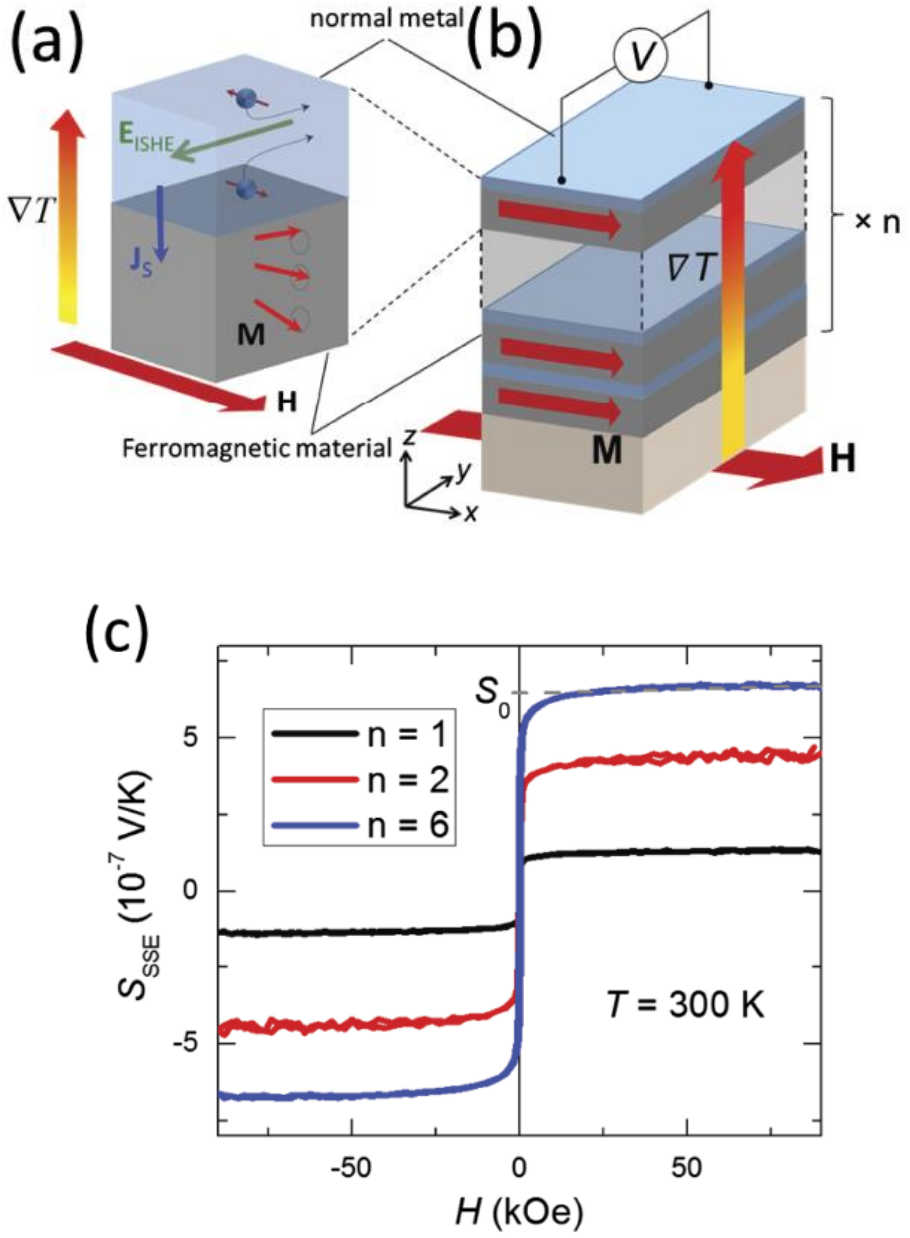
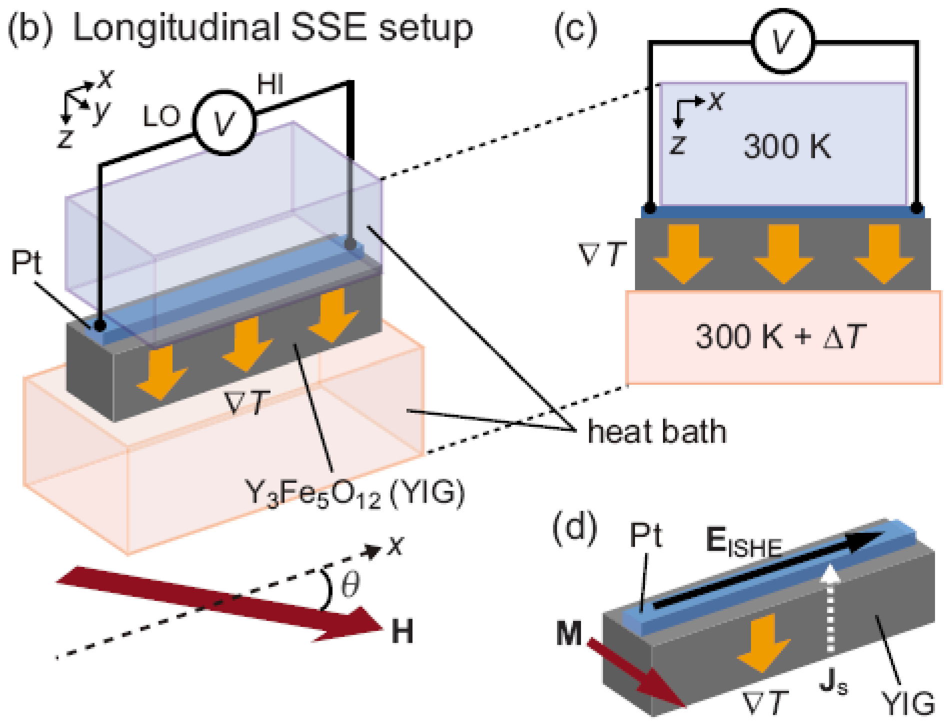
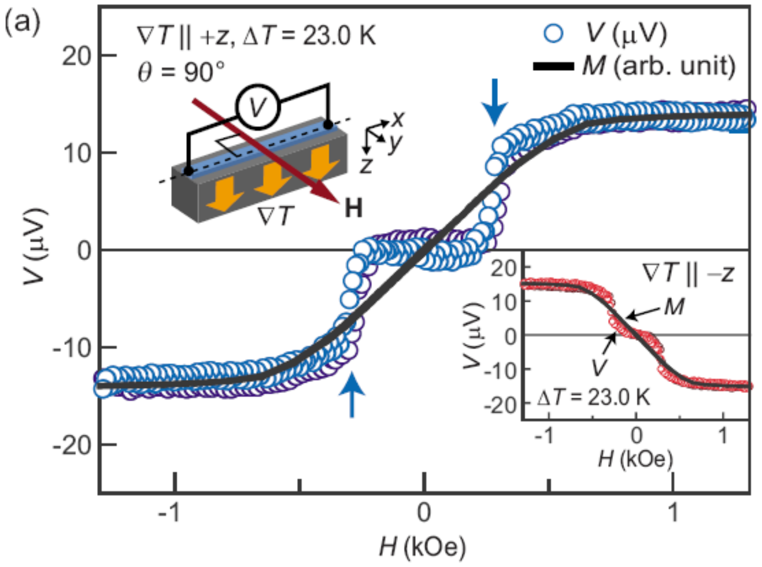
We report temperature dependent measurements of the spin Seebeck effect (SSE) in multilayers formed by repeated growth of a Fe_3O_4/Pt bilayer junction. The magnitude of the observed enhancement of the SSE, relative to the SSE in the single bilayer, shows a monotonic increase with decreasing the temperature. This result can be understood by an increase of the characteristic length for spin current transport in the system, in qualitative agreement with the recently observed increase in the magnon diffusion length in Fe_3O_4 at lower temperatures. Our result suggests that the thermoelectric performance of the SSE in multilayer structures can be further improved by careful choice of materials with suitable spin transport properties. [http://dx.doi.org/10.1063/1.4974060]



Ramos, et al, AIP. Adv. (2017)

除了依靠扩散作用从铁磁体向非磁体非局域地注入自旋流之外(此自旋流方向与温度梯度方向是垂直的)，还可以用沿着温度梯度方向即热流方向直接向非磁体注入自旋流，即以热驱动的办法直接从FM绝缘体向普通金属转移角动量，这就是**纵向自旋塞贝克效应(longitudinal spin Seebeck effect)** 。





we have measured, using a YIG/Pt system, a spin current generated in the Pt film along the temperature gradient: the longitudinal spin-Seebeck effect (SSE), by means of the inverse spin-Hall effect (ISHE) in Pt.

