Chapter 6

Spin Caloritronics

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量子材料科学中心

2018年11月30日

Review of last class

1. Spin transfer torque

2. Spin orbit torque and spin Hall effect

3. Spin orbit torque and Rashba-Edestein effect

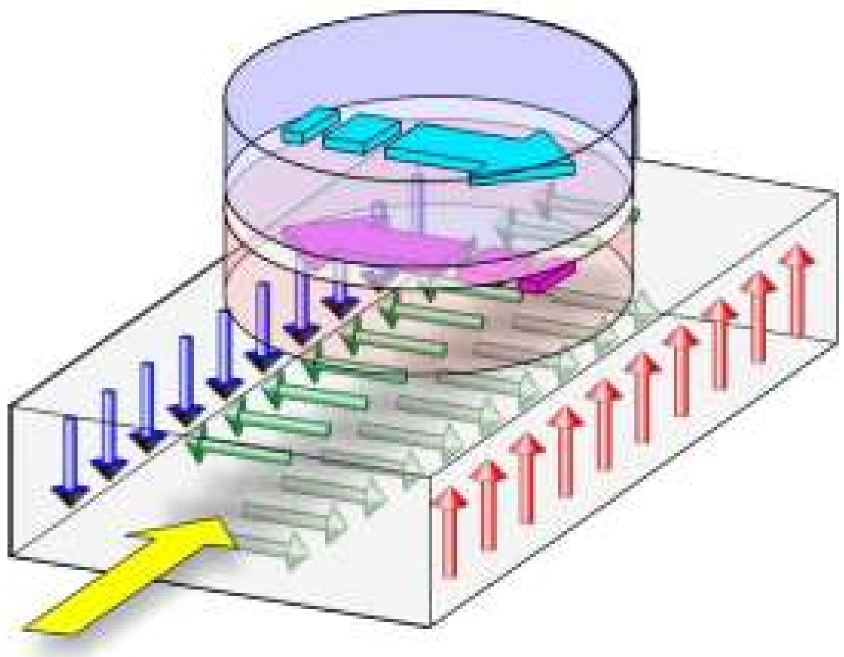
Review of last class

John Slonczewski

Luc Berger

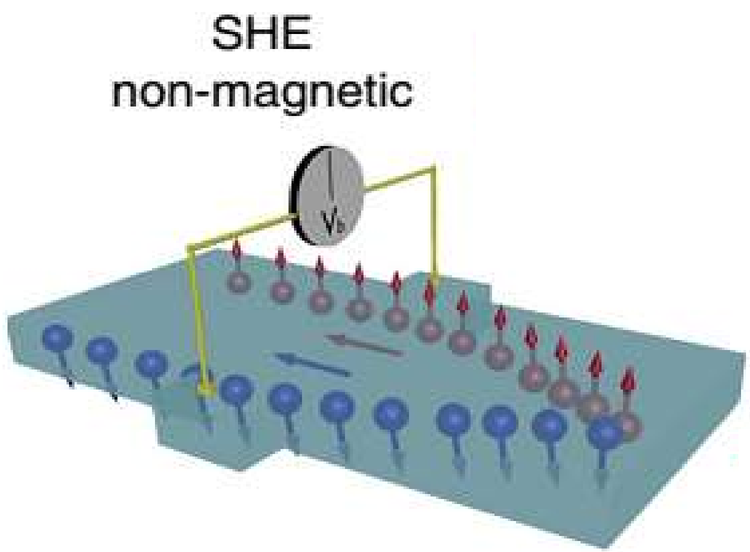
Summary of this class

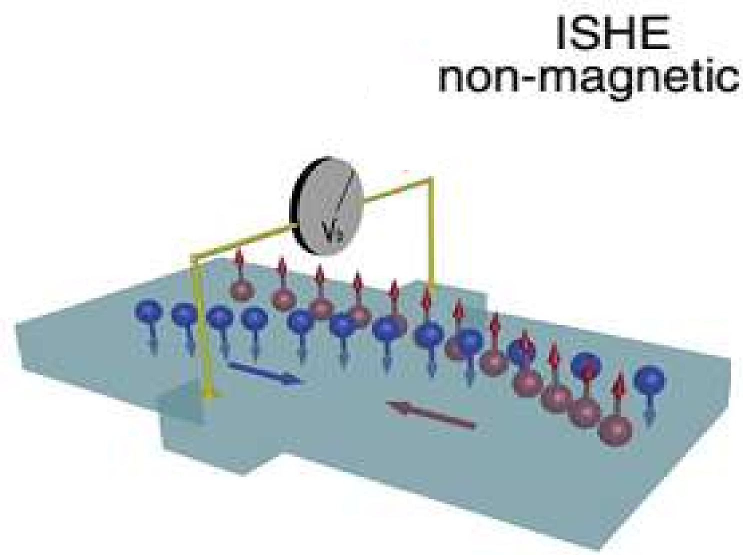
1. Spin orbit torque



$$\tau_{ST} = \frac{\hbar}{2}\hat{m} \times (\hat{\sigma} \times \hat{m})$$

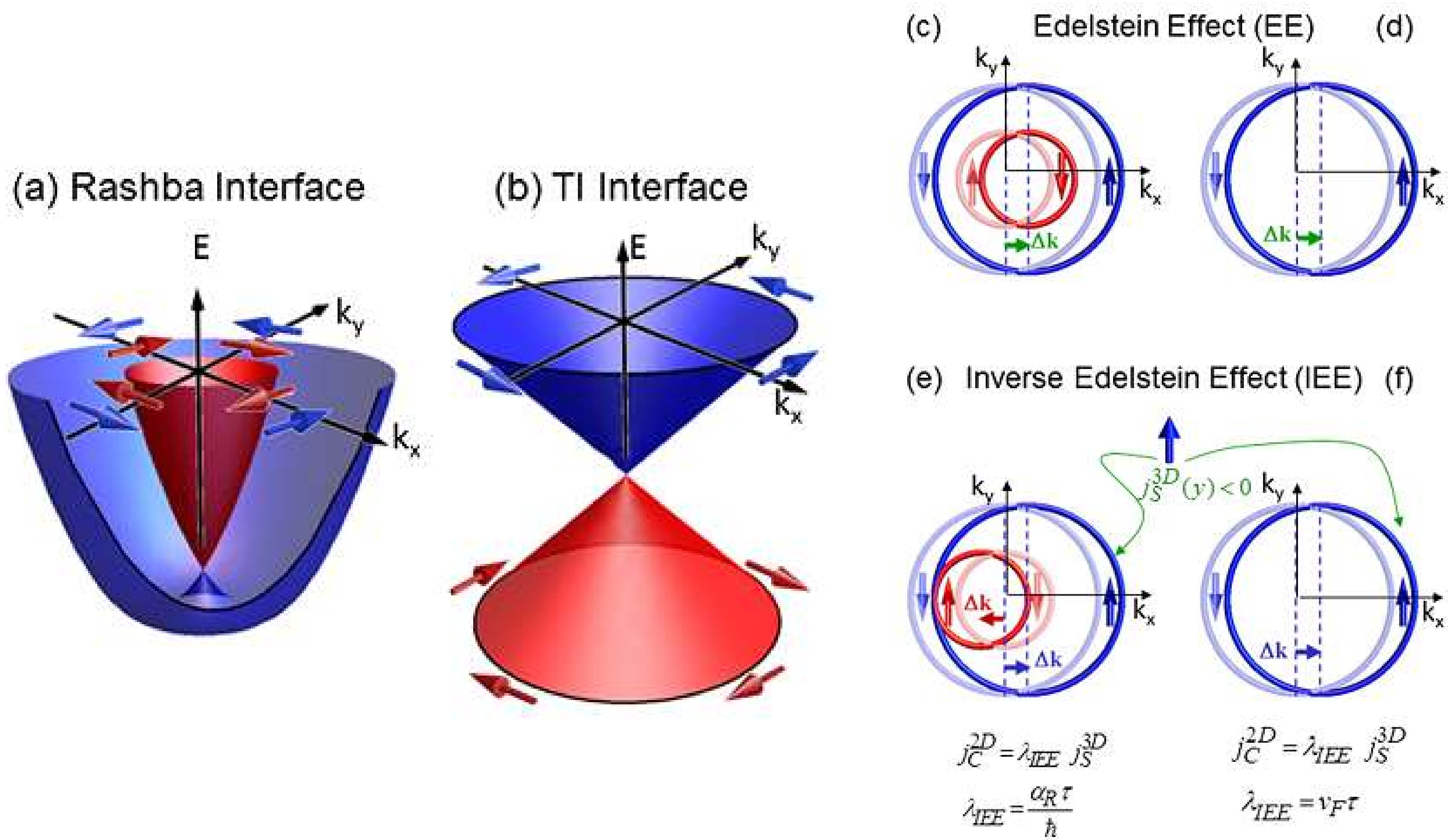
2. Spin Hall effect





Summary of this class

3. Rashba-Edelstein effect



Outline

1. Seebeck and Peltier effect

2. Spin Seebeck effect

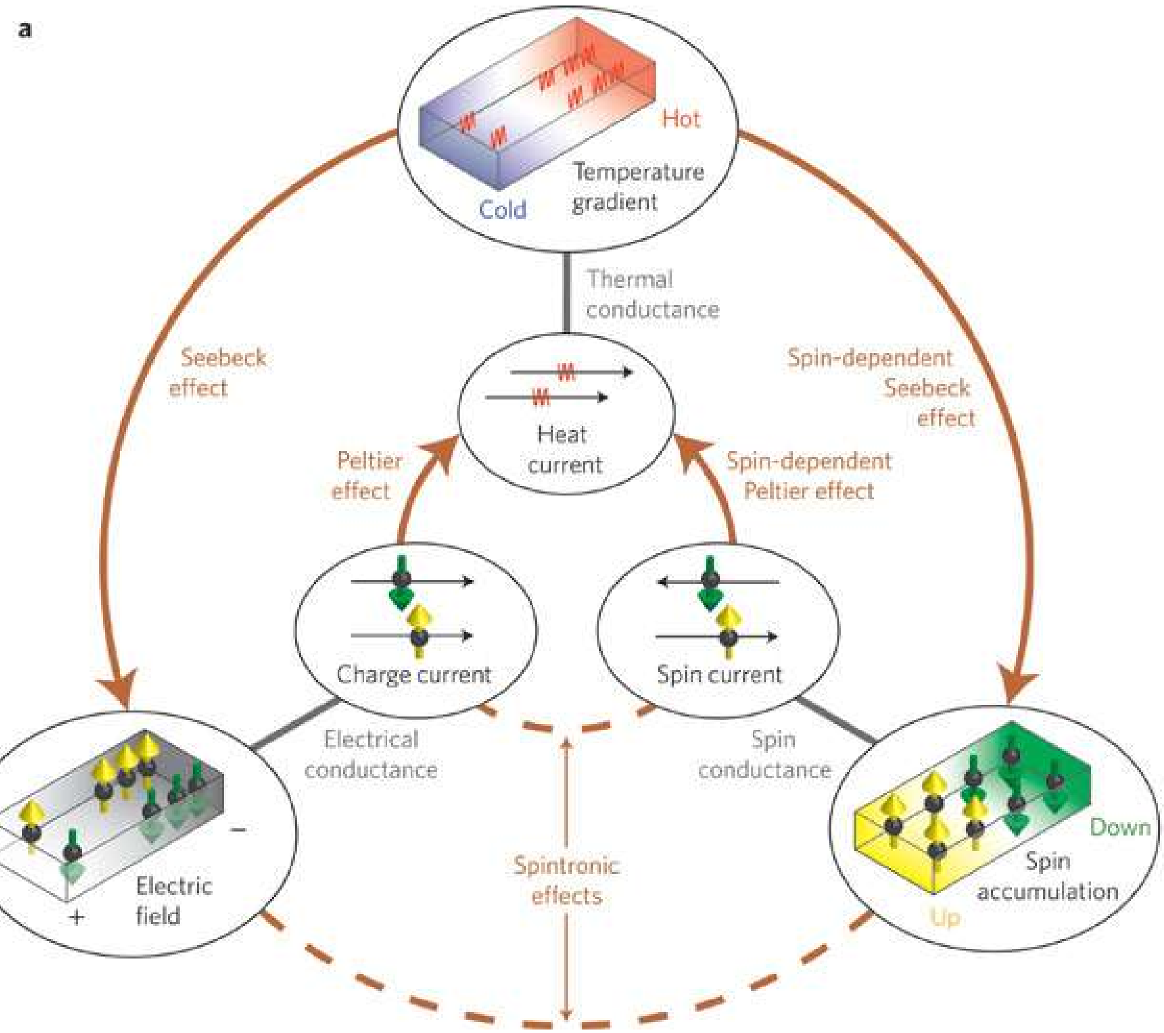
3. Spin Peltier effect

4. Thermal spin injection

5. Thermal spin torque

6. Spin energy

Outline



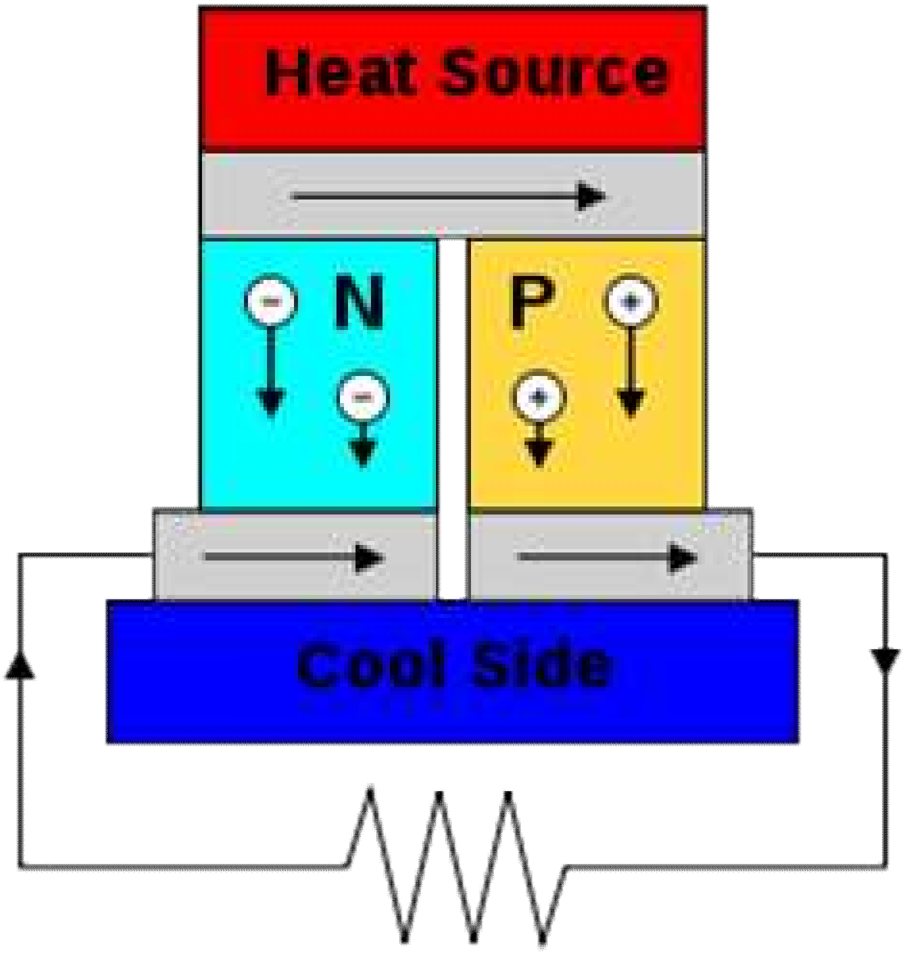
Goennenwein & Bauer, Nature Nanotech. (2012)

Outline

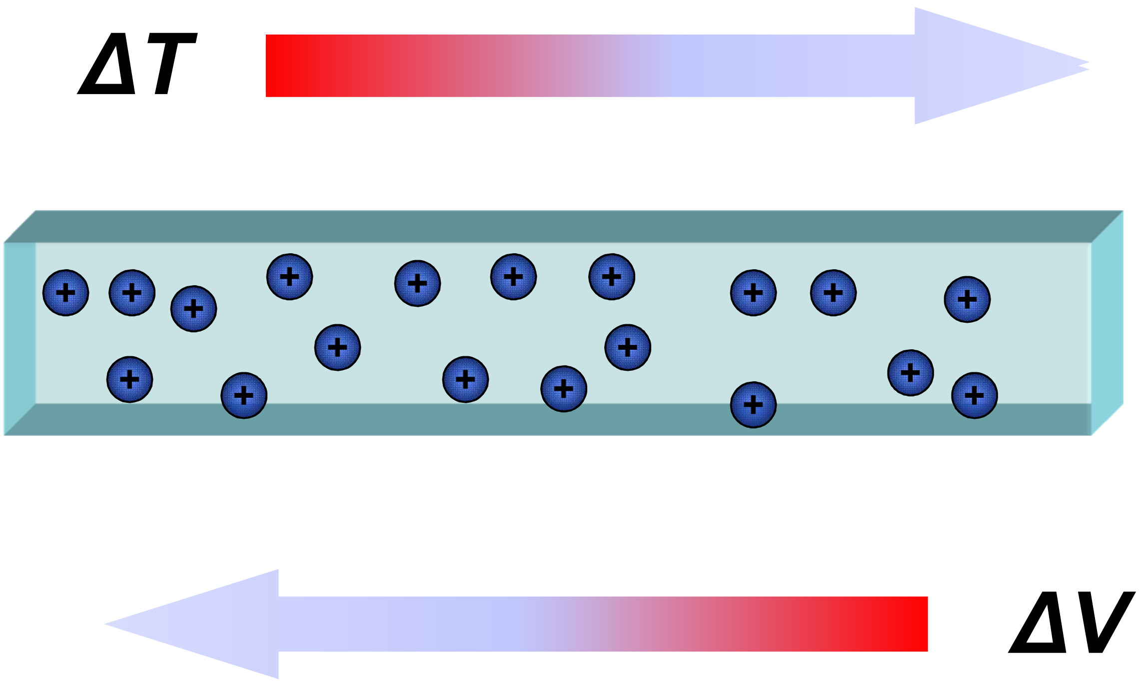
1. Seebeck and Peltier effect

Seebeck effect

Thomas Johann Seebeck



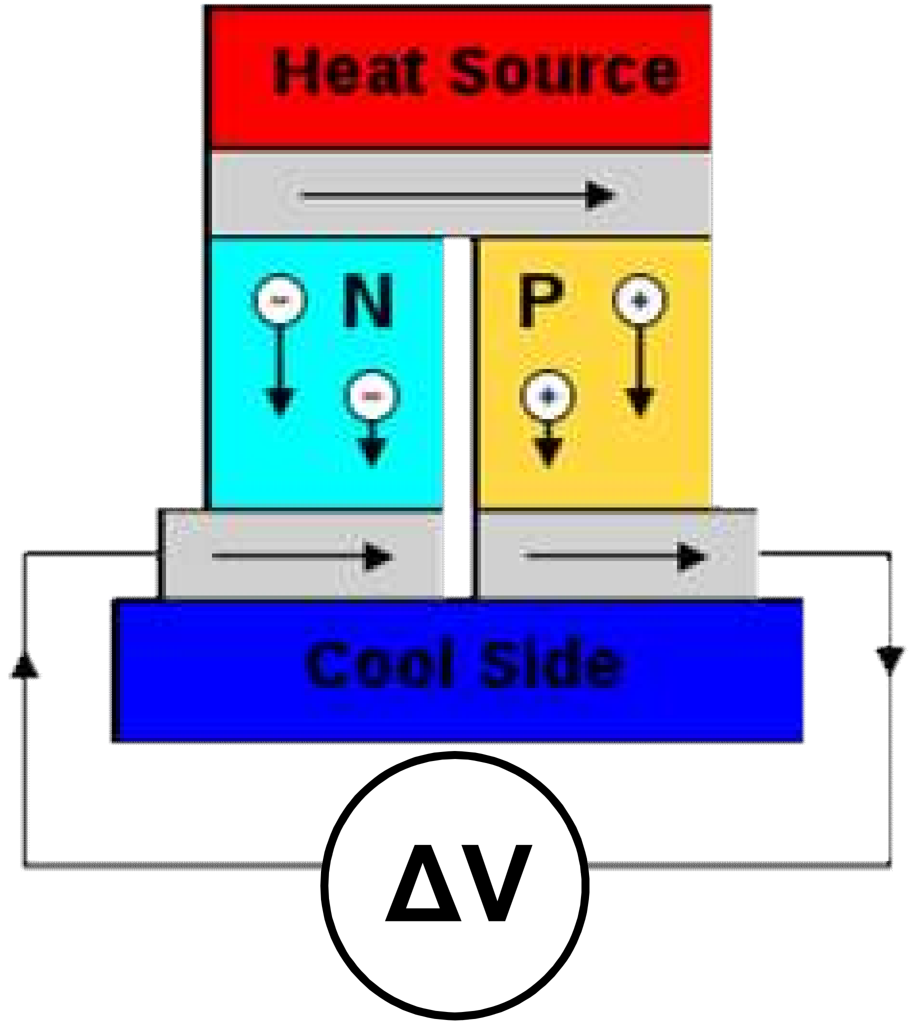
Seebeck effect



$$Seebeck\ Coefficient(\alpha) = -\frac{\Delta V}{\Delta T}$$

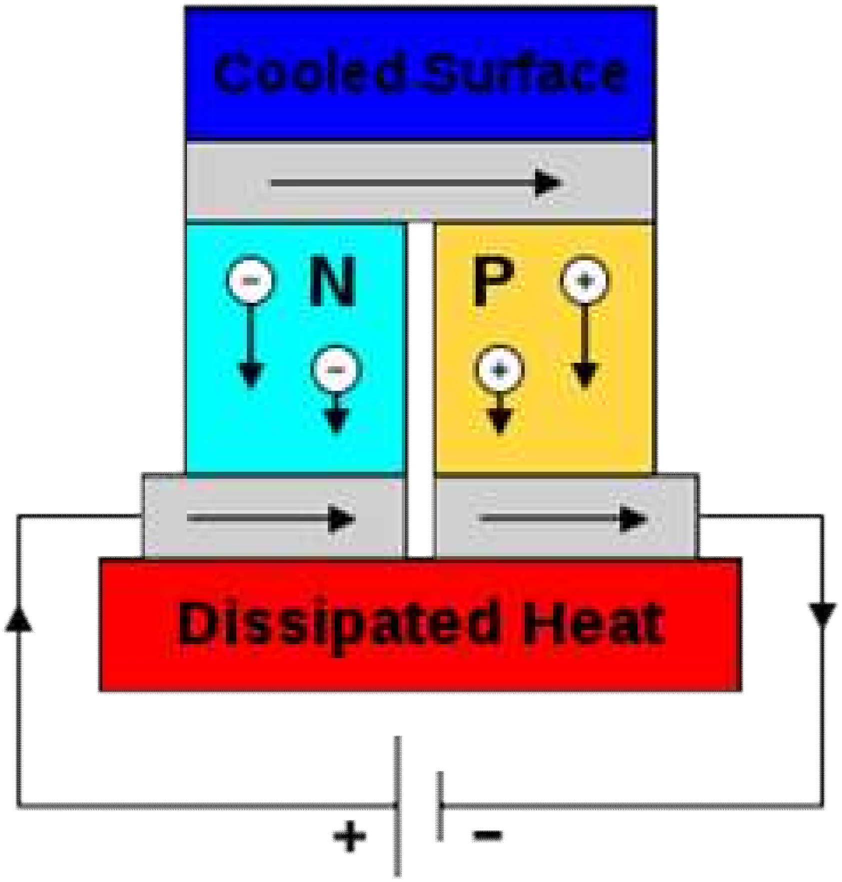
Seebeck effect

Thermocouple

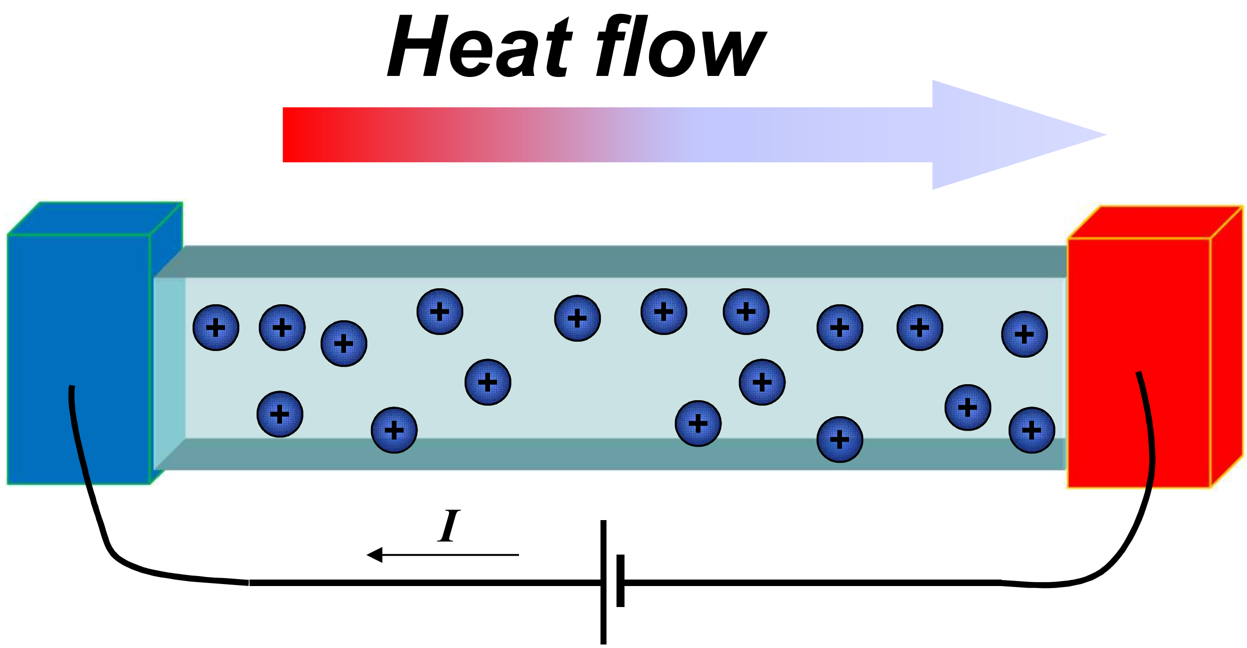


Peltier effect

Jean Charles Athanase Peltier

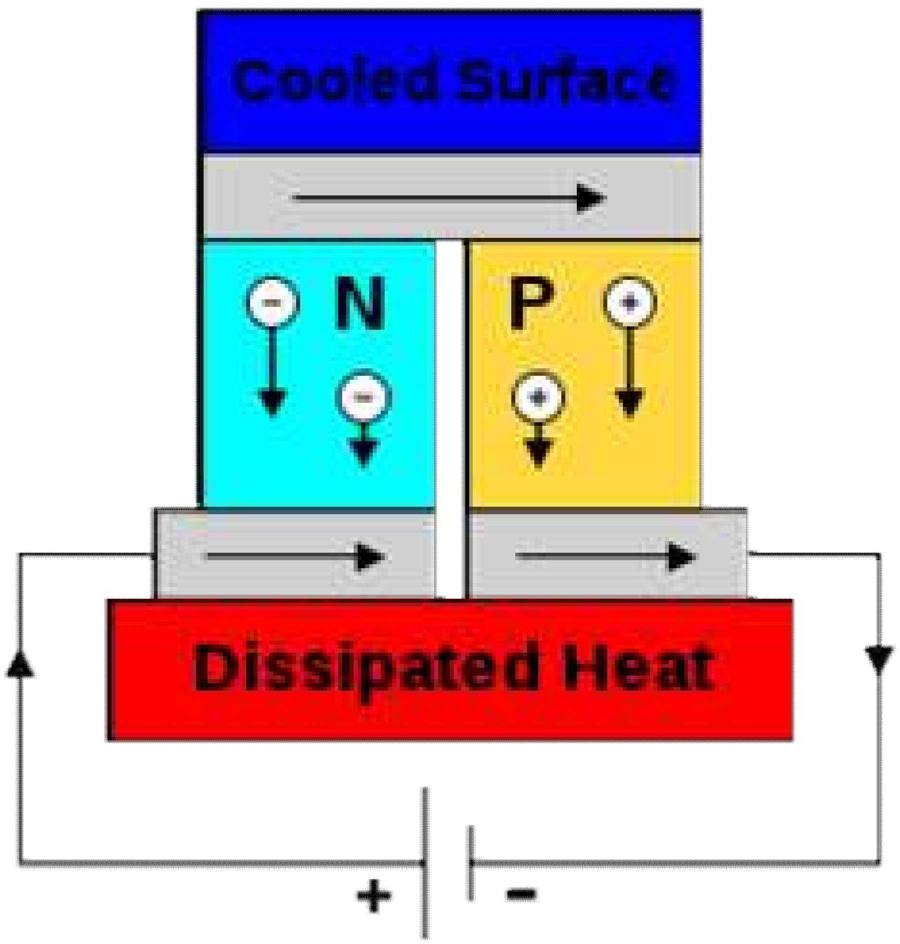


Peltier effect



Peltier effect

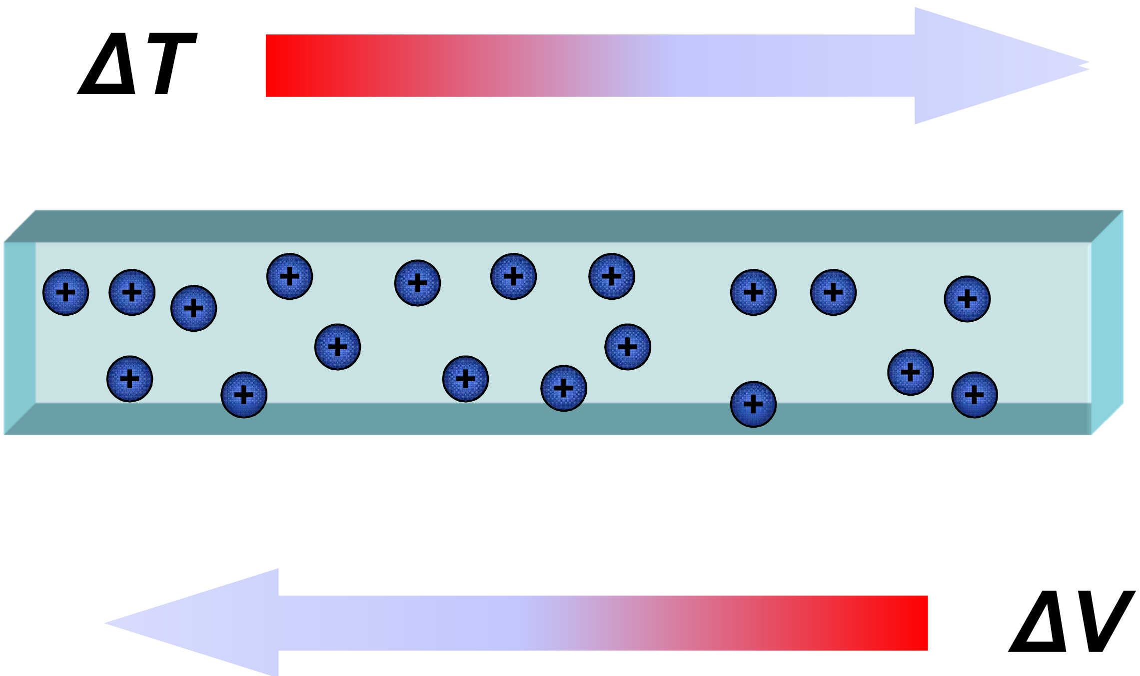
Thermoelectric cooling, such as refrigerators



