




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

Power Consumption of Information Technology

G-k-w-h

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)

IC Power density approaches that of nuclear reactor

Can spin provide a solution ?

S. Borkar, Intel

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

Electronics

Three important discoveries in Spintronics

*2007 Nobel

Giant Magnetoresistance (GMR) (1988*)

Tunnel Magnetoresistance (TMR) (1995)

Spin Transfer Torque (STT) (1996, 2000)



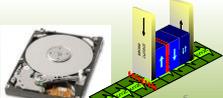
Grünberg/Fert

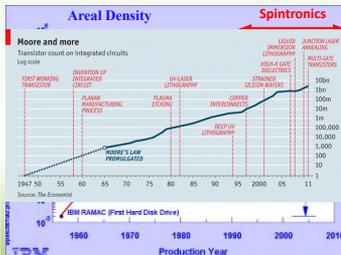
10¹² bits/in²

10⁹ increase in density

10⁻⁸ reduction in cost

Spin-valve read-head





Ed Geachowski at Almaden

Spintronic GMR and TMR Devices

GMR

Spin-dependent scattering

TMR

Spin-selective tunneling

free P "0" Storage AP "1"

fixed P Reference AP

Low R High R

Field Sensing & Non-Volatile Storage

Field (1G) Devices

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

Magnetic Tunnel Junction (MTJ)

high R "1"

low R "0"

Read Write

word/sense lines

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

Spin transfer torque

electrical current affects magnetic configurations

torque $\sim \sin \theta$

without a magnetic field

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)

1G and 2G Spintronic Devices

Field Sensing & Non-Volatile Storage

Low R Reference High R

(1G) Field Devices

Current (STT) Devices

$I > I_c$

(2G) Current (STT) Devices

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

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...

Charge, Spin, Thermal Transport in thin films

$E \propto V \times B$

$E_{ANE} \propto V_x T \times \vec{m}$

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

∇V_x : Hall Effect

Walther Nernst

∇T_x : Nernst Effect

Hall effect Anomalous Hall effect Spin Hall effect

1879

Ordinary Hall effect with magnetic field H
Hall voltage but no spin accumulation

Lorentz Force

Only Charge
Detect by voltage
 $F=q(E+V \times B)$
Definite Sign $q(v \times B)$

1880

Anomalous Hall effect with magnetization M (carrier spin polarization)
Hall voltage and spin accumulation

Charge + Spin

Detect by voltage
AHE can be either sign
Definite Axis but Not Definite Sign

2004

(Pure) spin Hall effect no magnetic field necessary
No Hall voltage but spin accumulation

Spin-Orbit Coupling

Only Spin
Why? Detect by what?
SHE can be either sign

(Nagaosa et al.,)

The mechanism of SHE

Spin-Orbit Coupling

Electron frame "sees" B_L field with gradient

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 ?

(Optical) Observation of Spin Hall effect

Charge current \rightarrow pure spin accumulation

Optical observation SHE in semiconductors

Kato et al. Science 306, 1910 (2004)

Spin Caloritronics

Electronics

Spin polarized charge current

$J_c \neq 0$
 $J_s = 0$

Pure spin current

$J_c = 0$
 $J_s \neq 0$

T_1 T_2

ΔV

Thermal conductivity $\kappa_x = -\left(\frac{J_c}{\Delta T}\right)_{T_1, T_2}$

Seebeck coefficient $S = \left(\frac{\Delta V}{\Delta T}\right)_{J_c=0}$

Spin Seebeck effect

Spin Seebeck Effect

$\Delta V = S \Delta T$

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

$\mathbf{j}_s = \mathbf{j}_\uparrow - \mathbf{j}_\downarrow = (\sigma_\uparrow S_\uparrow - \sigma_\downarrow S_\downarrow)(-\nabla T)$

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

How to detect J_s ?

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}

$E_y = E_{SHE} = D_{ISHE} \mathbf{J}_S \times \boldsymbol{\sigma}$

Asymmetric in H
Sign change

Proportional to ΔT

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

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?

