Charge, Spin, and Heat Transport in the Proximity of Metal/Ferromagnet Interface

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Outline

- Introduction
- 1G and 2G Spintronic devices
- Spin current
- Spin Hall effect
- Spin Seebeck Effect (SSE)
  - Entangled with anomalous Nernst effect (ANE)
  - Intrinsic spin-dependent thermal transport
  - Entangled with magnetic proximity effect (MPE)
  - Intrinsic Spin Seebeck effect
- New MR by MPE (or Spin Hall MR)
- Summary

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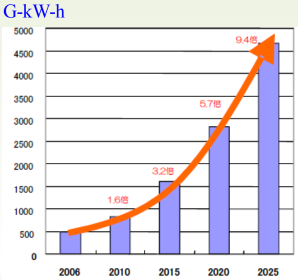
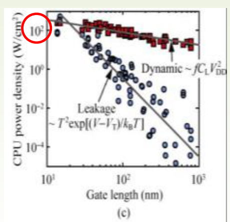
Power Consumption of Information Technology





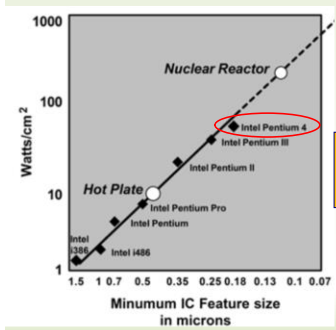
Refreshing in "off" state

5% 20% of total electrical power

Monumental problem

METI / Green IT Promotion Council (2008)
E. Pop, Nano Res 3, 147 (2010)

3



1. High efficiency devices
2. Reduction of heat dissipation

IC Power density approaches that of nuclear reactor

Can *spin* provide a solution ?

S. Borkar, Intel

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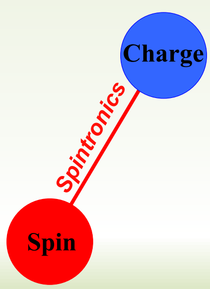
In the beginning, there was only electronics……..

Electronics



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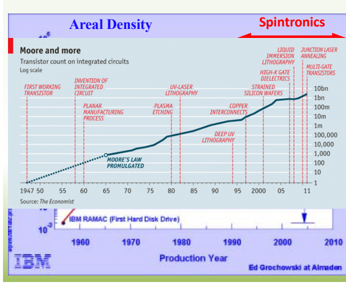
Three important discoveries in Spintronics

Giant Magnetoresistance (GMR) (1988*)
Tunnel Magnetoresistance (TMR) (1995)
Spin Transfer Torque (STT) (1996, 2000)

*2007 Nobel

Grünberg/Fert

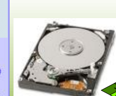


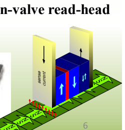
10^{+12} bits/in²

10^{+9} increase in density

10^{-8} reduction in cost

Spin-valve read-head





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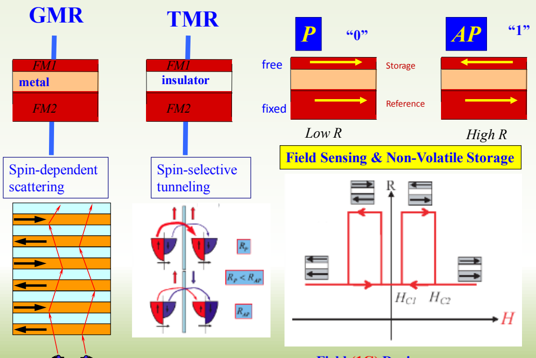
Spintronic GMR and TMR Devices



Field (1G) Devices

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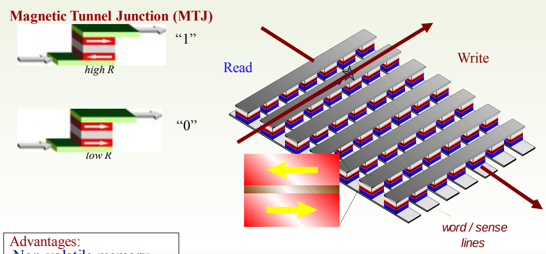
Non-Volatile Storage: Magnetic Random Access Memory (MRAM)



Advantages:
Non-volatile memory
Short access time
Low power consumption

Key Challenges: High density
Eliminate field writing

Universal memory: speed as SRAM, density as DRAM, rewritability as flash

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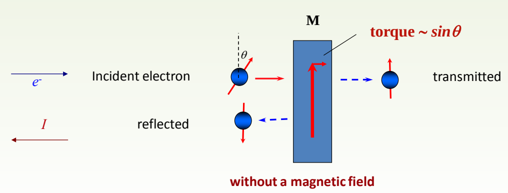
Spin transfer torque

electrical current affects magnetic configurations



Large **M**: spin polarizer
Small **M**: **M** can be *rotated*

Slonczewski, JMMM **159**, L1 (1996)
Berger, PR B **54**, 9353 (1996), JAP **57**, 1266 (1984), JAP **49**, 2156 (1978)
Waintal *et al.*, PRB **62**, 12317 (2000)

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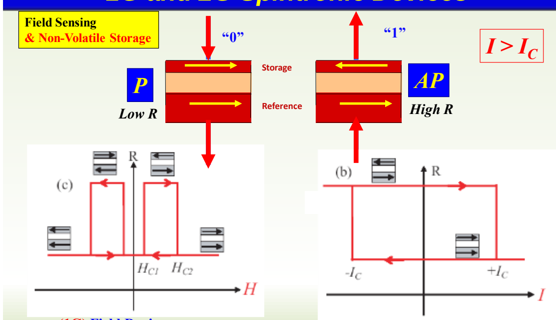
1G and 2G Spintronic Devices



(1G) Field Devices

(2G) Current (STT)Devices

Requires very large $j_c > 10^6$ A/cm² !!
What are new Spintronic Effects for 3G devices?