Outline

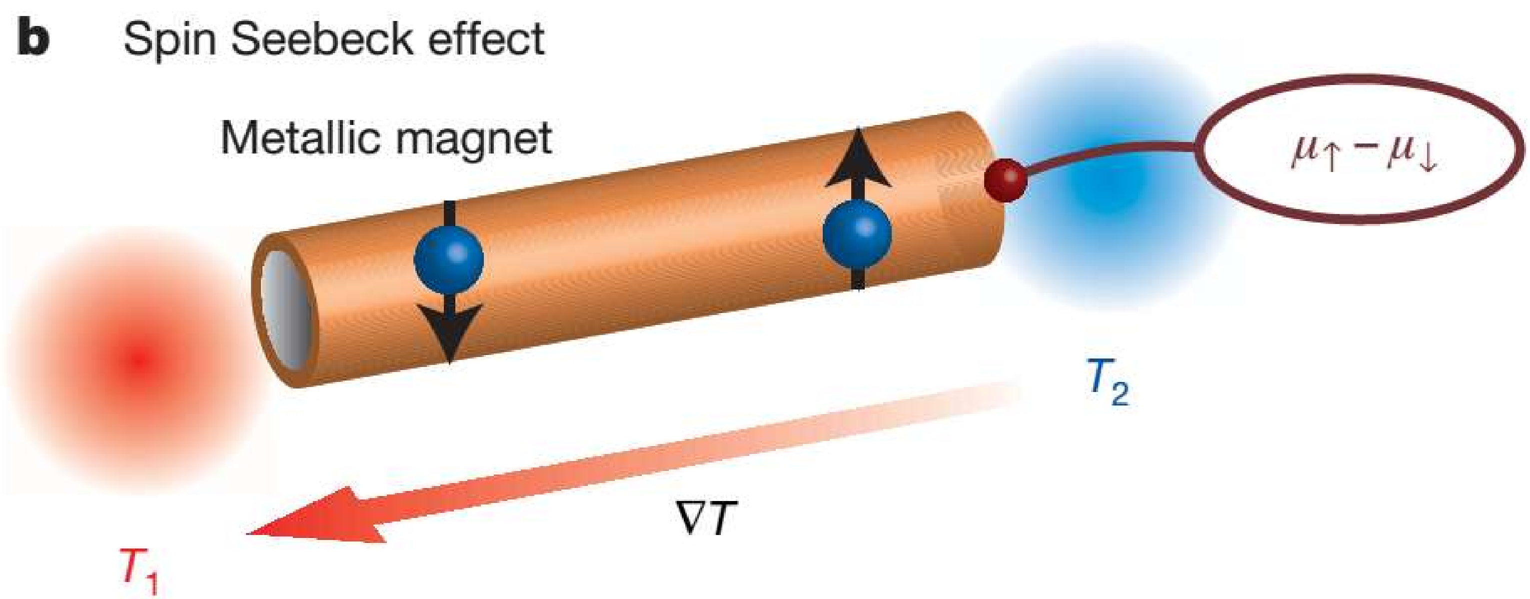
2. Spin Seebeck effect

Seebeck effect



$$Seebeck\ Coefficient(\alpha) = -\frac{\Delta V}{\Delta T}$$

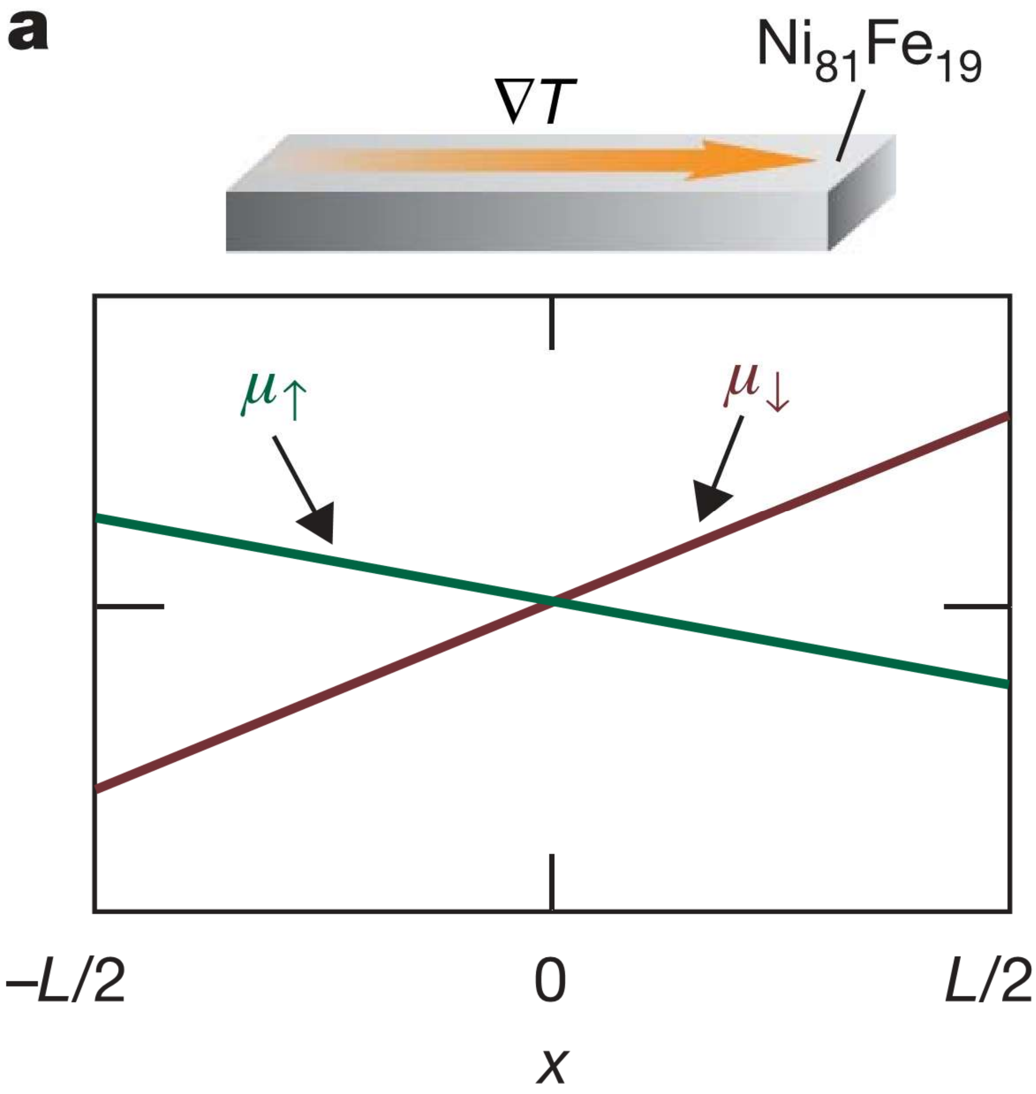
Spin Seebeck effect in FM Metal



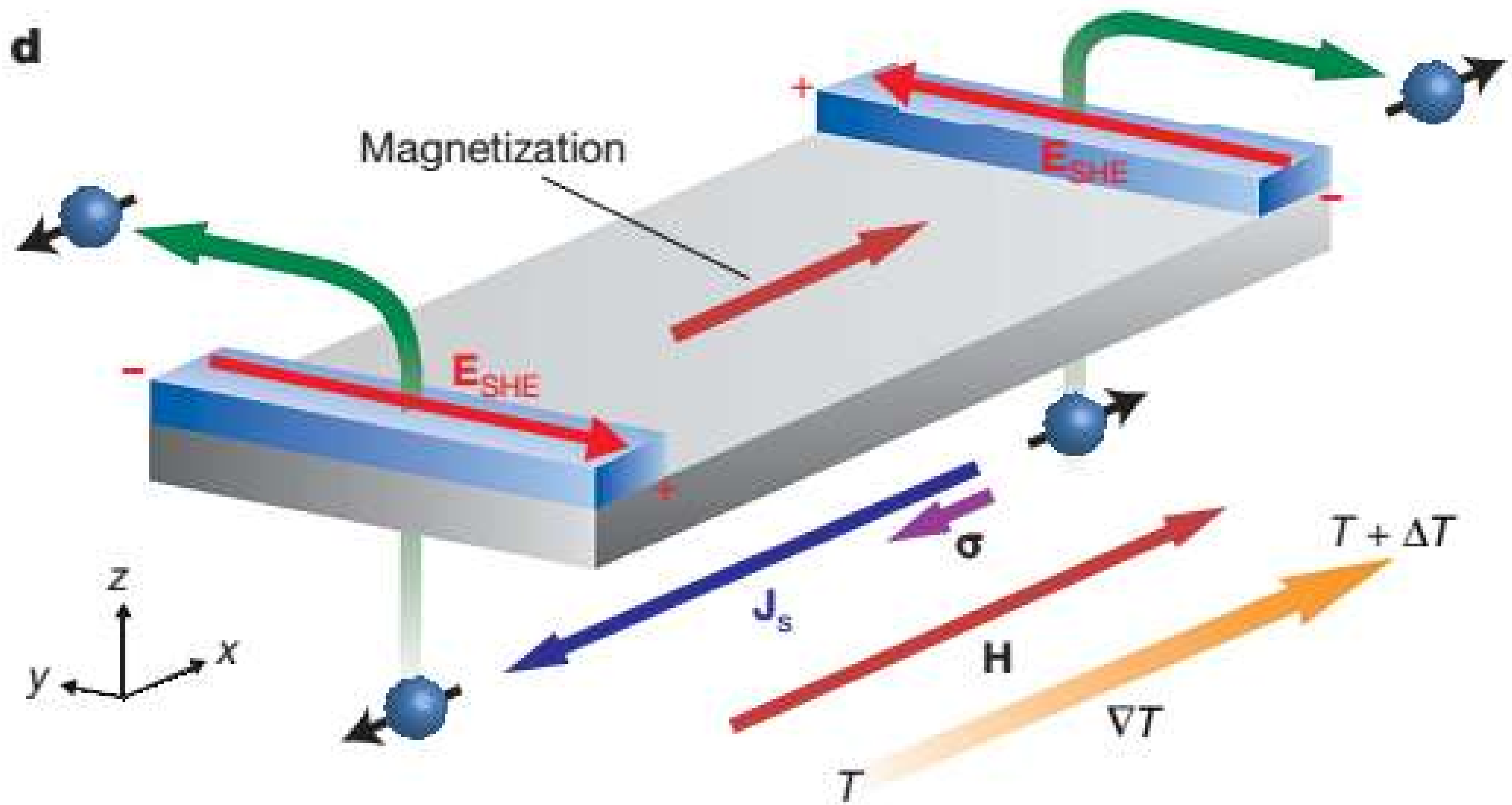
Eiji Saitoh

Uchida, et al, Nature (2008)

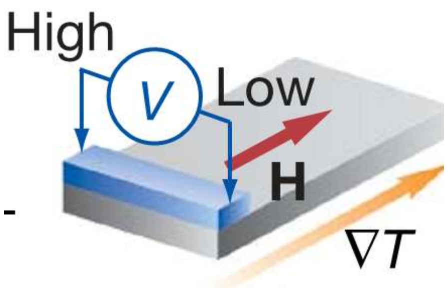
Spin Seebeck effect in FM Metal



Spin Seebeck effect in FM Metal



Spin Seebeck effect in FM Metal



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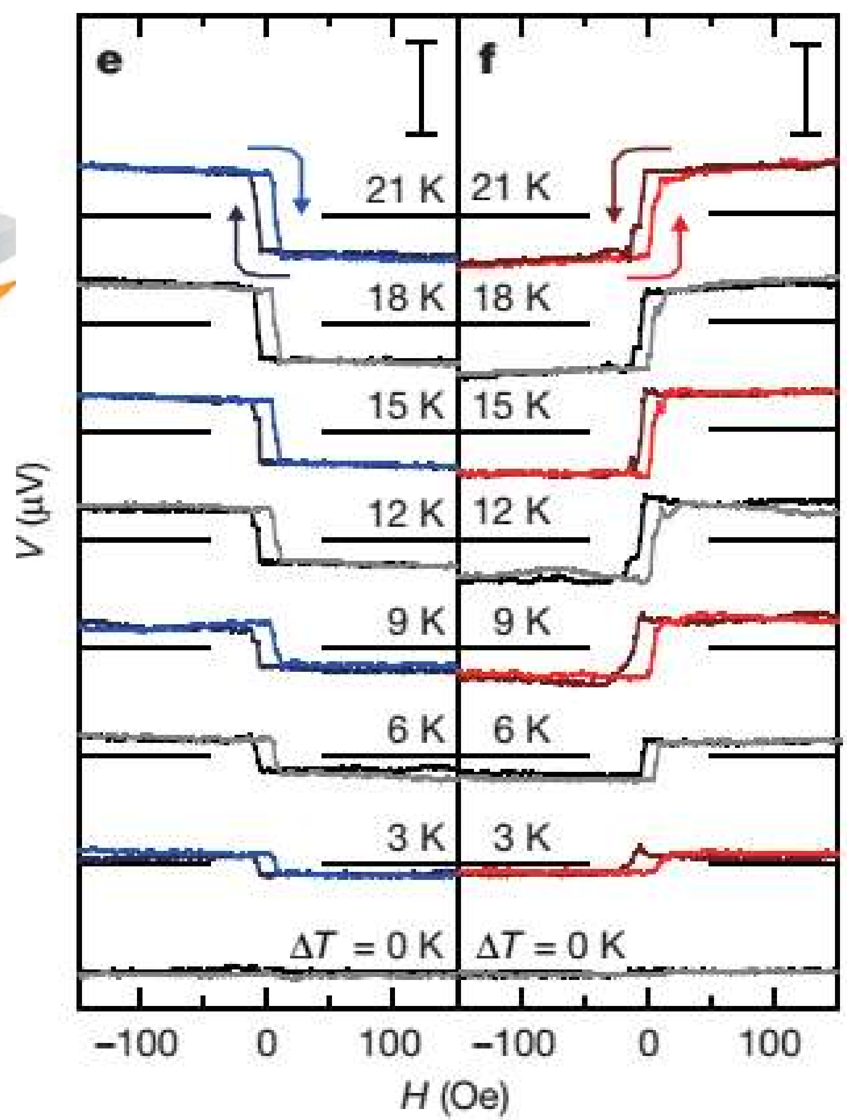
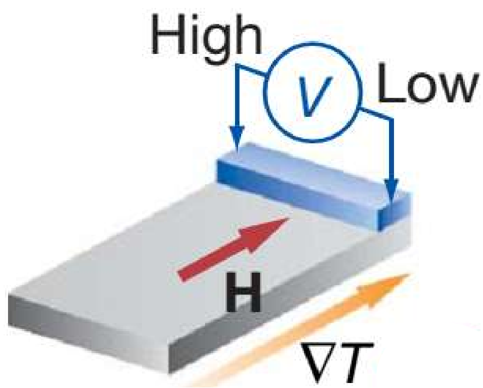
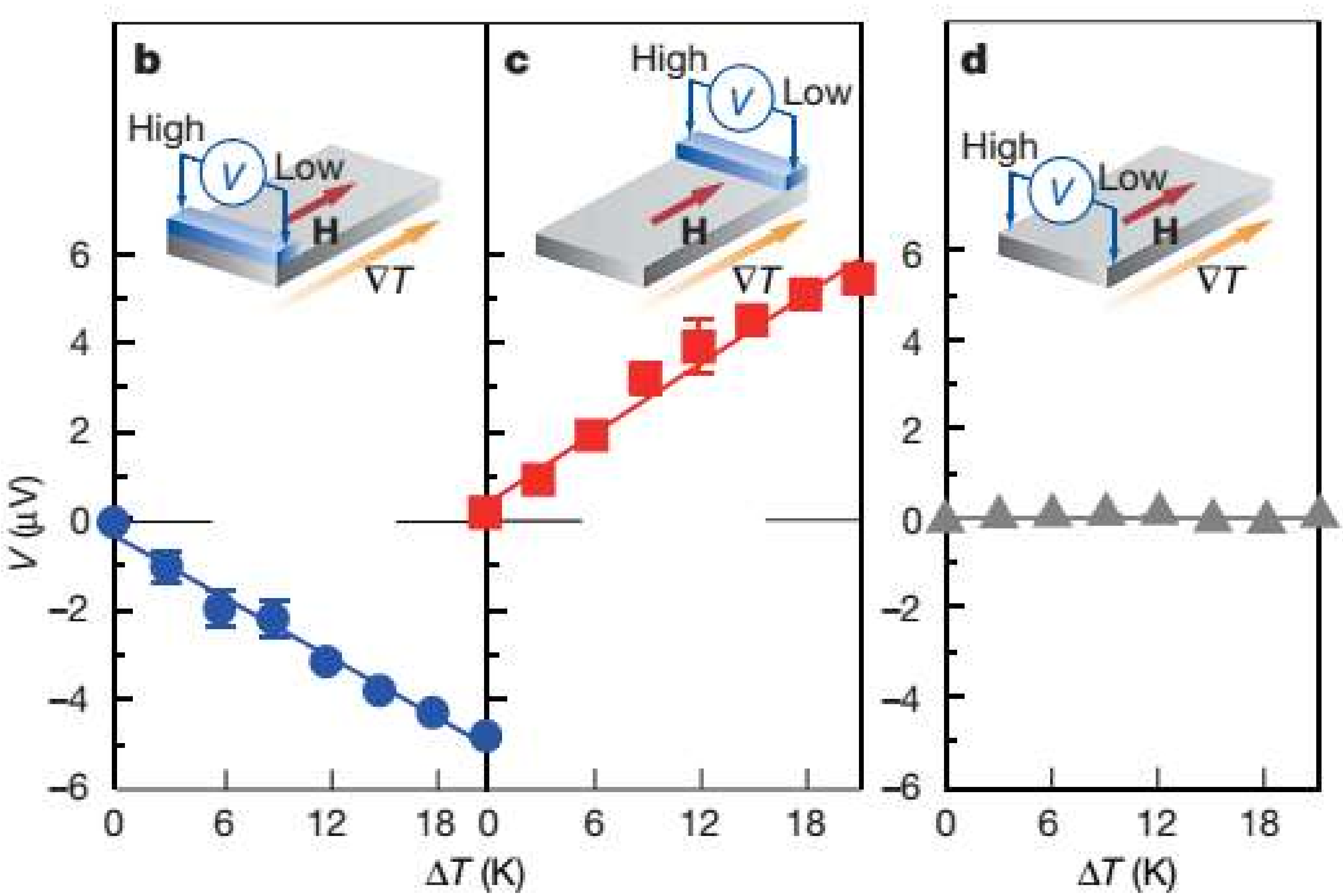
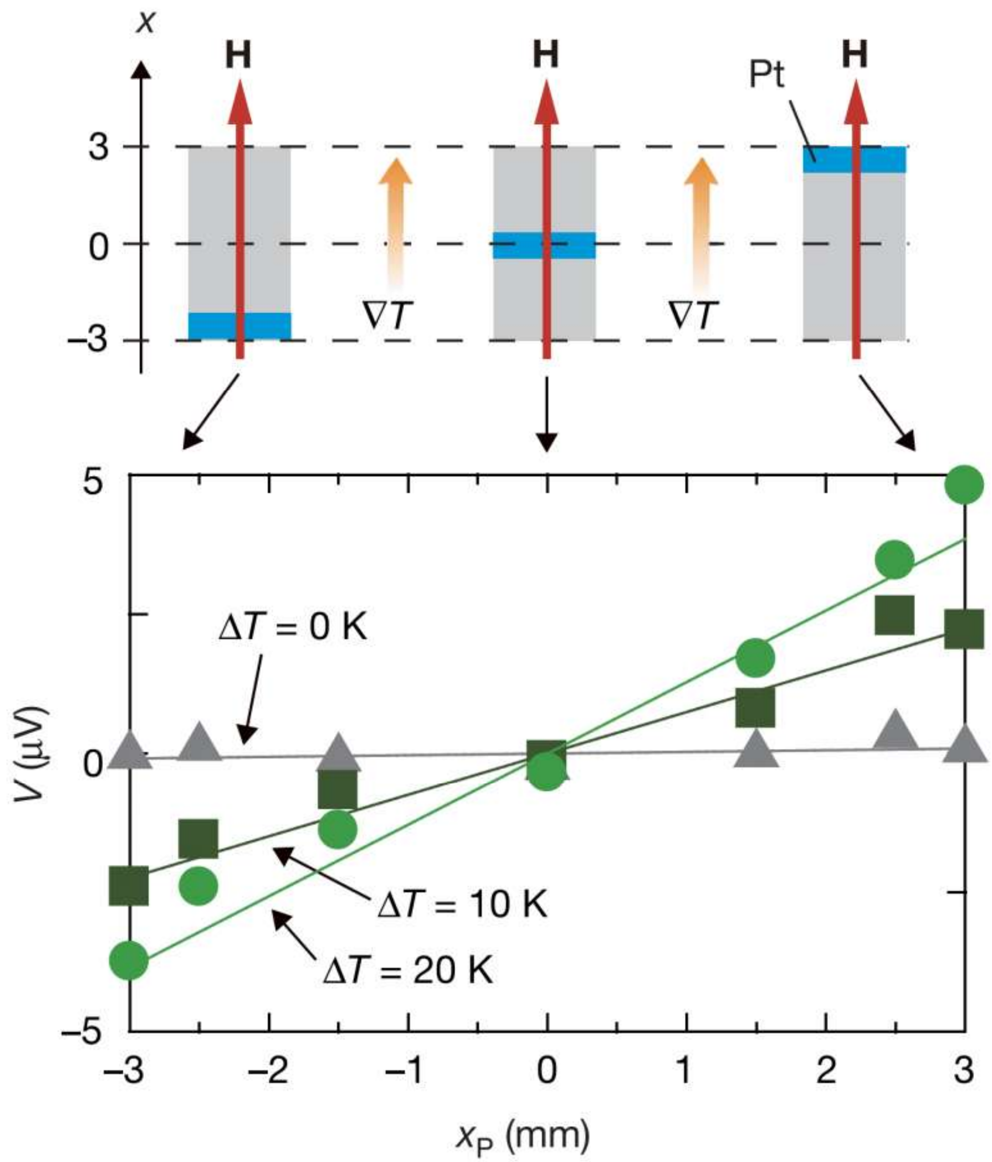




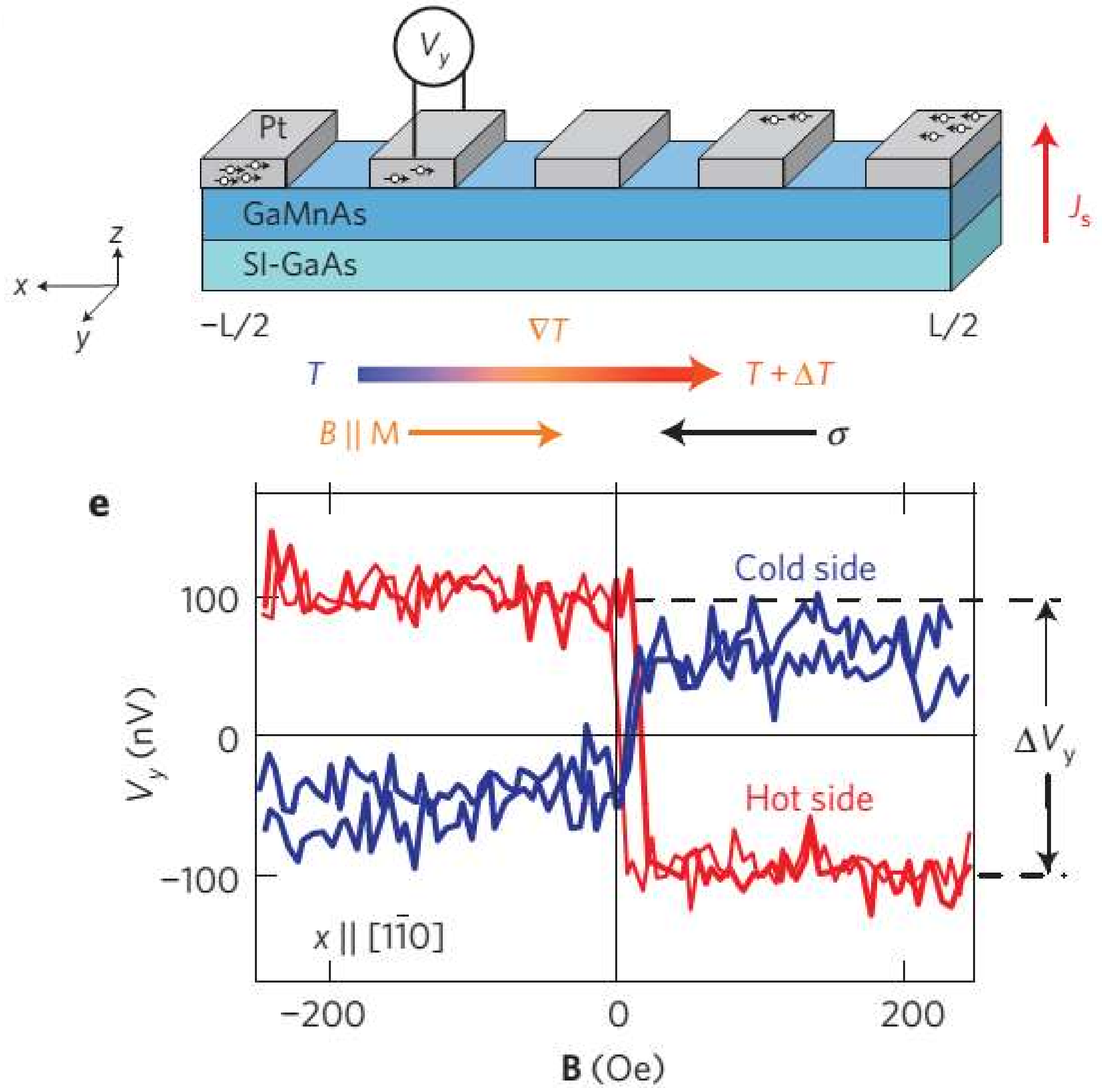
Spin Seebeck effect in FM Metal



Spin Seebeck effect in FM Metal

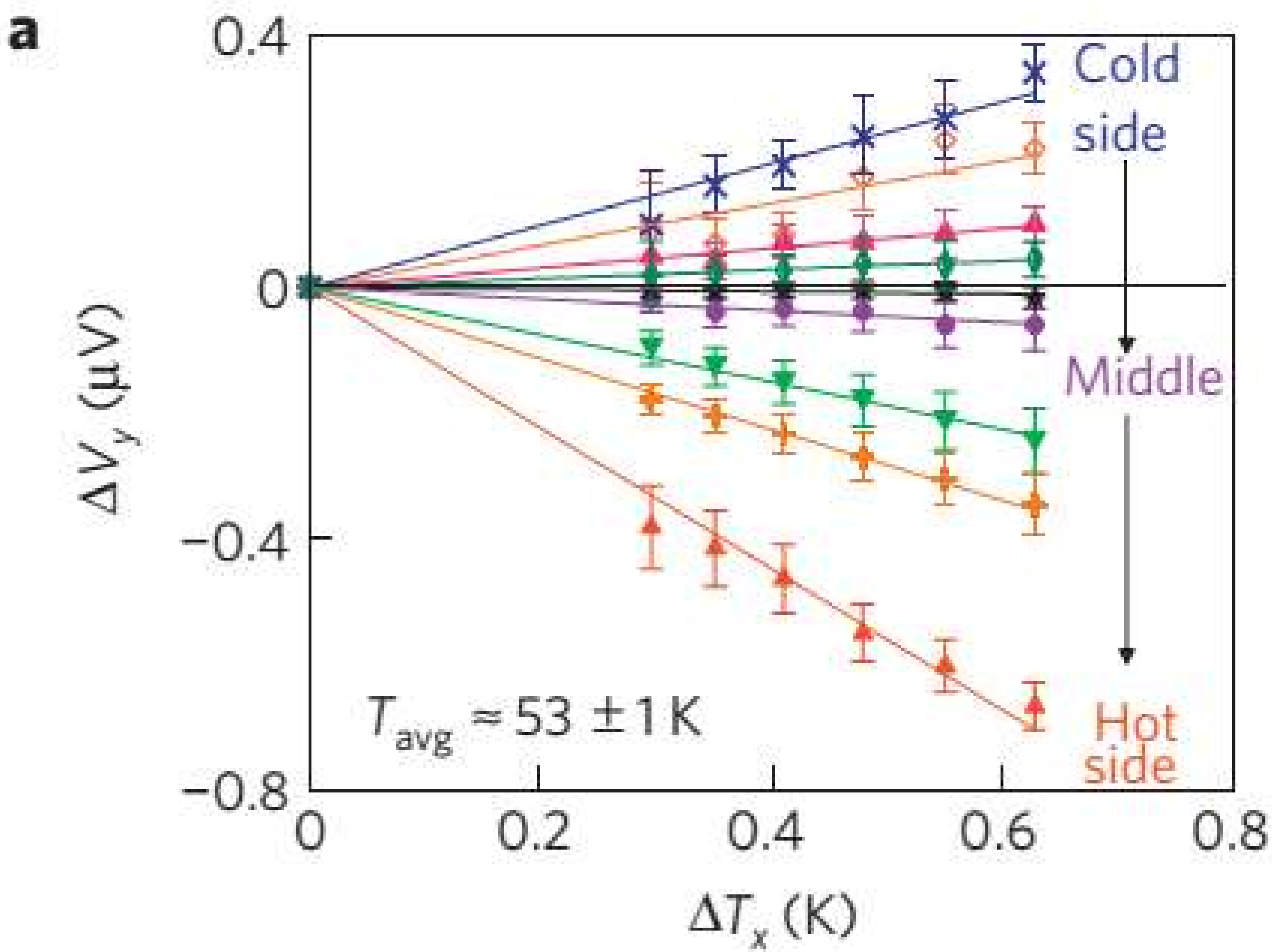


SSE in FM Semiconductor

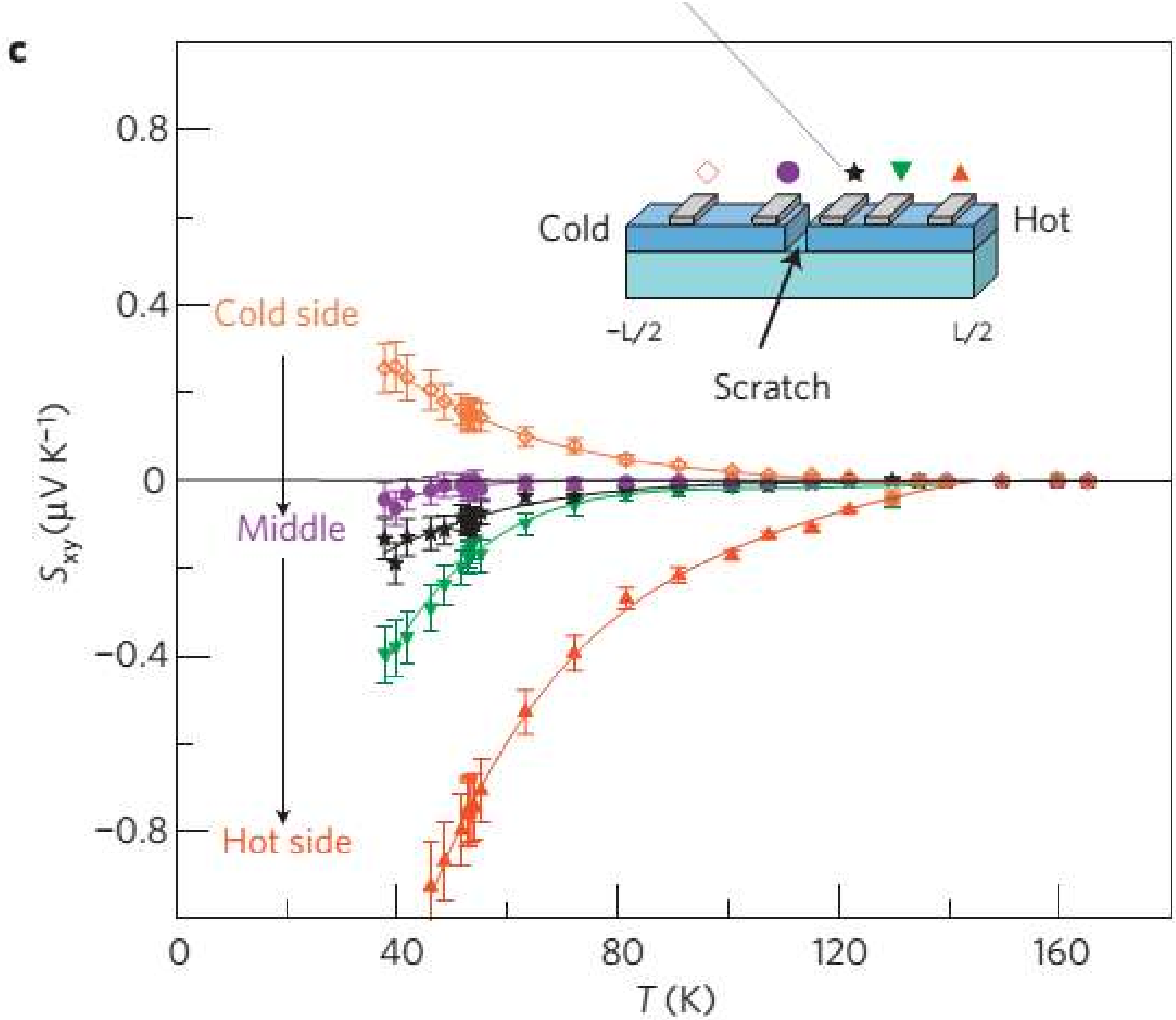


Jaworski, et al, Nature Materials (2010)