Uchida, et al, Appl. Phys. Lett (2011)

Chen Xiao-Bin & Duan Wen-Hui, Acta Phys. Sin. (2015)

Local Charge and Spin Currents in Magnetothermal Landscapes

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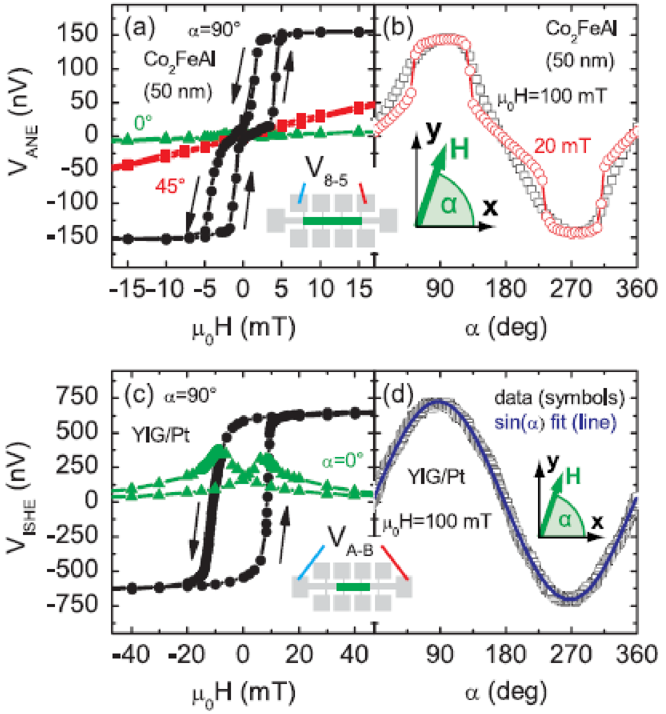
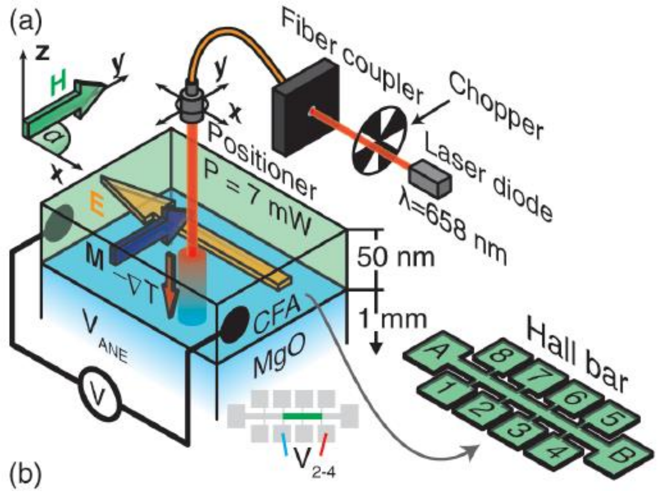
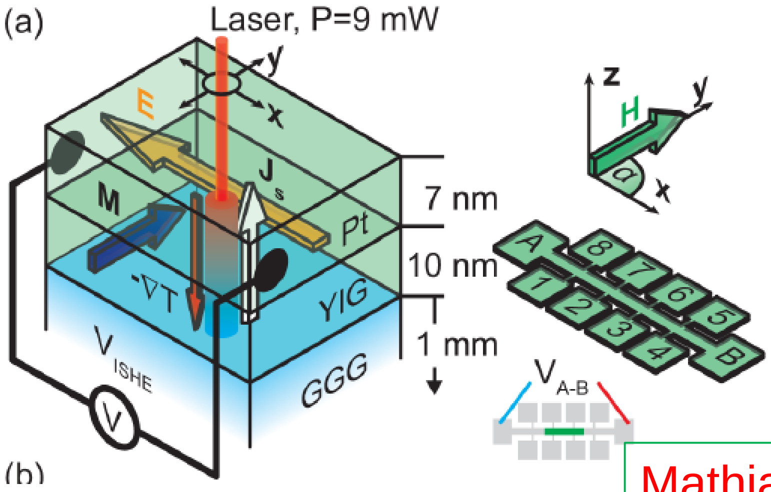
(Received 18 October 2011; published 5 March 2012)

A scannable laser beam is used to generate local thermal gradients in metallic (Co_2FeAl) or insulating ($Y_3Fe_5O_{12}$) ferromagnetic thin films. We study the resulting local charge and spin currents that arise due to the anomalous Nernst effect (ANE) and the spin Seebeck effect (SSE), respectively. In the local ANE experiments, we detect the voltage in the Co_2FeAl thin film plane as a function of the laser-spot position and external magnetic field magnitude and orientation. The local SSE effect is detected in a similar fashion by exploiting the inverse spin Hall effect in a Pt layer deposited on top of the $Y_3Fe_5O_{12}$. Our findings establish local thermal spin and charge current generation as well as spin caloritronic domain imaging.







Mathias, et al, Phys. Rev. Lett (2012)

Spin-dependent Seebeck coefficients of $Ni_{80}Fe_{20}$ and Co in nanopillar spin valves

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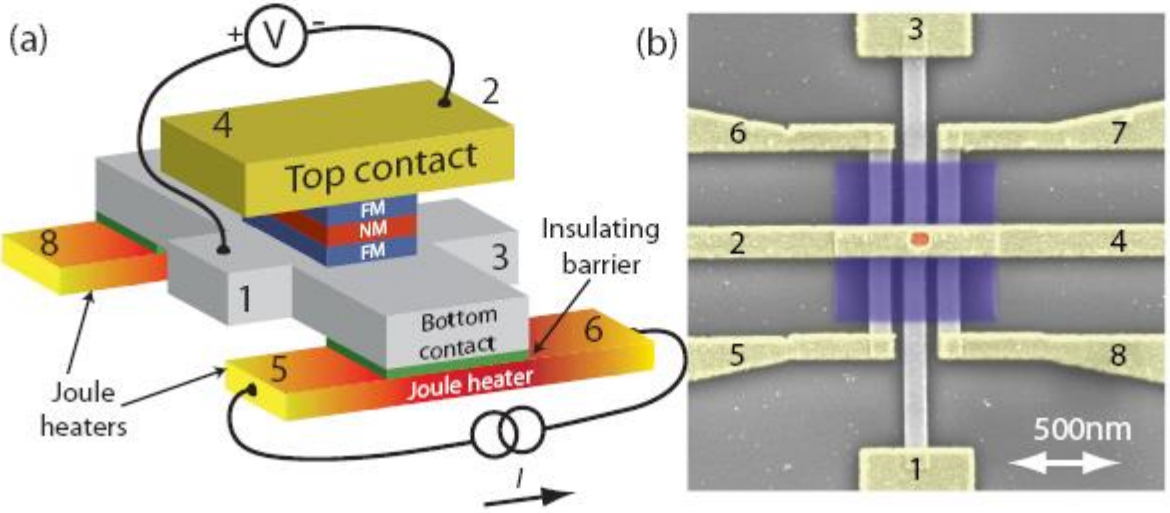
(Received 25 May 2012; published 27 July 2012)