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Various Hall effects

Ordinary Hall effect (E. H. Hall, 1879)

Anomalous Hall effect (E. H. Hall, 1880)

Integer quantum Hall effect (von Klitzing, Nobel 1985)

Fractional quantum Hall effect (Stormer, Tsui, Laughlin, Nobel 1998)

Spin Hall effect

Inverse spin Hall effect

Magnon Hall effect

Topological Hall effect

maybe more…

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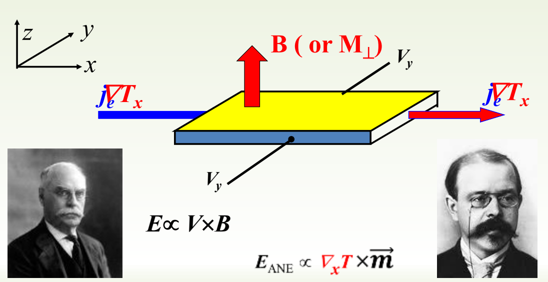
Charge, Spin, Thermal Transport in thin films



Edwin Hall (1879, 1880)
A student of Henry Rowland @ JHU

Walther Nernst

∇V_x **: Hall Effect**

∇T_x **: Nernst Effect**

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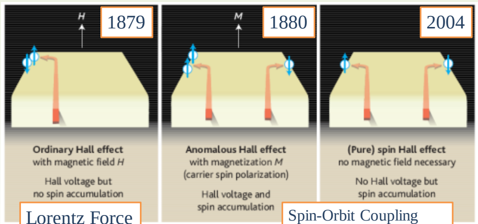
Hall effect *Anomalous Hall effect* *Spin Hall effect*



Only Charge	Charge + Spin	Only Spin
Detect by voltage	Detect by voltage	Why? Detect by what ?
$F=q\,(E+V\times B)$	AHE can be either sign	SHE can be either sign
Definite Sign $q(v\times B)$	Definite Axis but Not Definite Sign	

(Nagaosa *et al.*,)

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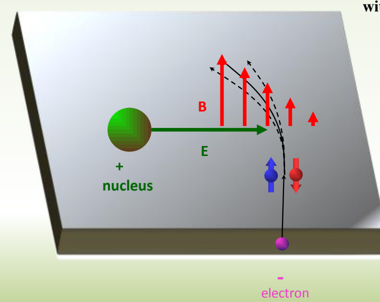
The mechanism of SHE

Spin-Orbit Coupling

Electron frame "sees" $B_\perp$ field with gradient



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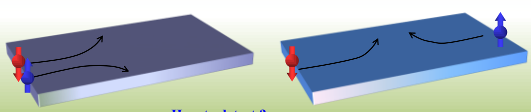
Direct Spin Hall vs. Inverse Spin Hall effects

ISHE in **Pt** detects pure spin current

Direct Spin Hall	Inverse Spin Hall
Charge Current	Spin Current
⇓ Spin Dependent Scattering	⇓
Transverse Spin Imbalance (measured by what ?)	Transverse Charge Imbalance (measured by side voltage)



How to detect ?

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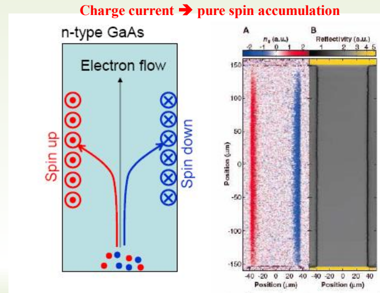
(Optical) *Observation of Spin Hall effect*

Charge current ➔ pure spin accumulation



Optical observation SHE in semiconductors

Kato et. al. Science 306, 1910 (2004)

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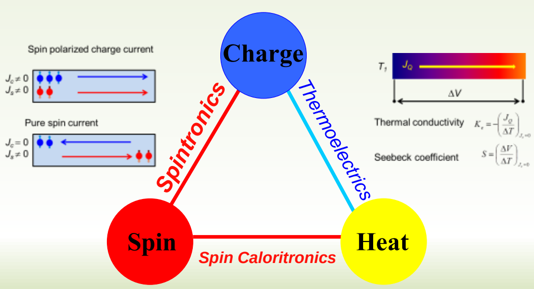
Spin Calortronics

Electronics



Spin Seebeck effect

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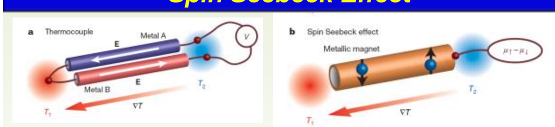
Spin Seebeck Effect

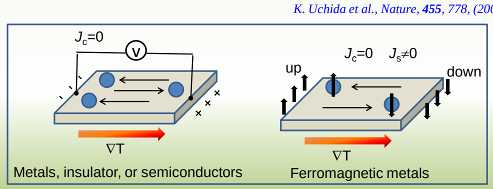


$\delta V = S\delta T$

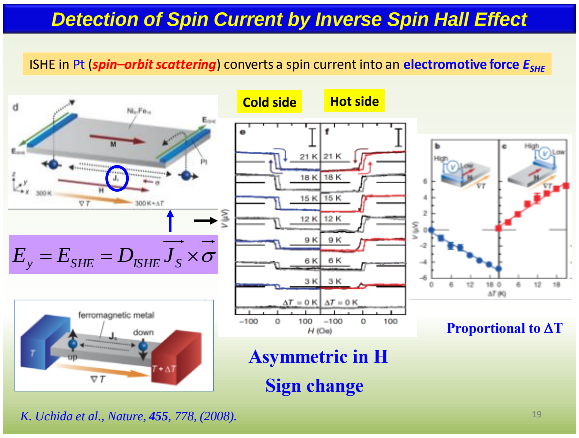
$\delta V_{spin} = S_{spin}\delta T$

$j_s = j_\uparrow - j_\downarrow = (\sigma_\uparrow S_\uparrow - \sigma_\downarrow S_\downarrow)(-\nabla T)$