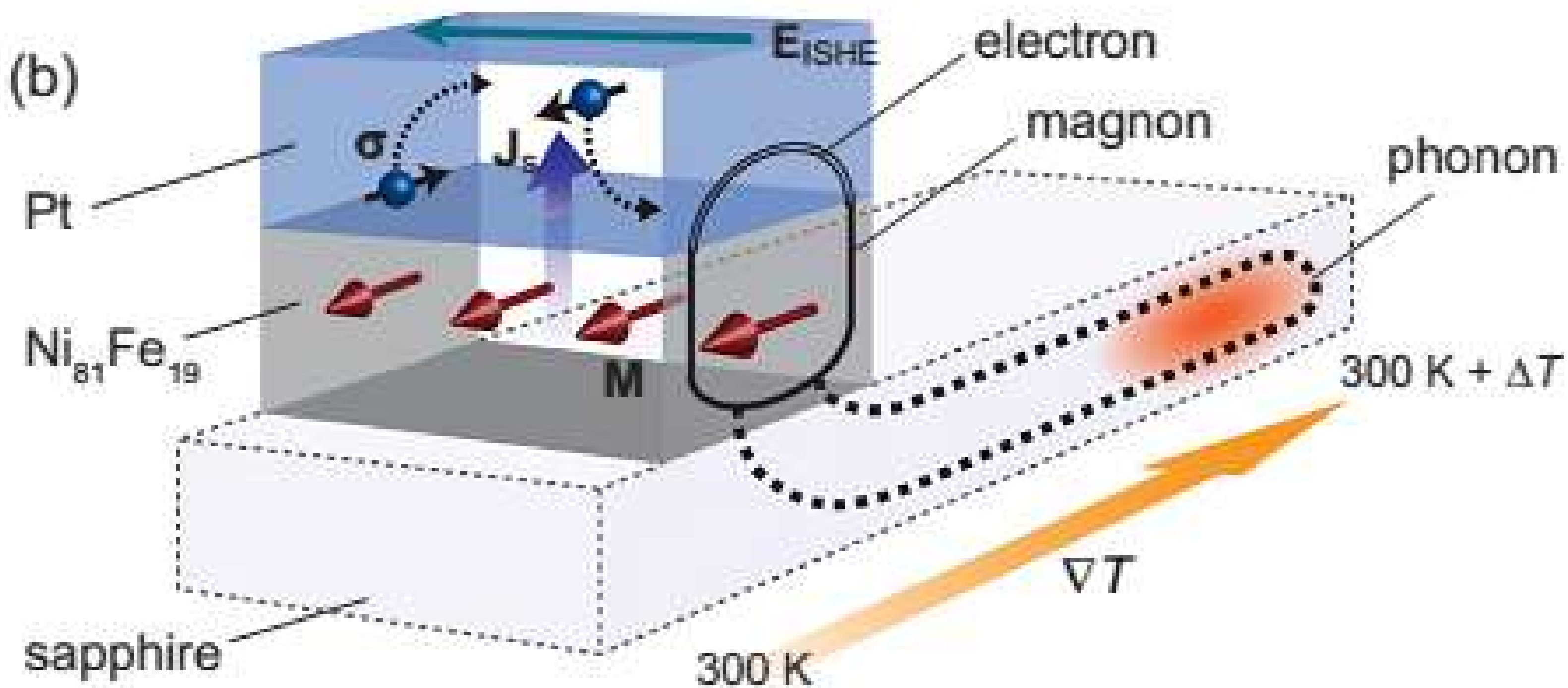
SSE in FM Semiconductor



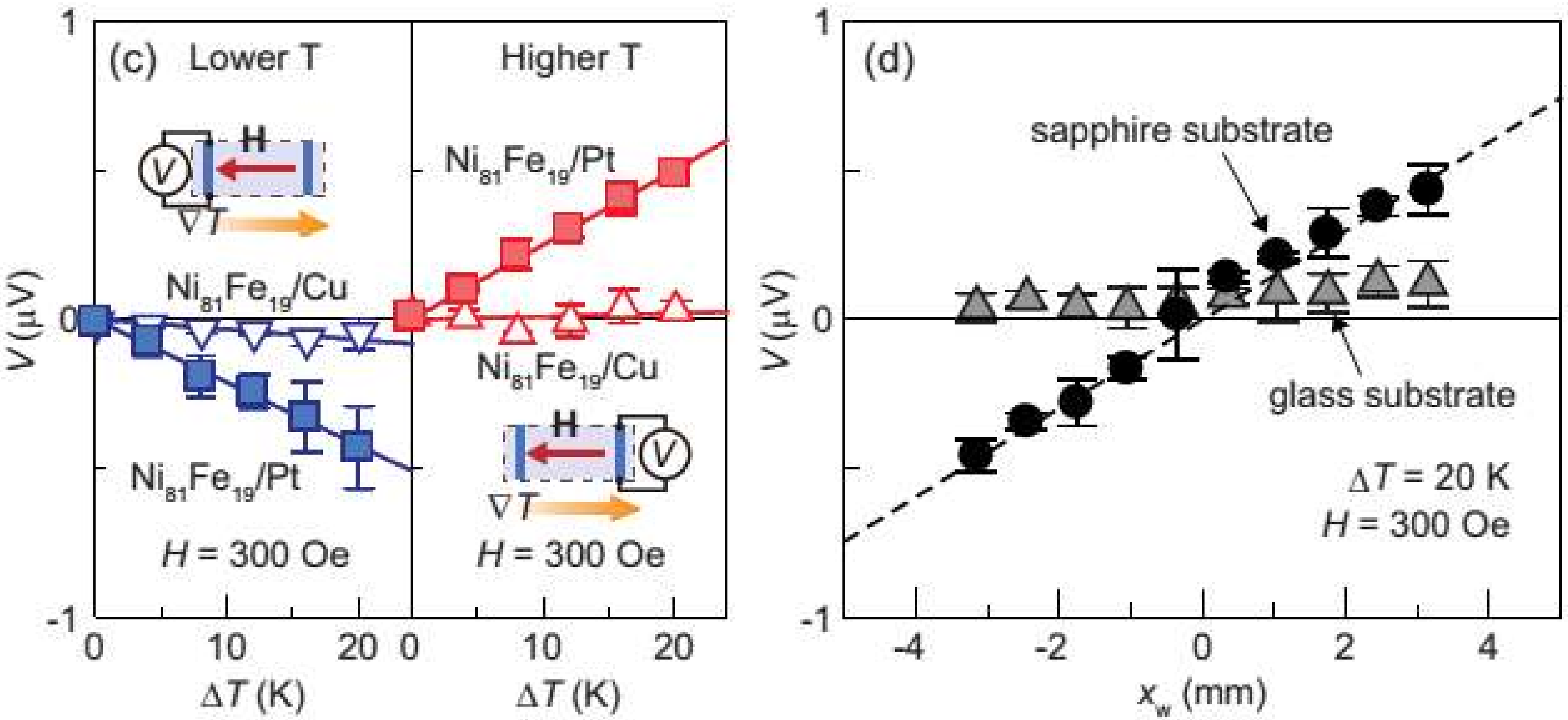
Magnon-phonon interaction



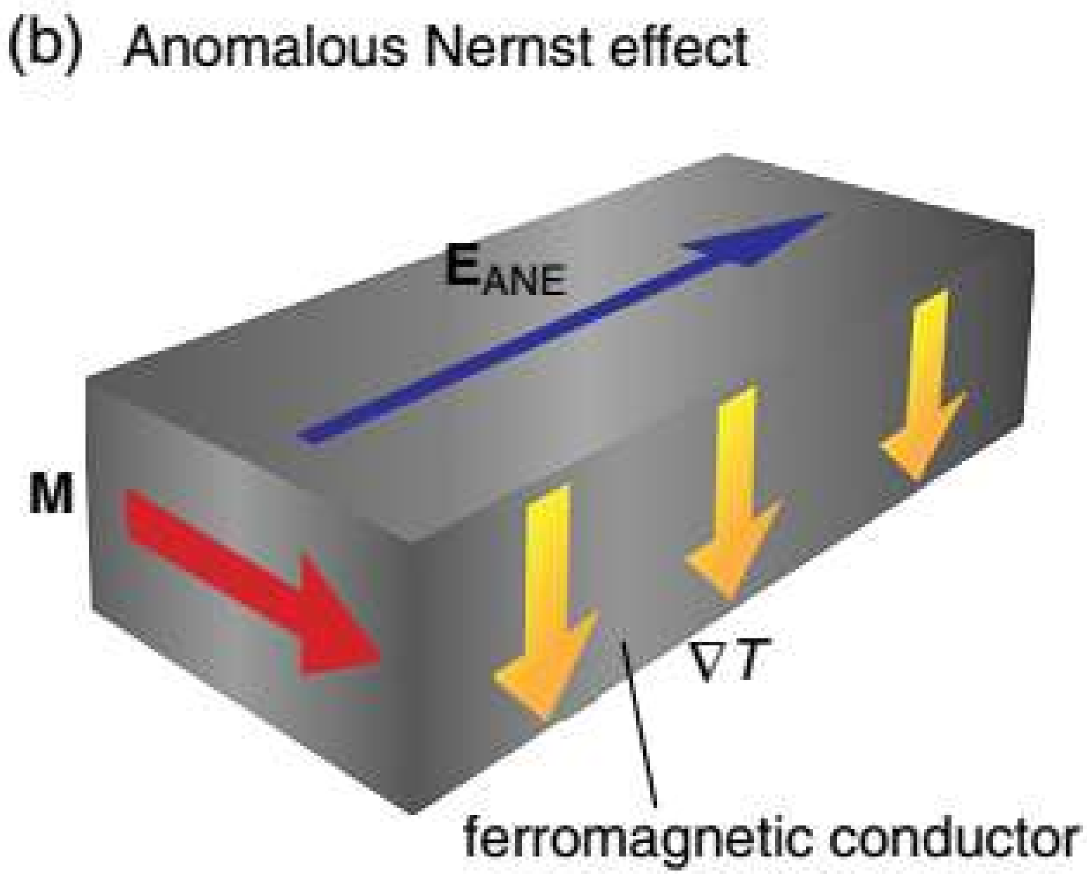
Magnon-phonon interaction



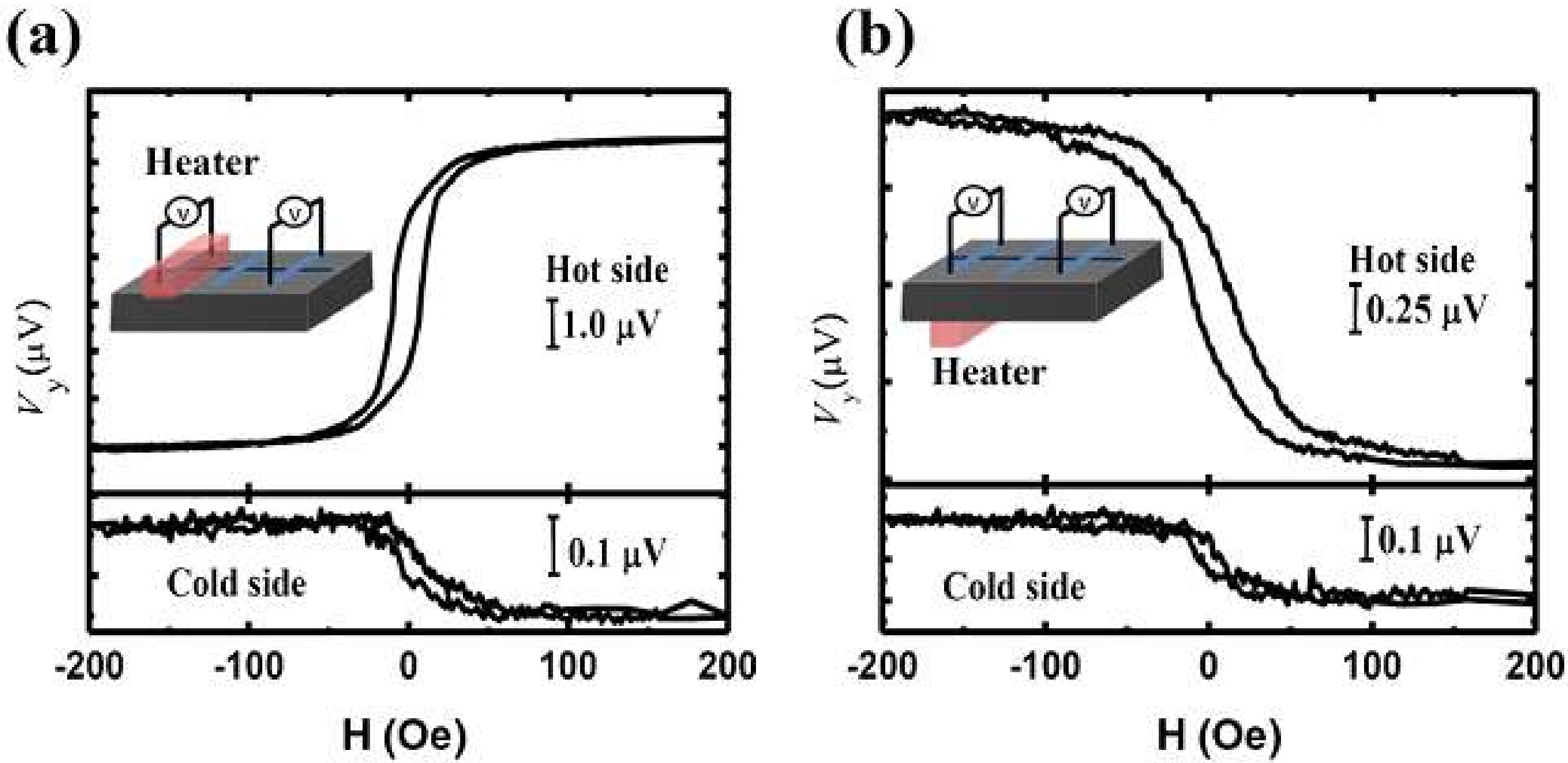
SSE in FM Semiconductor



Argument: SSE vs ANE

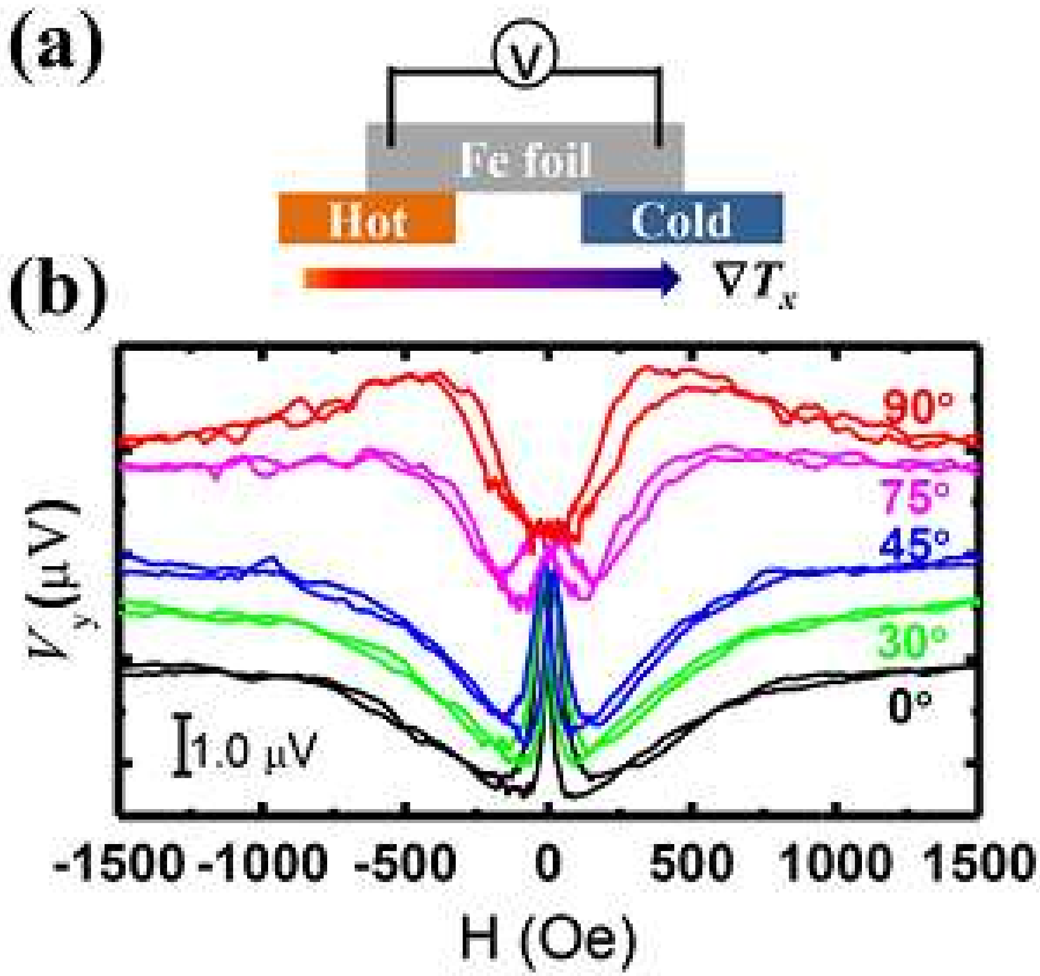


Argument: SSE vs ANE



Huang, et al, PRL (2010)

Argument: SSE vs ANE



Chia-Ling Chien

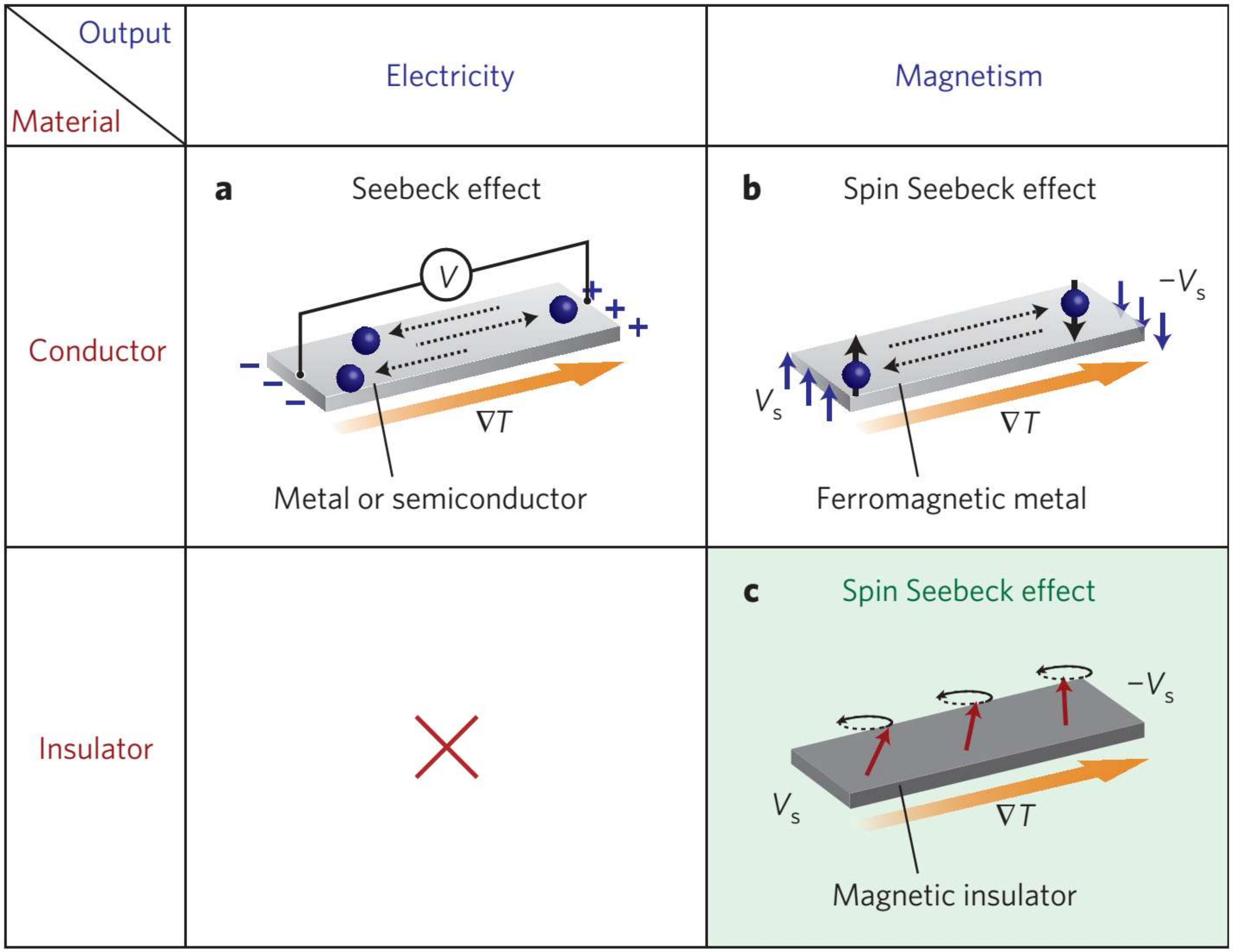
Huang, et al, PRL (2010)

SSE in FM insulator

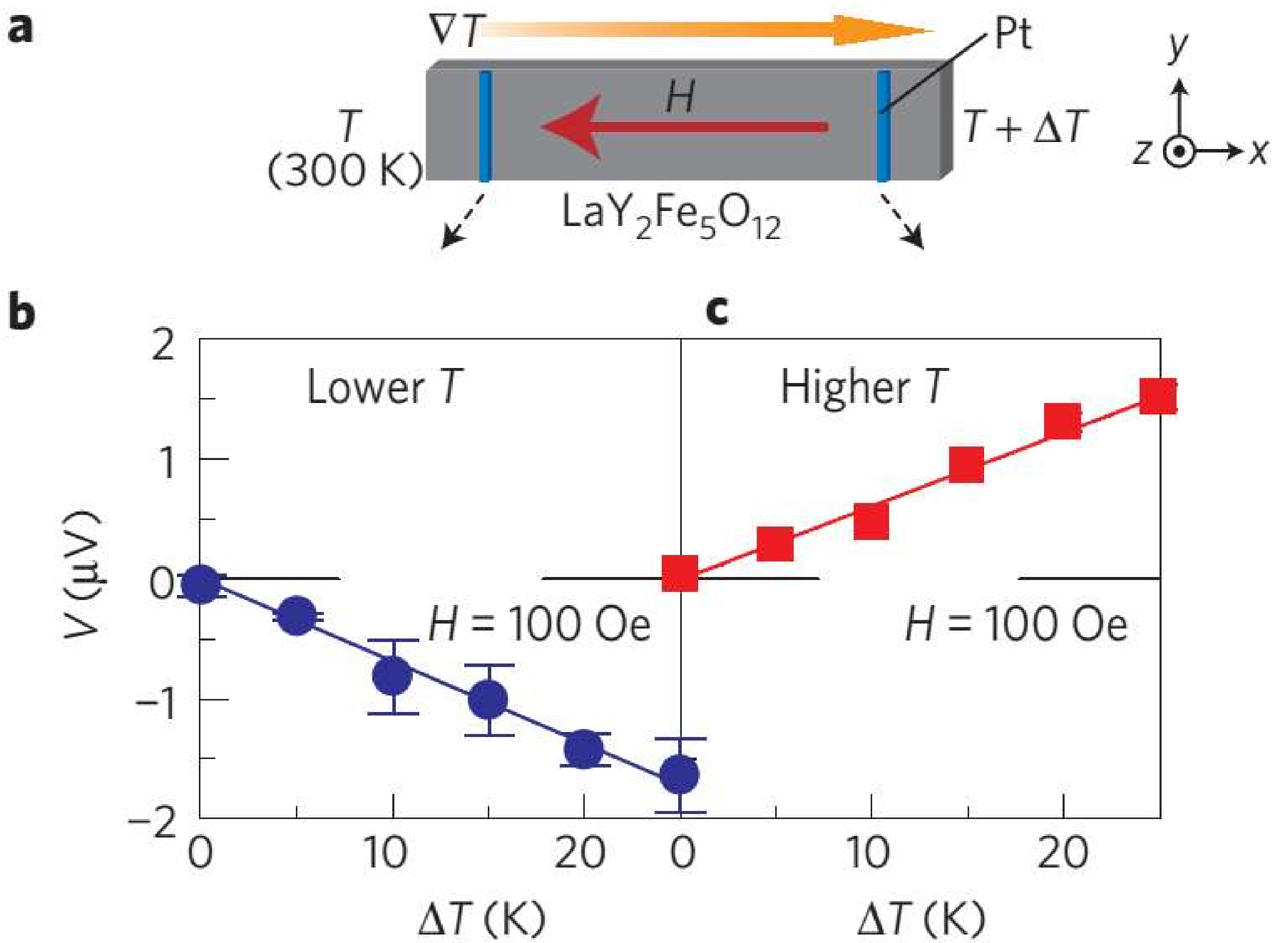
ANE generated in conducting FM?

How about insulating FM?

SSE in FM insulator

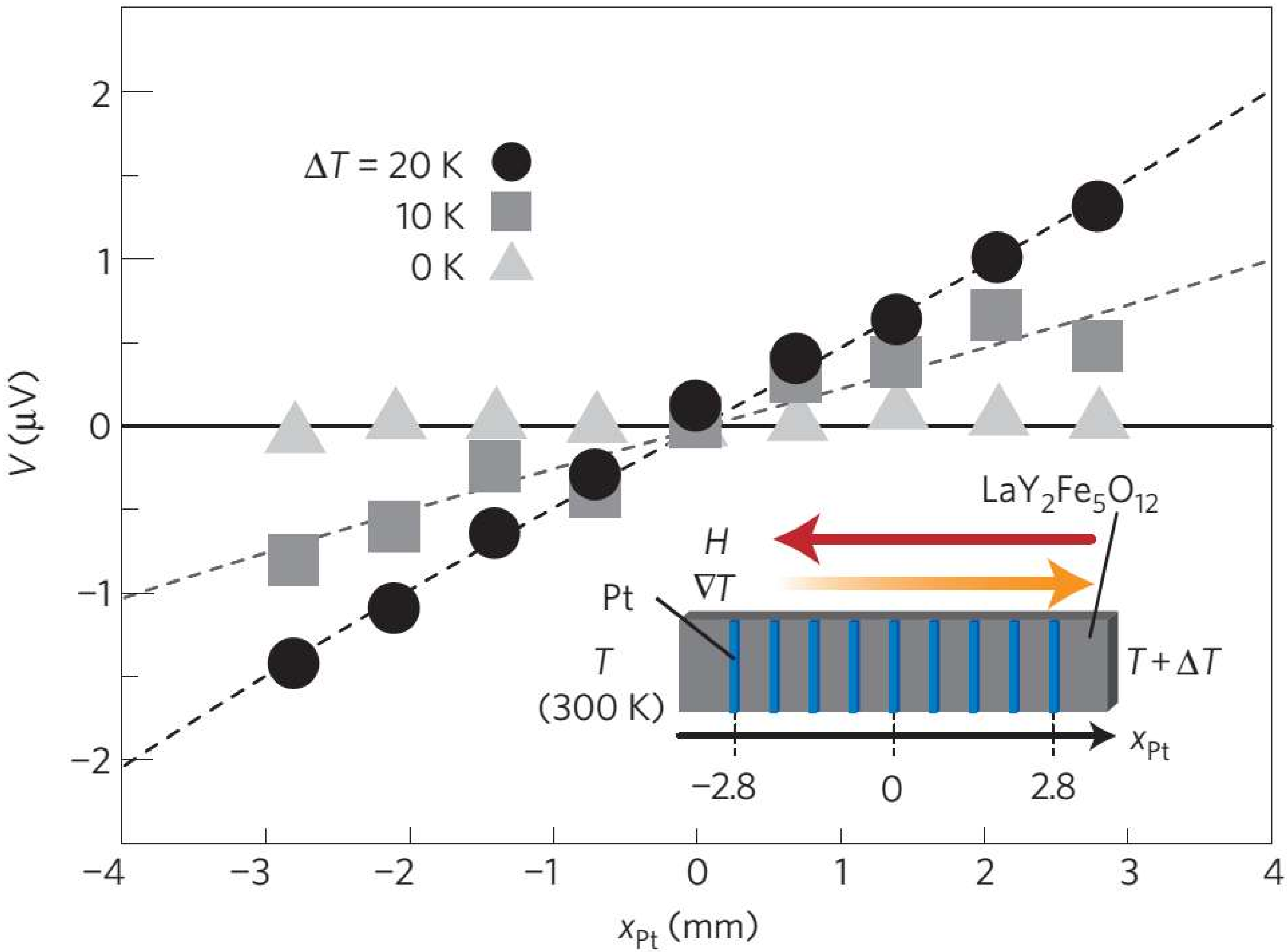


SSE in FM insulator



Uchida, et al, Nature Materials (2010)

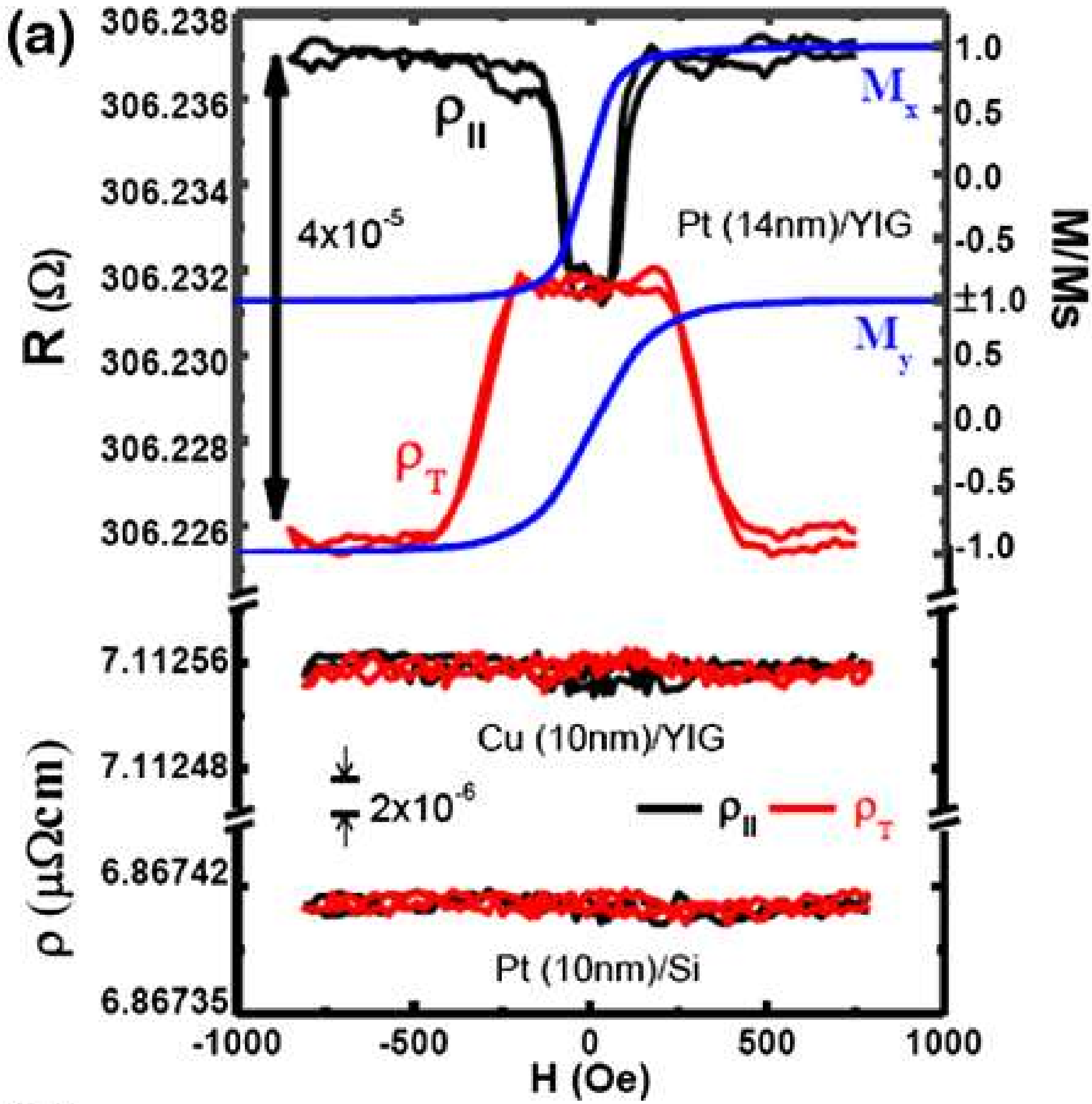
SSE in FM insulator



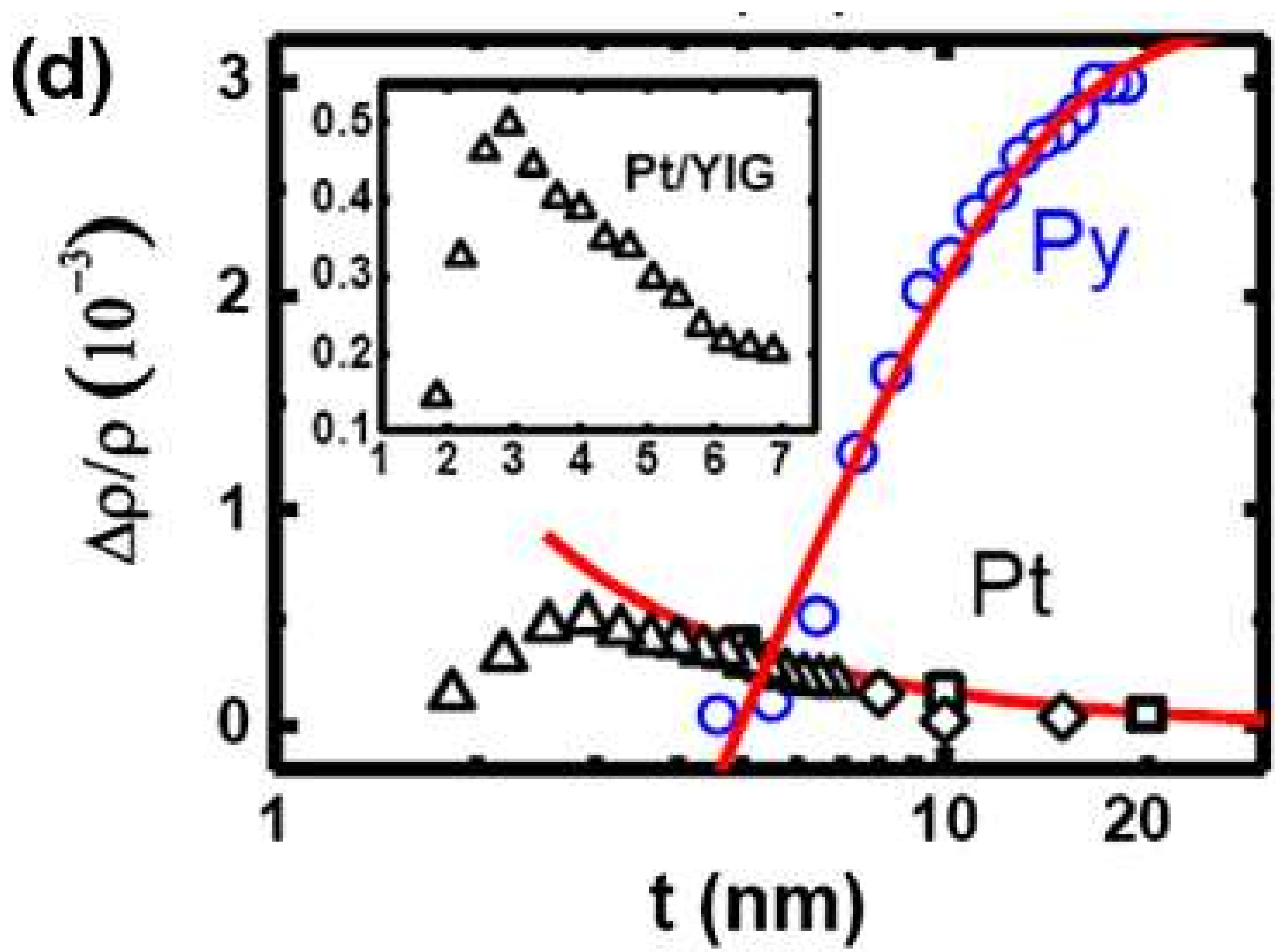
SSE in FM insulator

Is this the key to solve the issue between SSE and ANE?

Proximity effect

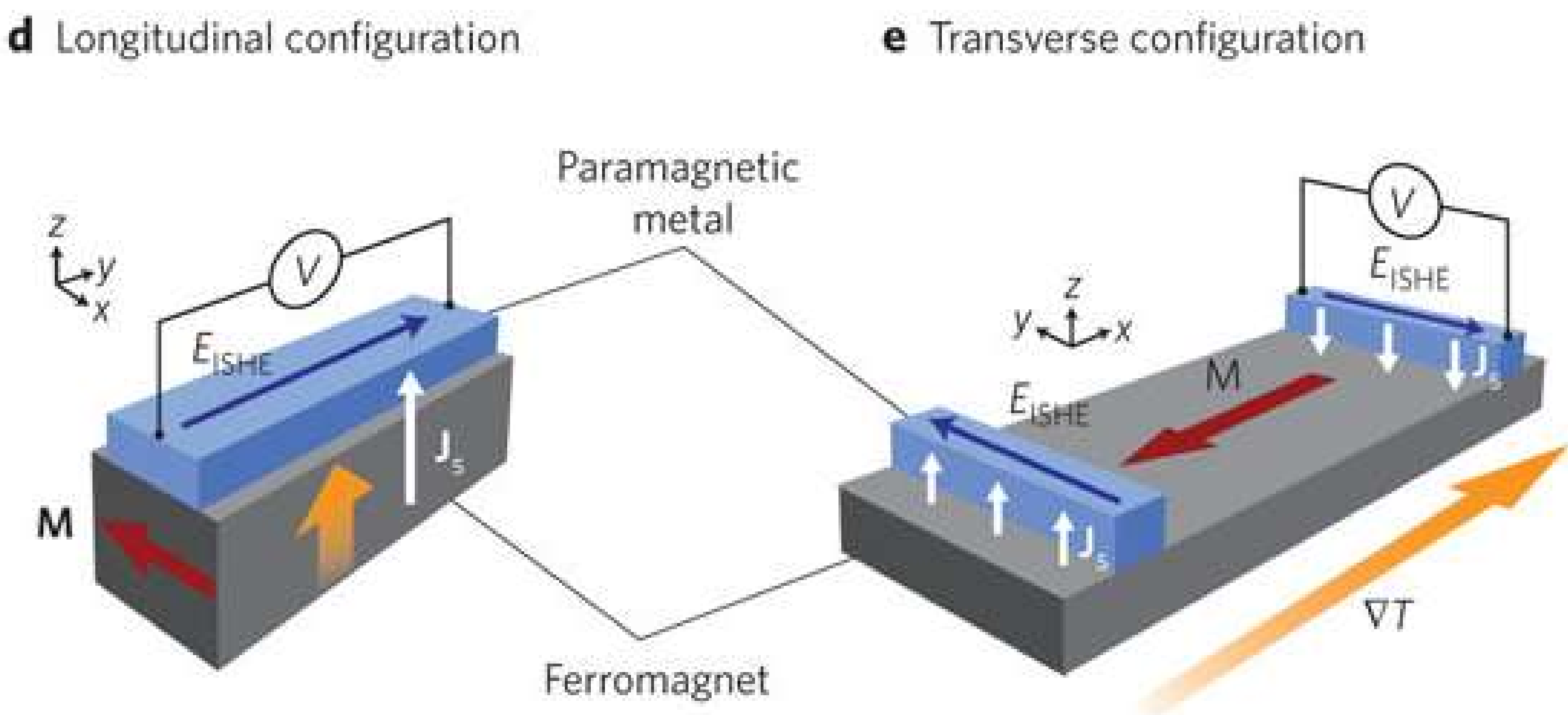


SSE in FM insulator



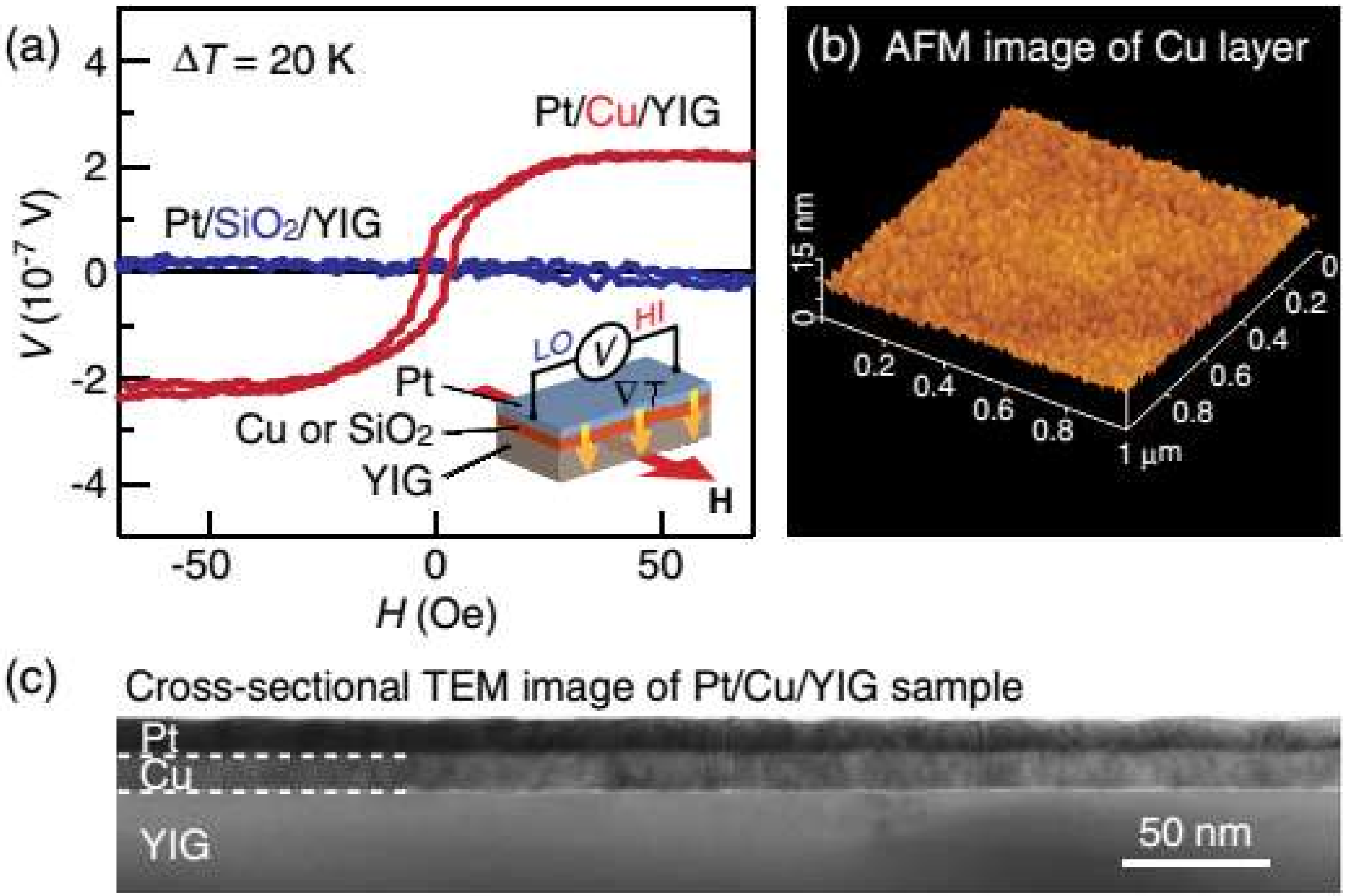
Huang, et al, PRL (2012)