We have experimentally determined the spin-dependent Seebeck coefficient of permalloy ($Ni_{80}Fe_{20}$) and cobalt (Co) using nanopillar spin valve devices, a stack of two ferromagnetic layers separated by a nonmagnetic layer. The devices were specifically designed to separate heat-related effects from charge-related effects. A heat current, with no accompanying charge current, through the nanopillar spin valve leads to a thermovoltage proportional to the spin-dependent Seebeck coefficient $S_S = S_\uparrow - S_\downarrow$ of the ferromagnet, where $S_\uparrow$ and $S_\downarrow$ are the Seebeck coefficient for spin-up and spin-down electrons. By using a three-dimensional finite-element model based on spin-dependent thermoelectric theory, whose input material parameters were measured in separate devices, we were able to accurately determine a spin-dependent Seebeck coefficient of $-1.8\ \mu V\ K^{-1}$ and $-4.5\ \mu V\ K^{-1}$ for cobalt and permalloy, respectively, corresponding to a Seebeck coefficient polarization $P_S = S_S/S_F$ of 0.08 and 0.25, where S_F is the Seebeck coefficient of the ferromagnet. The results are in agreement with earlier theoretical work in Co/Cu multilayers and spin-dependent Seebeck and spin-dependent Peltier measurements in $Ni_{80}Fe_{20}$/Cu spin valve structures.



Dejene, et al, Phys. Rev. B (2012)

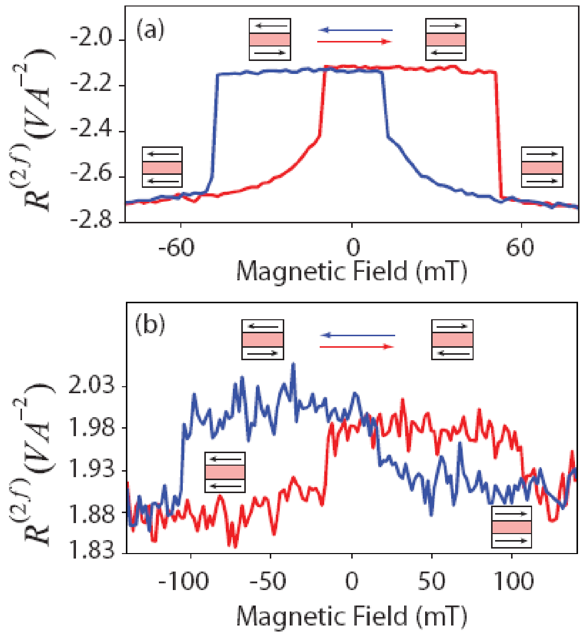


FIG. 5. (Color online) Spin-dependent Seebeck resistance $V^{(2f)}/I^2$ for (a) $Ni_{80}Fe_{20}$ and (b) Co at a current of 1 mA. Clear jumps in the measured voltage across the nanopillar occur at fields where the two magnetizations switch.

Observation of longitudinal spin-Seebeck effect in cobalt-ferrite epitaxial thin films

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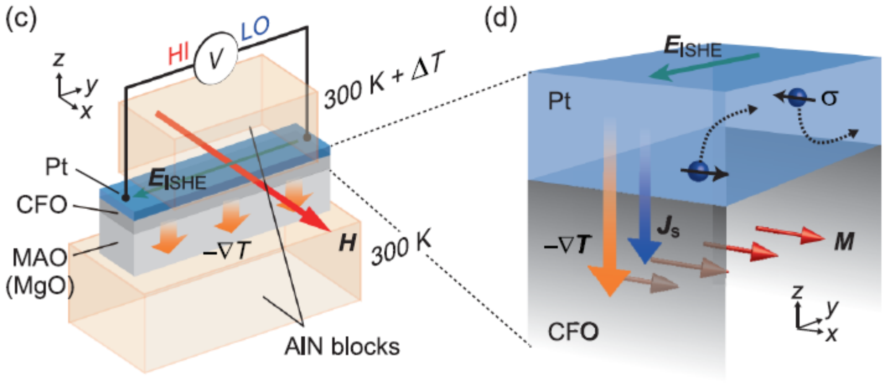
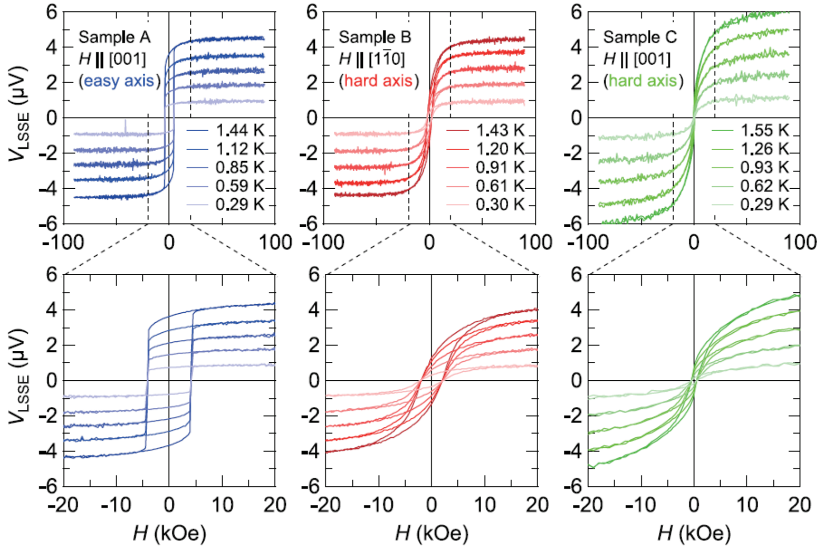
(Received 5 February 2015; accepted 25 March 2015; published online 1 April 2015)

The longitudinal spin-Seebeck effect (LSSE) has been investigated in cobalt ferrite (CFO), an exceptionally hard magnetic spinel ferrite. A bilayer of a polycrystalline Pt and an epitaxially-strained CFO(110) exhibiting an in-plane uniaxial anisotropy was prepared by reactive rf sputtering technique. Thermally generated spin voltage in the CFO layer was measured via the inverse spin-Hall effect in the Pt layer. External-magnetic-field (H) dependence of the LSSE voltage (V_{LSSE}) in the Pt/CFO(110) sample with $H \parallel [001]$ was found to exhibit a hysteresis loop with a high squareness ratio and high coercivity, while that with $H \parallel [1\bar{1}0]$ shows a nearly closed loop, reflecting the different anisotropies induced by the epitaxial strain. The magnitude of V_{LSSE} has a linear relationship with the temperature difference (ΔT), giving the relatively large $V_{\mathrm{LSSE}}/\Delta T$ of about 3 μV/K for CFO(110) which was kept even at zero external field. [http://dx.doi.org/10.1063/1.4916978]





Tomohiko, et al, AIP. Adv. (2015)

Longitudinal spin Seebeck effect in permalloy separated from the anomalous Nernst effect: Theory and experiment