*K. Uchida et al., Nature, **455**, 778, (2008).*



How to detect J_S ? 18


Detection of Spin Current by Inverse Spin Hall Effect
ISHE in Pt (spin–orbit scattering) converts a spin current into an electromotive force E_{SHE}
Cold side
Hot side
$E_y = E_{SHE} = D_{ISHE} \vec{J_S} \times \vec{\sigma}$
ferromagnetic metal
Asymmetric in H
Sign change
Proportional to ΔT
K. Uchida et al., Nature, 455, 778, (2008).
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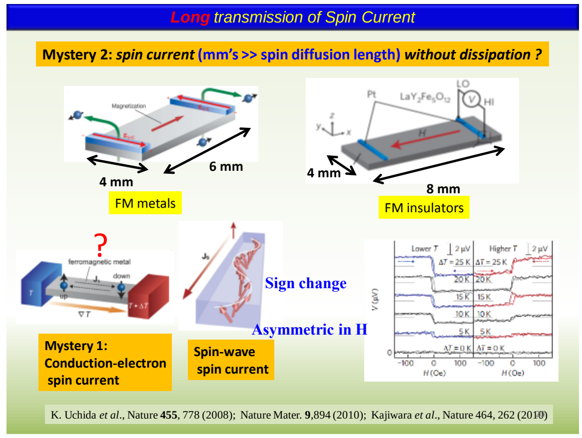
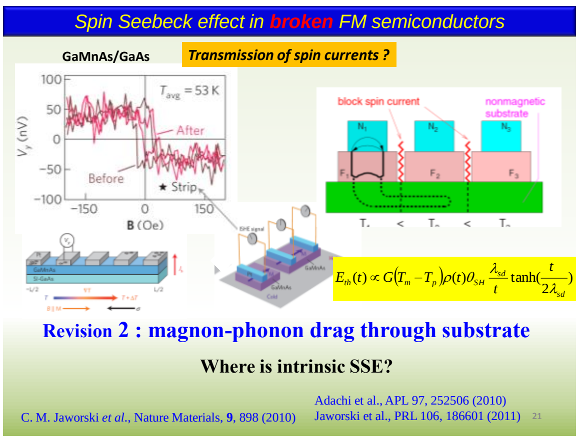
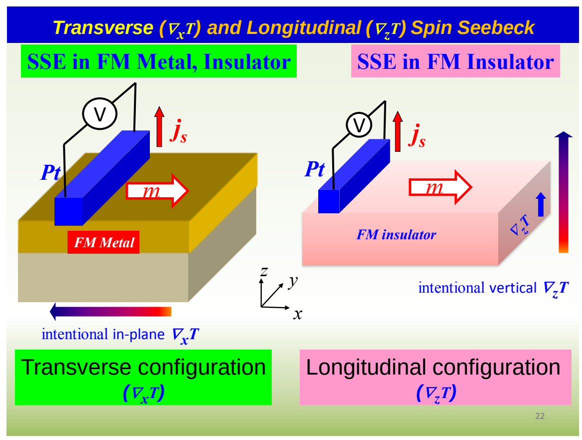

Long transmission of Spin Current
Mystery 2: spin current (mm's >> spin diffusion length) without dissipation ?
4 mm
6 mm
FM metals
4 mm
8 mm
FM insulators
Sign change
Asymmetric in H
Mystery 1: Conduction-electron spin current
Spin-wave spin current
K. Uchida et al., Nature 455, 778 (2008); Nature Mater. 9,894 (2010); Kajiwara et al., Nature 464, 262 (2010)


Spin Seebeck effect in broken FM semiconductors
GaMnAs/GaAs
Transmission of spin currents ?
block spin current
nonmagnetic substrate
$E_{th}(t) \propto G(T_m - T_p)\rho(t)\theta_{SH}\frac{\lambda_{sd}}{t}\tanh(\frac{t}{2\lambda_{sd}})$
Revision 2 : magnon-phonon drag through substrate
Where is intrinsic SSE?
C. M. Jaworski et al., Nature Materials, 9, 898 (2010)
Adachi et al., APL 97, 252506 (2010)
Jaworski et al., PRL 106, 186601 (2011)
21


Transverse ($\nabla_x T$) and Longitudinal ($\nabla_z T$) Spin Seebeck
SSE in FM Metal, Insulator
SSE in FM Insulator
Pt
j_s
m
FM Metal
FM insulator
intentional in-plane $\nabla_x T$
intentional vertical $\nabla_z T$
Transverse configuration ($\nabla_x T$)
Longitudinal configuration ($\nabla_z T$)
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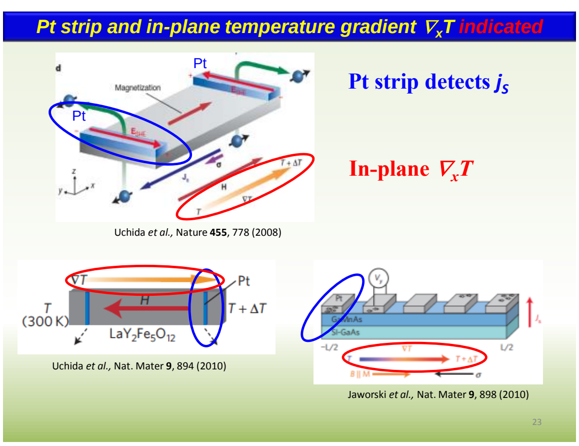
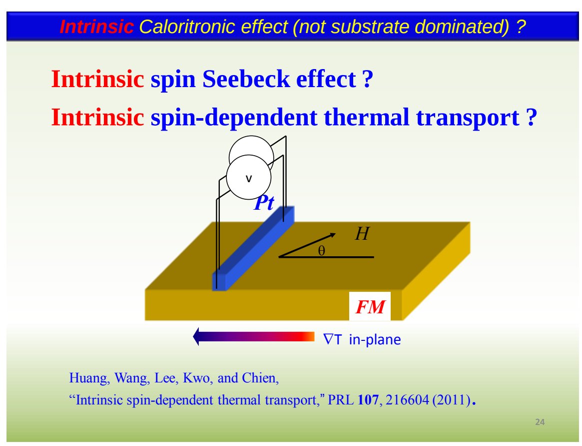

