MONASH University

FLEET
ARC CENTRE OF EXCELLENCE IN FUTURE LOW-ENERGY ELECTRONICS TECHNOLOGIES

Towards Efficient Spin Current Generation using Amorphous Materials

Julie Karel

Department of Materials Science and Engineering, Monash University

FLEET and Materials Australia Seminar
September 3, 2020

About me


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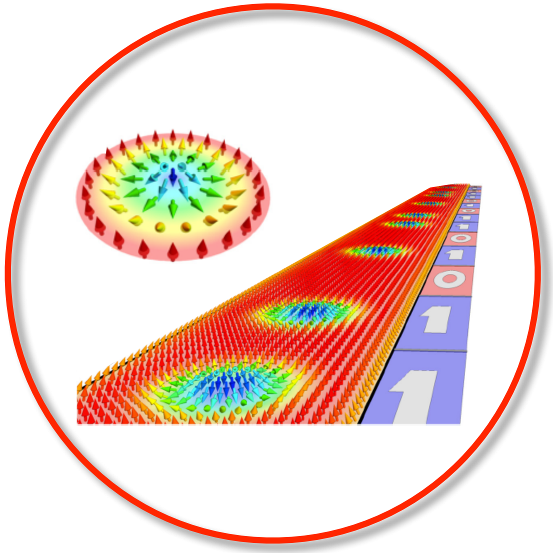
Postdoc, Max Planck
Institute Dresden, Germany
PhD, University of
California Berkeley
Minneapolis
B.S. University of
Wisconsin Madison
Intel Corporation
Phoenix
Lecturer, Monash University
Melbourne, Australia

Low Energy Electronics and Data Storage

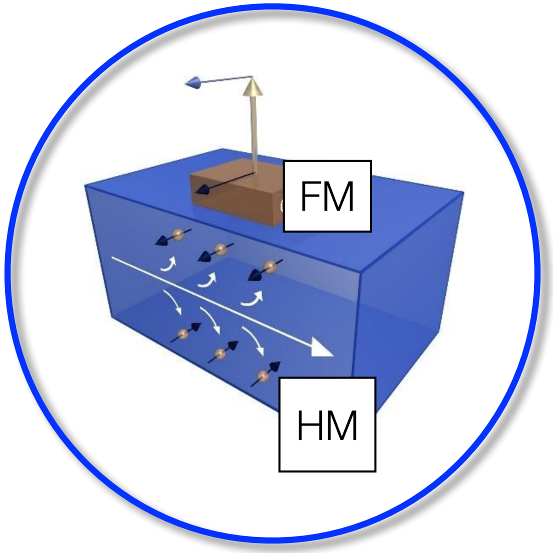
- Data is produced at a breathtaking rate
- By 2030, data centers could represent as much as 13% of total global electricity

Image: crn.com
https://theconversation.com/bingeing-netflix-under-lockdown-heres-why-streaming-comes-at-a-cost-to-the-environment-143190
J.M.D. Coey, J. Phys.:Condens. Matt. (2014)

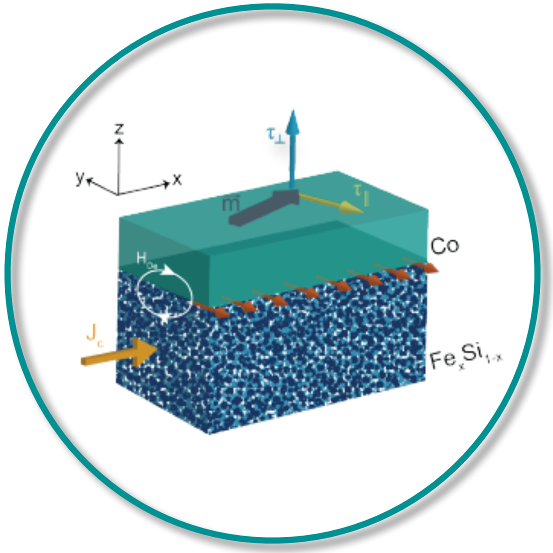
Outline



Non-volatile memory and current challenges

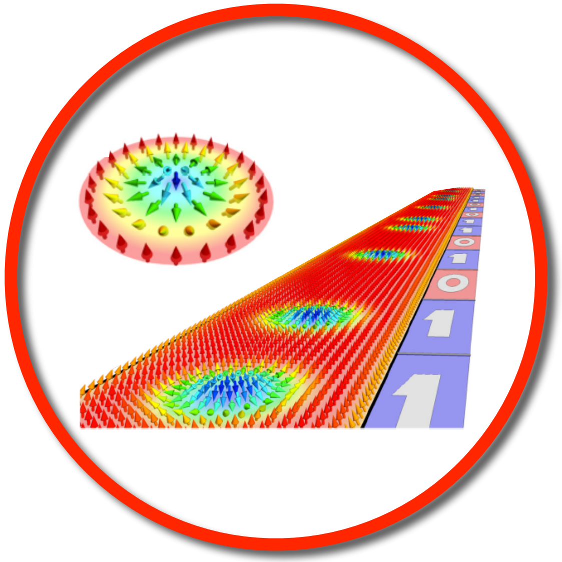


Methods for spin current generation



Using amorphous materials to create spin currents

Outline



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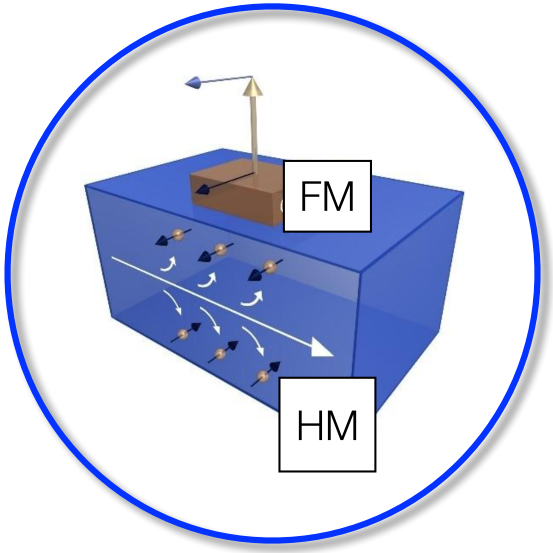