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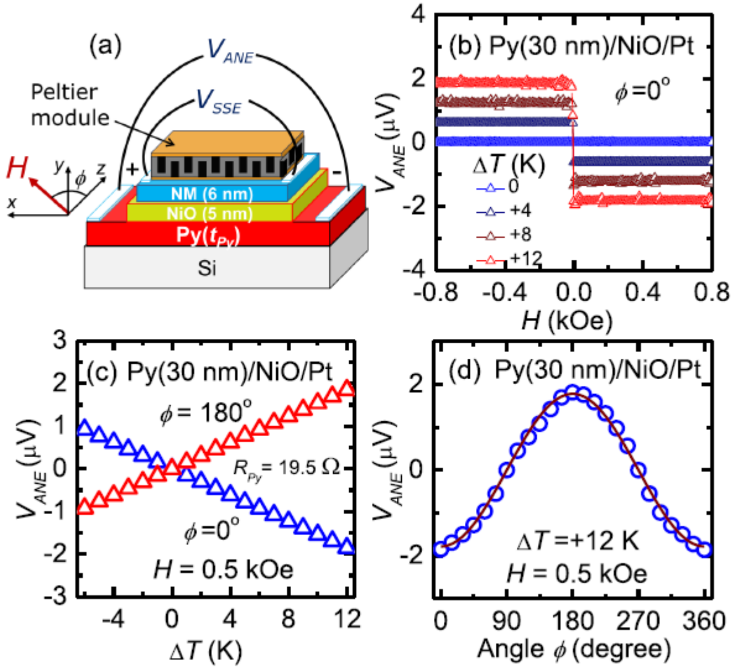
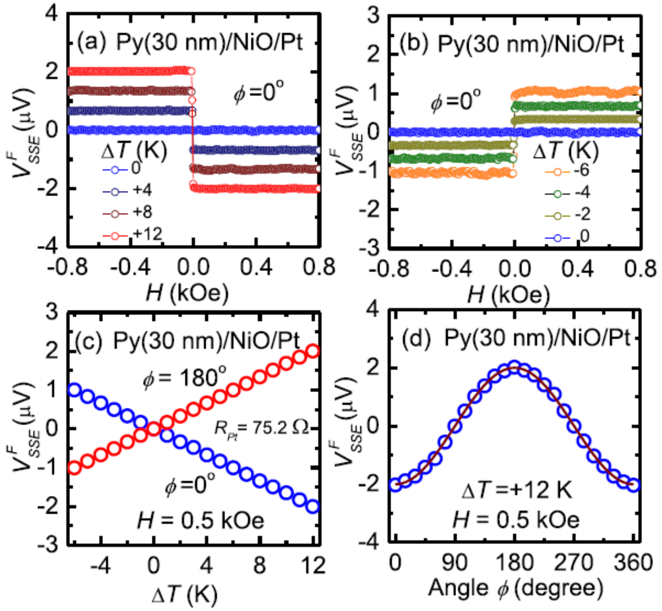
(Received 31 March 2017; published 26 June 2017)

The longitudinal spin Seebeck effect (LSSE) consists in the generation of a spin current parallel to a temperature gradient in a magnetic material. The LSSE has only been measured unequivocally in magnetic insulators because in metallic films it is contaminated by the anomalous Nernst effect (ANE). Here we report theoretical and experimental studies of the LSSE in the metallic ferromagnet $N_{81}Fe_{19}$ (permalloy-Py) separated from the ANE. We have used trilayer samples of Py/NiO/NM (NM is a normal metal, Pt or Ta) under a temperature gradient perpendicular to the plane to generate a spin current in Py that is transported across the NiO layer and reaches the NM layer, where it is converted into a charge current by the inverse spin Hall effect. The LSSE is detected by a voltage signal in the NM layer while the ANE is measured by the voltage induced in the Py layer. The separation of the two effects is made possible because the antiferromagnetic insulator NiO layer transports spin current while providing electrical insulation between the Py and NM layers. The measured spin Seebeck coefficient for Py has a value similar to the one for the ferrimagnetic insulator yttrium iron garnet, with the same sign, and is in good agreement with the value calculated with a thermoelectric spin drift-diffusion model.

Holanda, et al, Phys. Rev. B (2017)





Concomitant enhancement of the longitudinal spin Seebeck effect and the thermal conductivity in a Pt/YIG/Pt system at low temperatures

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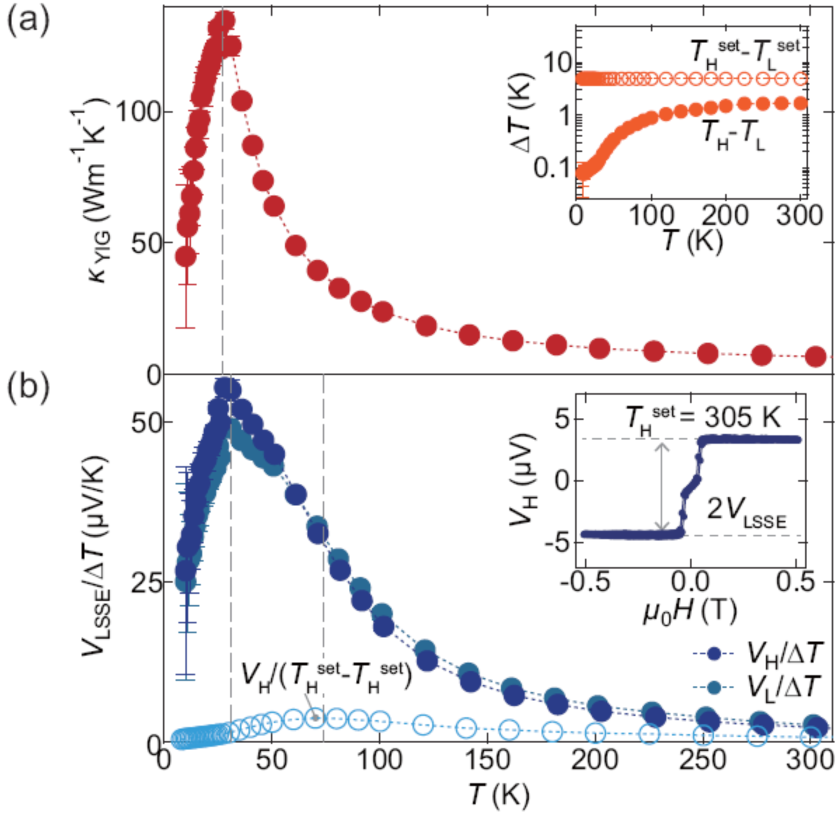
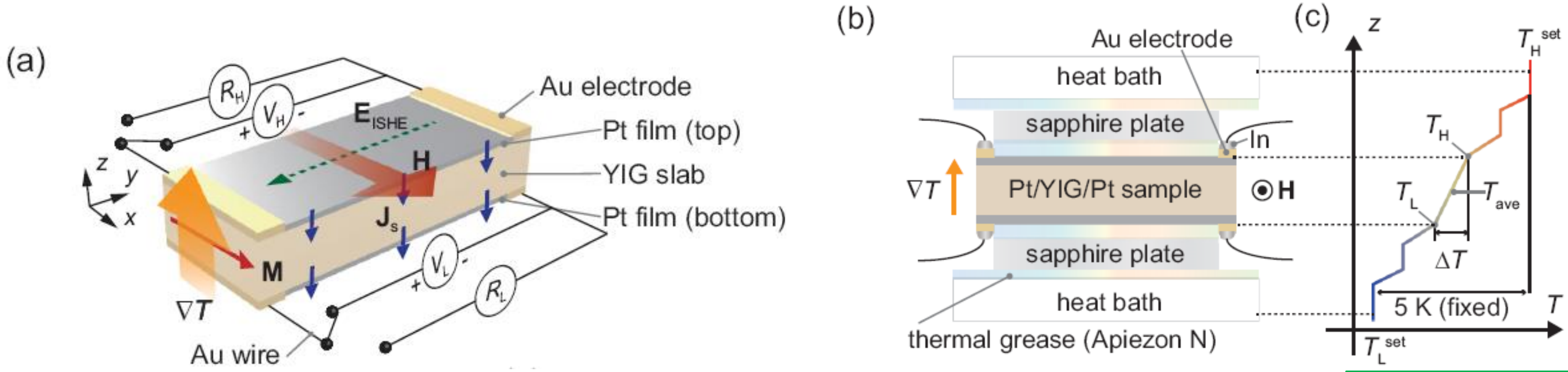
We report a simultaneous measurement of a longitudinal spin Seebeck effect (LSSE) and thermal conductivity in a Pt/$Y_3Fe_5O_{12}$ (YIG)/Pt system in a temperature range from 10 to 300 K. By directly monitoring the temperature difference in the system, we excluded thermal artifacts in the LSSE measurements. It is found that both the LSSE signal and the thermal conductivity of YIG exhibit sharp peaks at the same temperature, different from previous reports. The maximum LSSE coefficient is found to be $S_{LSSE} > 10\ \mu V/K$, one-order-of magnitude greater than the previously reported values. The concomitant enhancement of the LSSE and thermal conductivity of YIG suggests the strong correlation between magnon and phonon transport in the LSSE.