Pt strip and in-plane temperature gradient $\nabla_x T$ indicated
Pt strip detects j_S
In-plane $\nabla_x T$
Uchida et al., Nature 455, 778 (2008)
$LaY_2Fe_5O_{12}$
Uchida et al., Nat. Mater 9, 894 (2010)
Jaworski et al., Nat. Mater 9, 898 (2010)
23


Intrinsic Caloritronic effect (not substrate dominated) ?
Intrinsic spin Seebeck effect ?
Intrinsic spin-dependent thermal transport ?
Pt
H
θ
FM
∇T in-plane
Huang, Wang, Lee, Kwo, and Chien,
"Intrinsic spin-dependent thermal transport," PRL 107, 216604 (2011).
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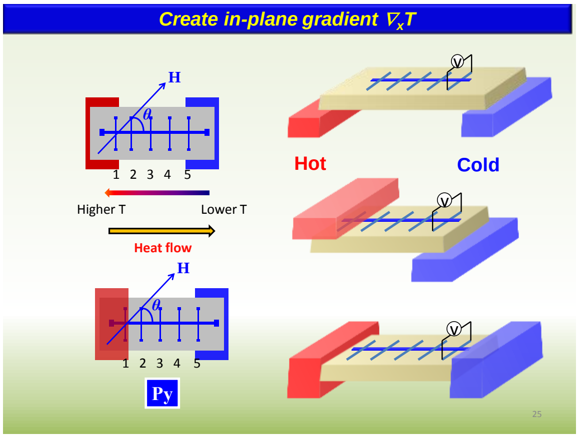
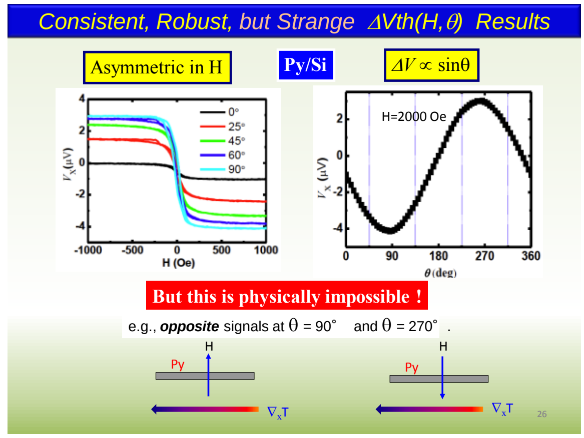
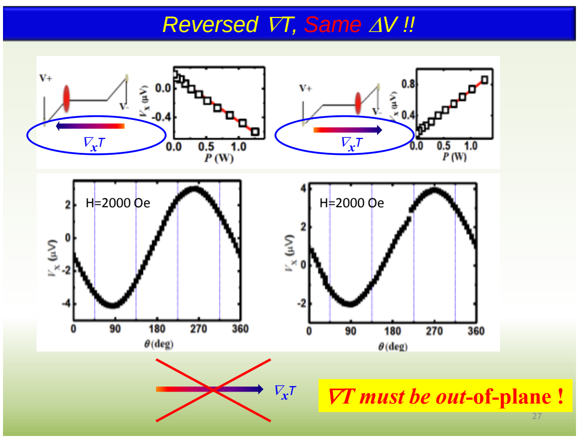
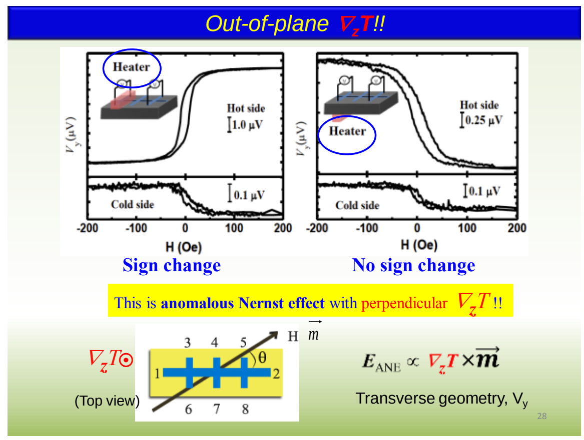

Create in-plane gradient $\nabla_x T$
H
θ
1 2 3 4 5
Higher T
Lower T
Heat flow
Py
Hot
Cold
V
25


Consistent, Robust, but Strange ΔVth(H,θ) Results
Asymmetric in H
Py/Si
$\Delta V \propto \sin\theta$
0°
25°
45°
60°
90°
H (Oe)
H=2000 Oe
θ (deg)
But this is physically impossible !
e.g., opposite signals at θ = 90° and θ = 270° .
H
Py
$\nabla_x T$
26


Reversed ∇T, Same ΔV !!
V+
V-
$\nabla_x T$
P (W)
H=2000 Oe
θ (deg)
∇T must be out-of-plane !
27