$E_{ss}(t) \propto G(T_m - T_p) \rho(t) \theta_{SH} \frac{\lambda_{sd}}{t} \tanh(\frac{t}{2\lambda_{sd}})$

Revision 2 : magnon-phonon drag through substrate

Where is intrinsic SSE?

Adachi et al., APL 97, 252506 (2010)
Jaworski et al., PRL 106, 186601 (2011)

Transverse ($\nabla_x T$) and Longitudinal ($\nabla_z T$) Spin Seebeck

SSE in FM Metal, Insulator

SSE in FM Insulator

intentional in-plane $\nabla_x T$

intentional vertical $\nabla_z T$

Transverse configuration ($\nabla_x T$)

Longitudinal configuration ($\nabla_z T$)

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)

Uchida et al., Nat. Mater 9, 894 (2010)

Jaworski et al., Nat. Mater 9, 898 (2010)

Intrinsic Caloritronic effect (not substrate dominated) ?

Intrinsic spin Seebeck effect ?

Intrinsic spin-dependent thermal transport ?

∇T in-plane

Huang, Wang, Lee, Kwo, and Chien,
"Intrinsic spin-dependent thermal transport," PRL 107, 216604 (2011).

Create in-plane gradient $\nabla_x T$

Higher T → Lower T
Heat flow

Py

Consistent, Robust, but Strange $\Delta V_{th}(H, \theta)$ Results

Asymmetric in H Py/Si $\Delta V \propto \sin\theta$

But this is physically impossible !
e.g., **opposite** signals at $\theta = 90^\circ$ and $\theta = 270^\circ$.

Reversed ∇T , Same ΔV !!

~~$\nabla_x T$~~ ∇T must be out-of-plane !

Out-of-plane $\nabla_z T$!!

This is anomalous Nernst effect with perpendicular $\nabla_z T$!!

$\nabla_z T \otimes \vec{m}$ $E_{ANE} \propto \nabla_z T \times \vec{m}$
Transverse geometry, V_y

Only $\nabla_z T$!!

Uniform Heating from substrate

$E_{ANE} \propto \nabla_z T \times \vec{m}$

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 $\nabla_z T$

$E_{ANE} \propto \nabla_z T \times \vec{m}$

$\nabla_z T$ due to substrate

intentional in-plane $\nabla_x T$

What causes out-of-plane gradient $\nabla_z T$?

Thin film thickness: $10^1 \sim 10^2$ nm
Substrate thickness: 5×10^5 nm

	Si	GaAs	Py	Fe
Resistivity (Ωcm)	> 1	> 1	5×10^{-6}	10^{-6}
Thermal conductivity (W/m-K)	125	56	30	80

Thermal conduction through substrate overwhelms!

Electric Current vs. Heat Current

Electrical Current exclusively in-plane
Substrate ($10^4 \times$ thicker)
Electrically Insulating

Heat Current NOT exclusively in-plane
Substrate ($10^4 \times$ thicker)
Not thermally Insulating

Entanglement of ANE (due to $\nabla_z T$) and SSE (due to $\nabla_x T$)

Anomalous Nernst Effect (ANE) sensitive detector of ΔT_z and $\nabla_z T$
Spin Seebeck Effect (SSE)

$E_{\text{ANE}} \propto \nabla_z T \times m$ Both along y
 $(E_{\text{SSE}})_{\text{Pt}} \propto j_s \times m$

V_{ANE} and $(V_{\text{SSE}})_{\text{Pt}}$ **additive**, both are asymmetric in m (or H)
In transverse configuration: SSE and ANE are **entangled**

S. Y. Huang et al, Phys. Rev. Lett. 107, 216604 (2011)

Removal of out-of-plane gradient ($\nabla_z T$)

Substrate-Free sample ($\nabla_x T$ only)

Thermal AMR (Longitudinal)
Planar Nernst Effect (Transverse)

Intrinsic spin transport properties with in-plane $\nabla_x T$

Longitudinal voltage: thermal AMR
 $V_{\parallel} = V_{\text{thL}} + (V_{\text{thL}} - V_{\text{thT}}) \cos^2 \theta_M$
Symmetric in H by using a substrate free sample