Iguchi, et al, Phys. Rev. B (2017)

Enhancement of the spin Peltier effect in multilayers

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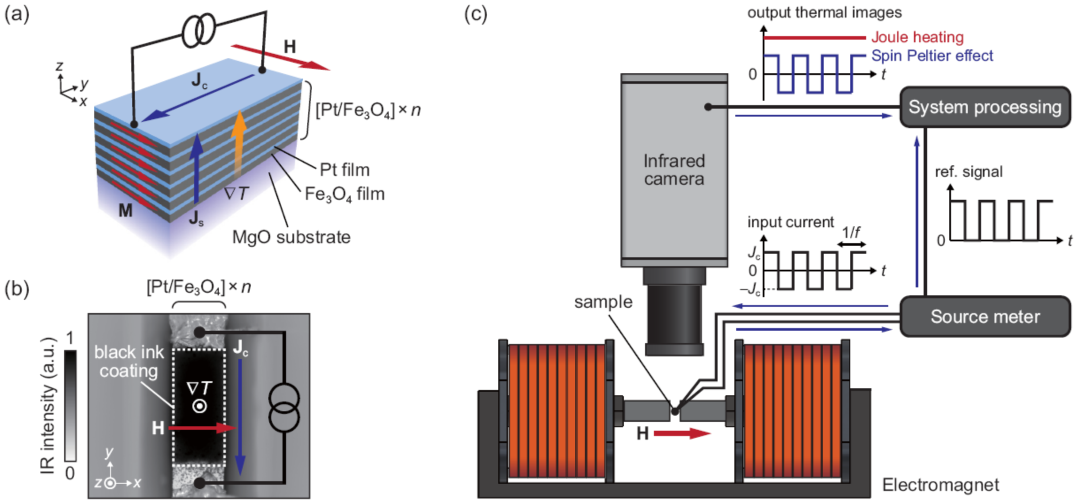
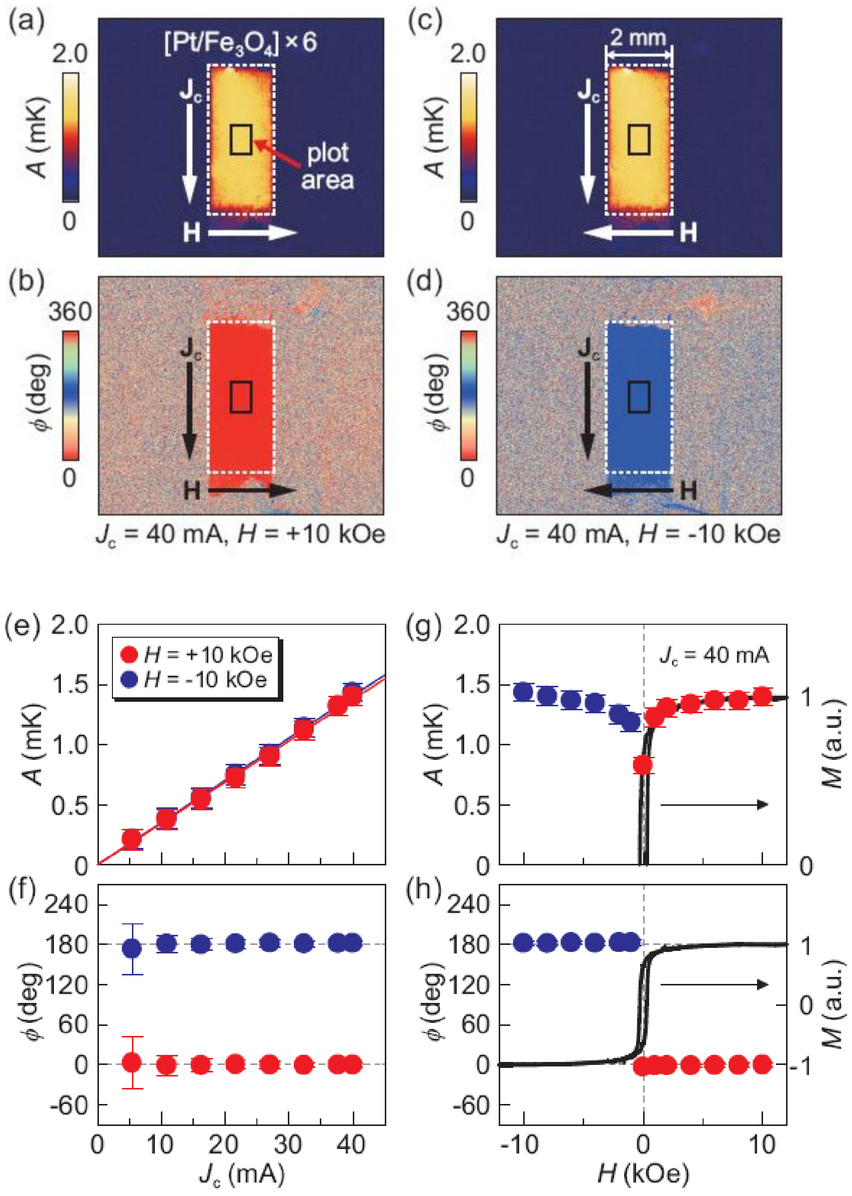
The spin Peltier effect (SPE), heat-current generation as a result of spin-current injection, has been investigated in alternately stacked Pt/Fe_3O_4 multilayer films. The temperature modulation induced by the SPE in the $[Pt/Fe_3O_4] \times n$ films was found to be significantly enhanced with increasing the number of Pt/Fe_3O_4 bilayers n. This SPE enhancement is much greater than that expected for a simple stack of independent Pt/Fe_3O_4 bilayers. The observed n dependence of the SPE can be explained by introducing spin-current redistribution in the multilayer films in the thickness direction, in a manner similar to the enhancement of the spin Seebeck effect in multilayers.





Uchida, et al, Phys. Rev. B (2017)

Magnetic-field-induced decrease of the spin Peltier effect in Pt/$Y_3Fe_5O_{12}$ system at room temperature

Ryuichi Itoh,[1] Ryo Iguchi,[1,2,*] Shunsuke Daimon,[1,3] Koichi Oyanagi,[1] Ken-ichi Uchida,[2,4,5] and Eiji Saitoh[1,3,5,6]

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We report the observation of magnetic-field-induced decrease of the spin Peltier effect (SPE) in a junction of a paramagnetic metal Pt and a ferrimagnetic insulator $Y_3Fe_5O_{12}$ (YIG) at room temperature. For driving the SPE, spin currents are generated via the spin Hall effect from applied charge currents in the Pt layer, and injected into the adjacent thick YIG film. The resultant temperature modulation is detected by a commonly used thermocouple attached to the Pt/YIG junction. The output of the thermocouple shows sign reversal when the magnetization is reversed and linearly increases with the applied current, demonstrating the detection of the SPE signal. We found that the SPE signal decreases with the magnetic field. The observed decreasing rate was found to be comparable to that of the spin Seebeck effect (SSE), suggesting the dominant and similar contribution of the low-energy magnons in the SPE as in the SSE.