Out-of-plane $\nabla_z T$!!
Heater
Hot side
1.0 μV
0.25 μV
Cold side
0.1 μV
H (Oe)
Sign change
No sign change
This is anomalous Nernst effect with perpendicular $\nabla_z T$!!
$\nabla_z T$
(Top view)
3 4 5
1
2
6 7 8
H
θ
$E_{ANE} \propto \nabla_z T \times \vec{m}$
Transverse geometry, V_y
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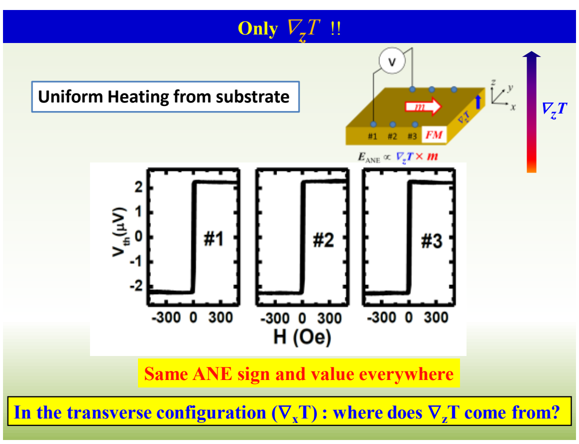
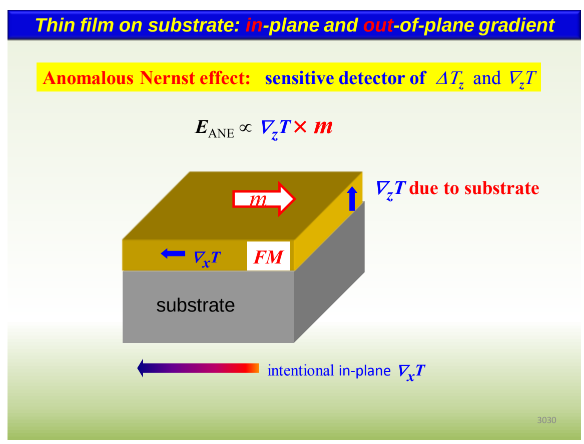
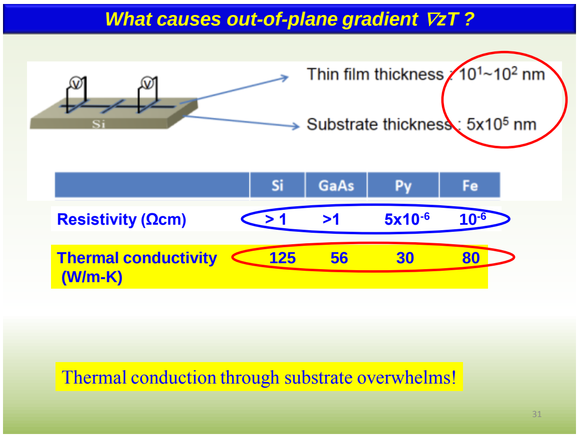

Only $\nabla_z T$!!
Uniform Heating from substrate
V
m
FM
#1 #2 #3
$E_{ANE} \propto \nabla_z T \times m$
$\nabla_z T$
V_{th} (μV)
#1
#2
#3
-300 0 300
H (Oe)
Same ANE sign and value everywhere
In the transverse configuration ($\nabla_x T$) : where does $\nabla_z T$ come from?


Thin film on substrate: in-plane and out-of-plane gradient
Anomalous Nernst effect: sensitive detector of ΔT_z and $\nabla_z T$
$E_{ANE} \propto \nabla_z T \times m$
m
$\nabla_z T$ due to substrate
$\nabla_x T$
FM
substrate
intentional in-plane $\nabla_x T$
3030