Transverse voltage: Planar Nernst effect
 $\sin 2\theta_M$

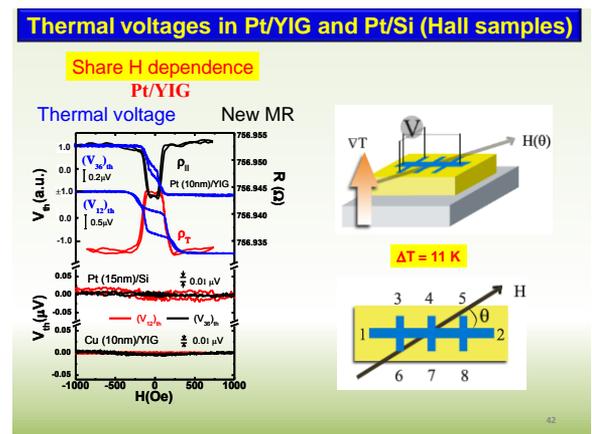
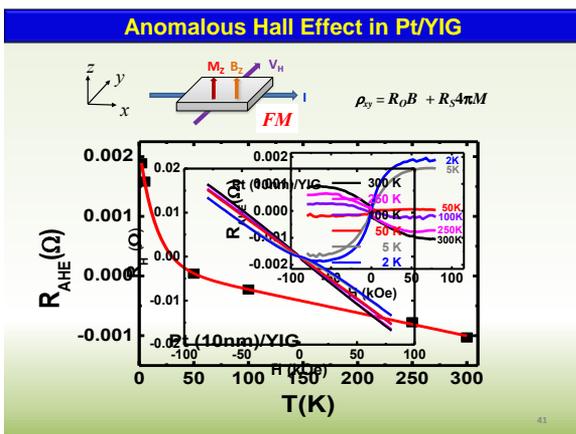
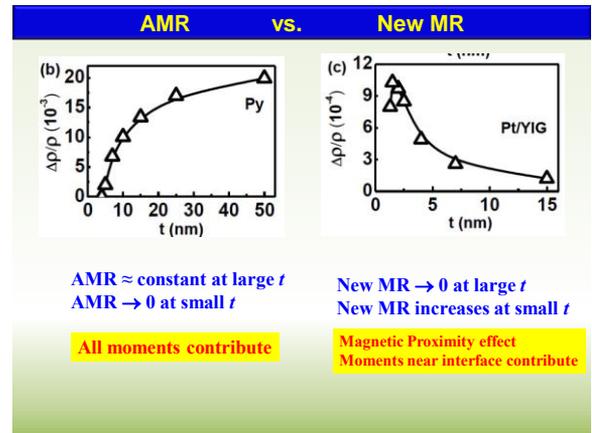
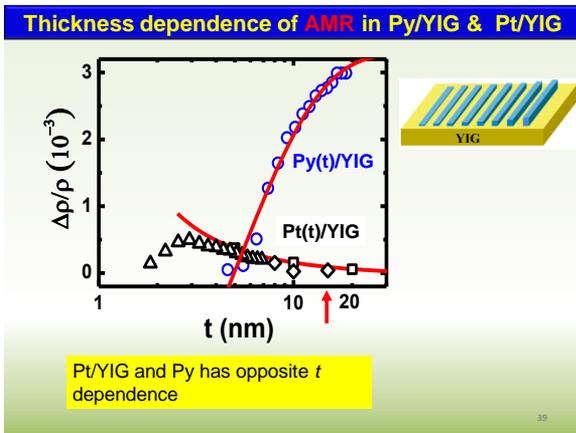
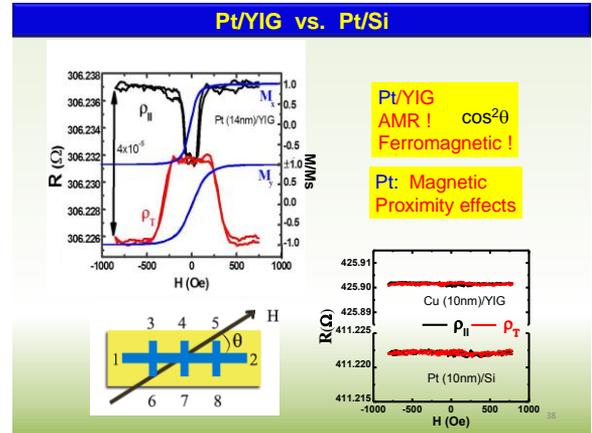
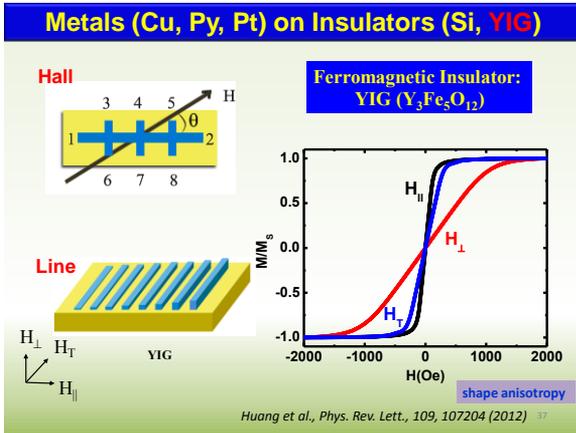
Necessary Signatures of FM film with in-plane $\nabla_x T$!