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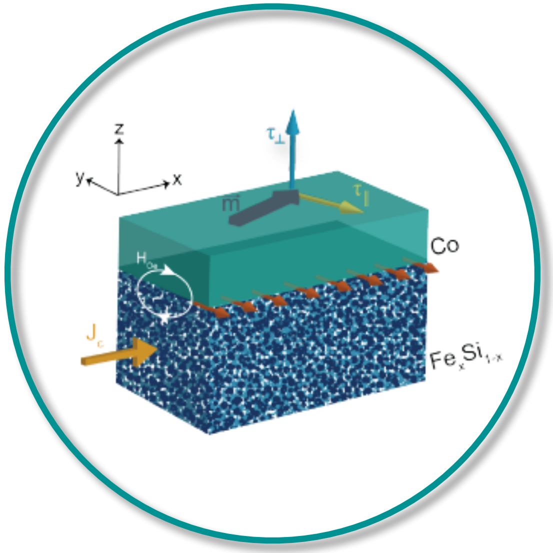


Using amorphous materials to create spin currents

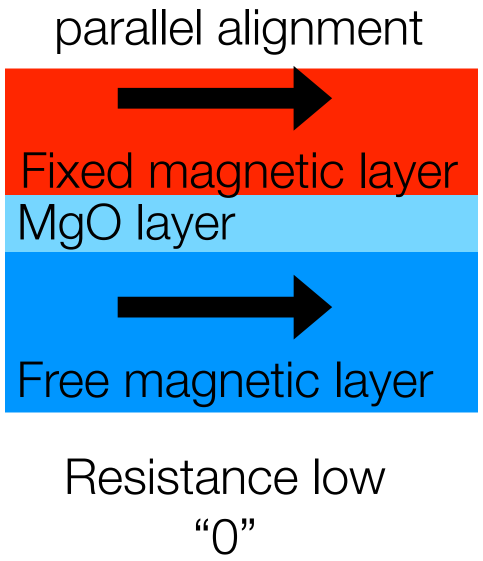
Non-Volatile Memory

- Data retained without power

Hard Disk Drive	Solid State Drive
Inexpensive ✓	Fast ✓
Slow ✗	Low endurance ✗

Emerging NVM: MRAM

- Magnetoresistive random access memory
- Array of magnetic tunnel junctions



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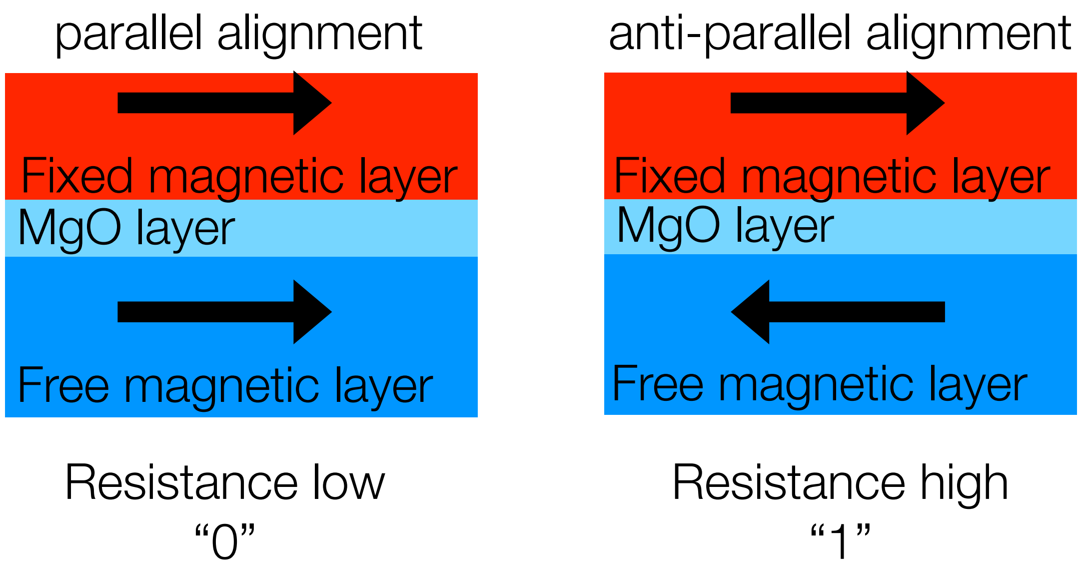