What causes out-of-plane gradient ∇zT ?
Thin film thickness : 10¹~10² nm
Substrate thickness : 5x10⁵ nm
Si
Si GaAs Py Fe
Resistivity (Ωcm) > 1 >1 5x10⁻⁶ 10⁻⁶
Thermal conductivity (W/m-K) 125 56 30 80
Thermal conduction through substrate overwhelms!
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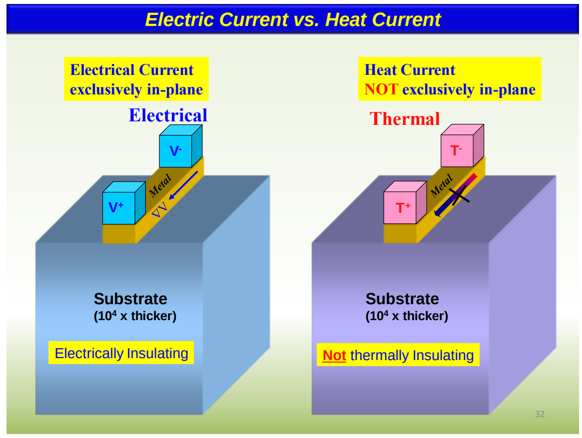
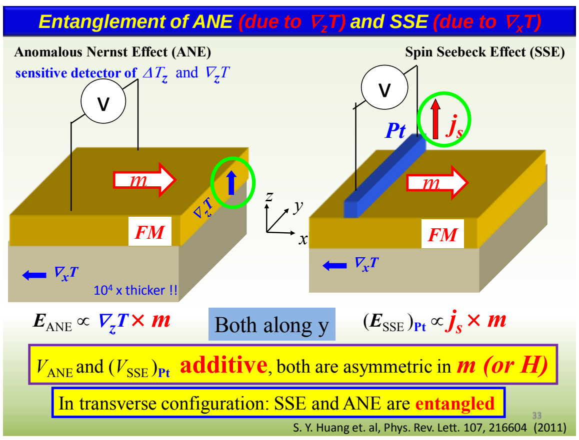
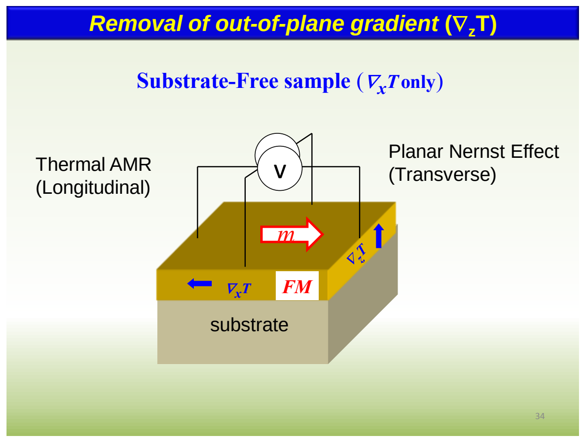
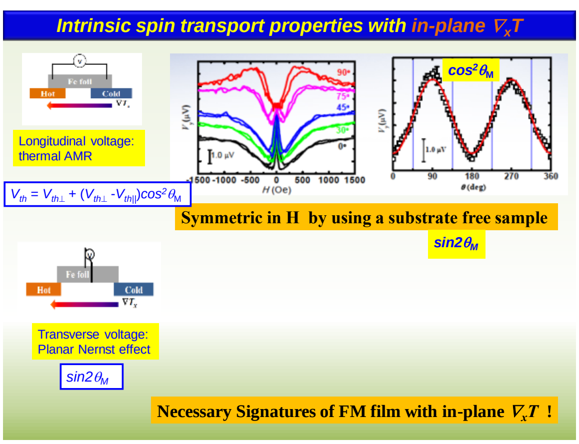
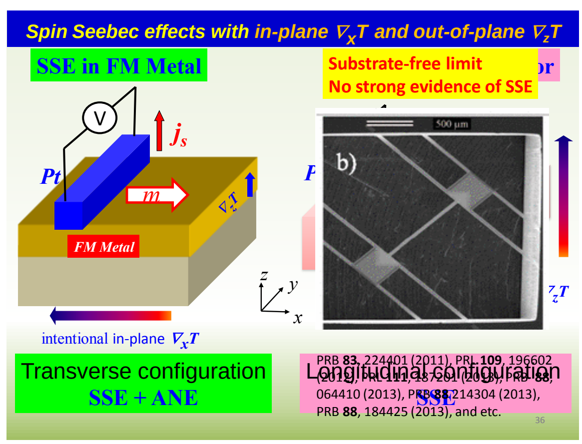

Electric Current vs. Heat Current
Electrical Current exclusively in-plane
Heat Current NOT exclusively in-plane
Electrical
Thermal
V⁻
V⁺
T⁻
T⁺
Metal
Substrate (10⁴ x thicker)
Electrically Insulating
Substrate (10⁴ x thicker)
Not thermally Insulating
32

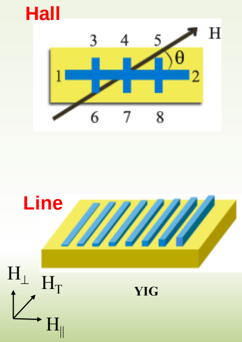

Entanglement of ANE (due to ∇zT) and SSE (due to ∇xT)
Anomalous Nernst Effect (ANE)
Spin Seebeck Effect (SSE)
sensitive detector of ΔTz and ∇zT
V
Pt
js
m
FM
∇xT
10⁴ x thicker !!
E_ANE ∝ ∇zT × m
Both along y
(E_SSE)Pt ∝ js × m
V_ANE and (V_SSE)Pt additive, both are asymmetric in m (or H)
In transverse configuration: SSE and ANE are entangled
33
S. Y. Huang et. al, Phys. Rev. Lett. 107, 216604 (2011)


Removal of out-of-plane gradient (∇zT)
Substrate-Free sample (∇xT only)
Thermal AMR (Longitudinal)
Planar Nernst Effect (Transverse)
V
m
∇xT
FM
substrate
34

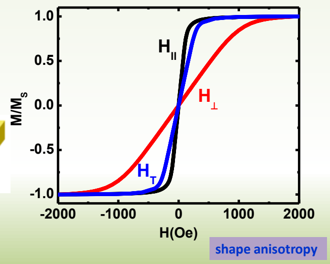

Intrinsic spin transport properties with in-plane ∇xT
Fe foil
Hot
Cold
Longitudinal voltage: thermal AMR
V_th = V_th⊥ + (V_th⊥ - V_th∥)cos²θ_M
cos²θ_M
H (Oe)
θ (deg)
Symmetric in H by using a substrate free sample
sin2θ_M
Transverse voltage: Planar Nernst effect
sin2θ_M
Necessary Signatures of FM film with in-plane ∇xT !


Spin Seebec effects with in-plane ∇xT and out-of-plane ∇zT
SSE in FM Metal
Substrate-free limit
No strong evidence of SSE
V
js
Pt
m
FM Metal
intentional in-plane ∇xT
Transverse configuration
SSE + ANE
Longitudinal configuration
PRB 83, 224401 (2011), PRL 109, 196602 (2012), PRL 111, 187201 (2013), PRB 88, 064410 (2013), PRB 88, 214304 (2013), PRB 88, 184425 (2013), and etc.
b)
500 μm
36

Metals (Cu, Py, Pt) on Insulators (Si, YIG)

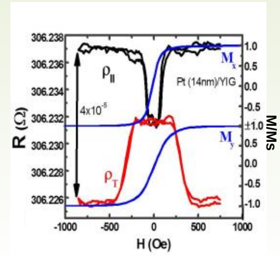


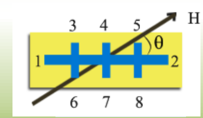
Ferromagnetic Insulator: YIG ($Y_3Fe_5O_{12}$)