Longitudinal vs. Transverse



Kikkawa, et al, PRL (2013)

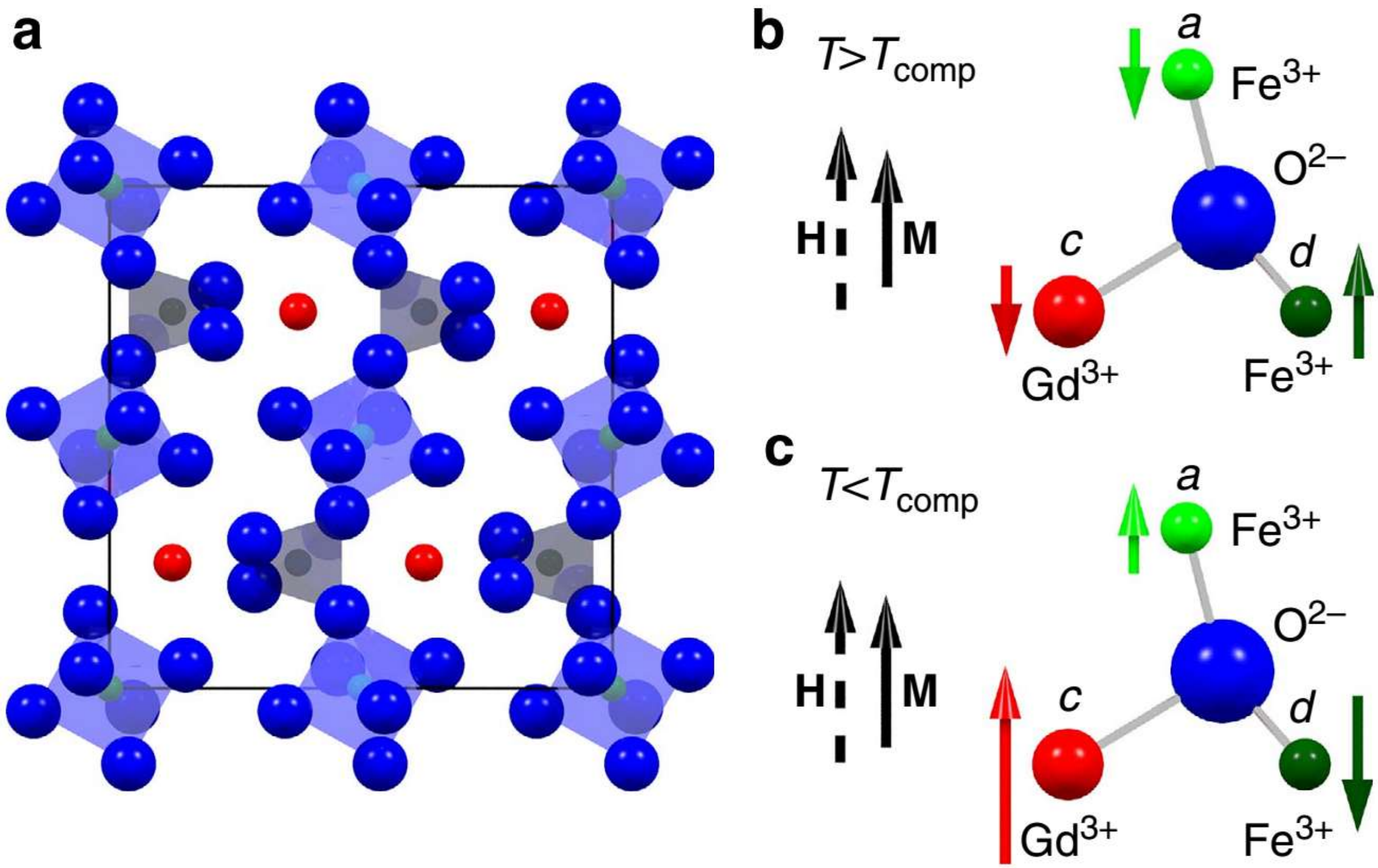
How to solve this issue?



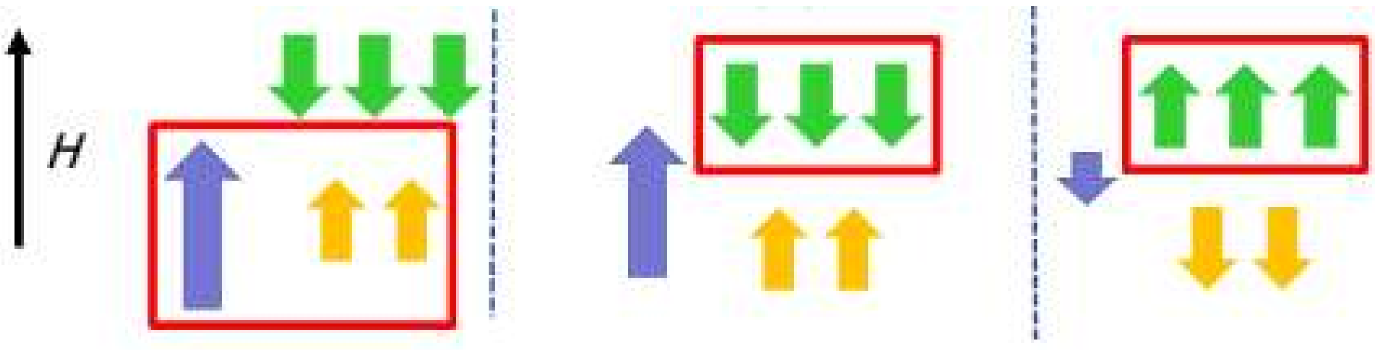
→ **Homework**

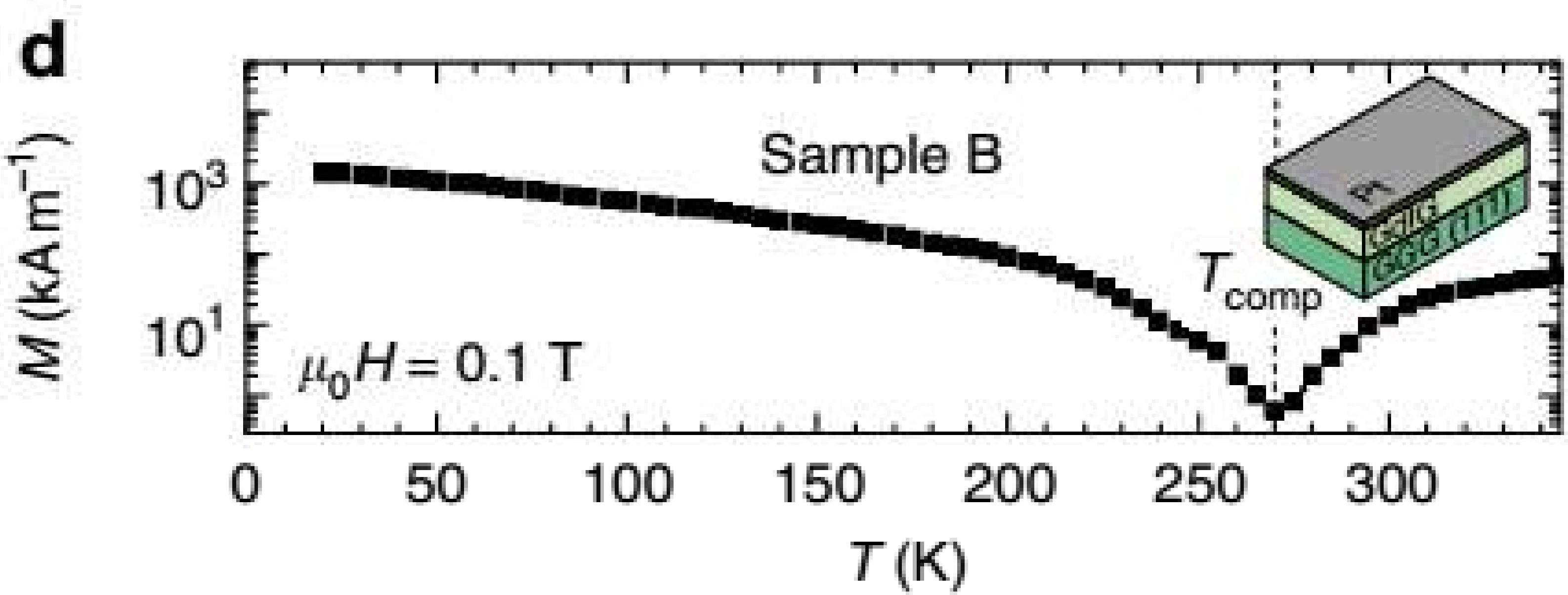
Kikkawa, et al, PRL (2013)

SSE in compensated ferrimagnets



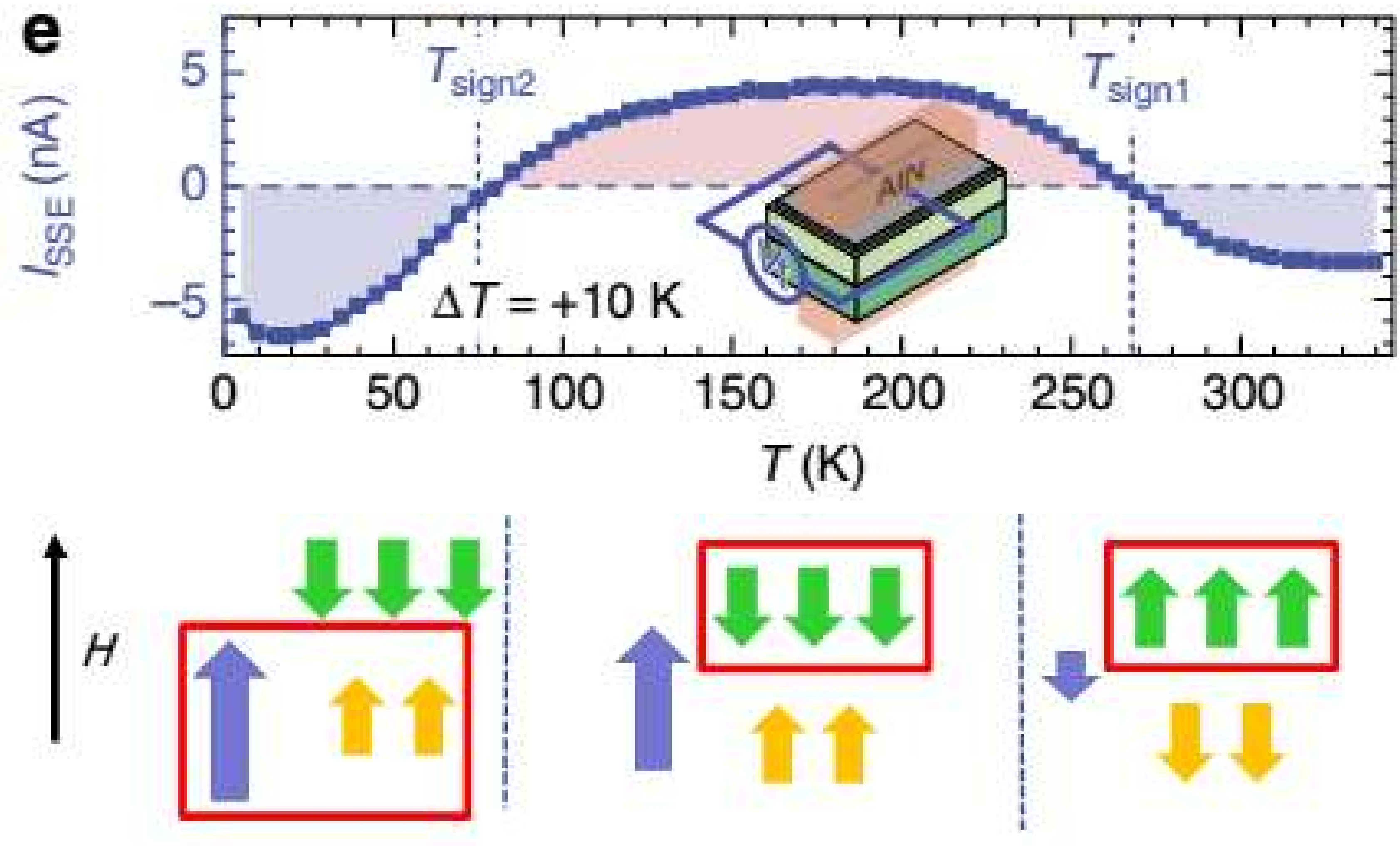
SSE in compensated ferrimagnets



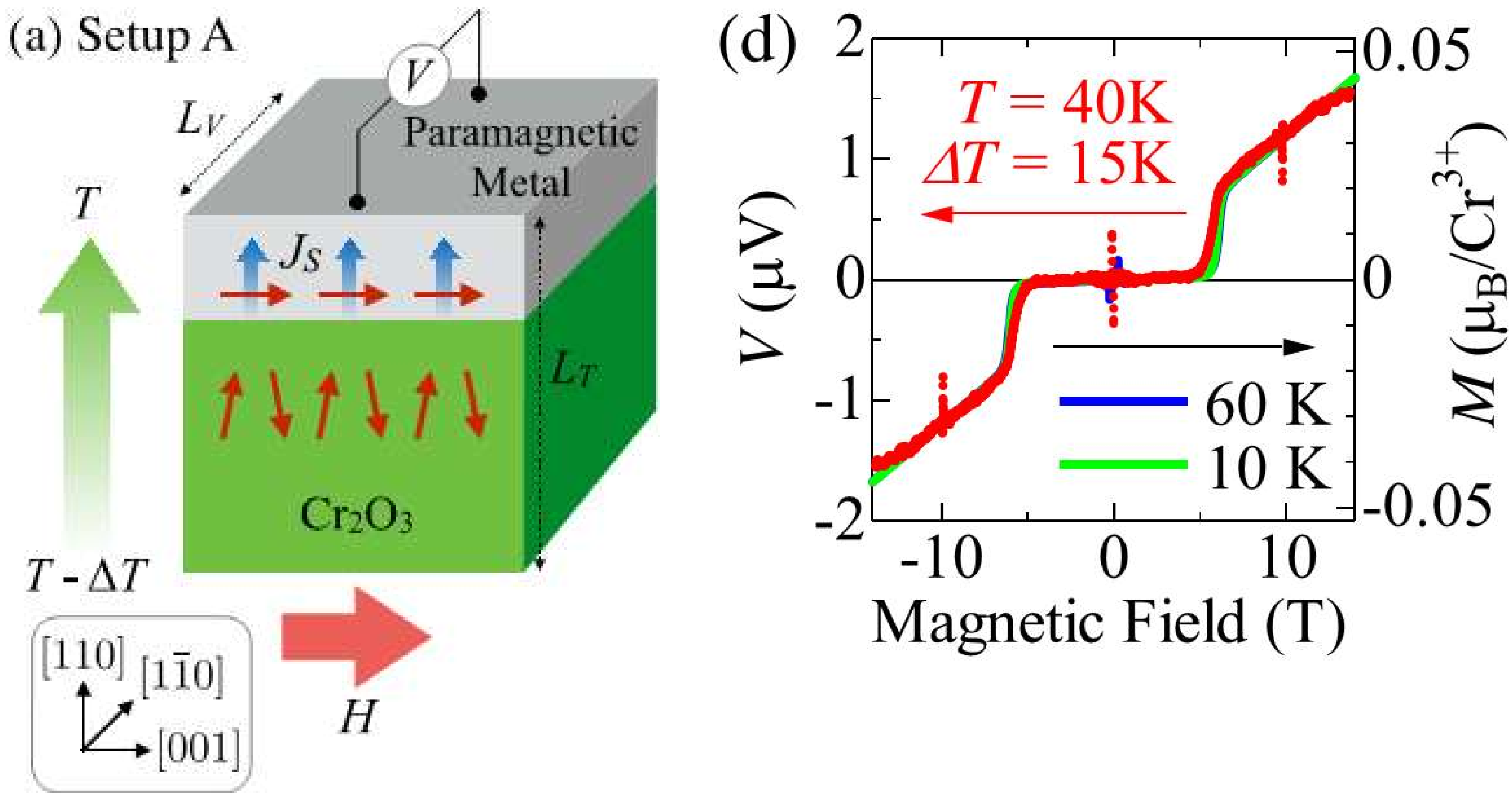


S Geprägs, et al, Nature Comm. (2016)

SSE in compensated ferrimagnets

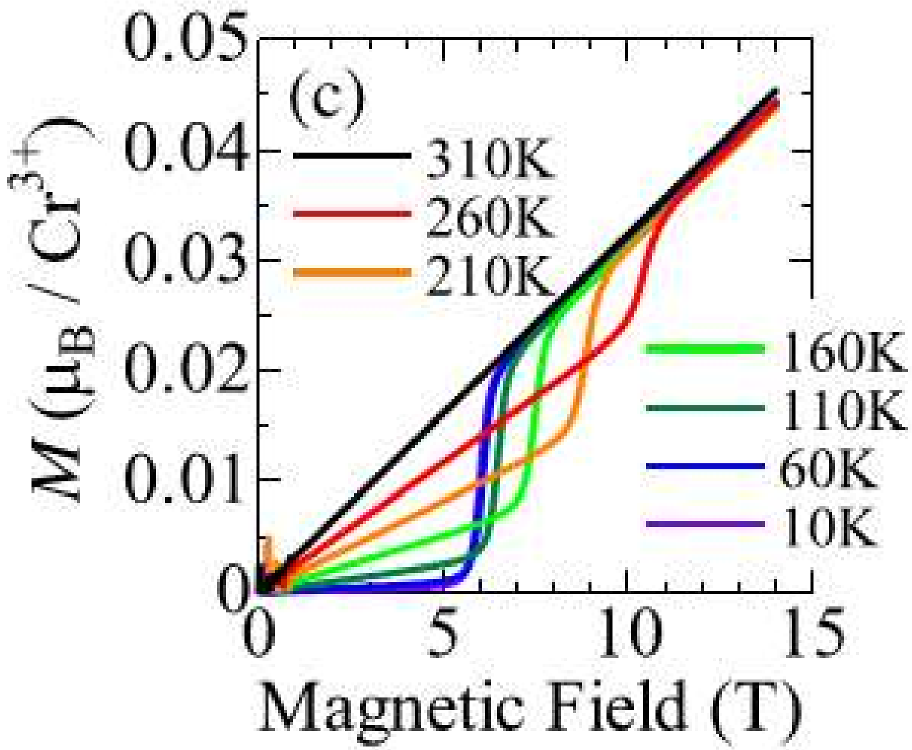


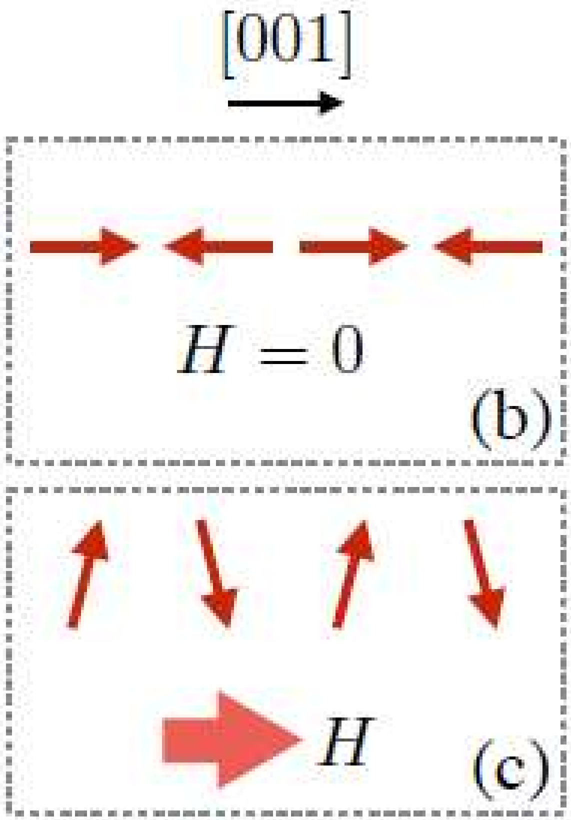
SSE in Antiferromagnets



Seki et al, PRL (2015).

SSE in Antiferromagnets





休息10分钟

Final Exam

Due date:

2019 01-04 (1:00 PM)

最后两节课: Dec. 21th, 28th

Student Presentations

Group Presentations

~40 mins talk + ~10 mins questions

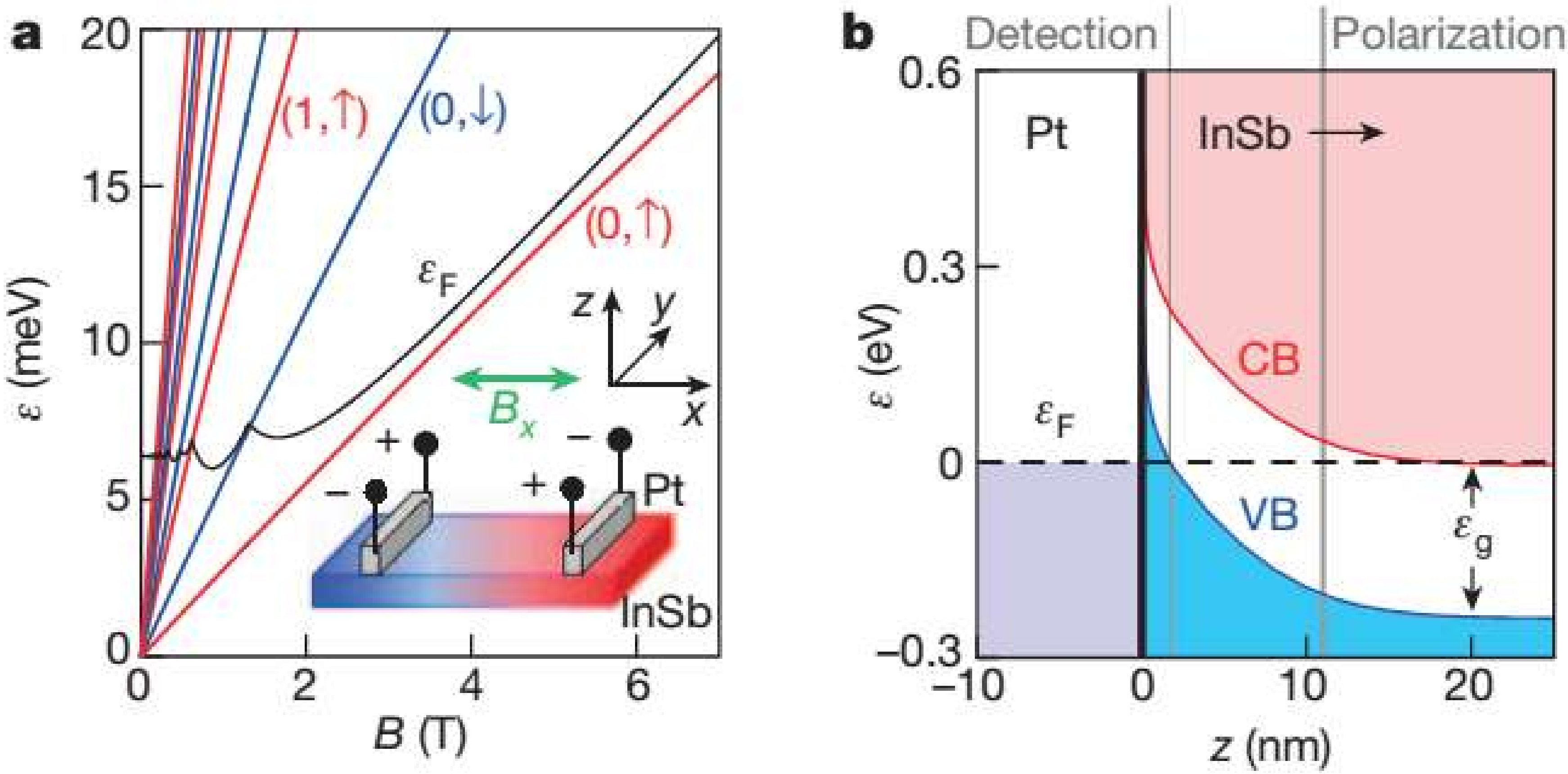
~5 persons in one group

最后两节课: Dec. 21th, 28th

Date	Group
Dec. 21^{th}	第一组： 丁石磊 齐少勉 闫姣婕 陈文杰 何梦云 第二组： 吉源 李龙飞 李娜 李思衡 孙慧敏
Dec. 28^{th}	第三组： 孙恺伟 王善 王政国 杨洁 赵嘉佶 朱鹏飞 第四组： 梁栋 张仕雄 赵利利 刘震 王一帆 尚念泽
Jan. 04^{th}	交期末考试（电子版和纸版都可以）

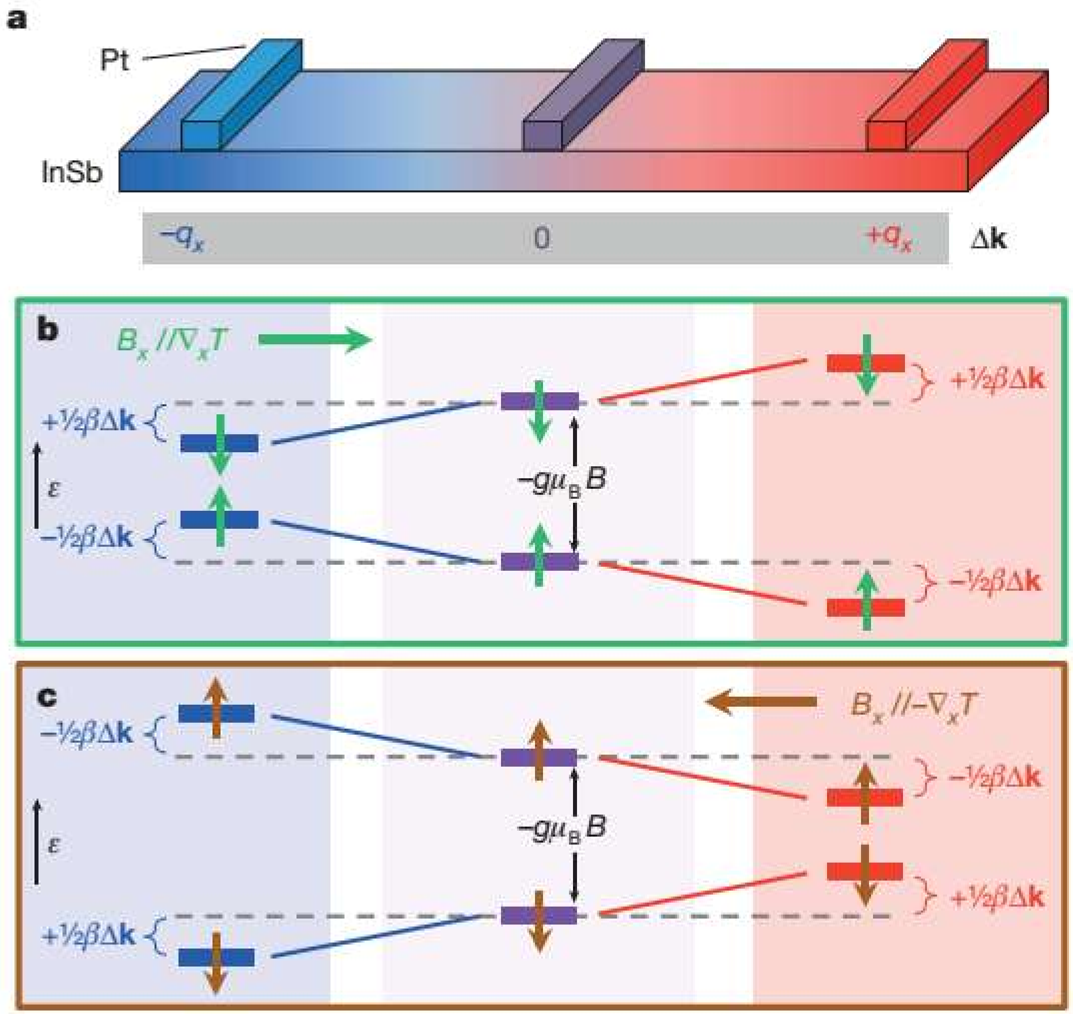
休息10分钟

Giant SSE in InSb

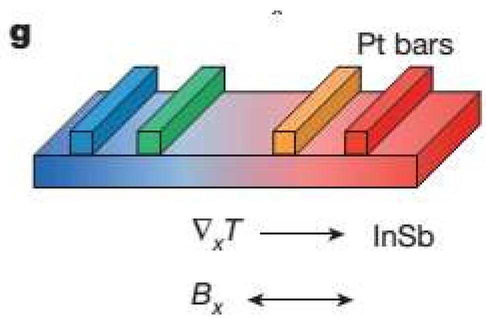


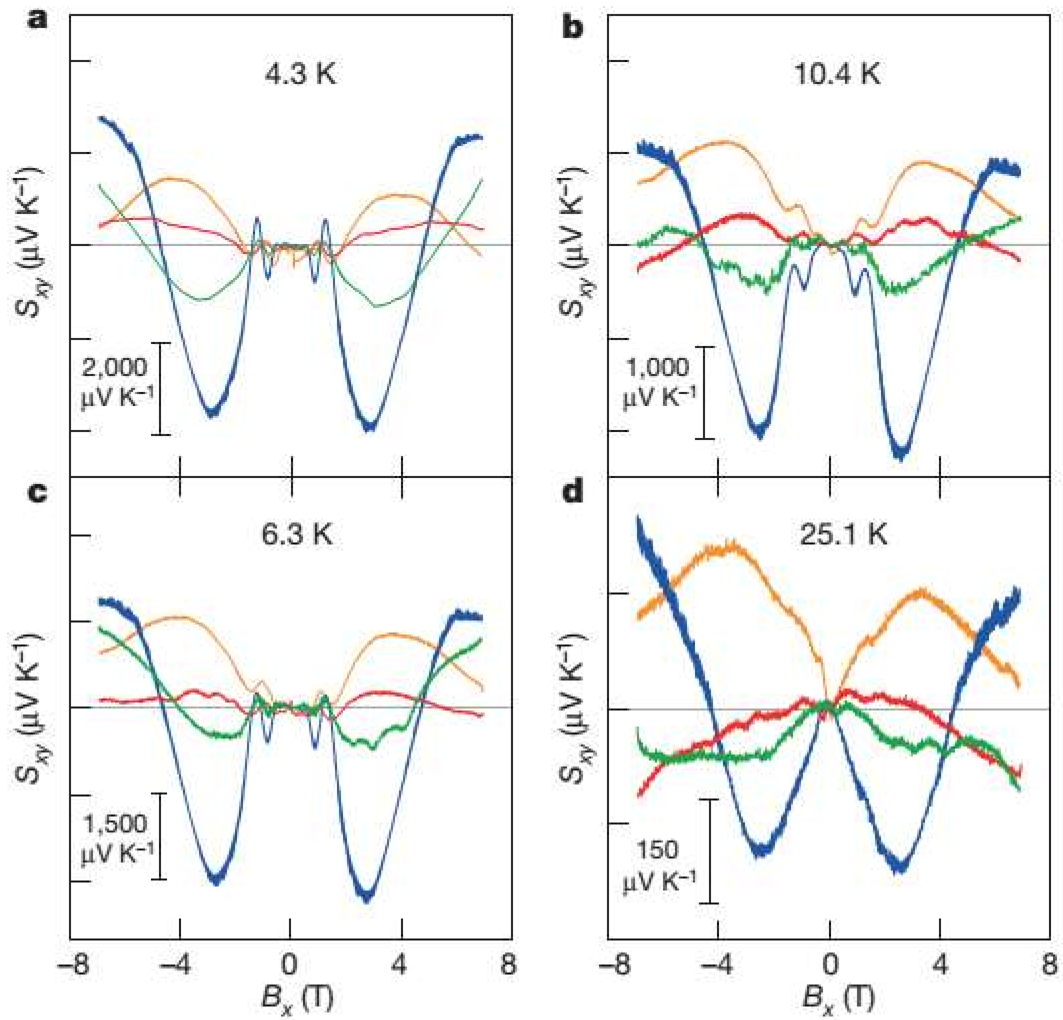
Jaworski, et al, Nature (2012)