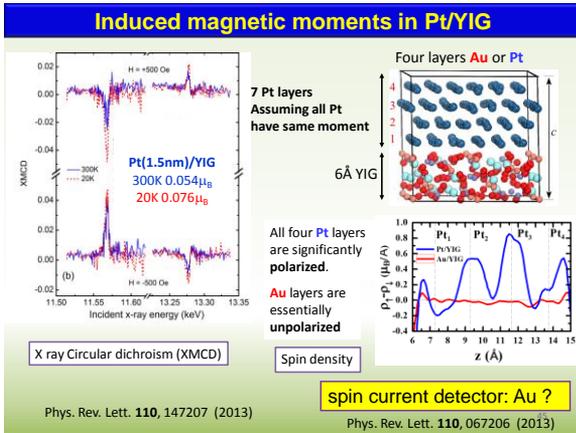
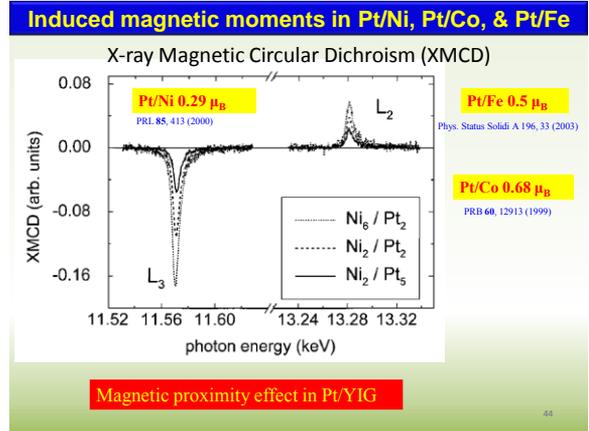
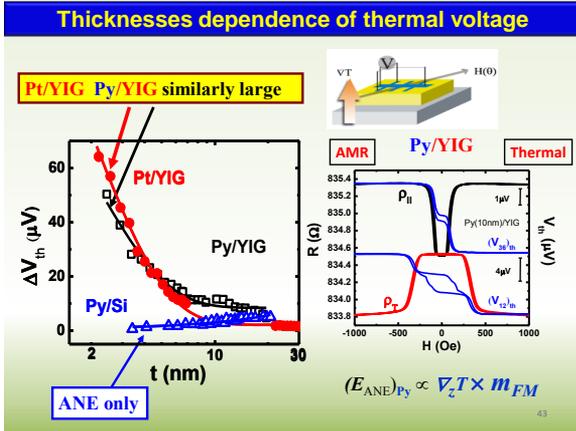
Spin Seebeck effects with in-plane $\nabla_x T$ and out-of-plane $\nabla_z T$