Huang et al., Phys. Rev. Lett., 109, 107204 (2012)

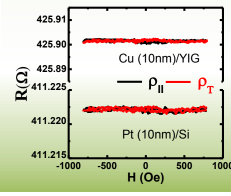
Pt/YIG vs. Pt/Si



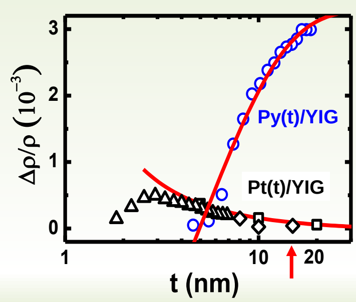


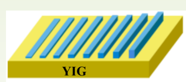
Pt/YIG
AMR ! $\cos^2\theta$
Ferromagnetic !

Pt: Magnetic Proximity effects



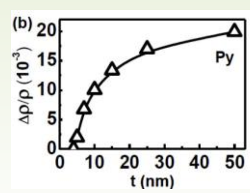
Thickness dependence of AMR in Py/YIG & Pt/YIG

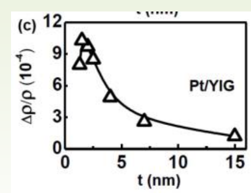




Pt/YIG and Py has opposite *t* dependence

AMR vs. New MR





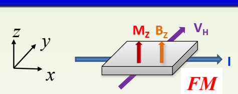
AMR ≈ constant at large *t*
AMR → 0 at small *t*

All moments contribute

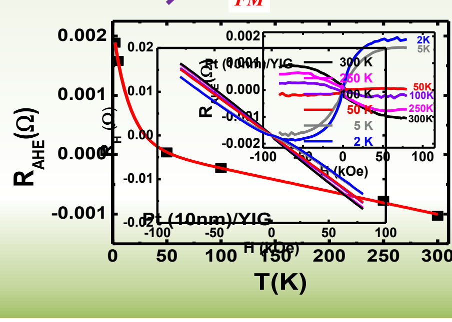
New MR → 0 at large *t*
New MR increases at small *t*

Magnetic Proximity effect
Moments near interface contribute

Anomalous Hall Effect in Pt/YIG



$\rho_{xy} = R_O B + R_S 4\pi M$

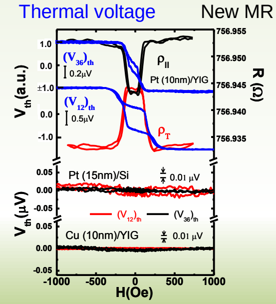


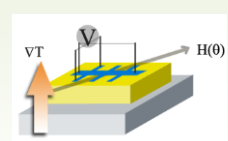
Thermal voltages in Pt/YIG and Pt/Si (Hall samples)

Share H dependence

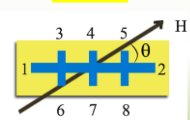
Pt/YIG

Thermal voltage New MR

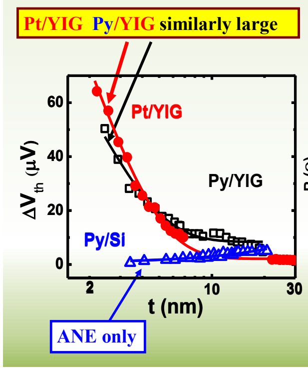


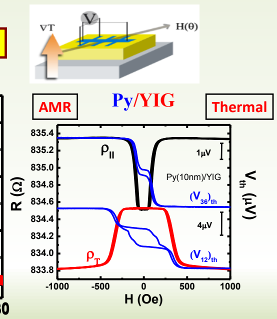


ΔT = 11 K



Thicknesses dependence of thermal voltage





$(E_{ANE})_{Py} \propto \nabla_z T \times m_{FM}$

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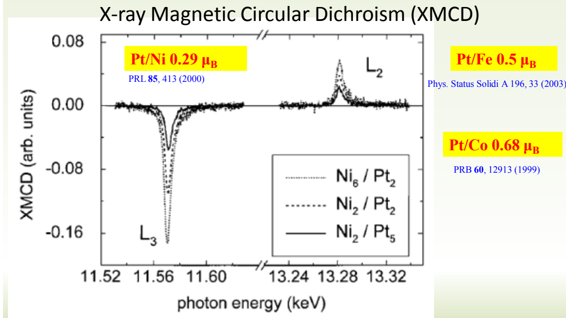
Induced magnetic moments in Pt/Ni, Pt/Co, & Pt/Fe



Magnetic proximity effect in Pt/YIG

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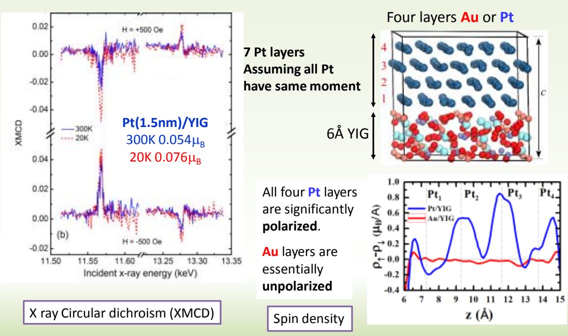
Induced magnetic moments in Pt/YIG



Phys. Rev. Lett. **110**, 147207 (2013)

spin current detector: Au ?