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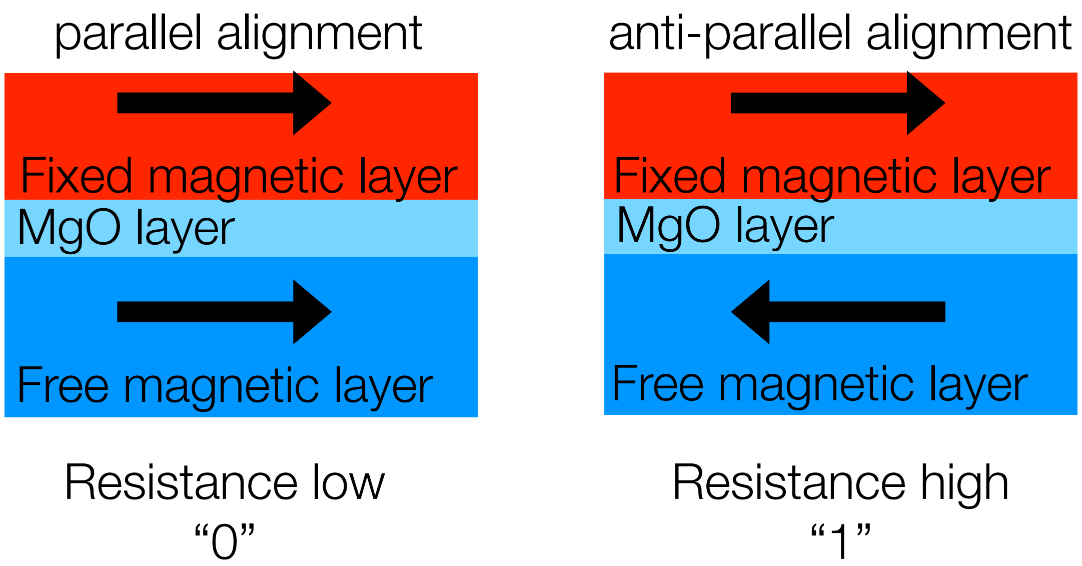
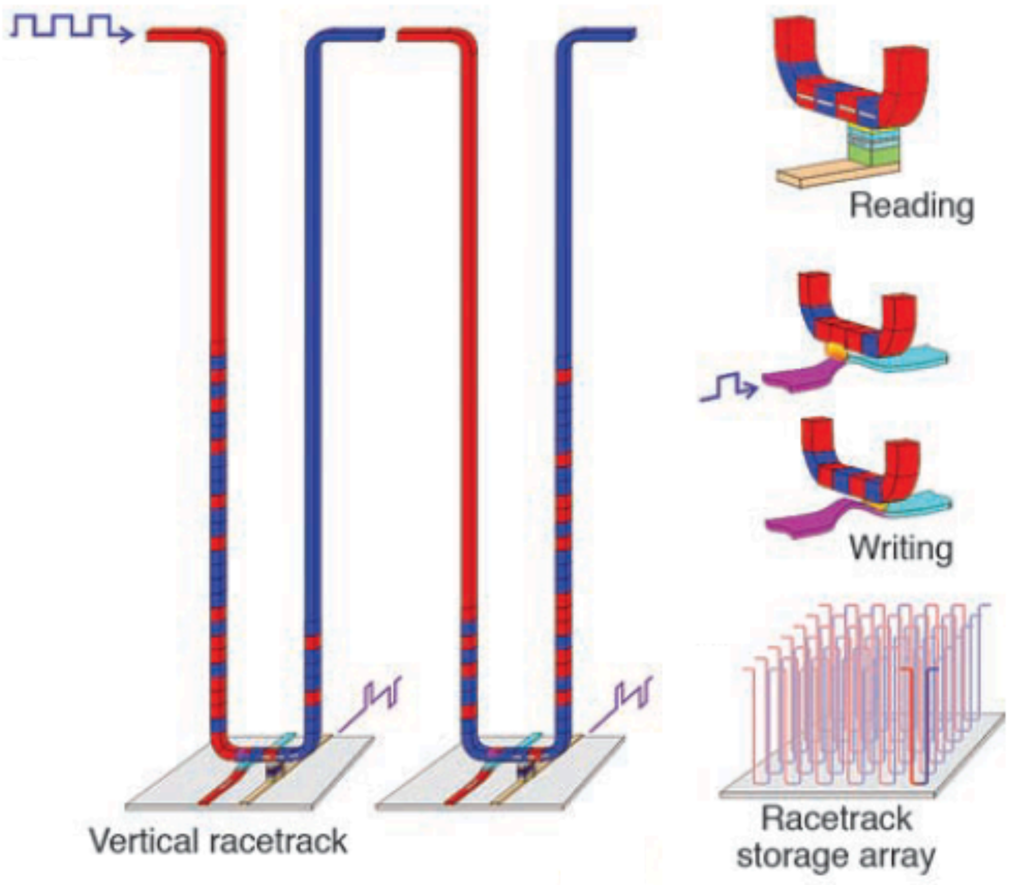
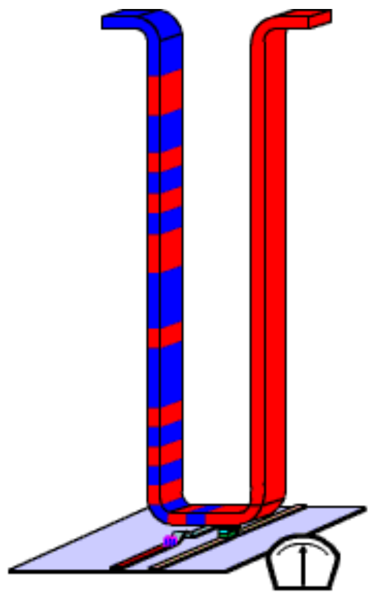


- Need to switch free layer → spin orbit torque (SOT)

Emerging NVM: Racetrack Memory

- Ferromagnetic nanowire
- Magnetic domain wall or Skyrmion





Everschorr-Sitte *et al. J. Appl. Phys.* (2018)
Parkin *et al. Science* (2008)

Vedmedenko *et al. J.Phys. D: Appl. Phys.* (2020)

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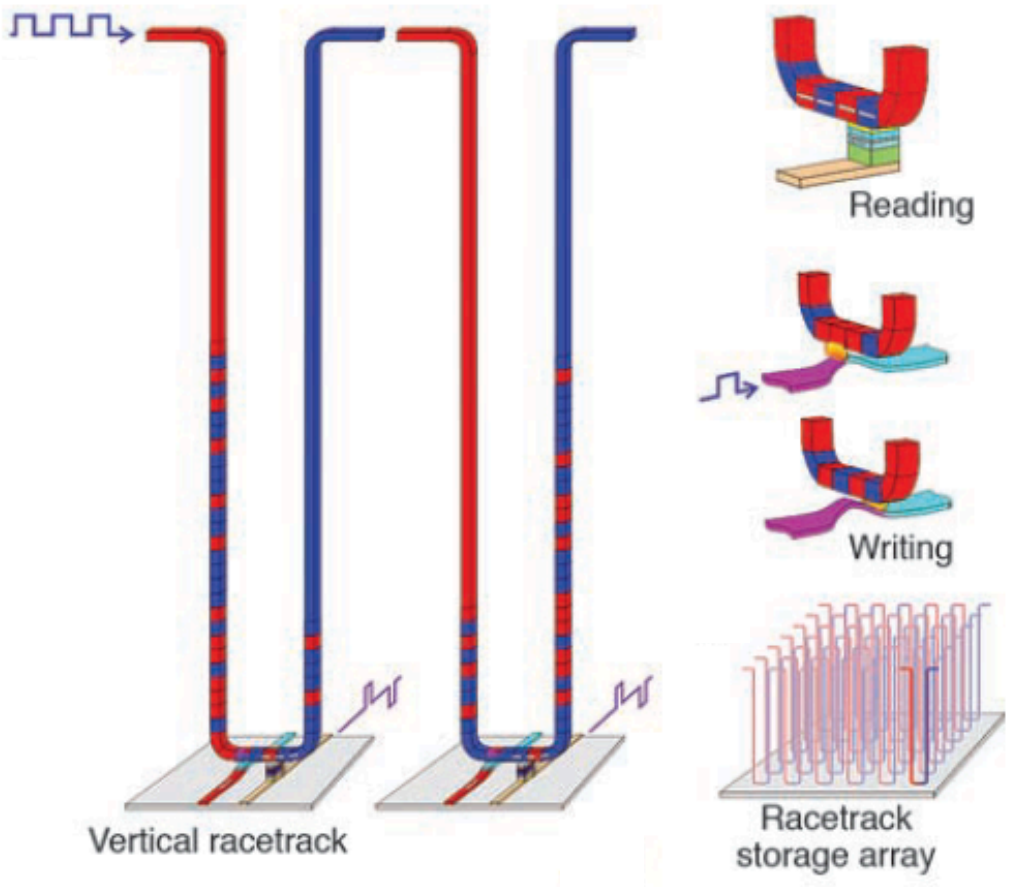