SSE in FM Metal
Substrate-free limit
No strong evidence of SSE

intentional in-plane $\nabla_x T$
Transverse configuration
SSE + ANE

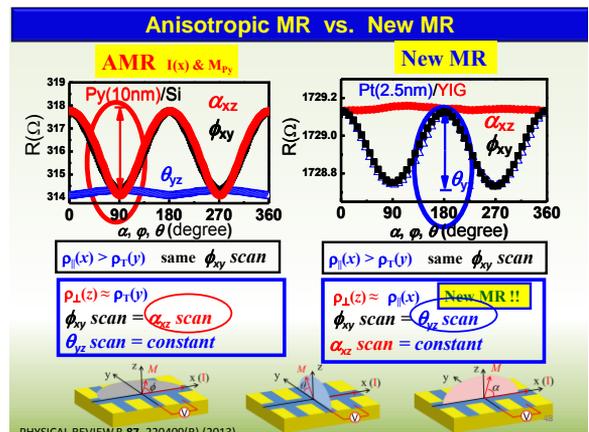
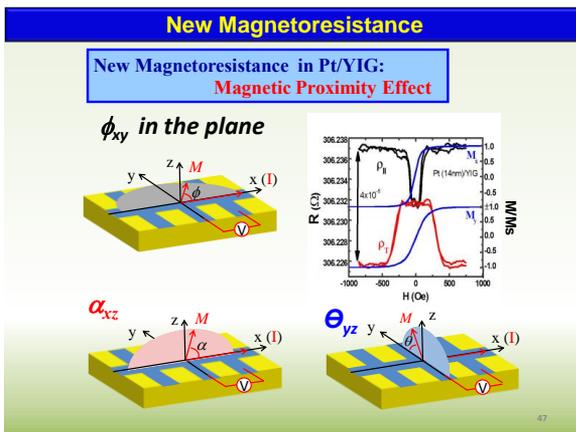
PRB 83, 224401 (2011), PRL 109, 196602 (2012), PRL 109, 196603 (2012), PRL 109, 196604 (2012), PRL 109, 196605 (2012), PRL 109, 196606 (2012), PRL 109, 196607 (2012), PRL 109, 196608 (2012), PRL 109, 196609 (2012), PRL 109, 196610 (2012), PRL 109, 196611 (2012), PRL 109, 196612 (2012), PRL 109, 196613 (2012), PRL 109, 196614 (2012), PRL 109, 196615 (2012), PRL 109, 196616 (2012), PRL 109, 196617 (2012), PRL 109, 196618 (2012), PRL 109, 196619 (2012), PRL 109, 196620 (2012), PRL 109, 196621 (2012), PRL 109, 196622 (2012), PRL 109, 196623 (2012), PRL 109, 196624 (2012), PRL 109, 196625 (2012), PRL 109, 196626 (2012), PRL 109, 196627 (2012), PRL 109, 196628 (2012), PRL 109, 196629 (2012), PRL 109, 196630 (2012), PRL 109, 196631 (2012), PRL 109, 196632 (2012), PRL 109, 196633 (2012), PRL 109, 196634 (2012), PRL 109, 196635 (2012), PRL 109, 196636 (2012), PRL 109, 196637 (2012), PRL 109, 196638 (2012), PRL 109, 196639 (2012), PRL 109, 196640 (2012), PRL 109, 196641 (2012), PRL 109, 196642 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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



Spin Hall Magnetoresistance (SMR)

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

$\vec{j}_e \xrightarrow{\text{SHE}} \vec{j}_s \xrightarrow{\text{ISHE}} \vec{j}_e$

The reflection J_s depends on STT
 $\rho_1(x) > \rho_1(z) ; \rho_1(z) = \rho_1(x)$

SMR:
 > SOC metals on YIG
 > No magnetic moment
 > Spin current
 > $\sigma_{xx} \parallel y$ 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

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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