Ryuichi, et al, Phys. Rev. B (2017)

Thermographic measurements of the spin Peltier effect in metal/yttrium-iron-garnet junction systems

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The spin Peltier effect (SPE), heat-current generation due to spin-current injection, in various metal (Pt, W, and Au single layers and Pt/Cu bilayer)/ferrimagnetic insulator [yttrium-iron-garnet (YIG)] junction systems has been investigated by means of a lock-in thermography (LIT) method. The SPE is excited by a spin current across the metal/YIG interface, which is generated by applying a charge current to the metallic layer via the spin Hall effect. The LIT method enables the thermal imaging of the SPE free from the Joule-heating contribution. Importantly, we observed spin-current-induced temperature modulation not only in the Pt/YIG and W/YIG systems, but also in the Au/YIG and Pt/Cu/YIG systems, excluding the possible contamination by anomalous Ettingshausen effects due to proximity-induced ferromagnetism near the metal/YIG interface. As demonstrated in our previous study, the SPE signals are confined only in the vicinity of the metal/YIG interface; we buttress this conclusion by reducing a spatial blur due to thermal diffusion in an infrared-emission layer on the sample surface used for the LIT measurements. We also found that the YIG-thickness dependence of the SPE is similar to that of the spin Seebeck effect measured in the same Pt/YIG sample, implying the reciprocal relation between them.

Daimon, et al, Phys. Rev. B (2017)

2012年，Flipse等人在$(Ni_{80}Fe_{20})$(Py)/copper/Py观测到了自旋关联的帕尔贴效应。

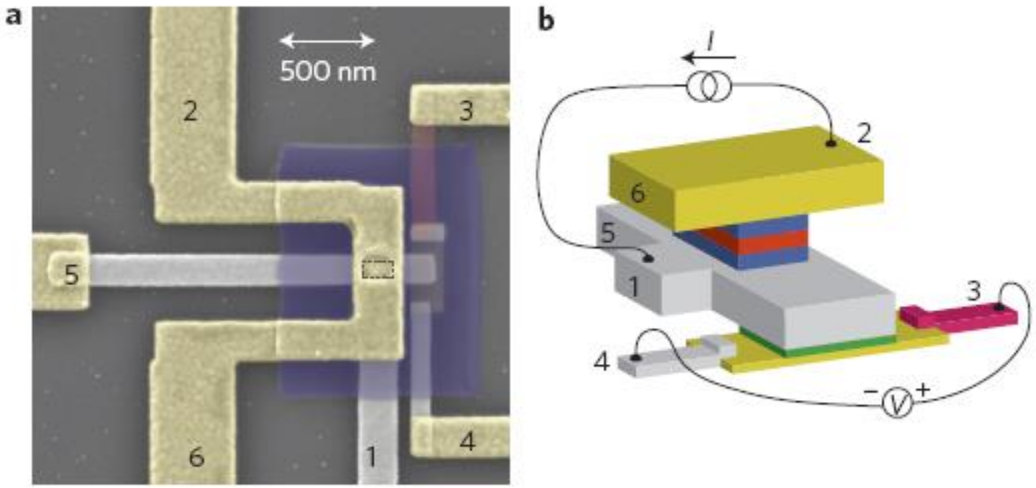
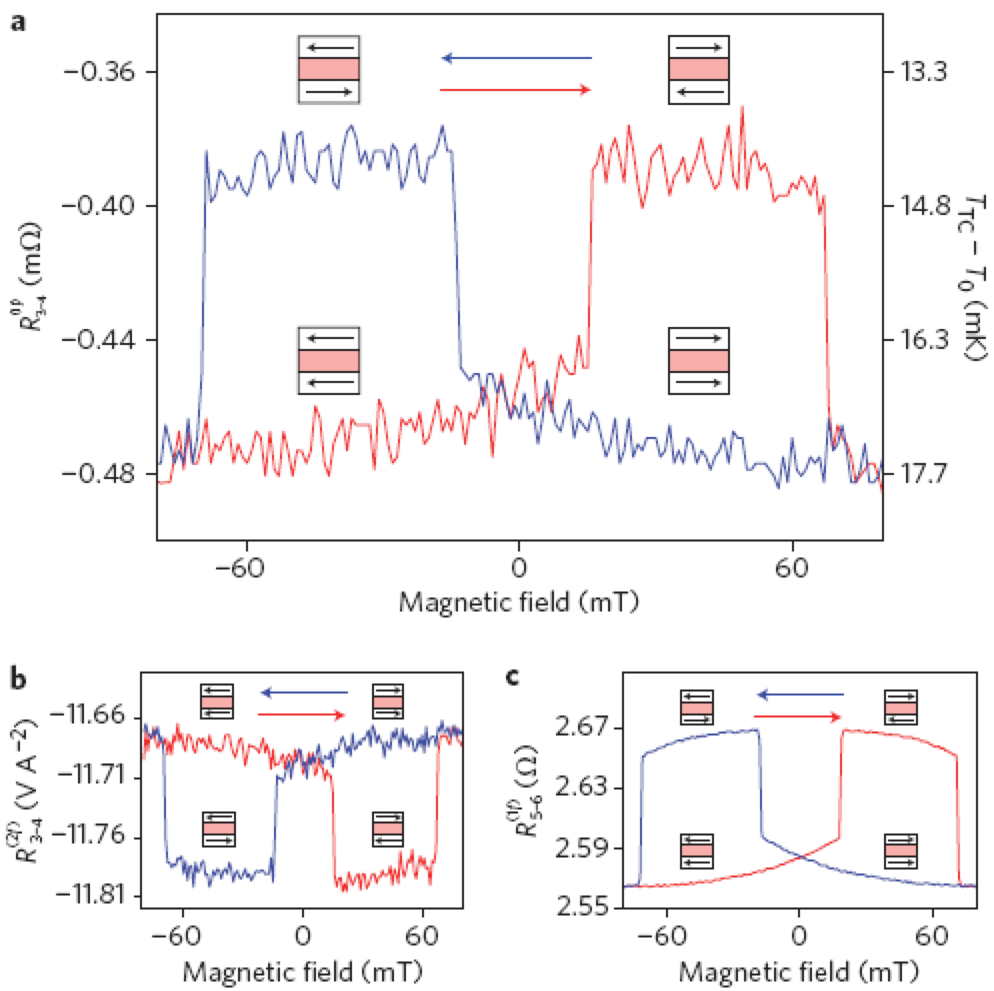


Figure 3 | Device geometry. a, Scanning electron microscopy image of the measured device. Yellow, gold contact; grey, platinum bottom contacts; blue, crosslinked PMMA; red, constantan ($Ni_{45}Cu_{55}$). **b**, Schematic representation of the device. Current is sent from contact 1 to contact 2, while recording the voltage between contacts 3 and 4. Contacts 1, 2, 5 and 6 are used for four-probe spin-valve measurements. The thermocouple is electrically isolated from the bottom contact by an Al_2O_3 (green) layer.



Flipse, et al, Nat. Nano (2012)