Giant SSE in InSb

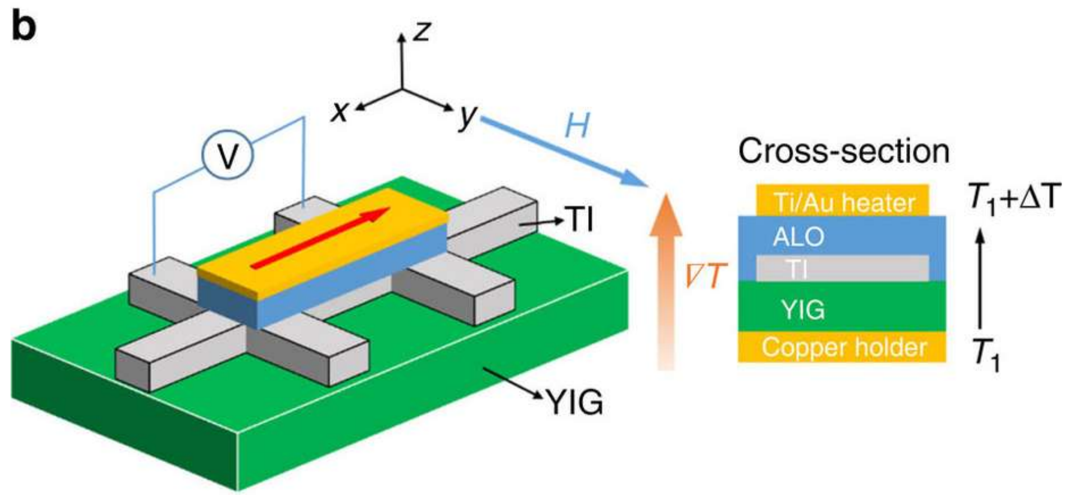


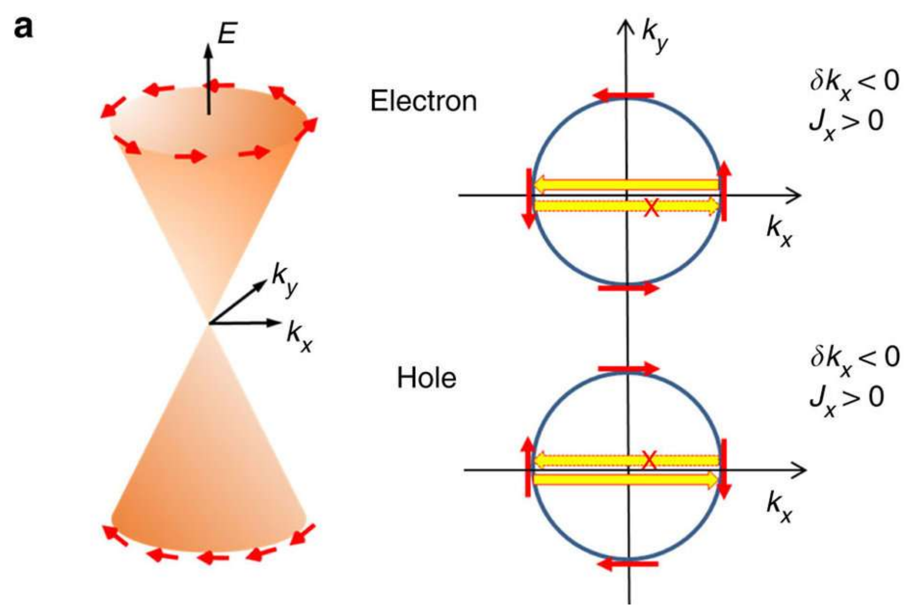
Giant SSE in InSb



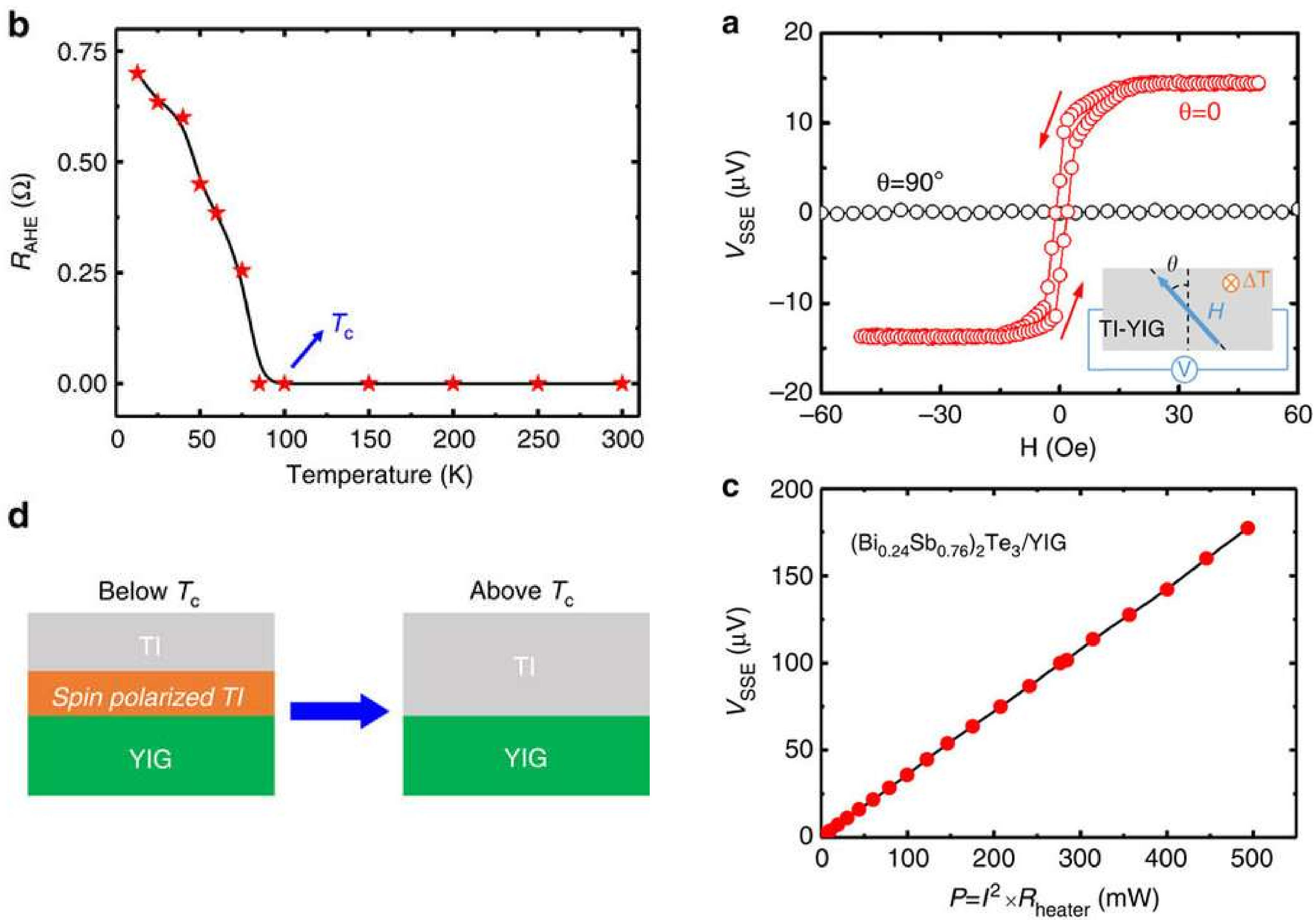


Enhanced SSE at YIG-TI

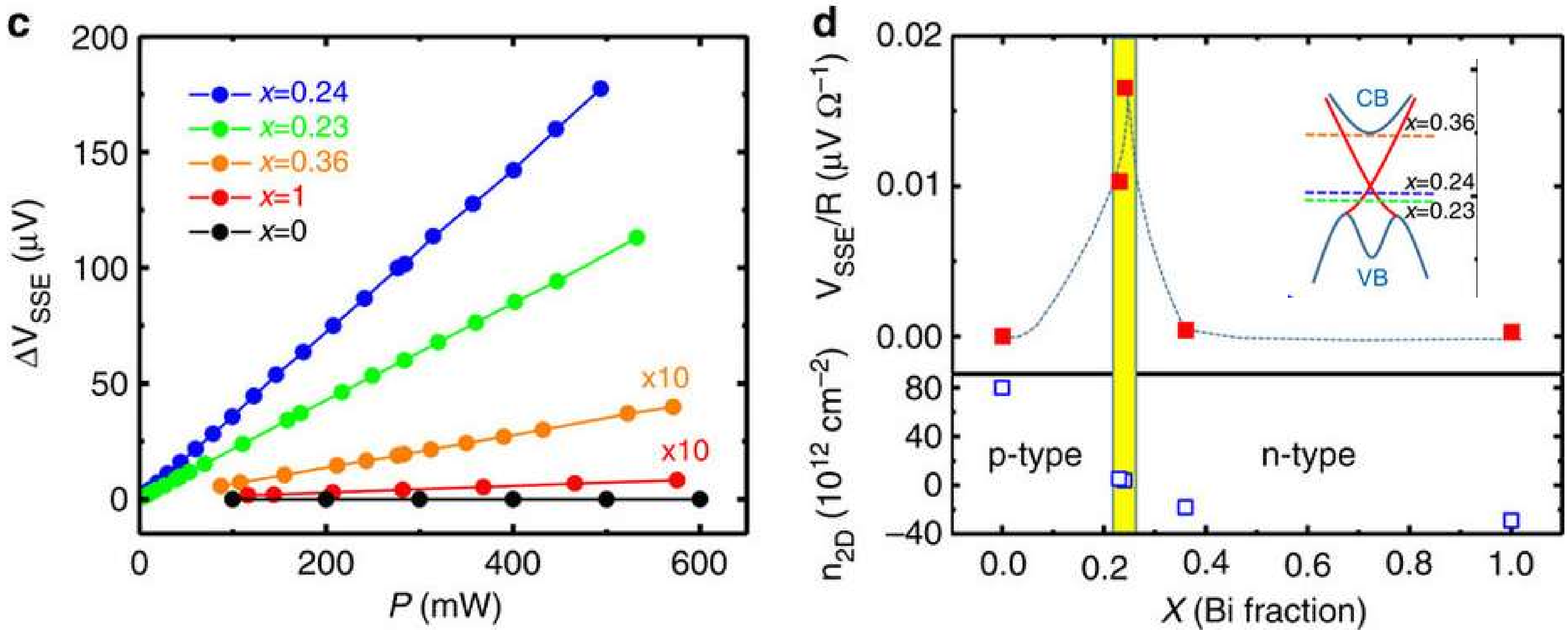




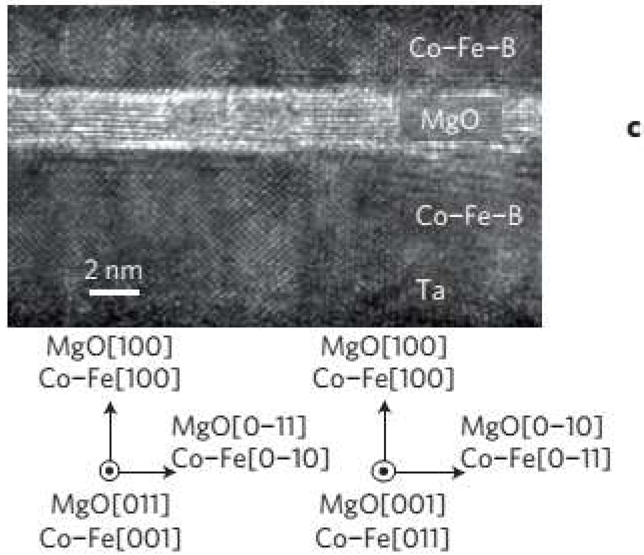
Enhanced SSE at YIG-TI

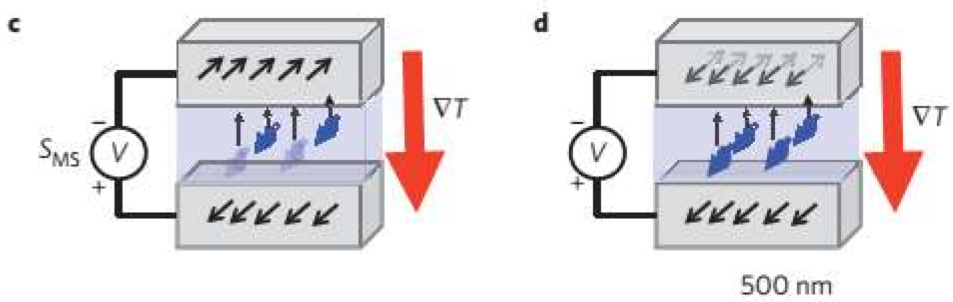


Enhanced SSE at YIG-TI



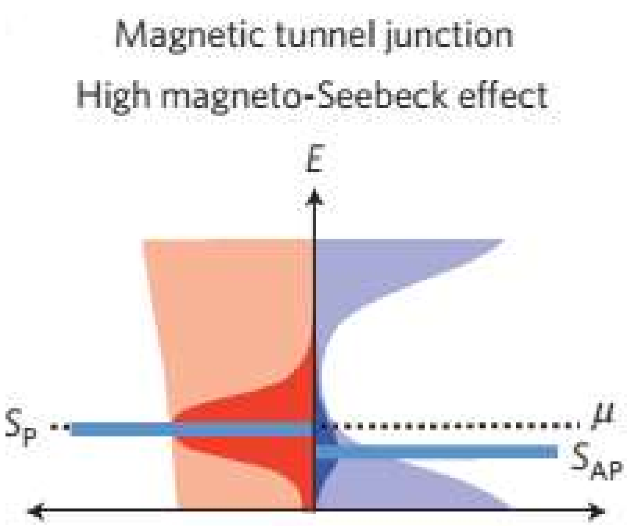
Seebeck effect of a MTJ

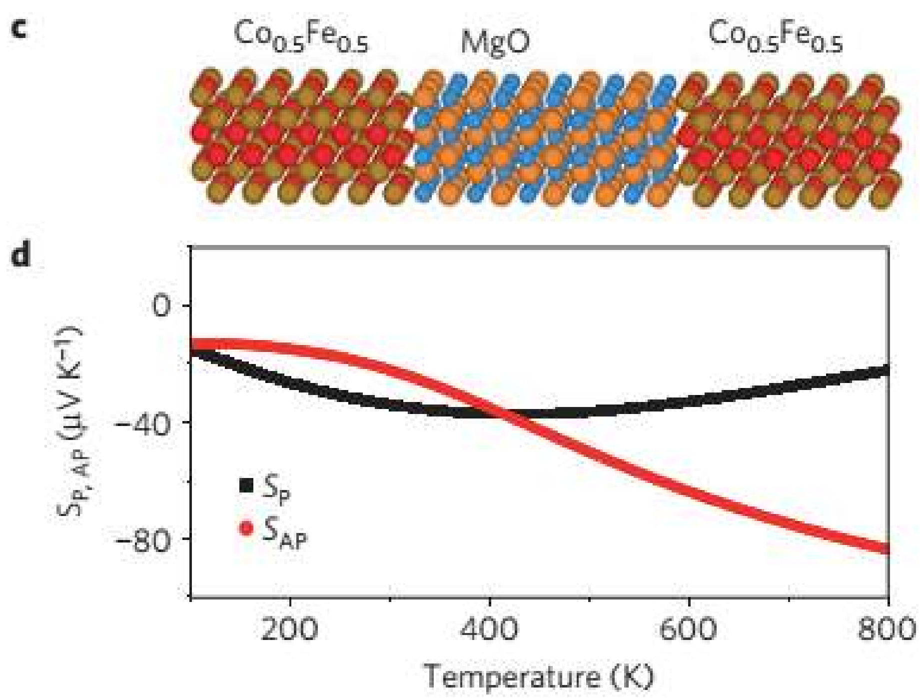




Walter, et al, Nature Materials (2011)

Seebeck effect of a MTJ





Seebeck effect of a MTJ

Table 1 | The Seebeck coefficients for parallel S_P and antiparallel S_{AP} configurations and the magneto-Seebeck effects calculated for different supercells at a temperature of 300 K.

FeCo/MgO/FeCo with a ten-monolayer MgO barrier

	S_P (μV K^{-1})	S_{AP} (μV K^{-1})	$S_P - S_{AP}$ (μV K^{-1})	S_{MS} (%)
CoFe	−19.7	−32.4	12.7	64.1
FeCo	45.9	−50.0	95.9	209.0
CFFC	9.4	−44.6	54.0	573.2
$Co_{0.5}Fe_{0.5}$	−34.0	−21.9	−12.1	−55.2
Experimental value	−107.9 (−1,300)	−99.2 (−1,195)	−8.7 (−105)	−8.8 (−8.8)

The results show the sensitivity to the interface composition. S_{MS} defines the relative change and can be negative or positive. Abbreviations: CoFe—$Co_{0.5}Fe_{0.5}$ layers with Co at the MgO interface. FeCo—$Co_{0.5}Fe_{0.5}$ layers with Fe at the MgO interface. CFFC—$Co_{0.5}Fe_{0.5}$ layers with Fe at one of the MgO interfaces and Co at the other. $Co_{0.5}Fe_{0.5}$—supercell in plane with Co:Fe 1:1 at the interface. The values derived from the experiment are given for a temperature difference at the MgO barrier of 53 mK (4.4 mK) respectively. The temperature difference ΔT is taken from the numerical simulation of the temperature gradients using the thin-film value (bulk value) of the thermal conductivity of MgO.

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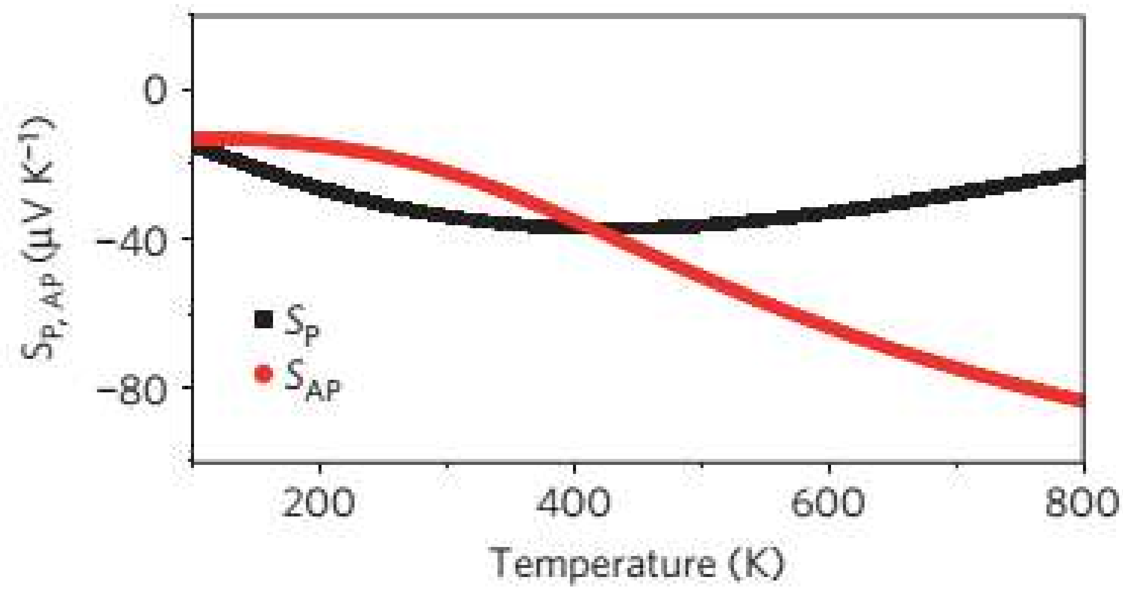
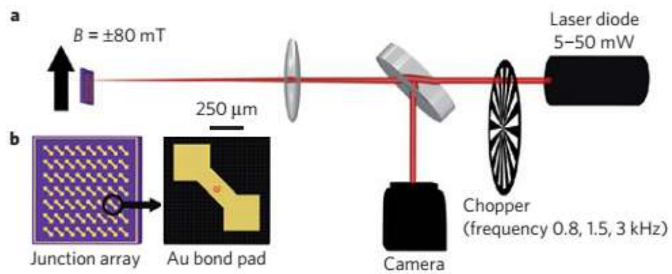
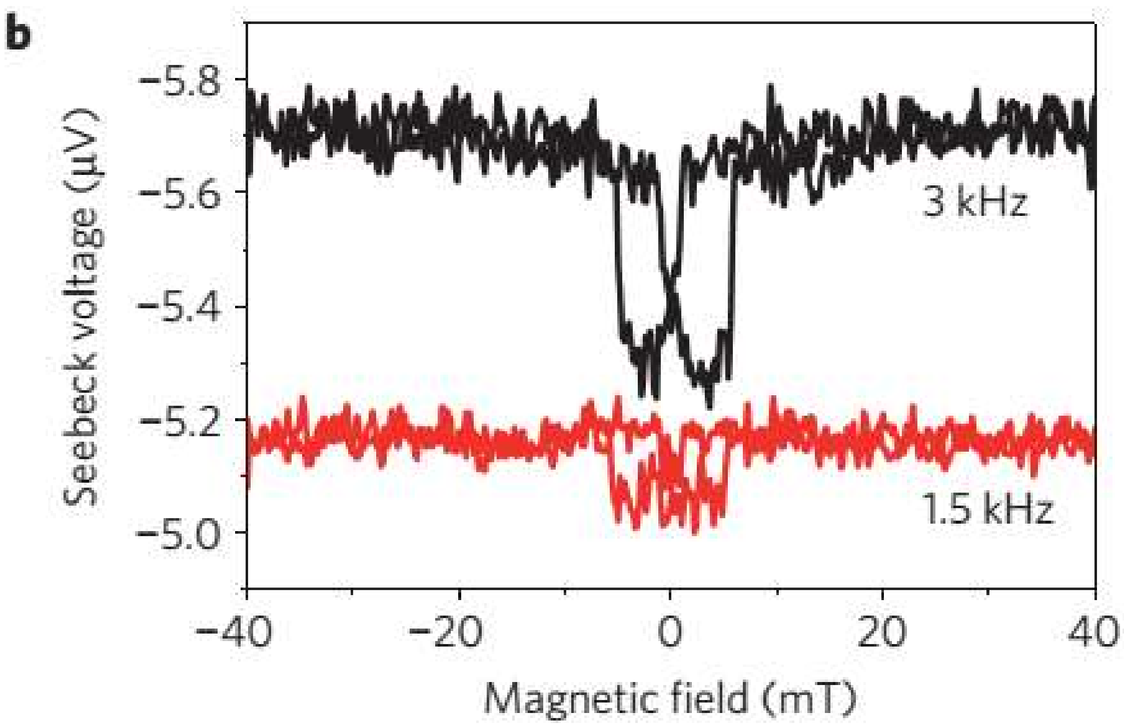


Seebeck effect of a MTJ

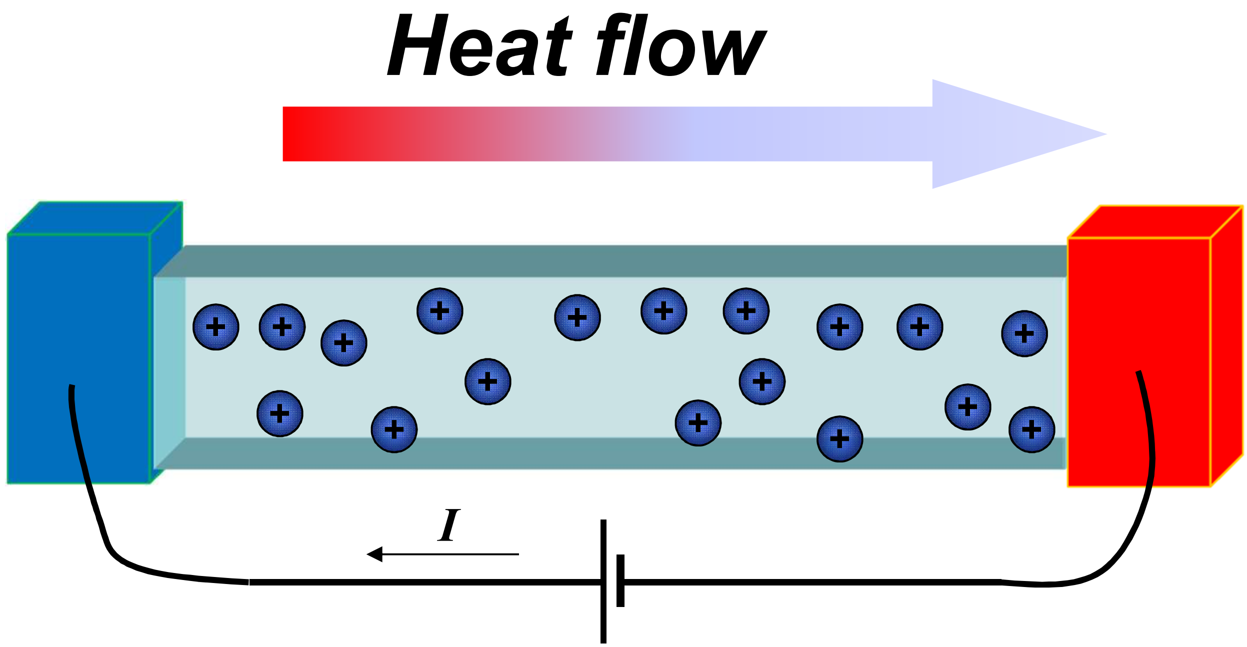




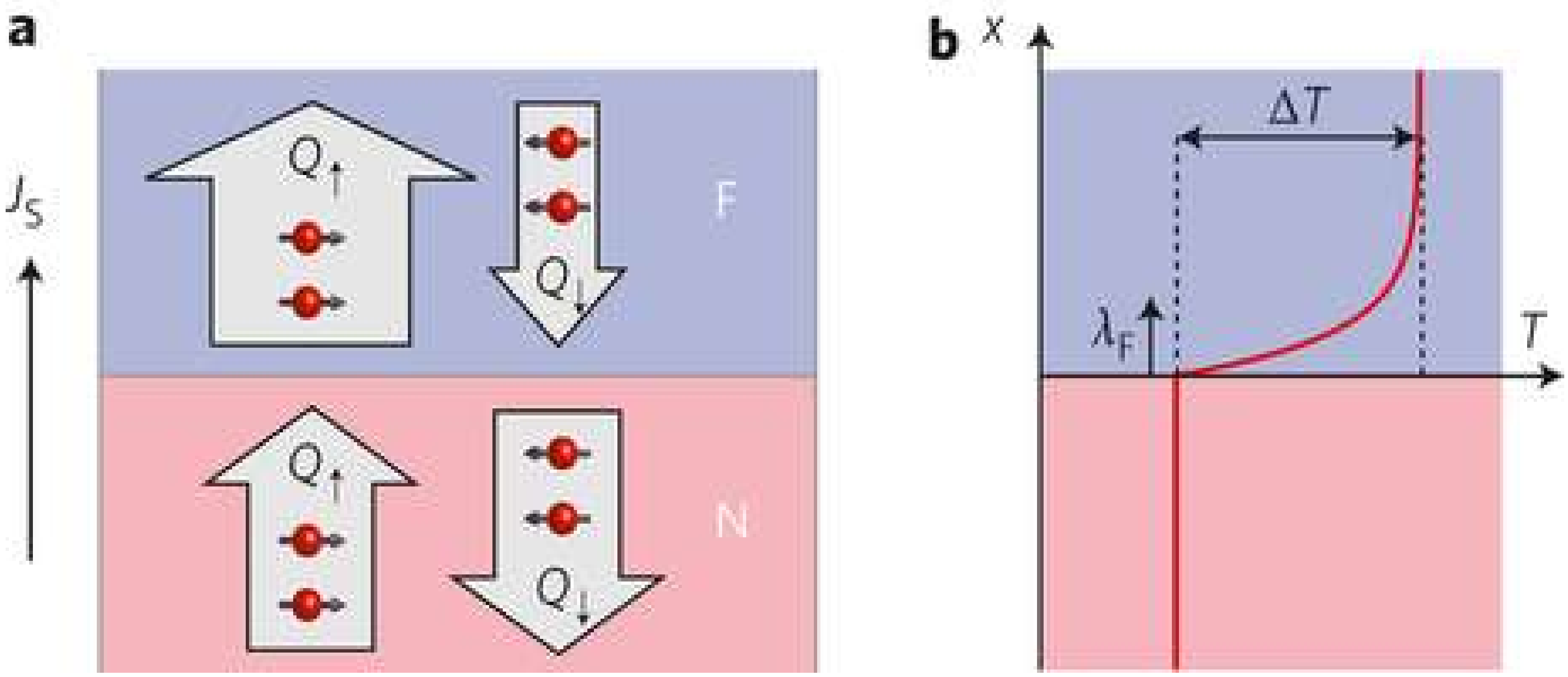
Outline

3. Spin Peltier effect

Peltier effect

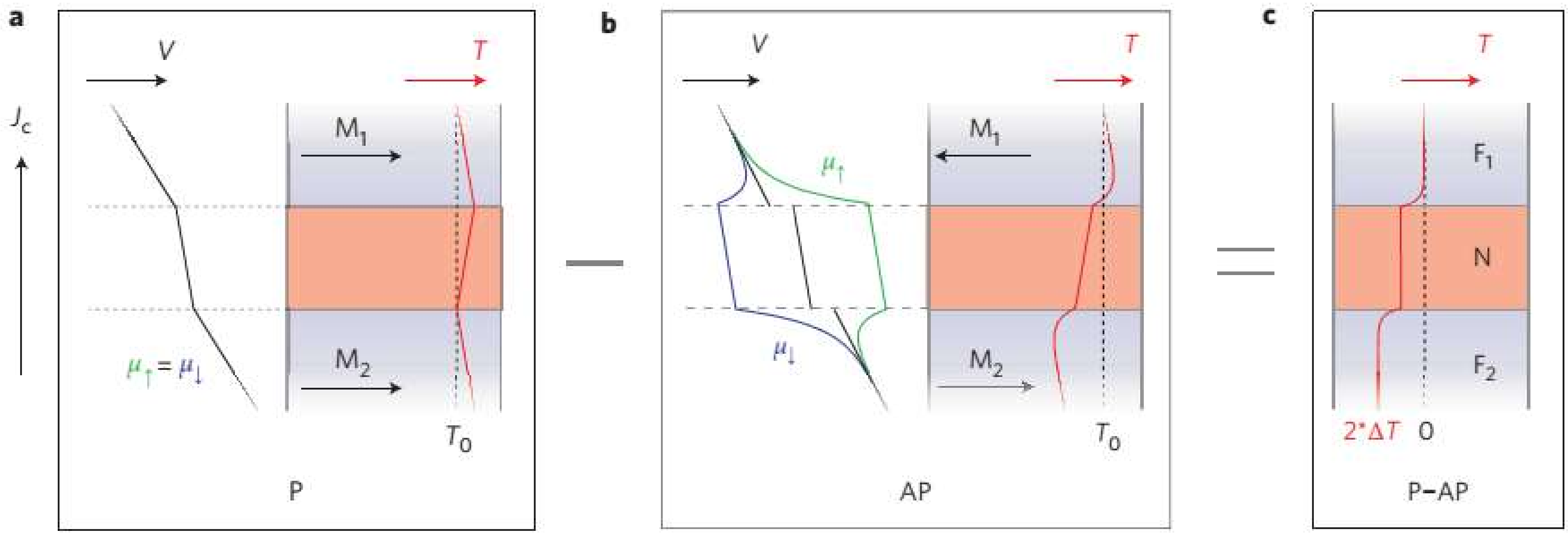


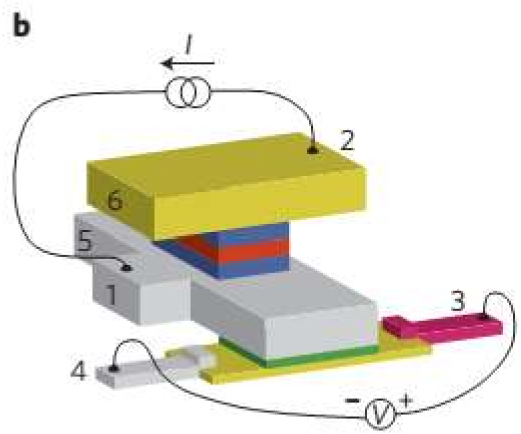
Spin Peltier effect



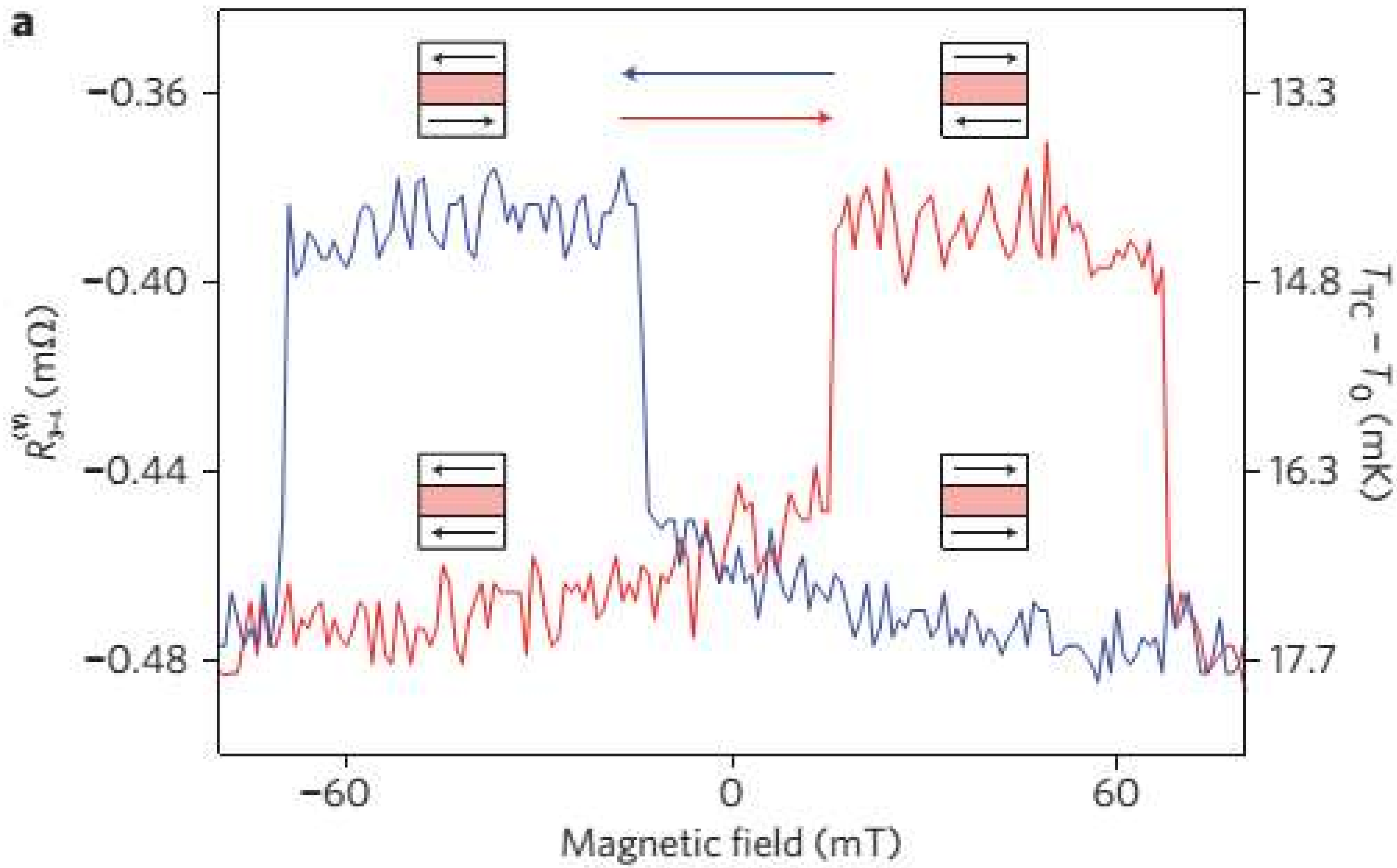
Flipse, et al, Nature Nanotech (2012)