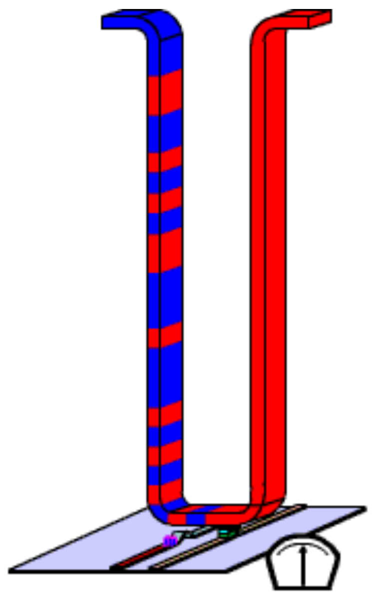

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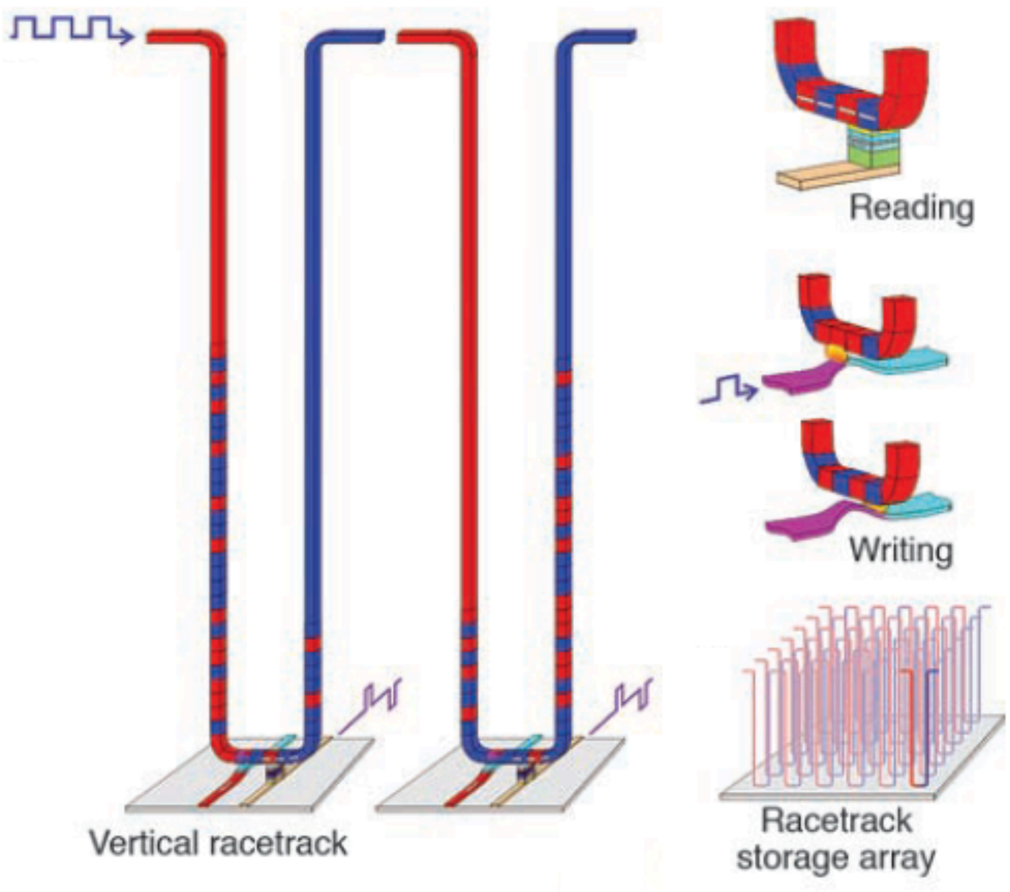