Observation of the Spin Peltier Effect for Magnetic Insulators

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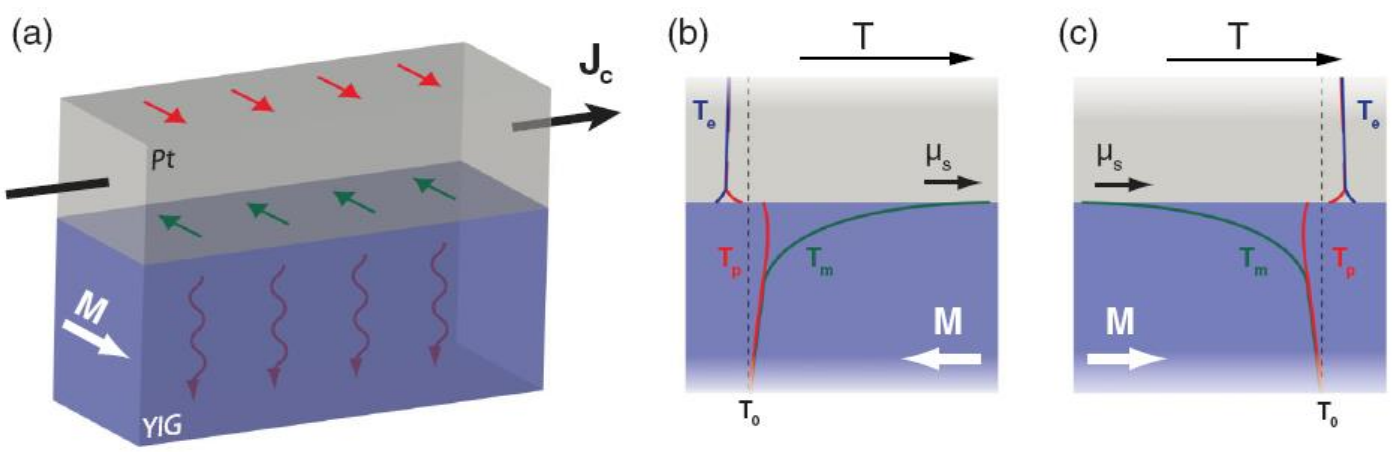
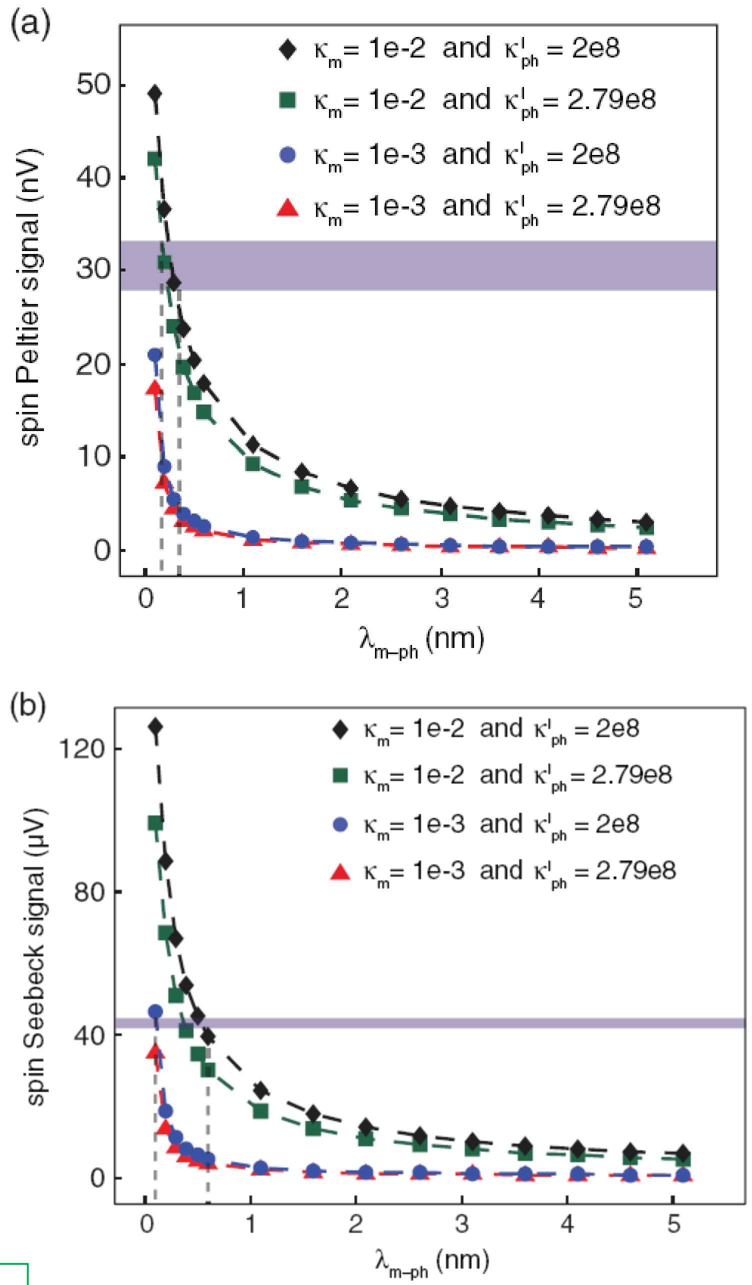
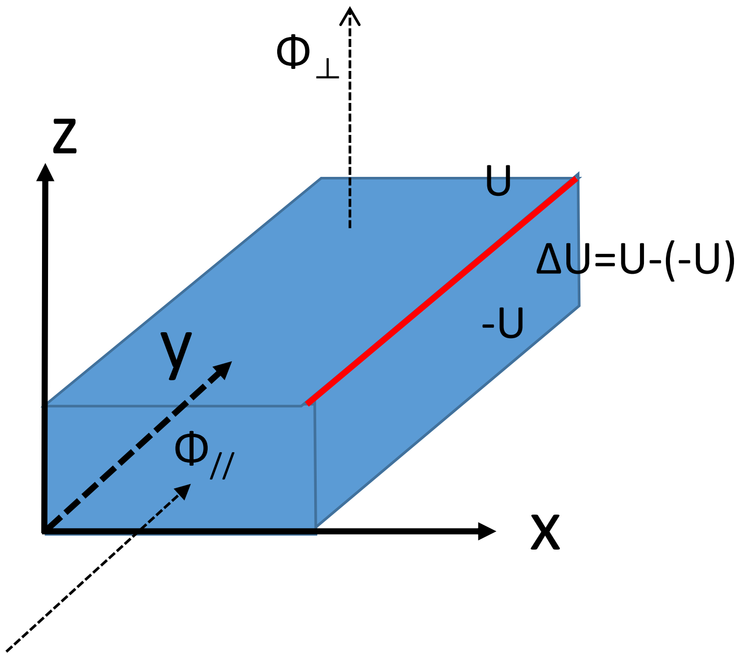
We report the observation of the spin Peltier effect (SPE) in the ferrimagnetic insulator yttrium iron garnet (YIG), i.e., a heat current generated by a spin current flowing through a platinum (Pt)|YIG interface. The effect can be explained by the spin transfer torque that transforms the spin current in the Pt into a magnon current in the YIG. Via magnon-phonon interactions the magnetic fluctuations modulate the phonon temperature that is detected by a thermopile close to the interface. By finite-element modeling we verify the reciprocity between the spin Peltier and spin Seebeck effect. The observed strong coupling between thermal magnons and phonons in YIG is attractive for nanoscale cooling techniques.





Flipse, et al, Phys. Rev. Lett (2014)

Model and Formalism



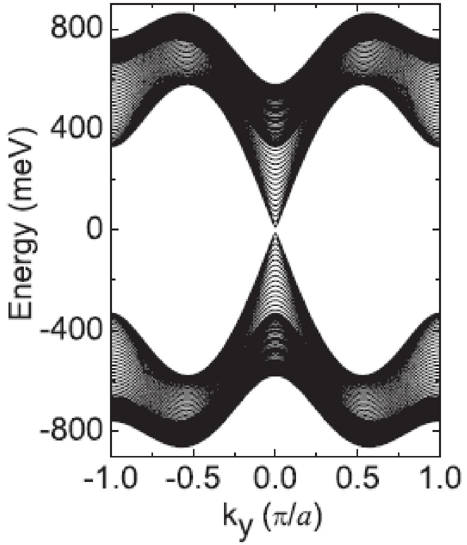
$$H^{2D} = \sum_{n}^{N-1}\sum_{m}[c_{nm}^{\dagger}T_0 c_{nm} + (c_{nm}^{\dagger}T_x c_{n+1,m} + c_{nm}^{\dagger}T_y c_{n,m+1} + \mathrm{H.c.})] - \sum_{\imath} c_{Nm}^{\dagger}T_x c_{1m} + \mathrm{H.c.}$$

$$T_0 = (2W/a)\sigma_z,$$

$$T_x = -(W/2a)\sigma_z + (i\hbar v_F/2a)\sigma_y,$$

$$T_y = -(W/2a)\sigma_z - (i\hbar v_F/2a)\sigma_x,$$

where c_{nm} and $c_{nm}^{\dagger}$ are the annihilation and creation operators at site (n,m) respectively. N is the total number of lattices encircling the TI nanowire.