Spin Peltier effect

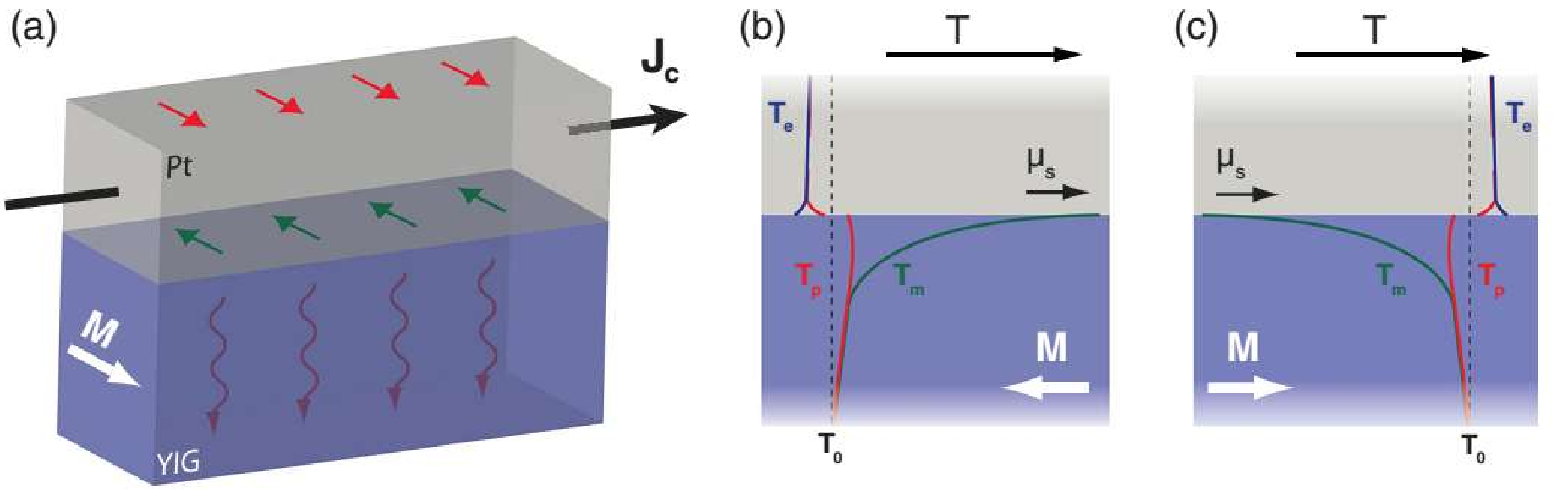




Spin Peltier effect

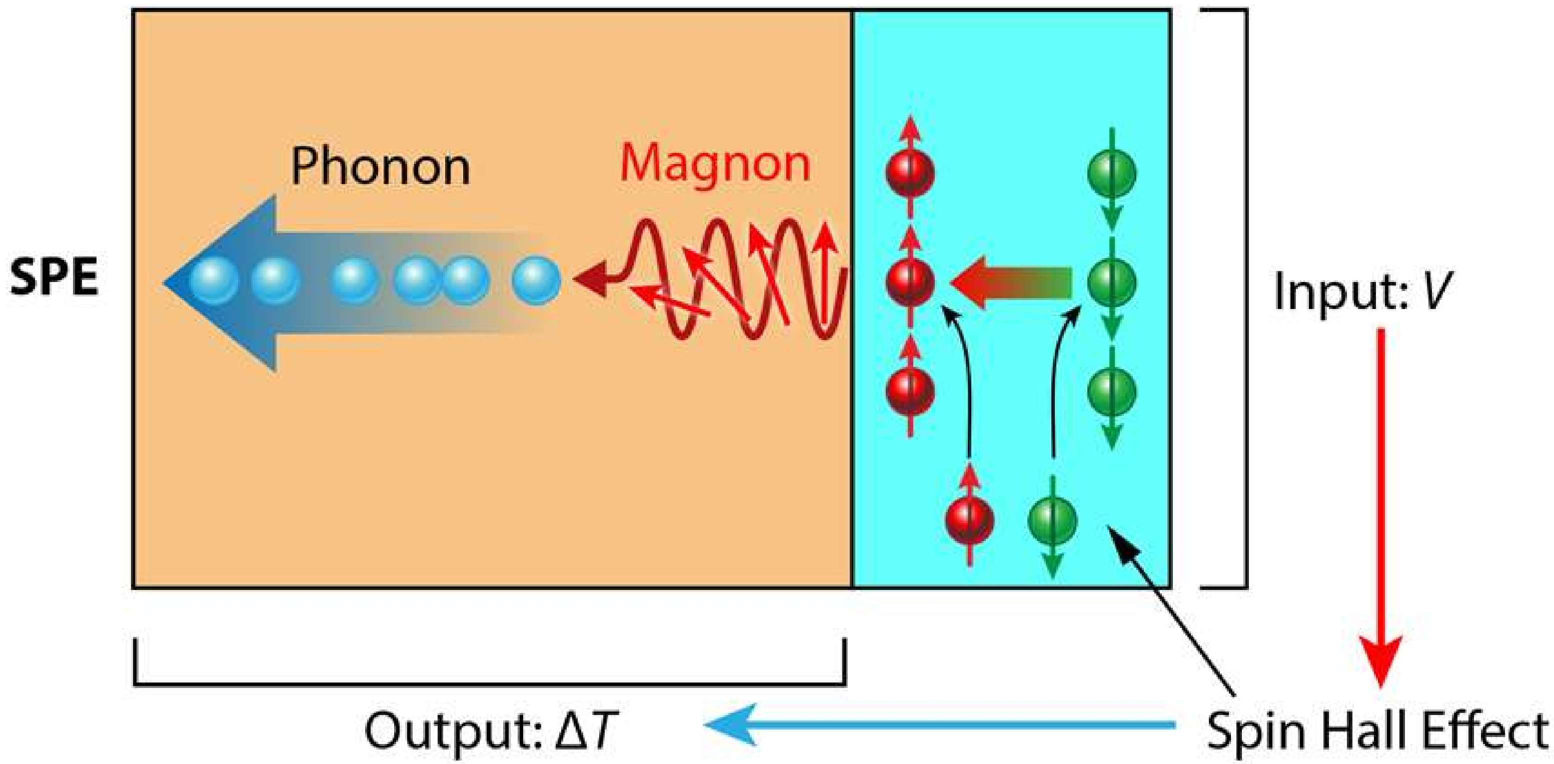


Spin Peltier effect

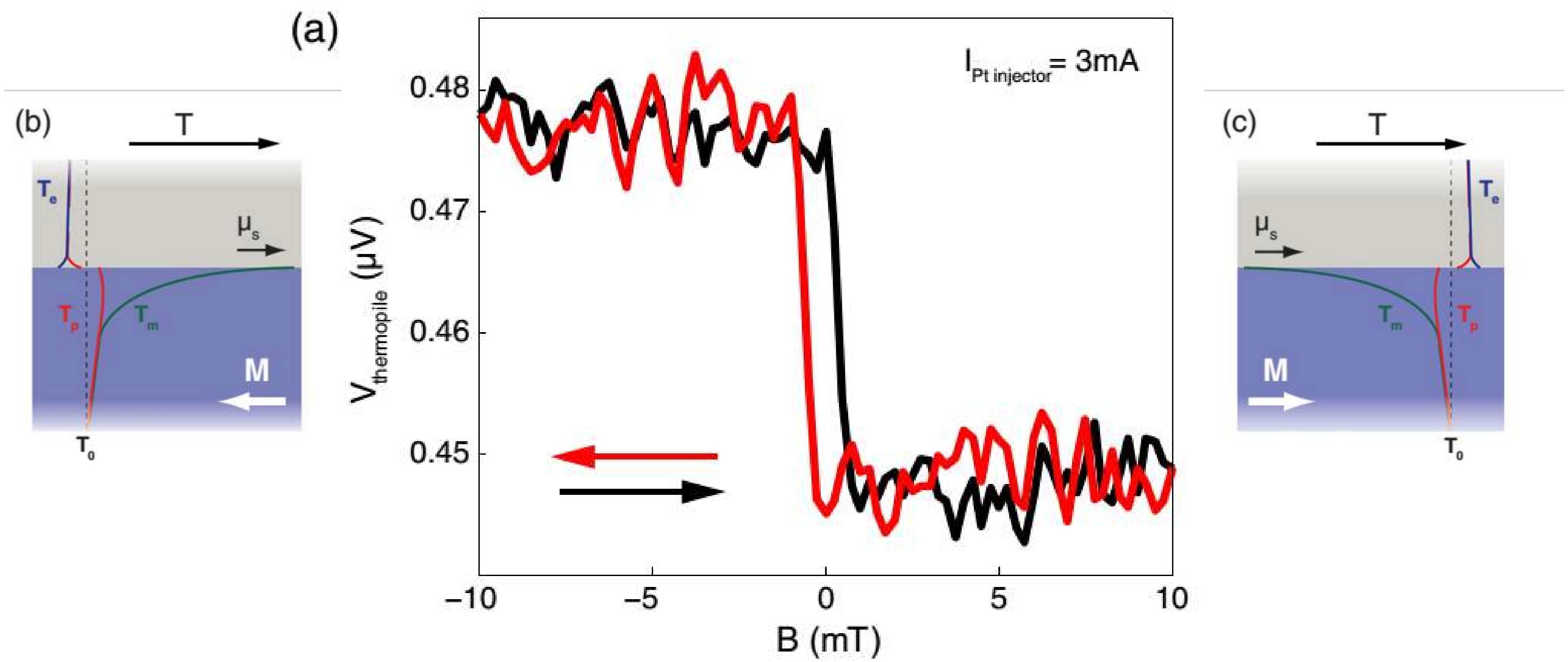


Flipse, et al, PRL (2014)

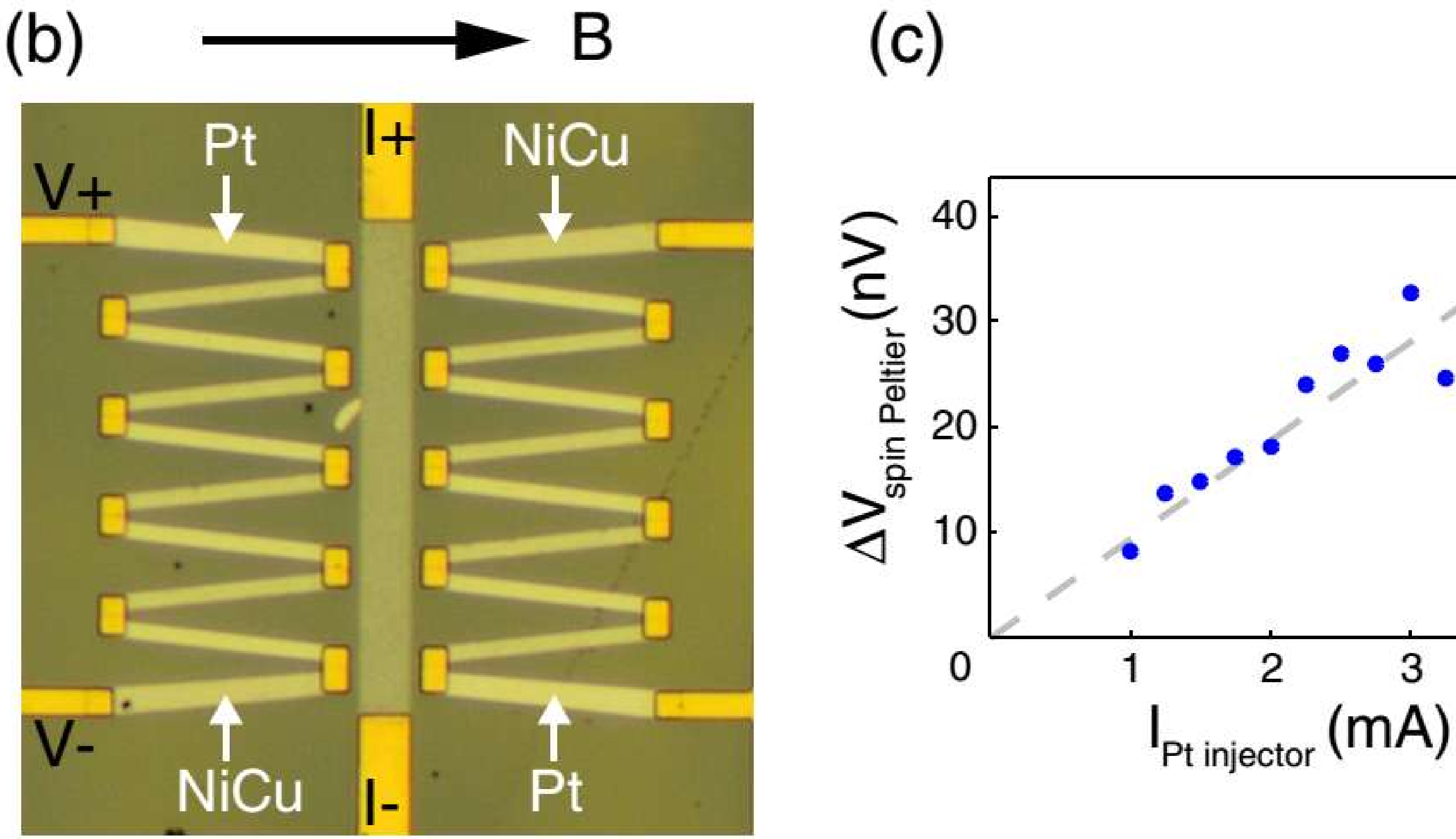
Spin Peltier effect



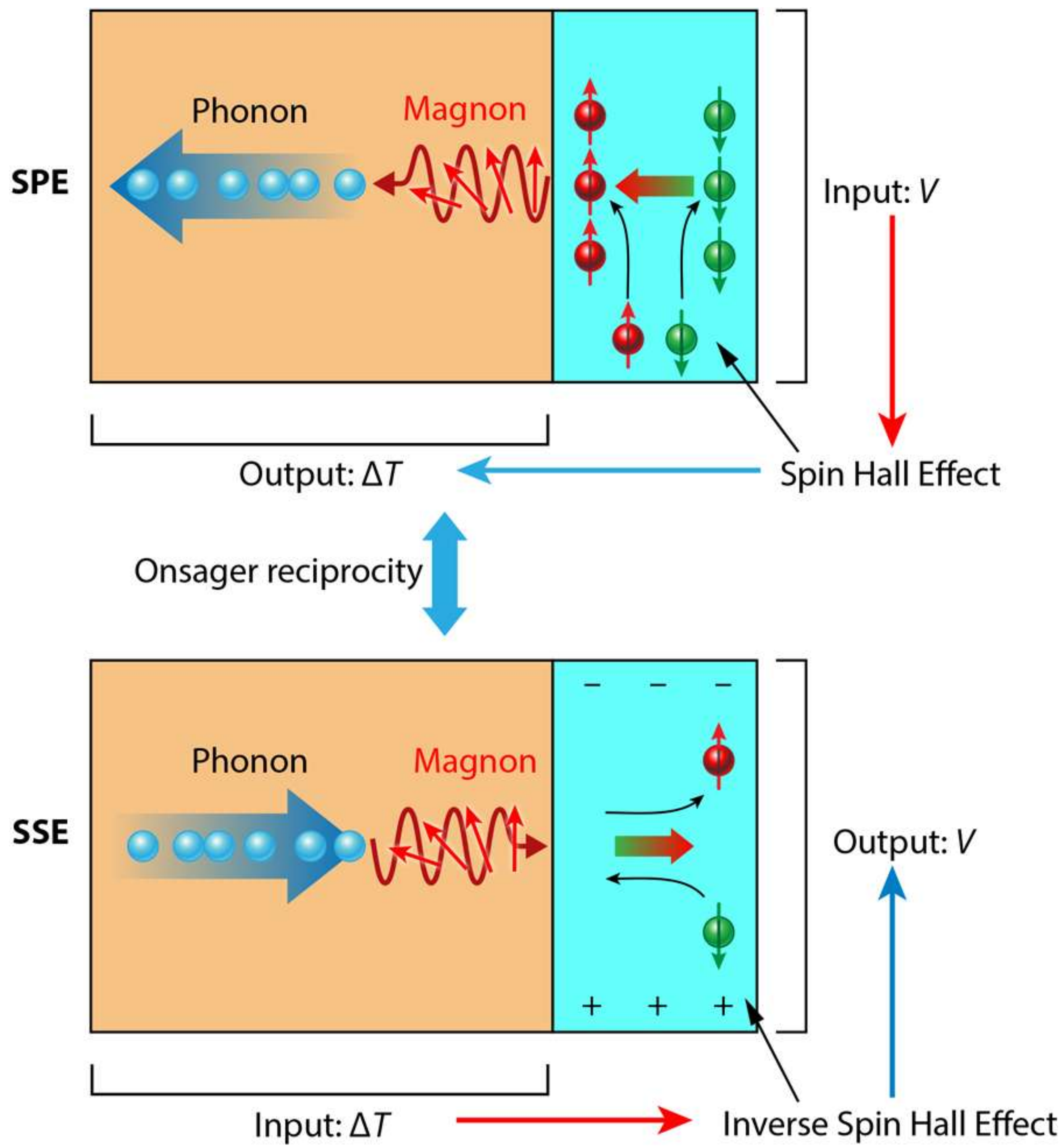
Spin Peltier effect



Spin Peltier effect

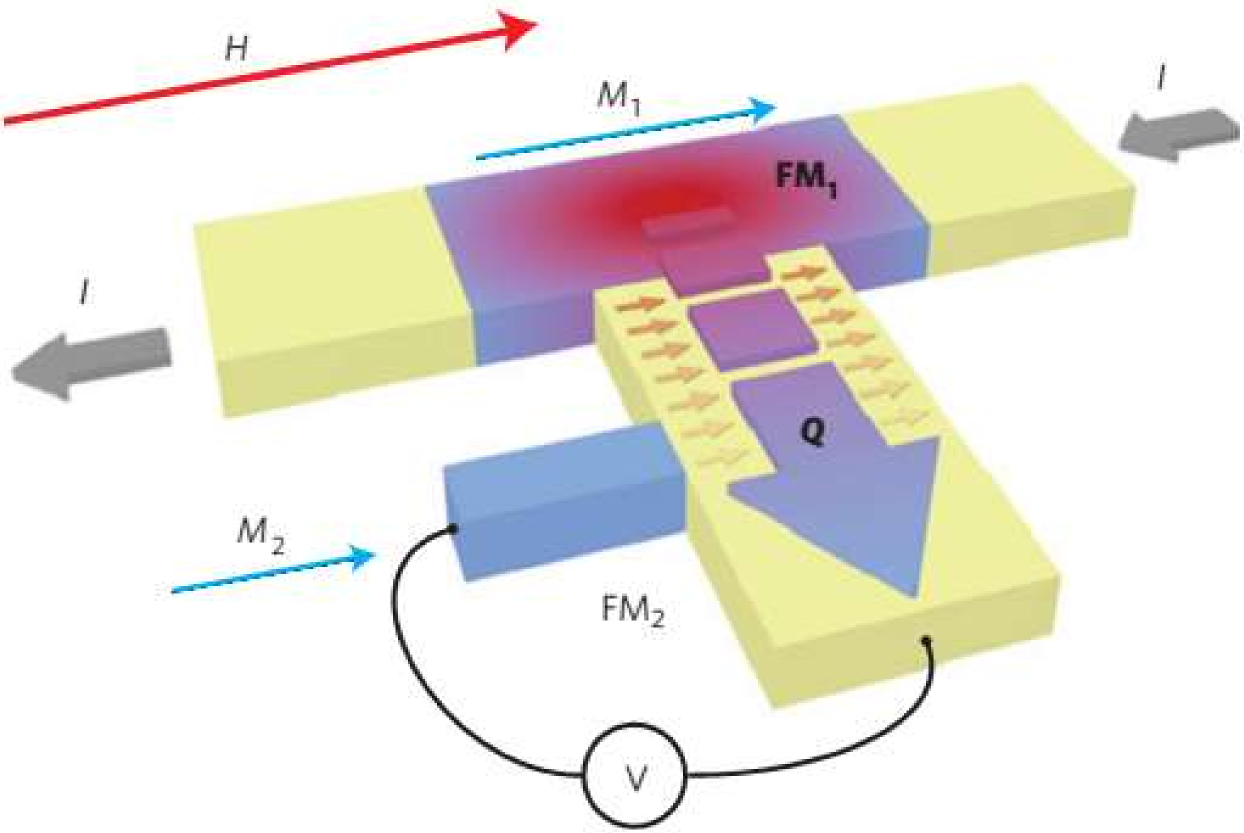


Spin Peltier vs. Spin Seebeck



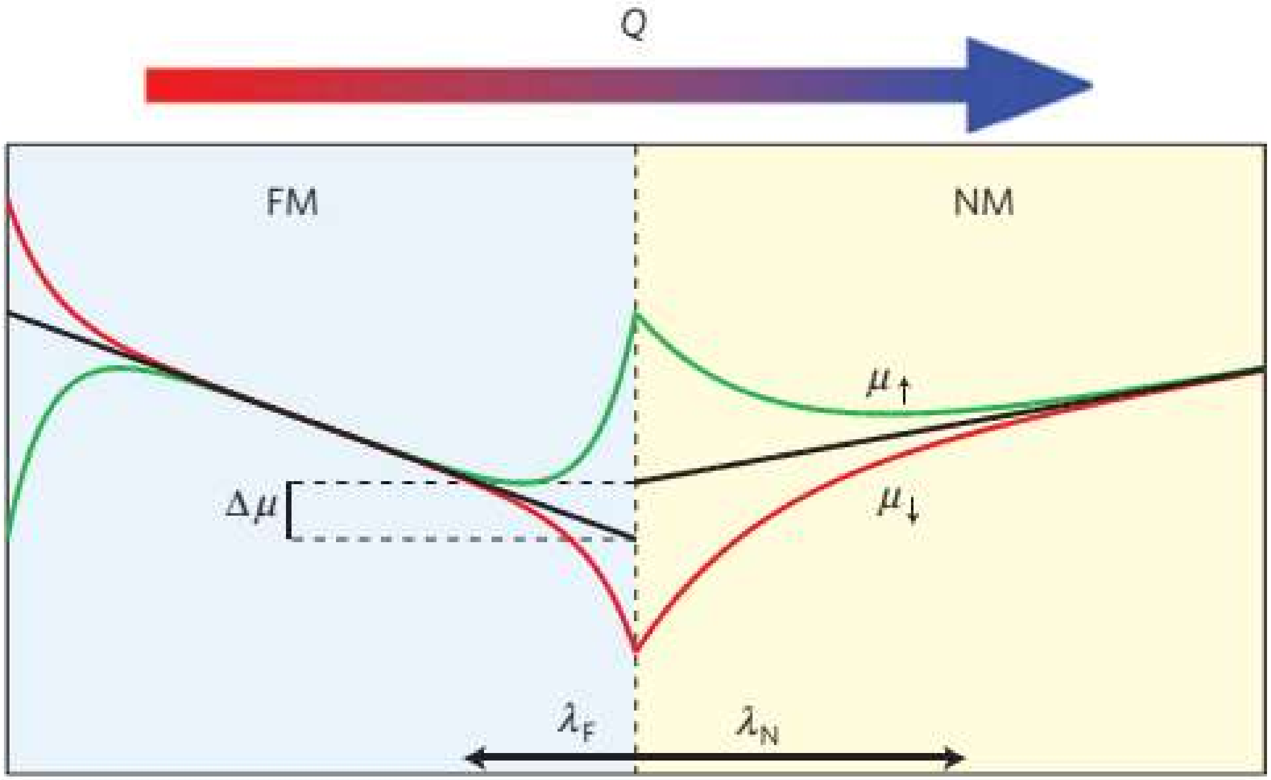
3. Thermal spin injection

Thermal Spin Injection



Slachter, et al, Nature Physics (2010)

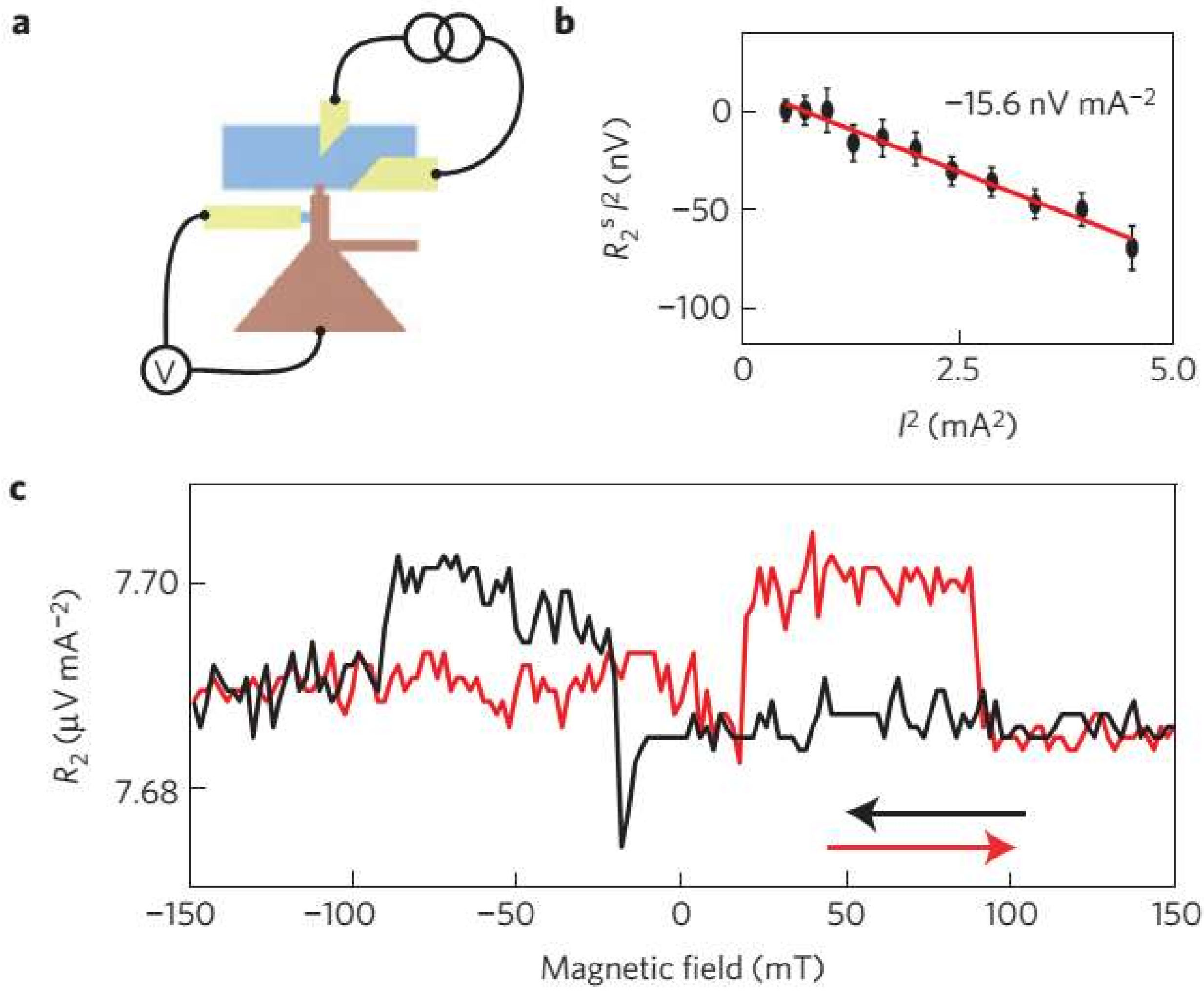
Thermal Spin Injection



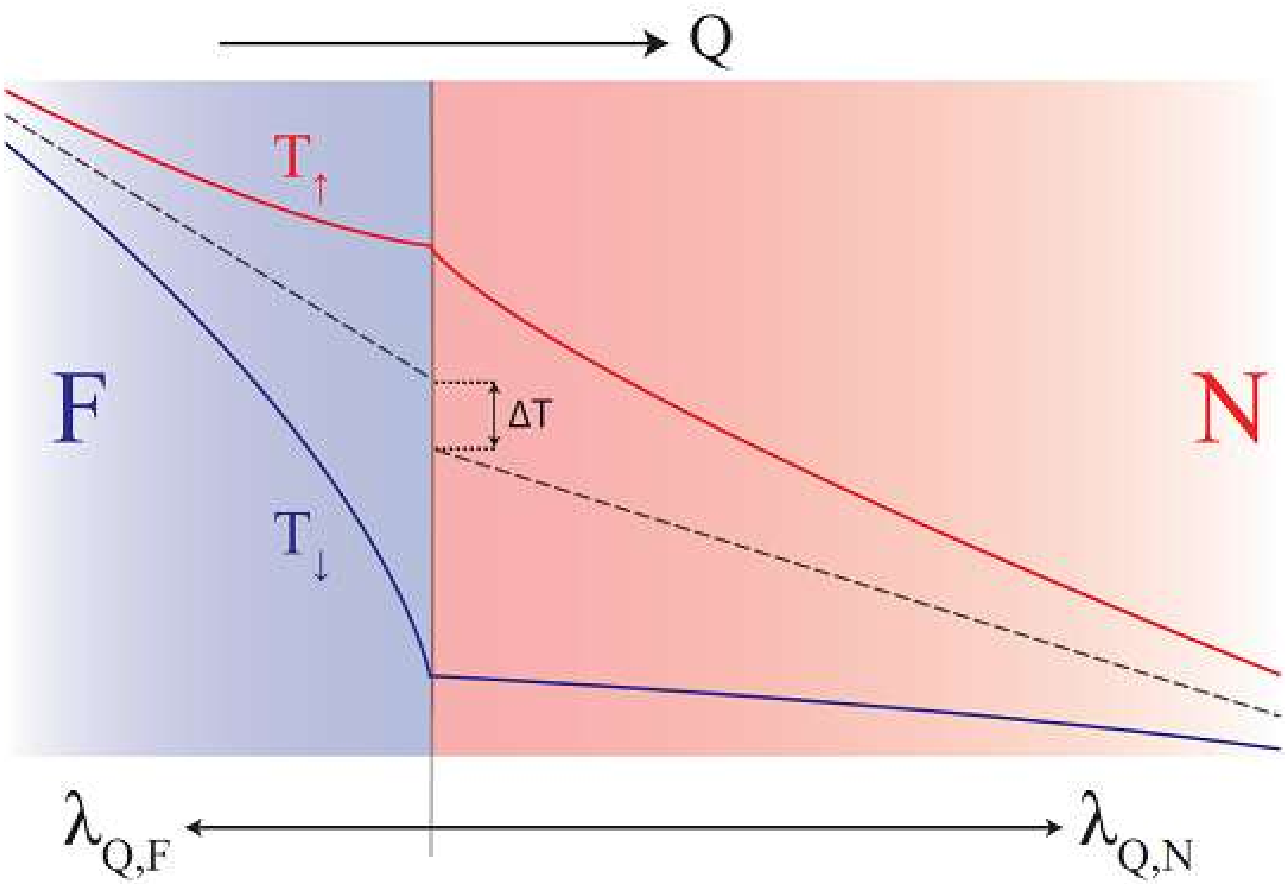
$$\begin{pmatrix} \mathbf{J}_\uparrow \\ \mathbf{J}_\downarrow \\ \mathbf{Q} \end{pmatrix} = -\begin{pmatrix} \sigma_\uparrow & 0 & \sigma_\uparrow S_\uparrow \\ 0 & \sigma_\downarrow & \sigma_\downarrow S_\downarrow \\ \sigma_\uparrow \Pi_\uparrow & \sigma_\downarrow \Pi_\downarrow & k \end{pmatrix} \cdot \begin{pmatrix} \nabla \mu_\uparrow / e \\ \nabla \mu_\downarrow / e \\ \nabla T \end{pmatrix}$$