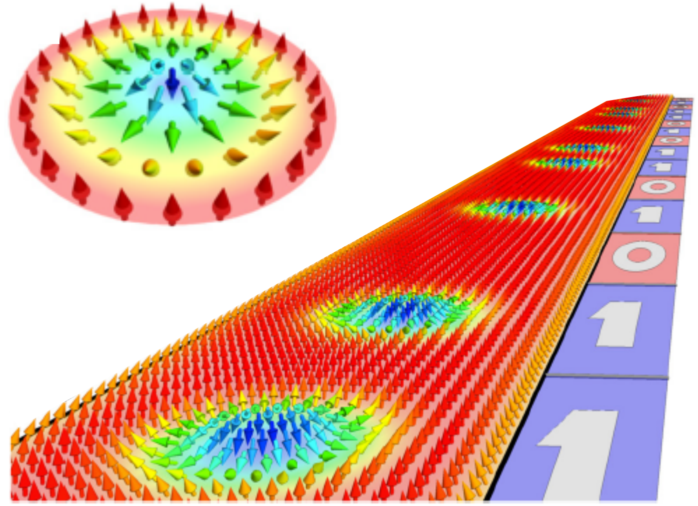

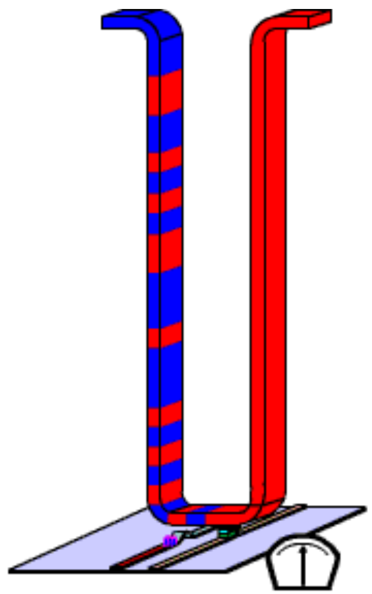

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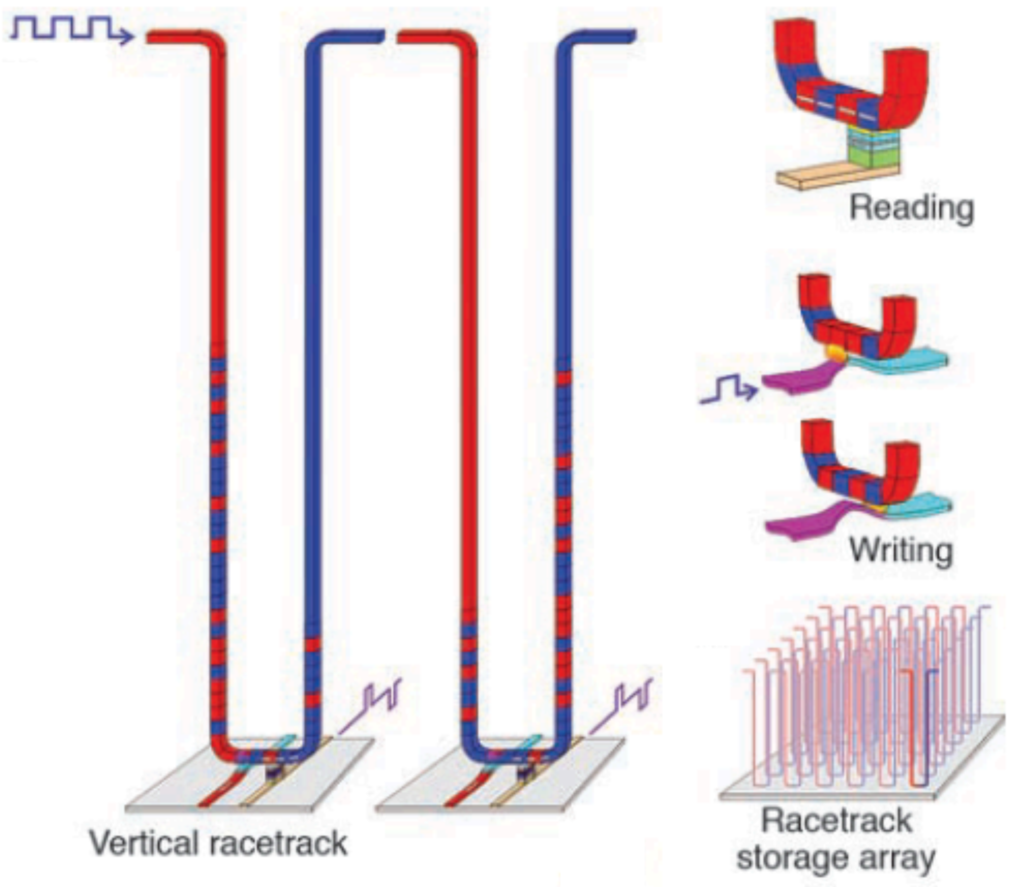

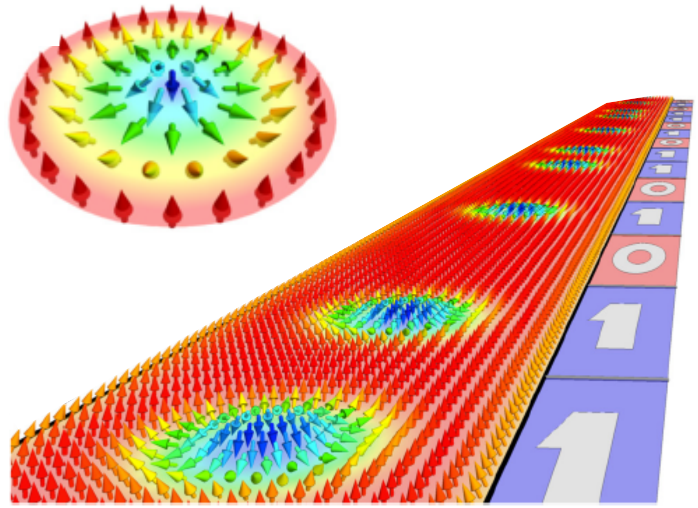

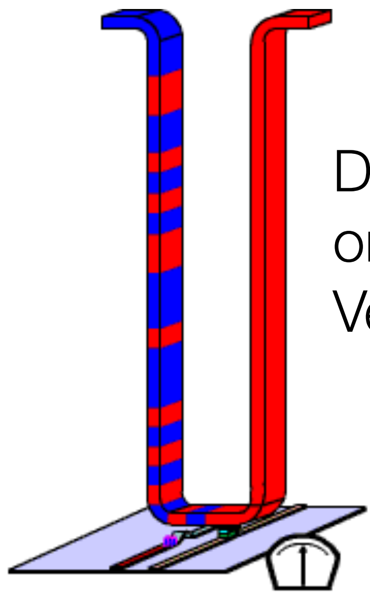

Driving domain walls
or Skyrmions →SOT
Velocities > 1km/s

Everschorr-Sitte *et al. J. Appl. Phys.* (2018)
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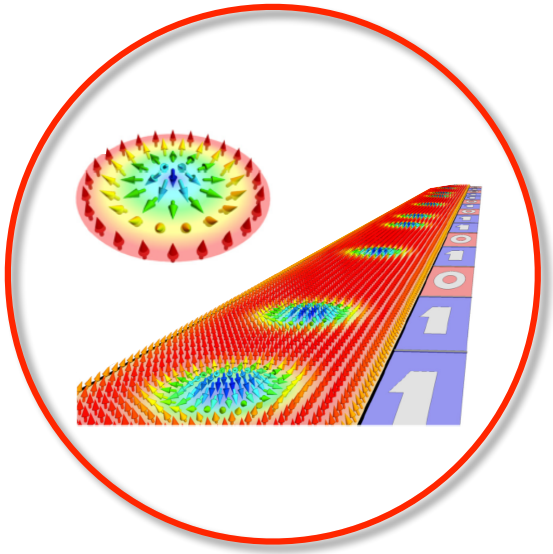