Phys. Rev. Lett. **110**, 067206 (2013)

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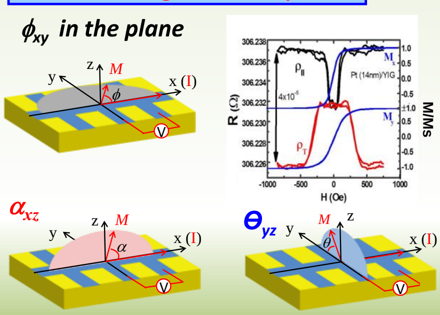
Comparison of Pt/YIG and Au/YIG

	Pt/YIG vs.	Au/YIG (Intrinsic SSE)
Spin Seebeck	50x larger	Observed
New MR	Yes	No
Anomalous Hall	Yes	No
Moment (Theory)	Yes	No
Moment (XMCD)	Yes	Not observed

New Magnetoresistance

New Magnetoresistance in Pt/YIG:
Magnetic Proximity Effect



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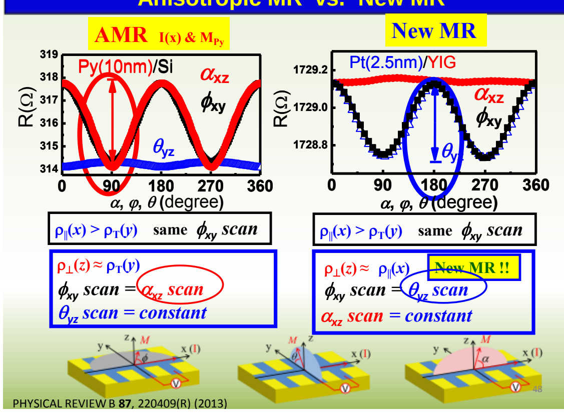
Anisotropic MR vs. New MR



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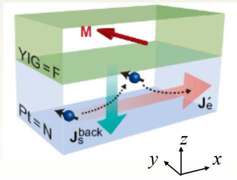
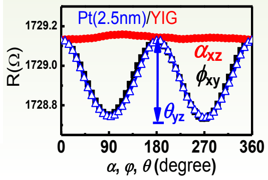
Spin Hall Magnetoresistance (SMR)

Spin Hall MR in Pt/YIG: charge/spin current conversion
(Nakayama et al.,) SOC metals/NO magnetic moment





j_e —SHE→ j_s —ISHE→ j_e

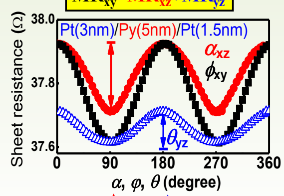
The reflection J_s depends on STT
$\rho_{||}(x) > \rho_T(y)$; $\rho_{\perp}(z) = \rho_{||}(x)$

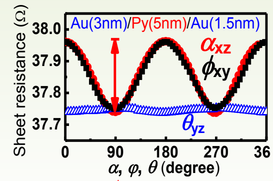
SMR:
- SOC metals on YIG
- No magnetic moment
- Spin current
- σ_{Pt}||y axis (independent of H)

Nakayama et al. Phys. Rev. Lett. **110**, 206601 (2013)

Pt/Py vs.

$MR_{xy} = MR_{xz} + MR_{yz}$





Magnetic Proximity can be detected in FM metal from XMCD and NEW MR

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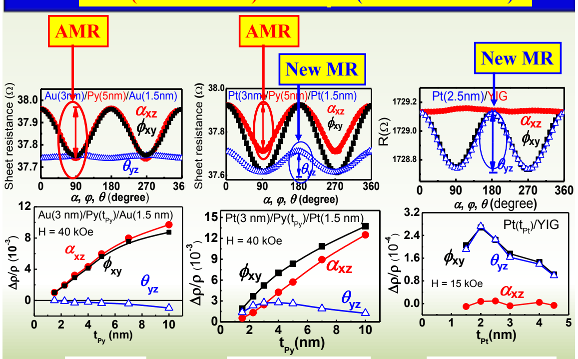
AMR(own Moments) + New MR (induced Moments)



$Py(t_{Py})$ $Pt/Py(t_{Py})/Pt$ $Pt(t_{Pt})/YIG$

New MR vs. Spin Hall MR

	Experimental observation	Induced Moment ? (AHE, XMCD)	Spin Hall MR Prediction ?
Pt/YIG	New MR	Yes	Yes
Pt/Py	AMR + New MR	Yes	?
Pt/YIG_{BB}	New MR	Yes	?
Au/Py	AMR	No	?
Au/YIG	No new MR	No	?

New MR observed in cases with induced moments

Magnetic proximity effect accounts for all cases

Summary

- Transverse Spin Seebeck ($\nabla_x T$) (metals, semiconductors, insulators):
  Entanglement with anomalous Nernst ($\nabla_z T$)
  Intrinsic spin-dependent thermal transport on substrate free sample
- Longitudinal Spin Seebeck Effect (ferromagnetic insulators):
  Complicated Magnetic proximity effects in Pt

  Entanglement of SSE and ANE
- New MR in FM metals and Insulator
  - new MR in Pt/YIG, Py/YIG, Pt/YIG_{BB}, and Pt/Py
  - No new MR in Au/YIG and Au/Py

  New MR by magnetic proximity effect or Spin Hall MR ?
- Pt is not an ideal spin current detector (magnetic proximity effects):

  Au is better spin current detector

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Acknowledgement

- **Johns Hopkins University:** Prof. Chia-Ling Chien, Danru Qu, Bingfeng Miao
- **University of Arizona:** Prof. Weigang Wang
- **National Tsing Hua University:** Prof. J. Raynien Kwo
- **Academia Sinica:** Dr. Shang-Fan Lee
- **University of Delaware**: Prof. John Q. Xiao
- **Arizona State University**: Prof. Tingyong Chen
- **University of California, irvine:** Prof. Ruaiqn Wu
- **Chinese Academy of Science:** Prof. Jianwang Cai

U.S. DEPARTMENT OF ENERGY US NSF Taiwan NSC

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