Thermal Spin Injection

Metal

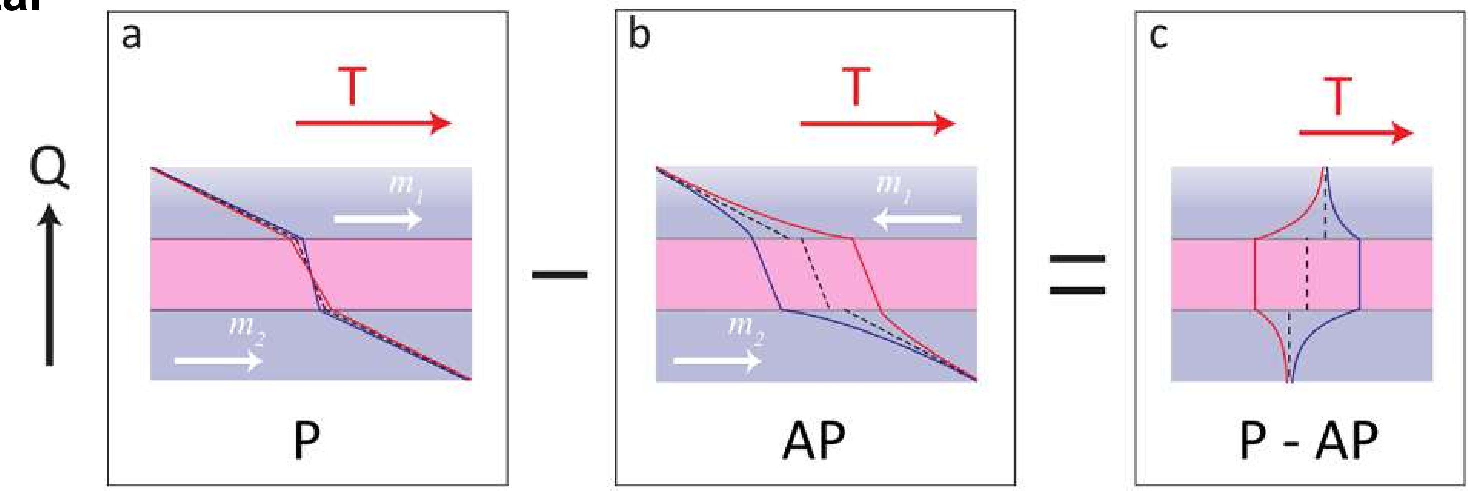


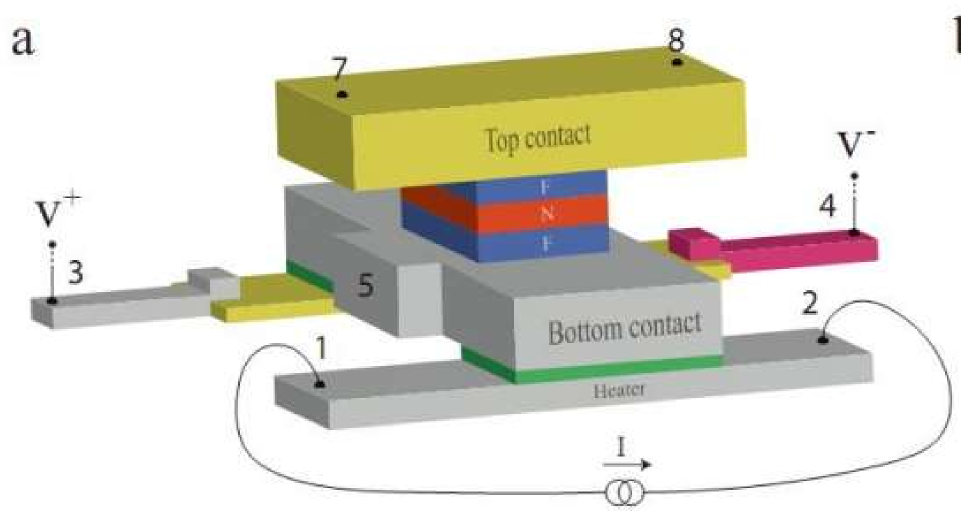
Thermal Spin Injection



Thermal Spin Injection

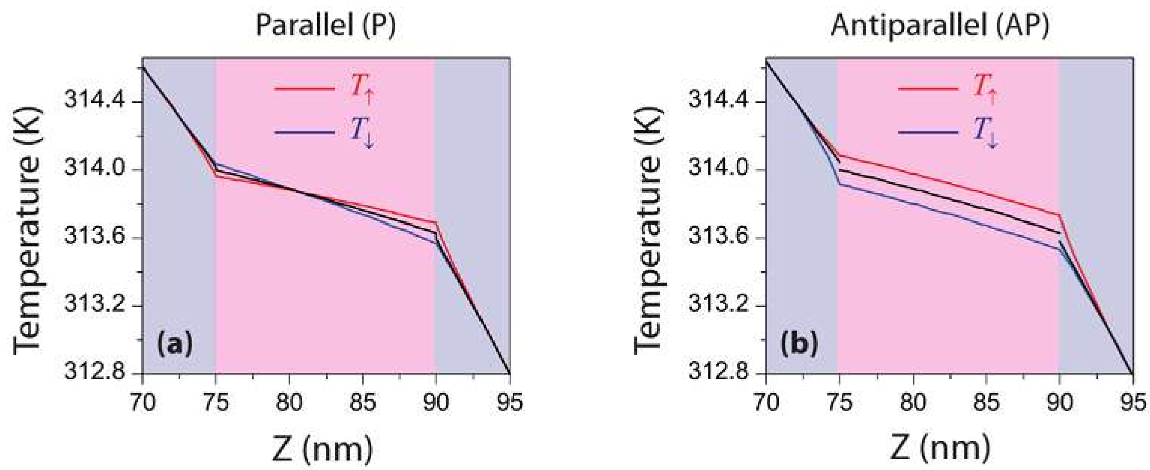
Metal

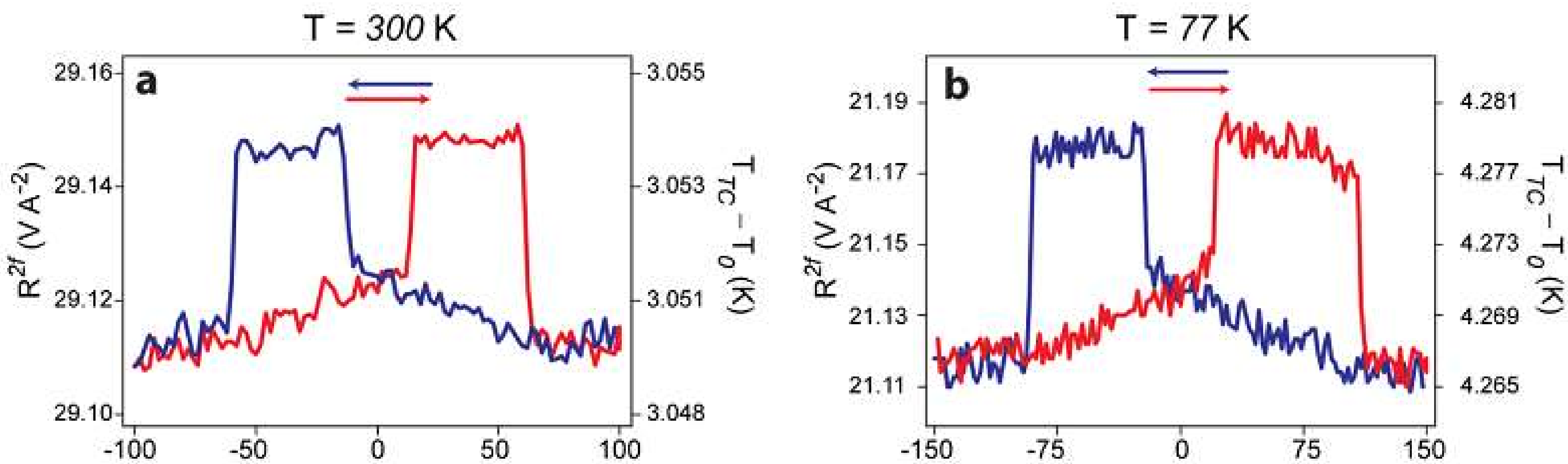




Thermal Spin Injection

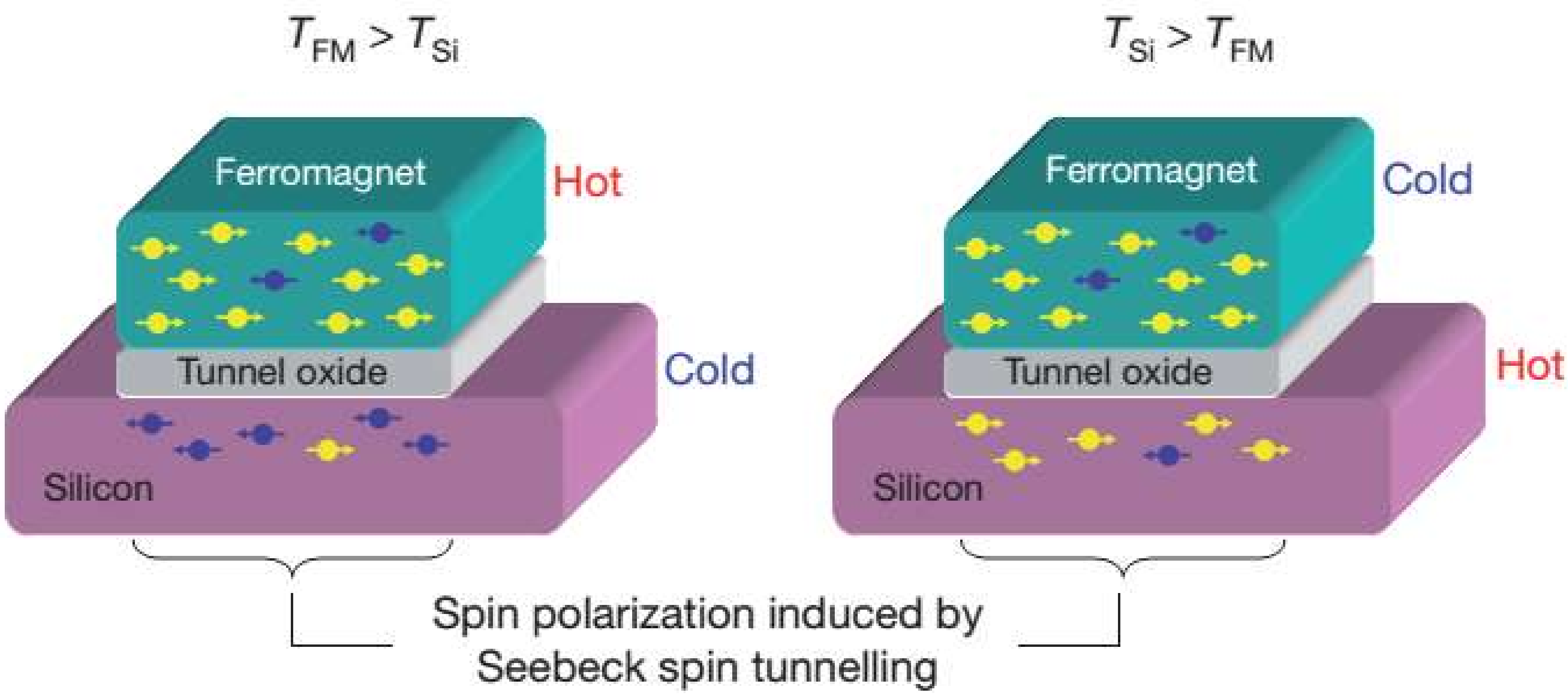
Metal





Thermal Spin Injection

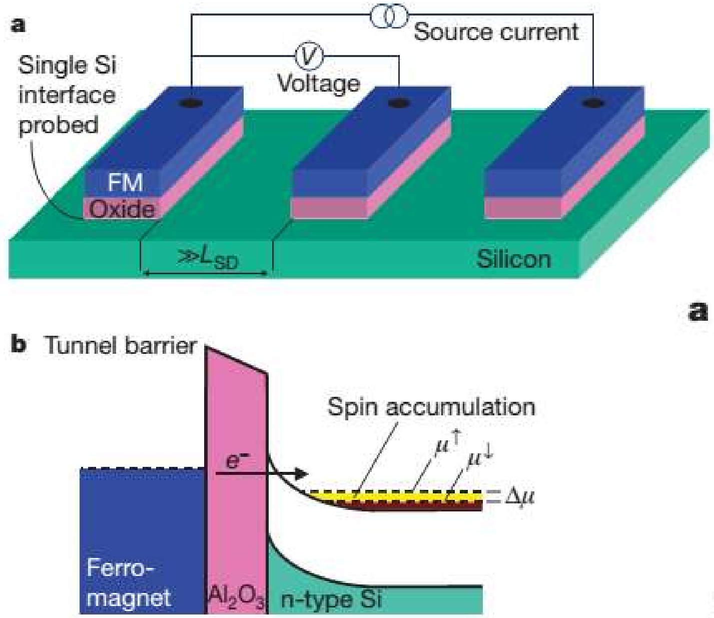
Semiconductor

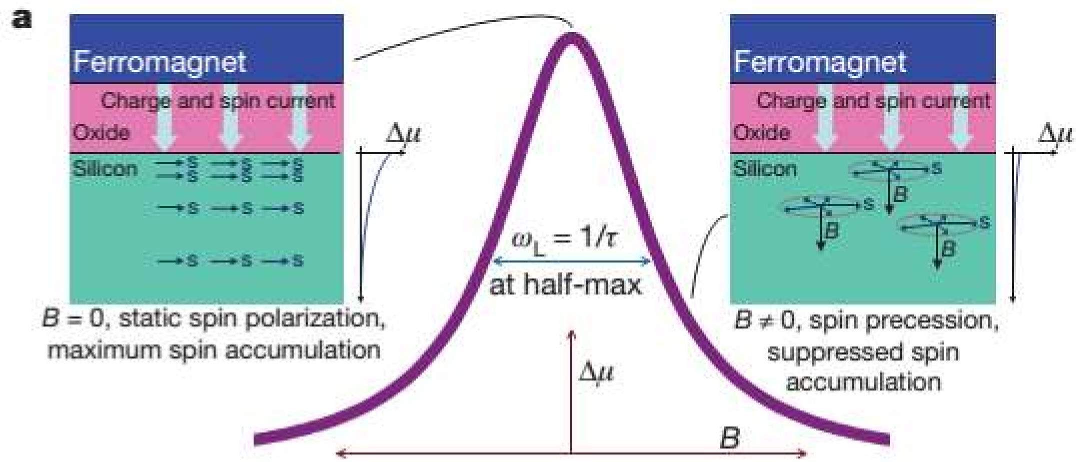


Breton, et al, Nature (2011)

Thermal Spin Injection

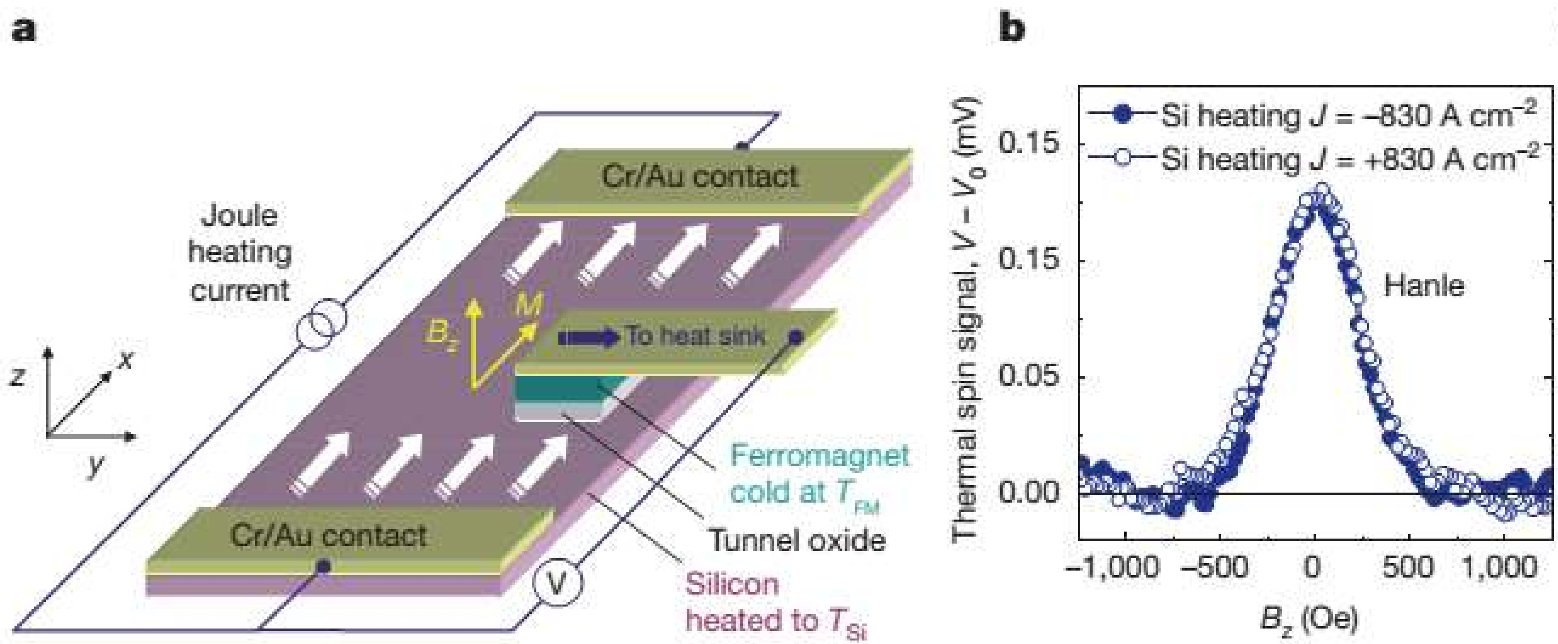
Electrical spin injection





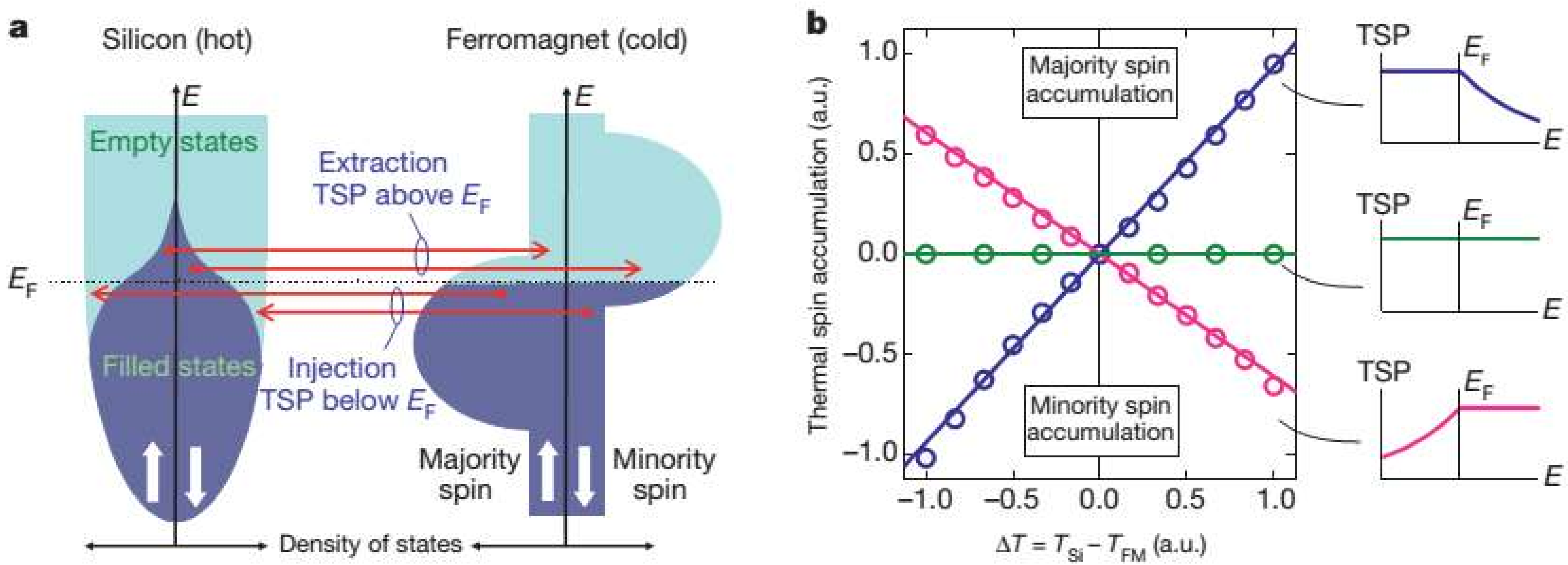
Dash, et al, Nature (2009)

Thermal Spin Injection

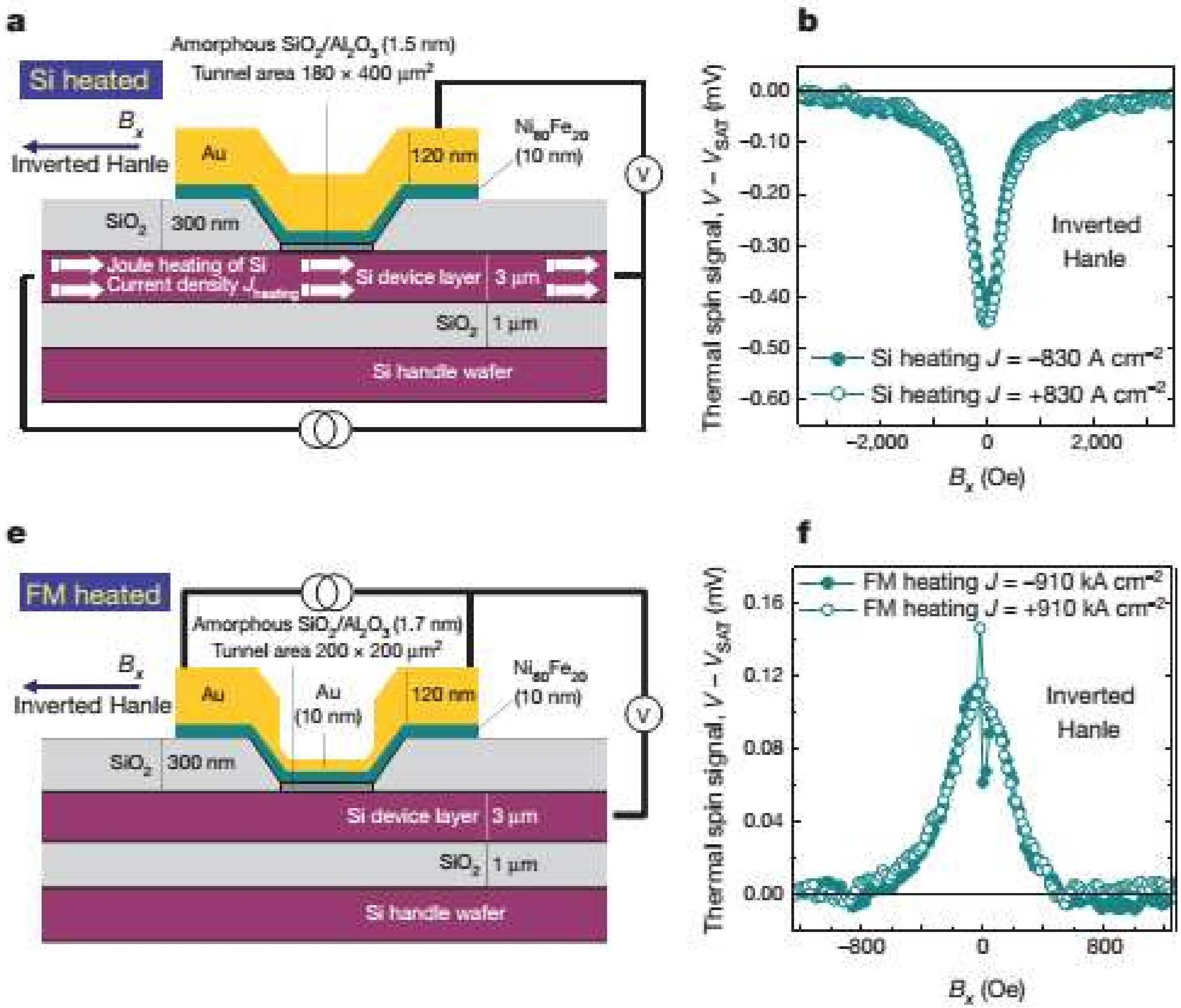


Breton, et al, Nature (2011)

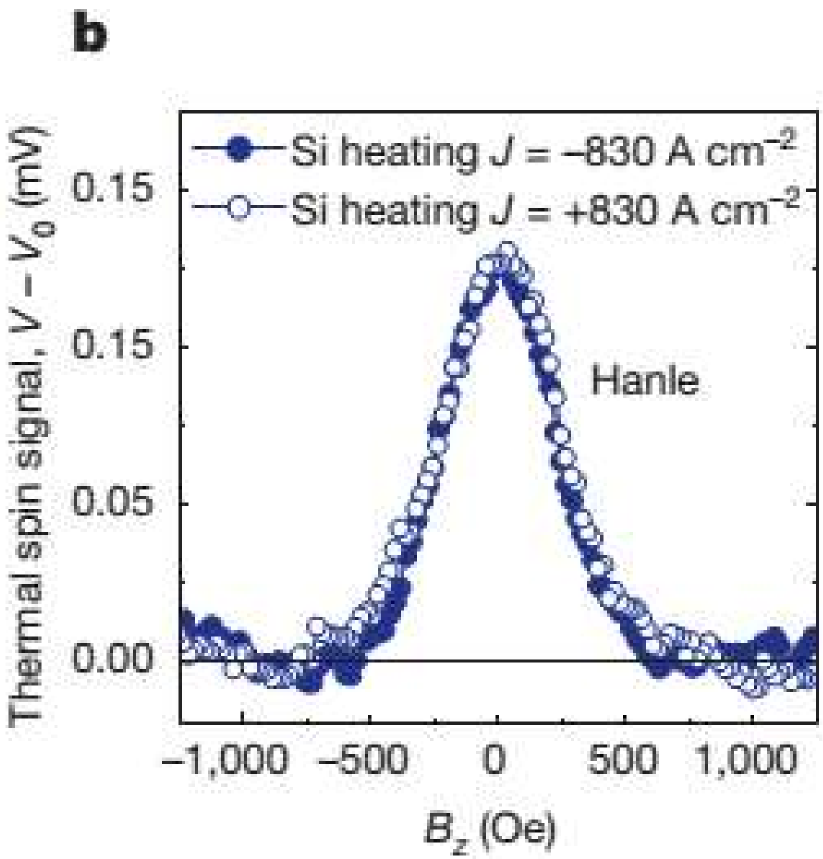
Thermal Spin Injection

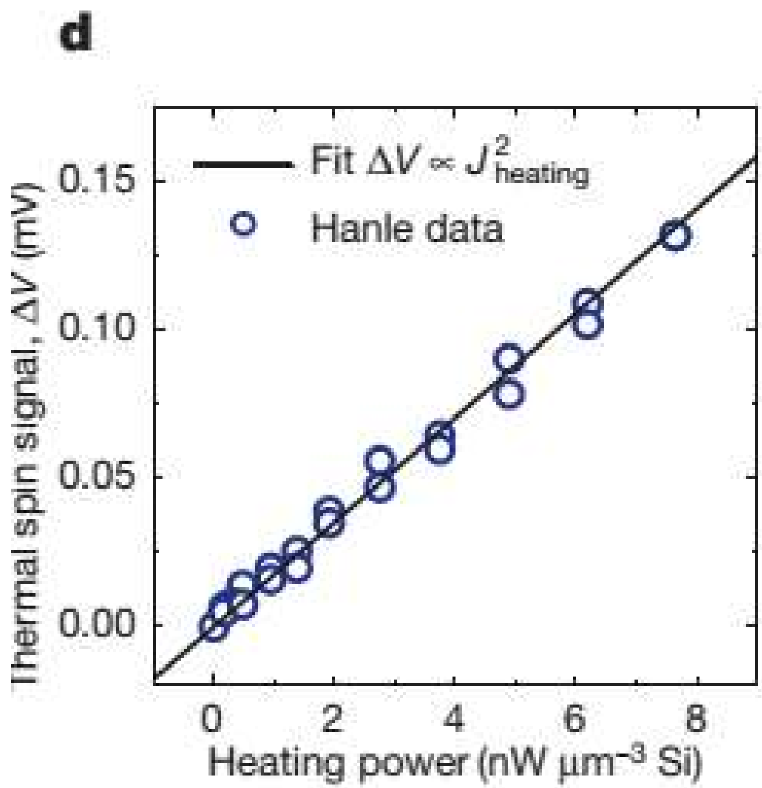


Thermal Spin Injection

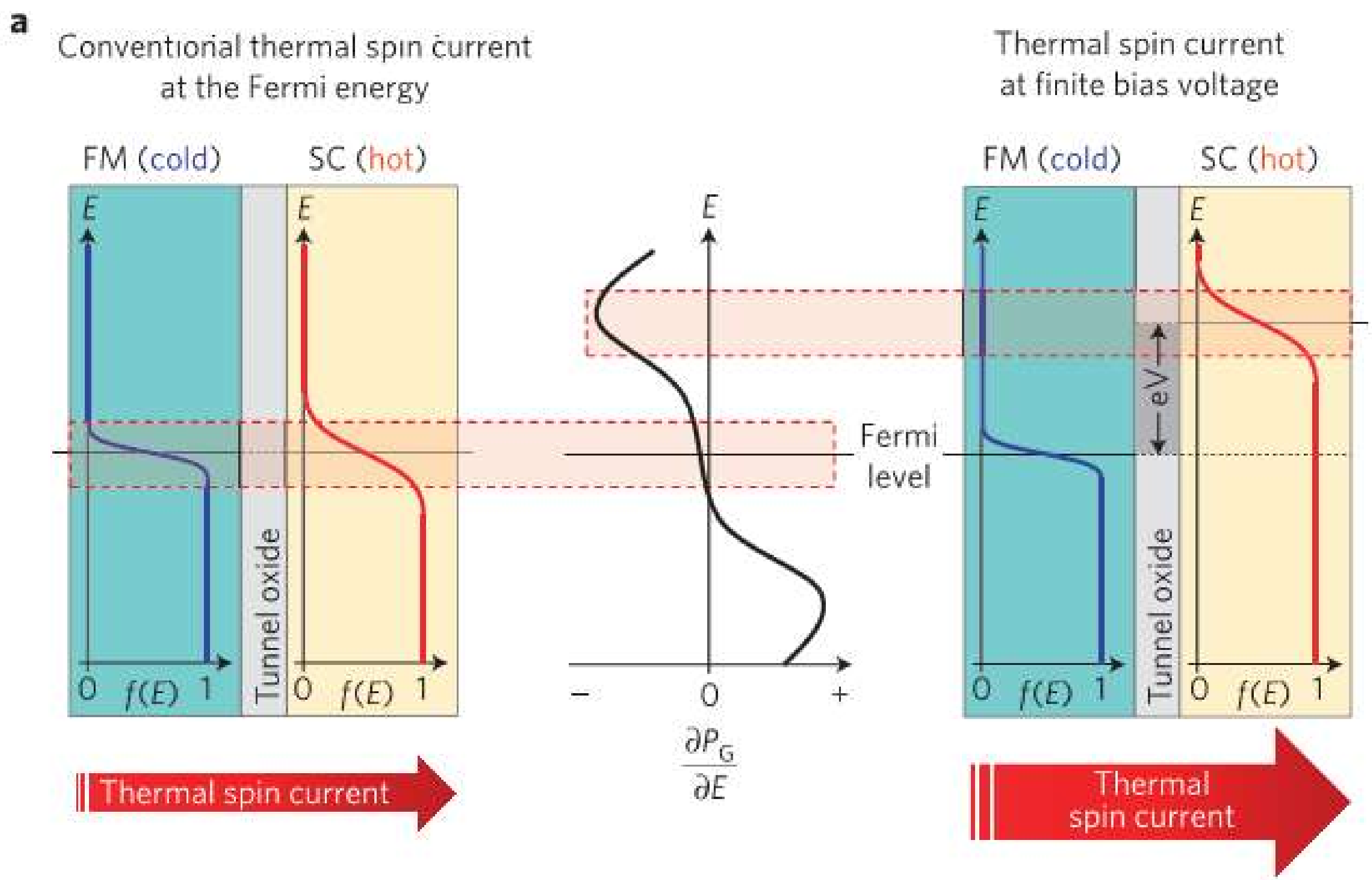


Thermal Spin Injection



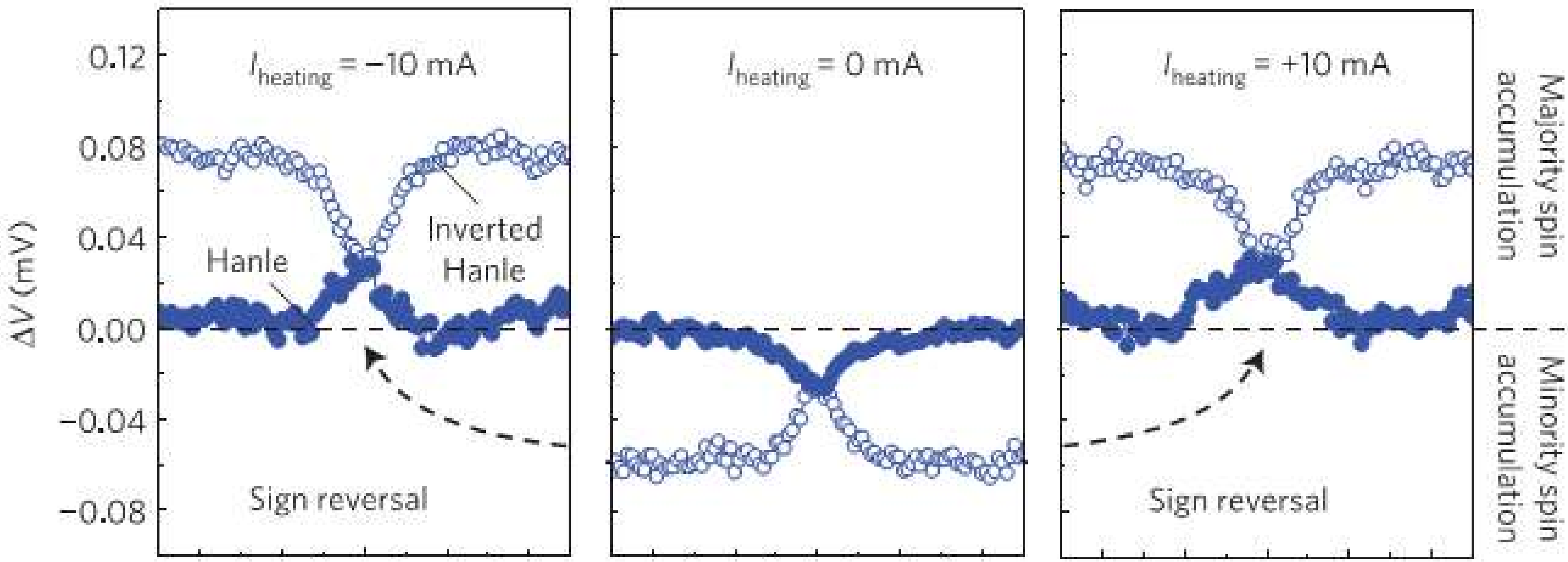


Thermal Spin Injection

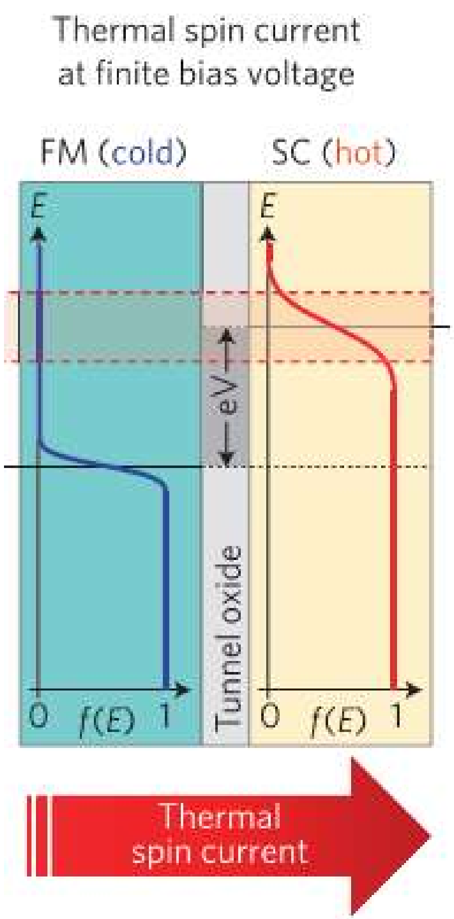


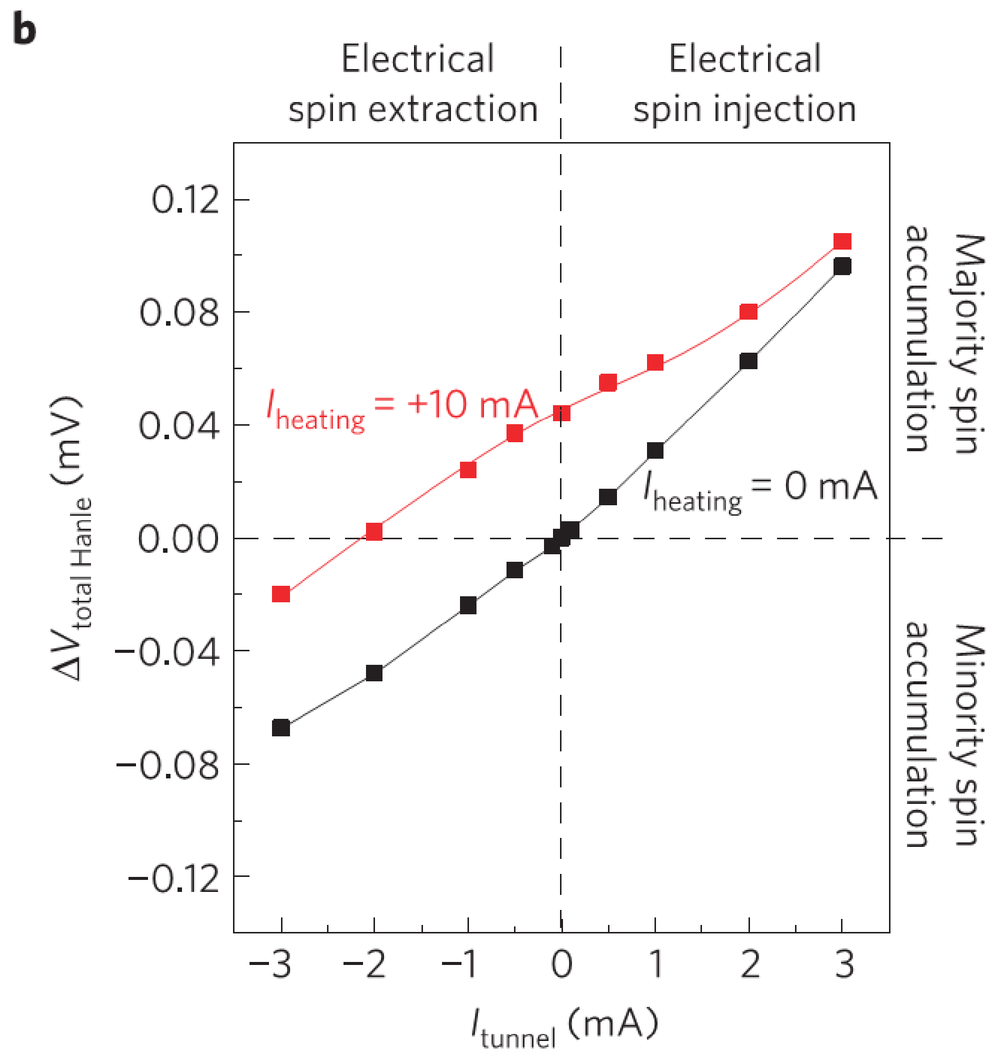
Jeon, et al, Nature Materials (2013)