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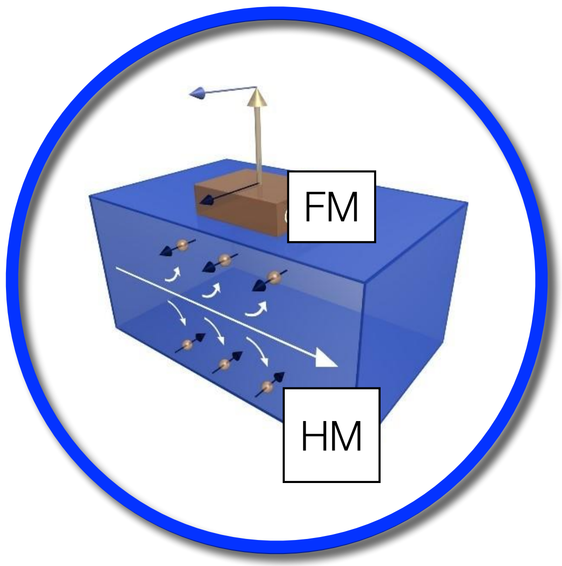

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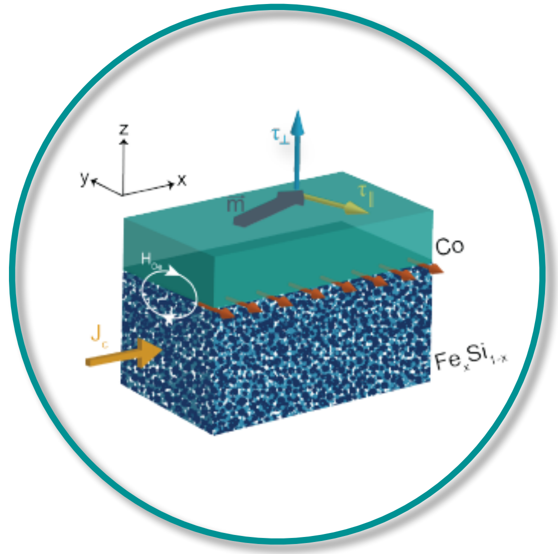
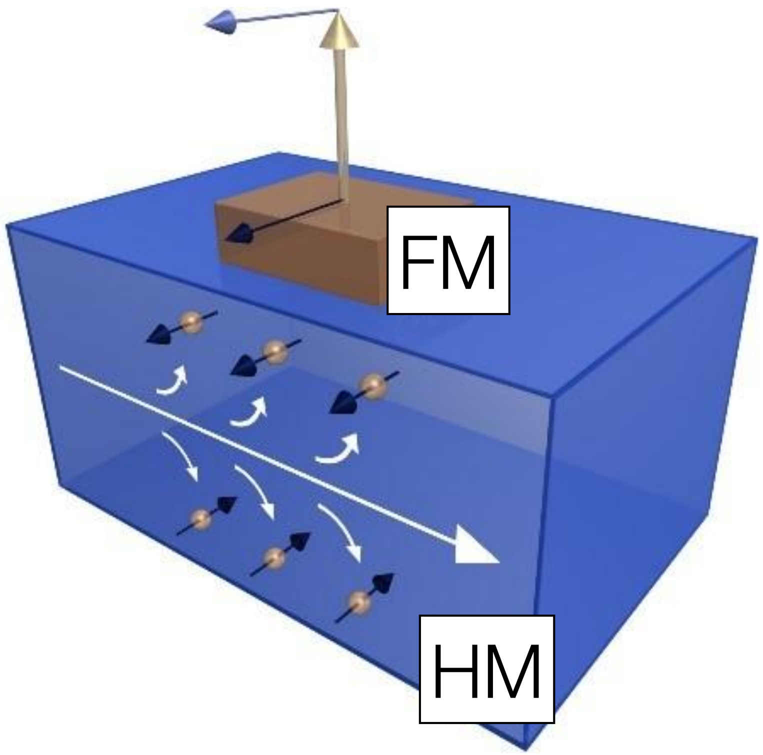


Using amorphous materials to create spin currents

Spin Currents and Spin Orbit Torque

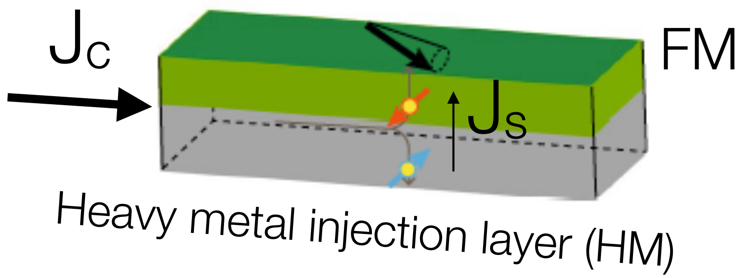
- Transfer of angular momentum from orbital to spins
- Different than spin transfer torque
- Charge to spin current conversion
  - Current induced switching



Vedmedenko *et al. J.Phys. D: Appl. Phys.* (2020)
Image: NIST Gaithersburg, MD USA

Charge to Spin Current Conversion

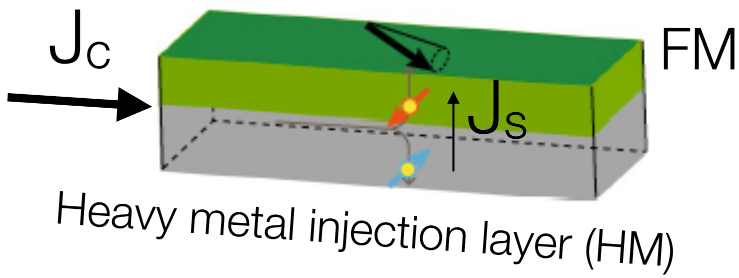
- Non-magnets



Iihama *et al. Nature Electronics* (2018)
Vedmedenko *et al. J.Phys. D: Appl. Phys.* (2020)