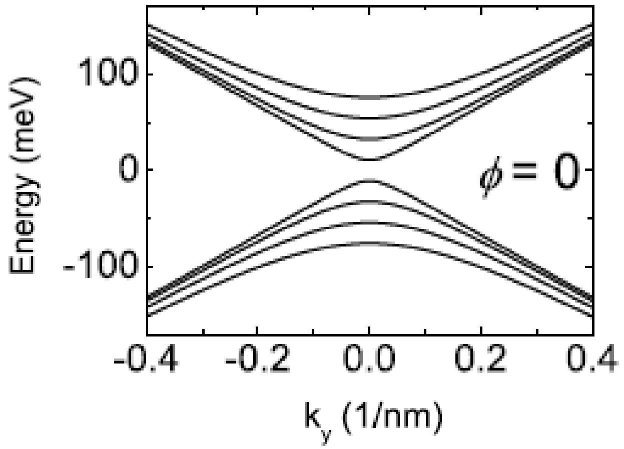
$a = 0.6nm$

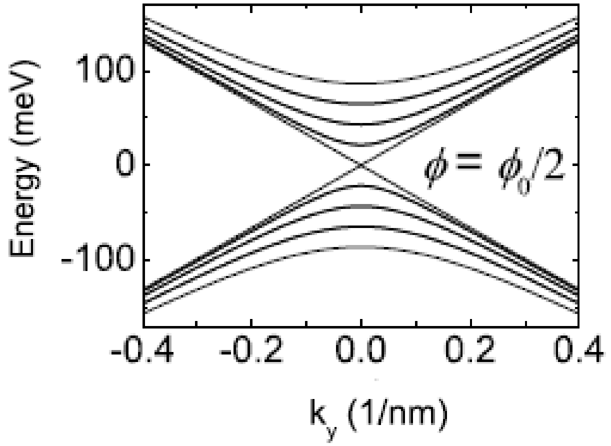
$Lx = 96nm, Lz = 24nm, Ly = 120nm$

Wilson term $W = 0.3\hbar V_F$

Fermi velocity $V_F = 5\times10^5 m/s$

$N_x = 160, N_z = 40$





Y.-F. Zhou, H. Jiang, X.C. Xie, Q.-F. Sun, *Phys. Rev. B* 95, 245137(2017)

构建模型

离散格点得紧束缚哈密顿量H_{00}, H_{01}

参数选取

计算导线的表面Green函数

$$G_{00}=[(E^{+}I_0-H_{00})-H_{01}S_1S_2^{-1}]^{-1}$$

$$G^{L}_{00},G^{R}_{00}$$

线宽函数$\Gamma_m(\varepsilon)$， 自能$\Sigma^{r}_{m}(\varepsilon)$

利用递归Green函数方法，求整体Green函数

$$G^{r}(E)=[G^{a}(E)]^{+}=[EI-H_{cen}-\sum_m \Sigma^{r}_{m}]^{-1}$$

透射系数

$$T_{nm}(E)=Tr[\Gamma_n G^{r}\Gamma_m G^{a}]$$

$$J_n=\frac{e}{h}\sum_m\int dE T_{nm}(E)[f_n(E)-f_m(E)]$$

$$Q_n=\frac{1}{h}\sum_m\int dE(E-\mu_n)T_{nm}(E)[f_n(E)-f_m(E)]$$

$$\begin{pmatrix}J_n\\Q_n\end{pmatrix}=\begin{pmatrix}L_{11}&L_{12}\\L_{21}&L_{22}\end{pmatrix}\begin{pmatrix}\delta V\\\delta T\end{pmatrix}$$

$$G(T)=\lim_{\delta V\to 0}\frac{J_n}{\delta V}\bigg|_{\delta T=0}$$

$$S(T)=-\lim_{\delta T\to 0}\frac{\delta V}{\delta T}\bigg|_{J_n=0}$$

$$k_e(T)=-\lim_{\delta T\to 0}\frac{Q_n}{\delta T}\bigg|_{J_n=0}$$

$$ZT=\frac{\sigma S^2}{\kappa}T$$

费米分布

$$f_n(E,\mu_n,T_n)=[e^{\frac{E-\mu_n}{k_BT_n}}+1]^{-1}$$

$$\mu_n=E_F+eV_n$$

$$J_{n\sigma}=\frac{e}{h}\sum_m\int dE T_{\sigma}(E)[f_n(E)-f_m(E)]$$

$$Q_{n\sigma}=\frac{1}{h}\sum_m\int dE(E-\mu_n)T_{\sigma}(E)[f_n(E)-f_m(E)]$$

$$J_\sigma=e\delta V_\sigma\cdot I_{0\sigma}+\frac{\delta T}{T}\cdot eI_{1\sigma}$$

$$Q_\sigma=\sum_\sigma(\delta V_\sigma\cdot I_{1\sigma}+\frac{\delta T}{T}\cdot I_{2\sigma})$$

$$\begin{pmatrix}J_\uparrow\\J_\downarrow\\Q_\sigma\end{pmatrix}=\begin{pmatrix}e^2I_{0\uparrow}&0&eI_{1\uparrow}/T\\0&e^2I_{0\downarrow}&eI_{1\downarrow}/T\\eI_{1\uparrow}&eI_{1\downarrow}&(I_{2\uparrow}+I_{2\downarrow})/T\end{pmatrix}\begin{pmatrix}\delta V_\uparrow\\\delta V_\uparrow\\\delta T\end{pmatrix}$$

Johnson M, et al, Phys. Rev. B (1987)   Dubi Y, et al, Phys. Rev. B (2009)   Swirkowicz R, et al, Phys. Rev. B (2009)

自旋关联/电荷塞贝克系数

$$S_s(T) = -\lim_{\delta T \to 0} \frac{\delta V_s}{\delta T}\bigg|_{J_n=0}$$

$$S_c(T) = -\lim_{\delta T \to 0} \frac{\delta V_c}{\delta T}\bigg|_{J_n=0}$$

有效电压与自旋压

$$eV_s = e\delta V_\uparrow - e\delta V_\uparrow = (\mu_{L\uparrow} - \mu_{L\downarrow}) - (\mu_{R\uparrow} - \mu_{R\downarrow})$$

$$eV_C = \mu_L - \mu_R = \frac{1}{2}(\mu_{L\uparrow} + \mu_{L\downarrow} - \mu_{R\uparrow} - \mu_{R\downarrow})$$

自旋关联/电荷塞贝克系数

$$S_S = S_\uparrow - S_\downarrow, S_c = \frac{1}{2}(S_\uparrow + S_\downarrow)$$

$$S_\sigma(T) = \frac{1}{eT}\frac{I_{1\sigma}}{I_{0\sigma}} = \frac{1}{eT}\frac{\int (E-E_F)T_{nm\sigma}(E)(-\frac{\partial f_0}{\partial E})dE}{\int T_{nm\sigma}(E)(-\frac{\partial f_0}{\partial E})dE}$$

自旋/电荷电导

$$G_S = \frac{J_S}{V_C} \quad G_C = \frac{J_C}{V_C}$$

$$G_S = G_\uparrow - G_\downarrow, \quad G_C = G_\uparrow + G_\downarrow$$

$$G_\sigma = e^2 I_{0\sigma} = \frac{e^2}{h}\frac{1}{k_B T}\int T_{nm\sigma}(E)(-\frac{\partial f_0}{\partial E})dE$$

热导

$$\kappa = \sum_\sigma \frac{1}{T}[\frac{I_{2\sigma}(T)I_{0\sigma}(T) - I_{1\sigma}^2(T)}{I_{0\sigma}(T)}]$$

自旋热电优值

$$Z_S T = \frac{|G_S S_S^2|}{\kappa} T$$

Johnson M, et al, Phys. Rev. B (1987) Dubi Y, et al, Phys. Rev. B (2009) Swirkowicz R, et al, Phys. Rev. B (2009)

Prospect

- To investigate the seebeck effect and spin seebeck effect
- To investigate the thermoelectric figure of merit ZT
- To investigate the influence of disorder

谢谢！