Thermal Spin Injection



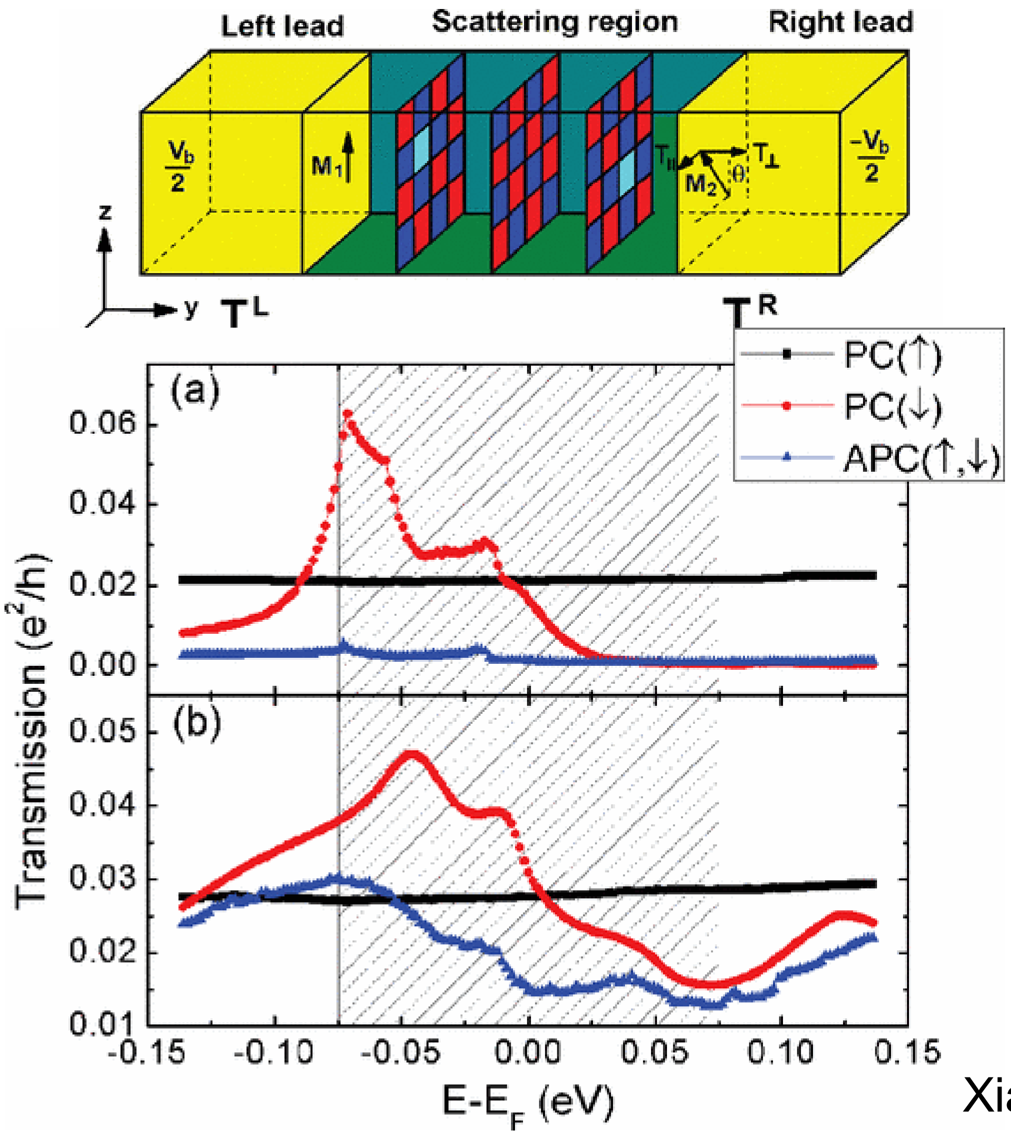
Thermal Spin Injection





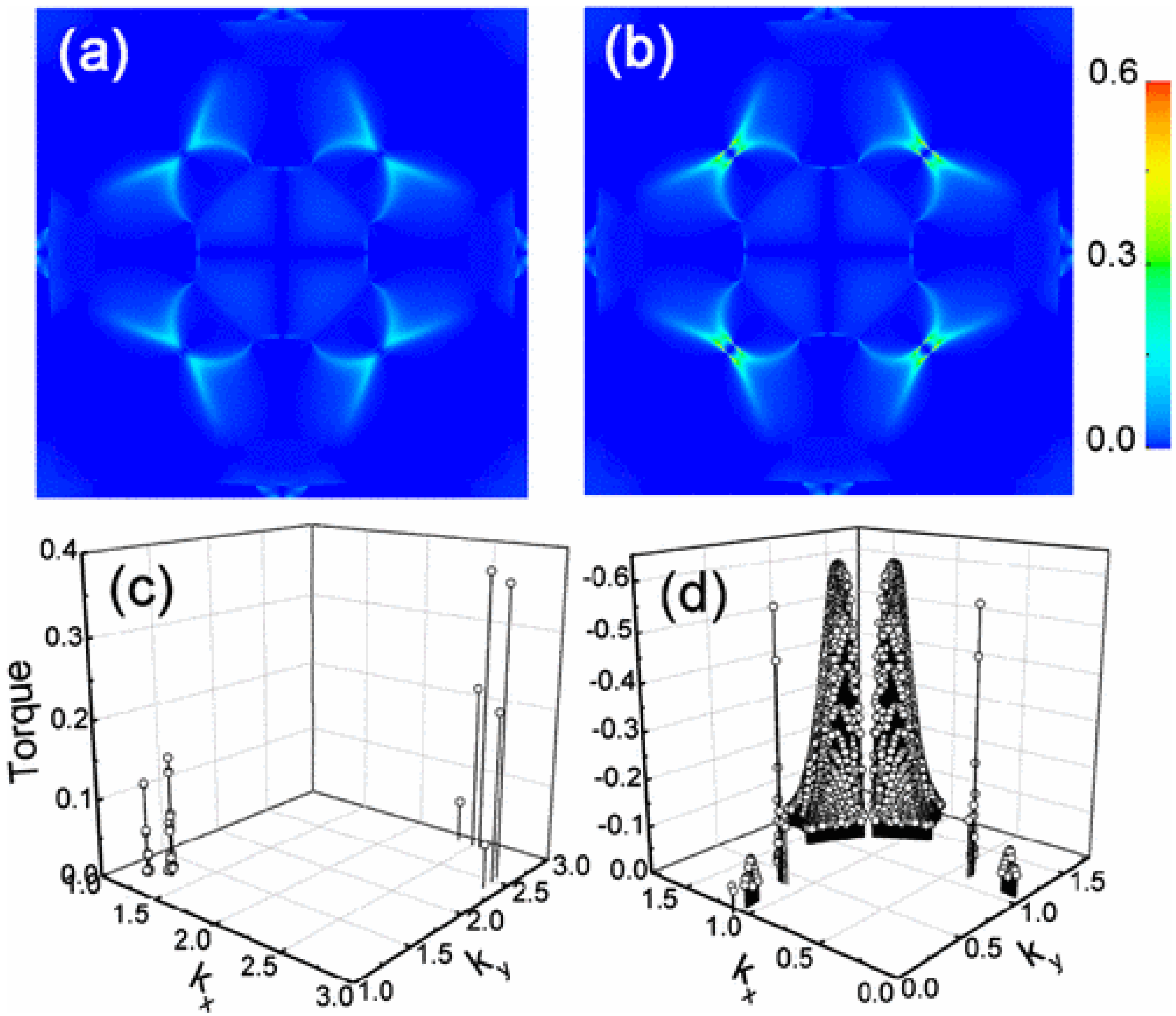
4. Thermal spin torque

Thermal Spin torque

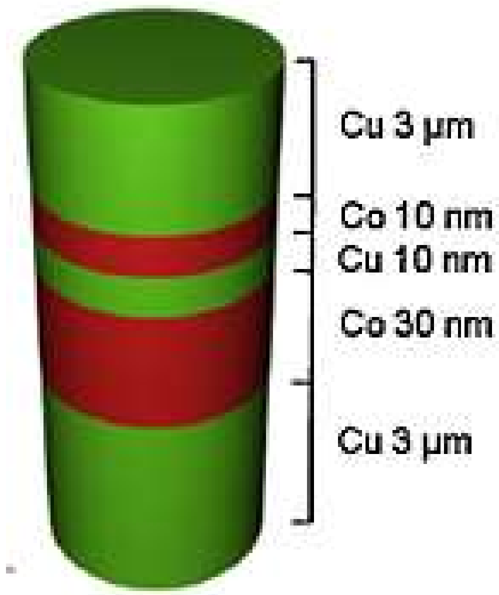


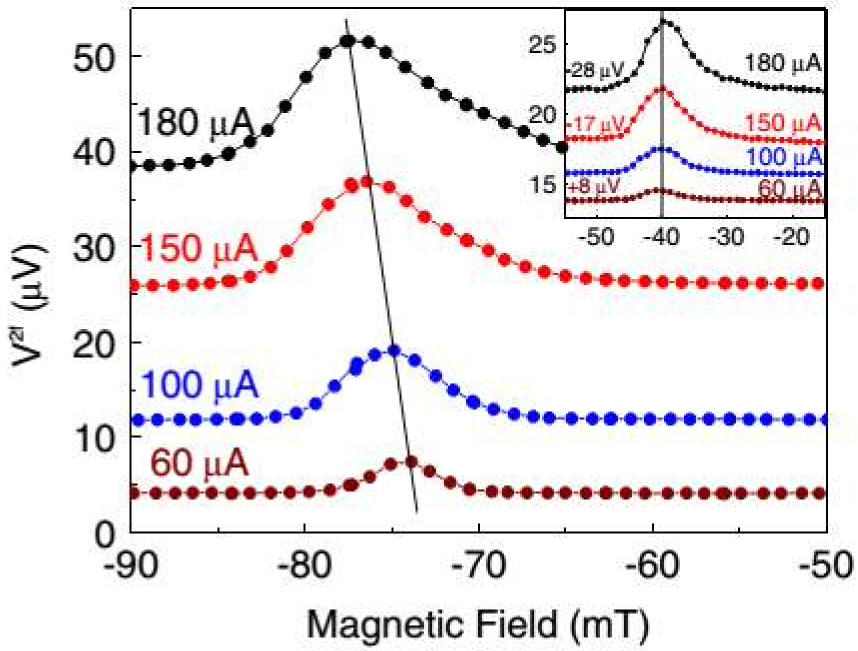
Xia, et al, PRL (2011)

Thermal Spin torque



Thermal Spin torque

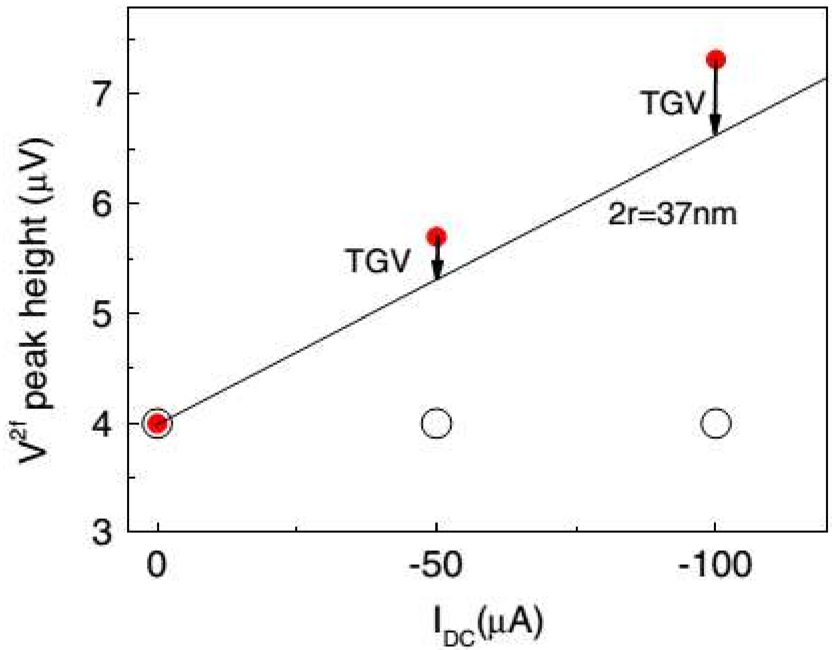


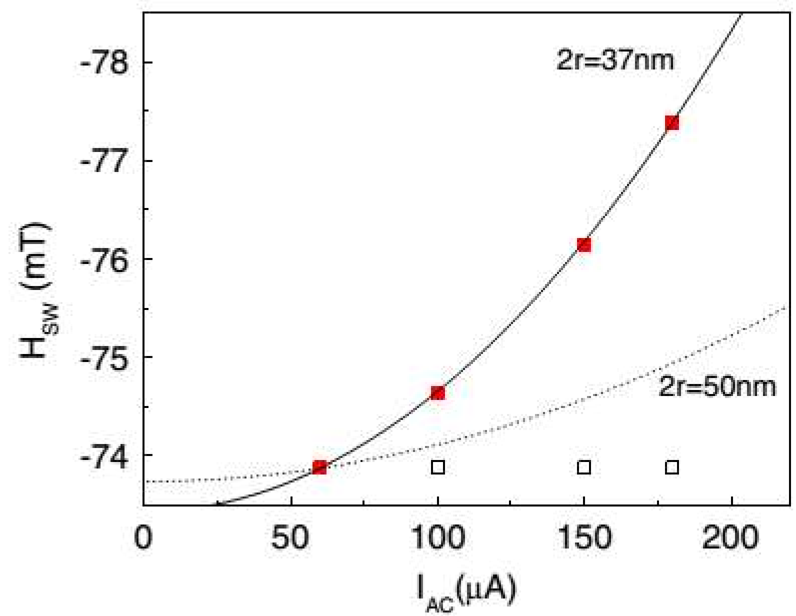


Yu, et al, PRL (2010)

Thermal Spin torque

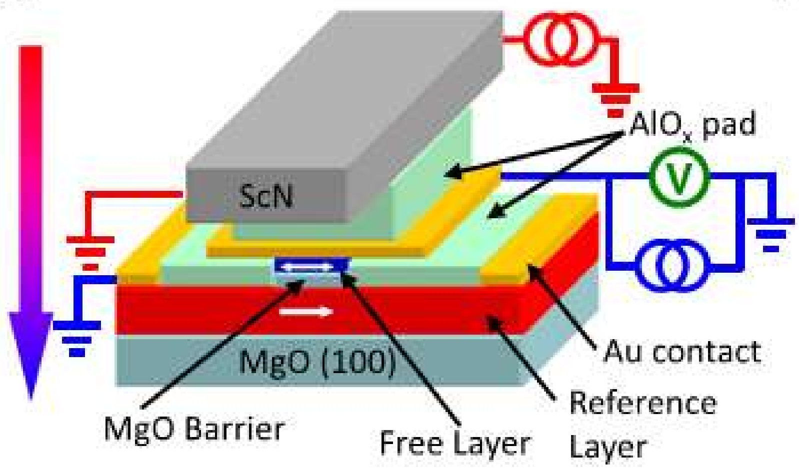
$$\tau \propto P\Delta V + P' S \Delta T,$$



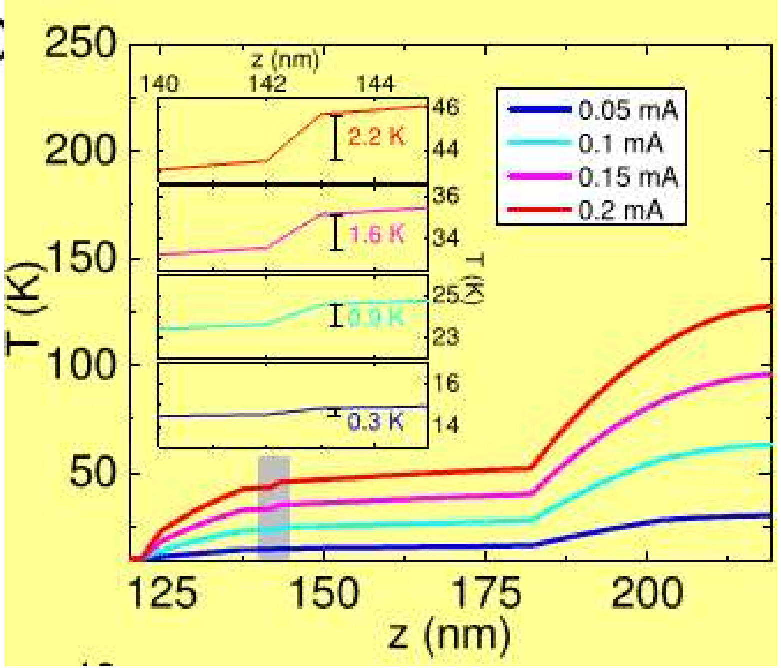


Thermal Spin torque

B

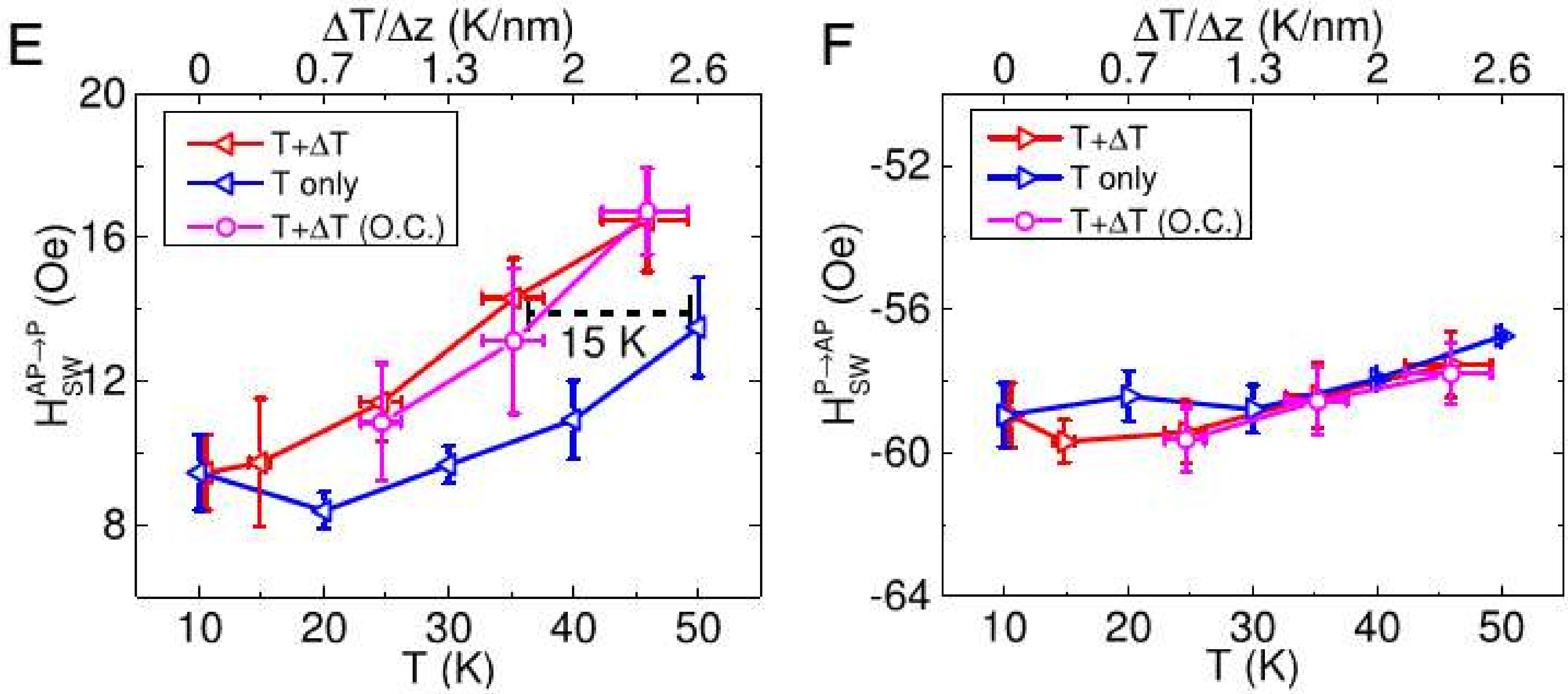


D



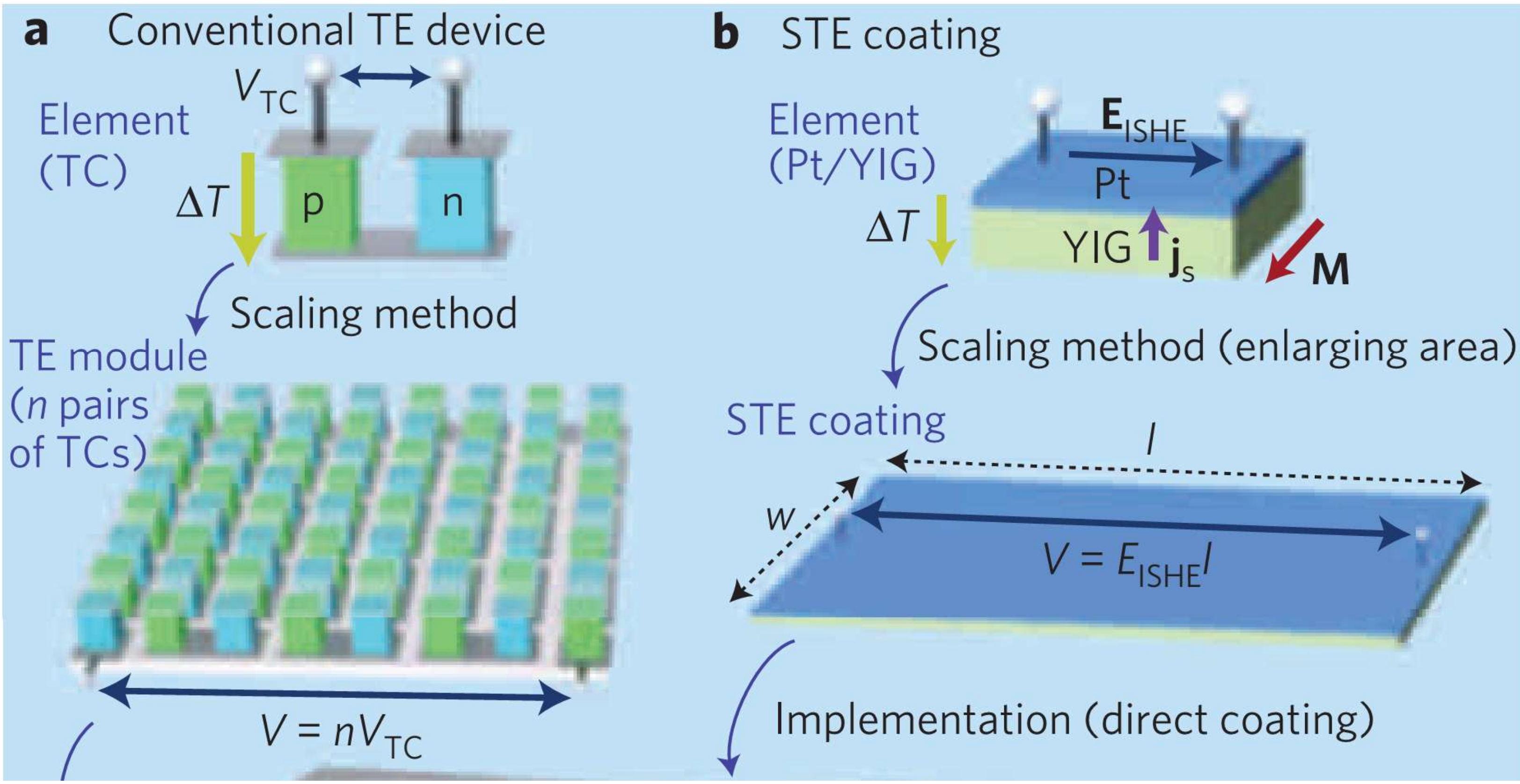
Pushup, et al, PNAS (2015)

Thermal Spin torque



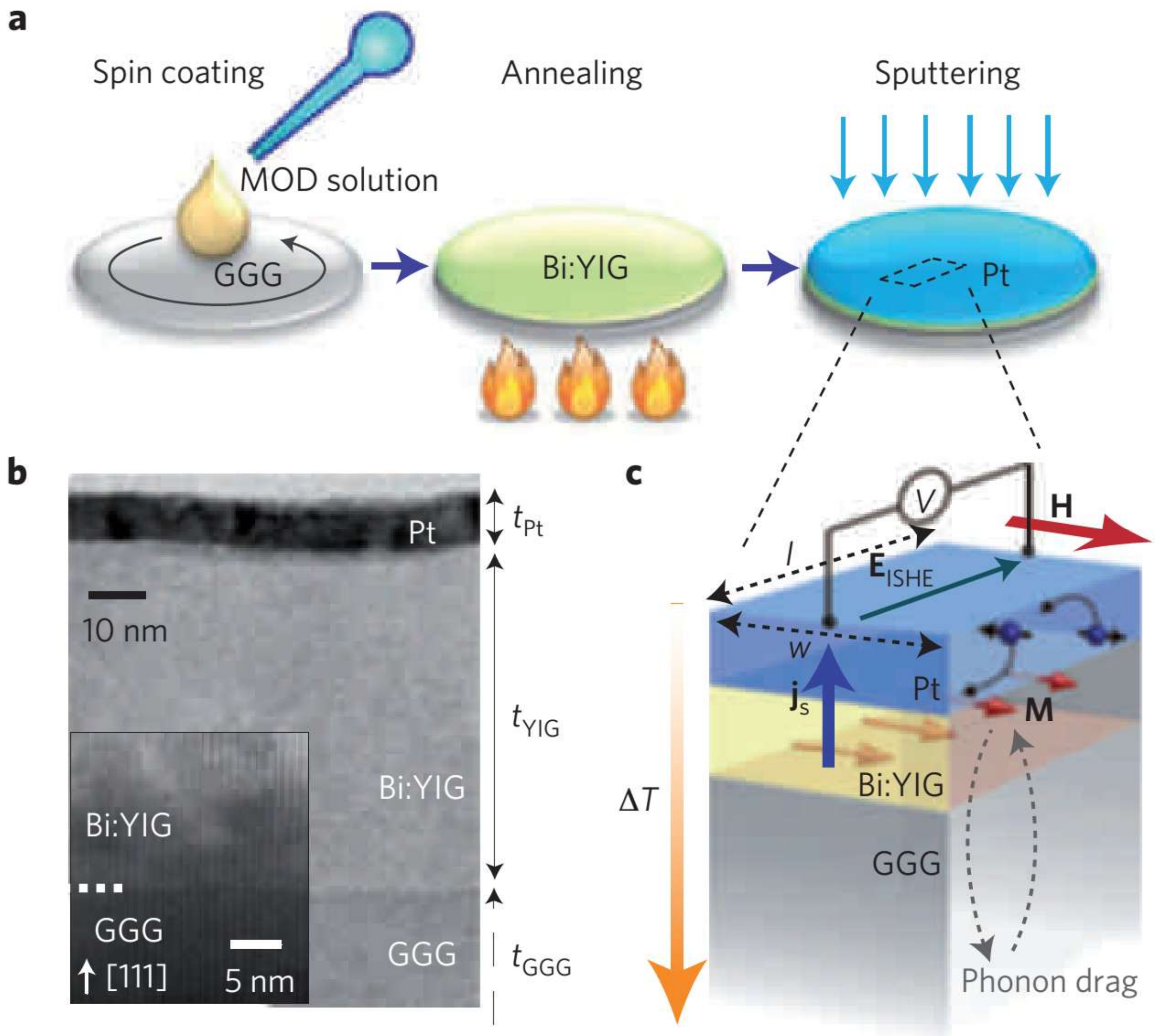
5. Spin energy

Spin Energy



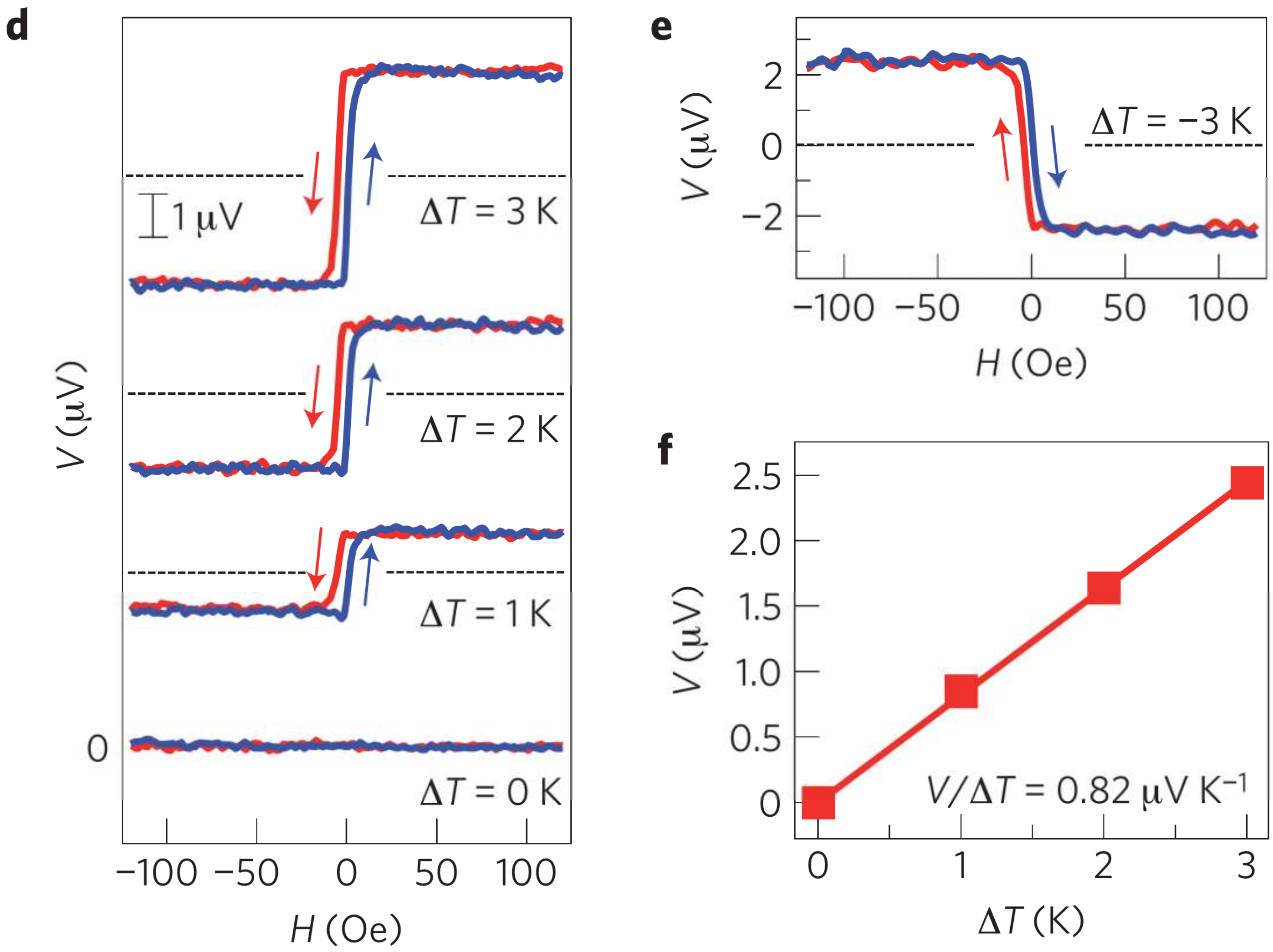
Kirihara, et al, Nature Materials (2012)

Spin Energy

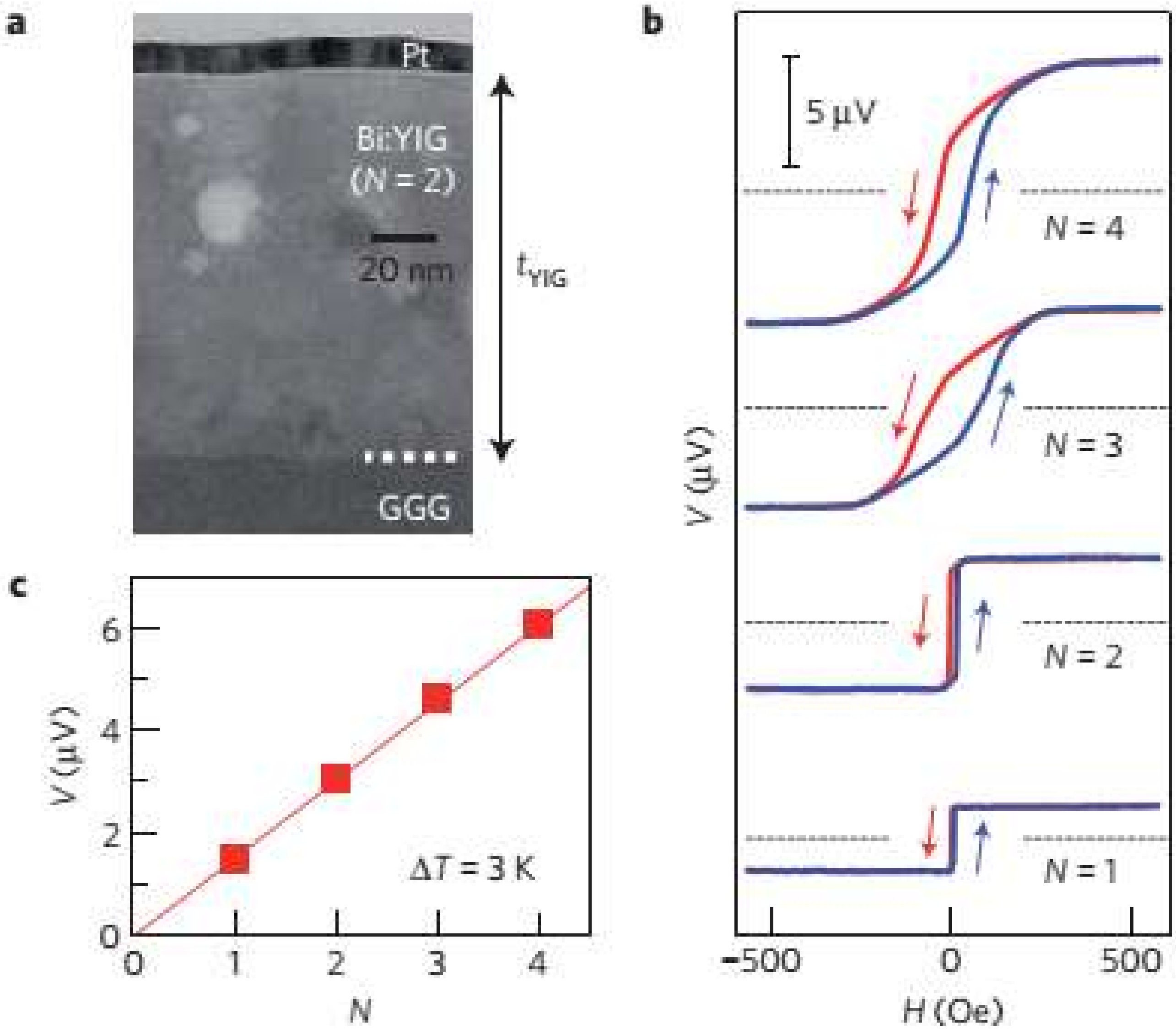


a
Spin coating
MOD solution
GGG
Annealing
Bi:YIG
Sputtering
Pt
b
Pt
10 nm
Bi:YIG
GGG
[111]
5 nm
Bi:YIG
GGG
t_{Pt}
t_{YIG}
t_{GGG}
c
V
H
l
E_{ISHE}
w
j_s
Pt
M
Bi:YIG
GGG
ΔT
Phonon drag

Spin Energy


d
1 μV
ΔT = 3 K
ΔT = 2 K
ΔT = 1 K
ΔT = 0 K
0
V (μV)
−100 −50 0 50 100
H (Oe)
e
2
0
−2
V (μV)
ΔT = −3 K
−100 −50 0 50 100
H (Oe)
f
2.5
2.0
1.5
1.0
0.5
0
V (μV)
V/ΔT = 0.82 μV K−1
0 1 2 3
ΔT (K)

Spin Energy



a
Pt
Bi:YIG
(N = 2)
20 nm
t_{YIG}
GGG
b
5 µV
N = 4
N = 3
N = 2
N = 1
V (µV)
−500
0
500
H (Oe)
c
ΔT = 3 K
V (µV)
0
2
4
6
0
1
2
3
4
N

Summary

1. Seebeck and Peltier effect

2. Spin Seebeck effect

3. Spin Peltier effect

4. Thermal spin injection

5. Thermal spin torque

6. Spin energy

下一节课: Dec. 07th

Chapter 7: Topological Spintronics

课件下载：
http://www.phy.pku.edu.cn/~LabSpin/teaching.html