Charge to Spin Current Conversion

- Non-magnets
  - Spin Hall effect



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Charge to Spin Current Conversion

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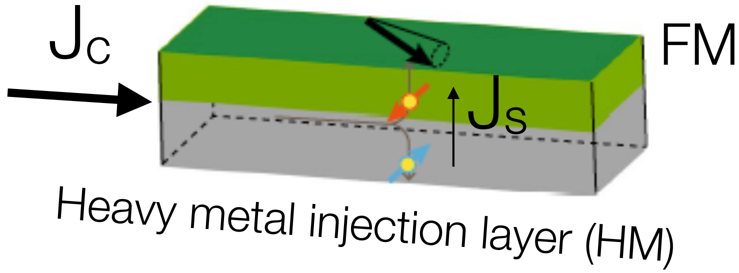
  - Rashba-Edelstein effect



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Charge to Spin Current Conversion

- Non-magnets
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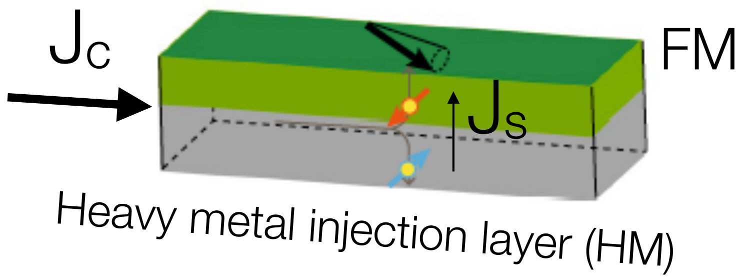
  - Rashba-Edelstein effect
  - Spin momentum locking in TI



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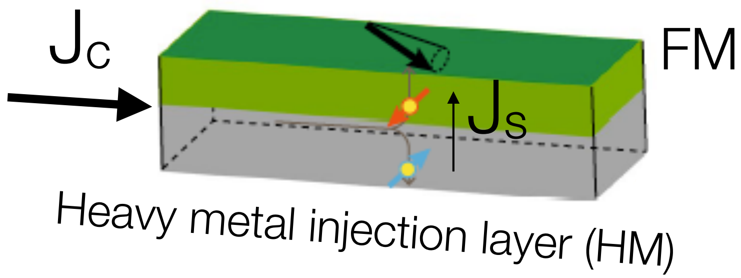

- Ferromagnets
  - Anomalous Hall effect

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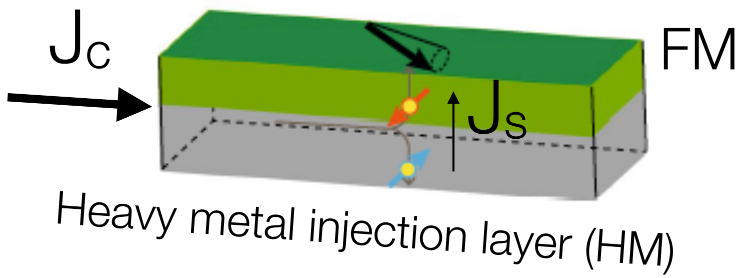

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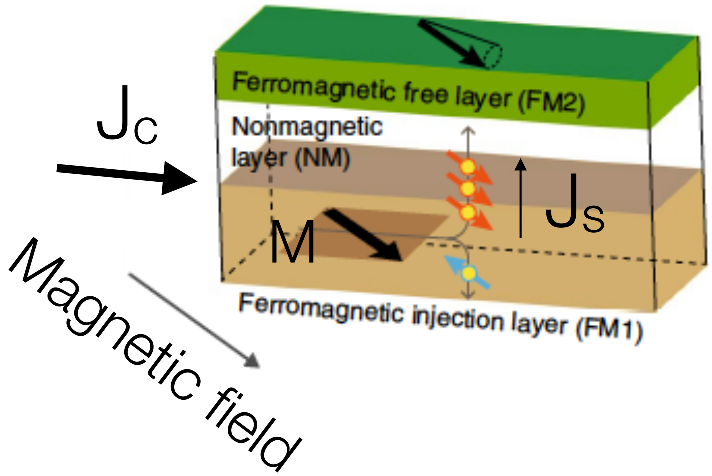

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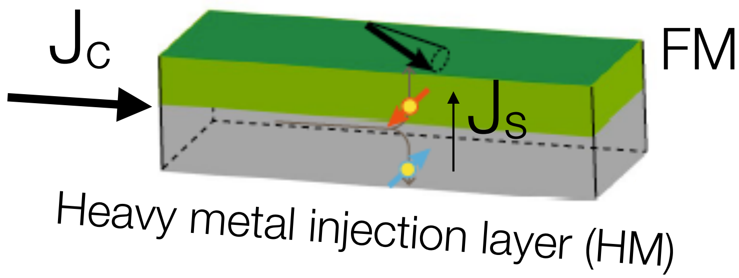

$$\xi = \frac{\text{spin current}}{\text{charge current}}$$

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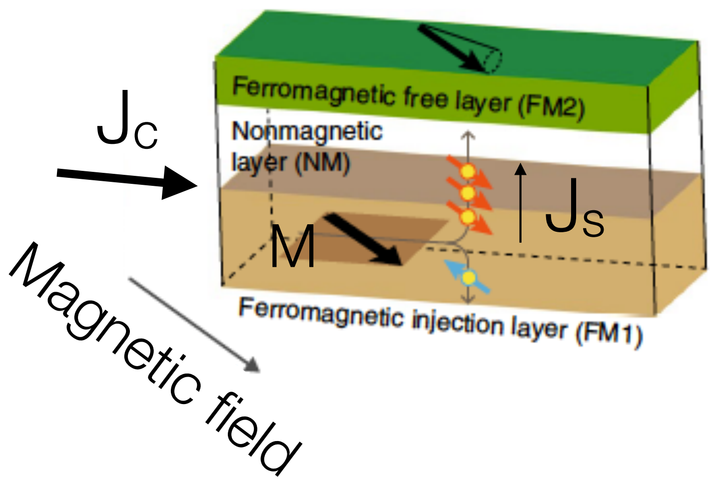

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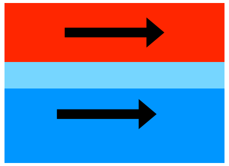
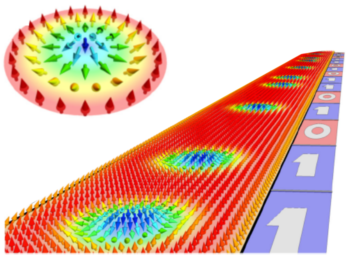
Materials and Challenges



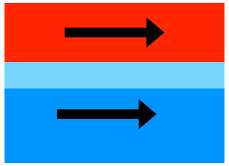
SOT-MRAM



Racetrack
Memory

Torrejon *et al. Nature* (2018)
Manipatruni *et al. Nature Physics* (2018)
Vedmedenko *et al. J.Phys. D: Appl. Phys.* (2020)

Materials and Challenges



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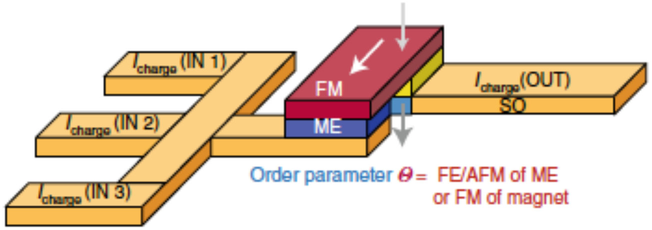
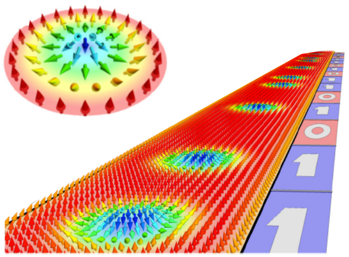


Spin Logic



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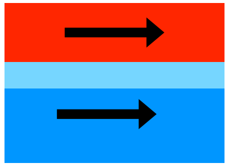

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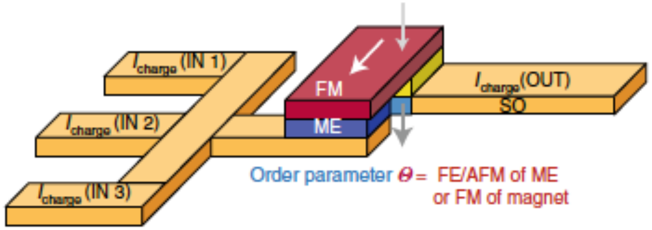

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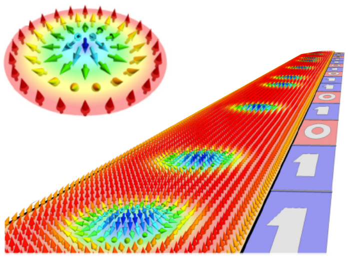

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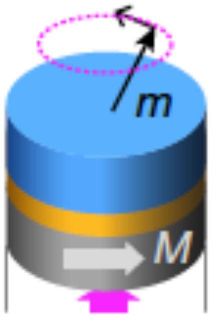

Spin Torque Nano-oscillators

Torrejon *et al. Nature* (2018)
Manipatruni *et al. Nature Physics* (2018)

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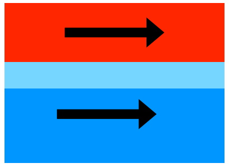

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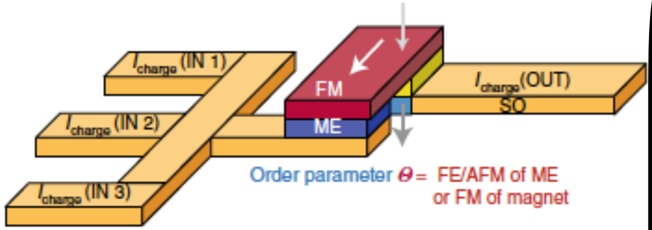

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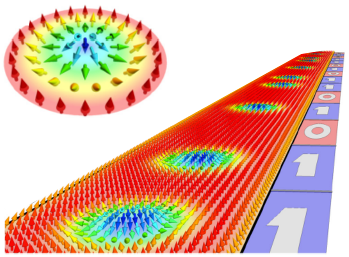

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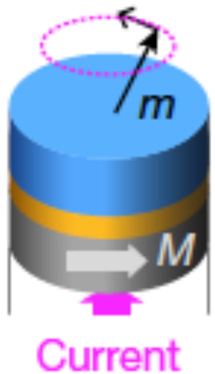
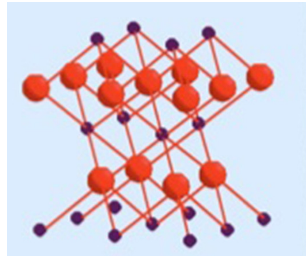


Spin Torque Nano-oscillators

Materials

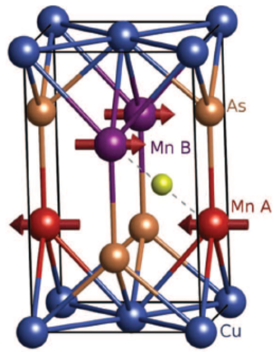


Topological Insulators

Bi_2Se_3, Bi_xSe_{1-x}, $Bi_{1-x}Sb_x$

Metals

Pt, W, Ta, Au, Ag, Dy….

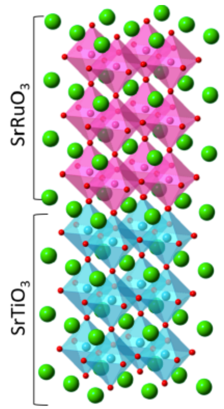


Antiferromagnets

CuMnAs, Mn_2Au, PtMn, IrMn, NiO

Oxides

$SrRuO_3$, $SrIrO_3$, IrO_2



Ferromagnets

CoFeB, $(Fe_{1-x}Mn_x)_{0.6}Pt_{0.4}$, NiFe

Torrejon *et al. Nature* (2018)
Manipatruni *et al. Nature Physics* (2018)

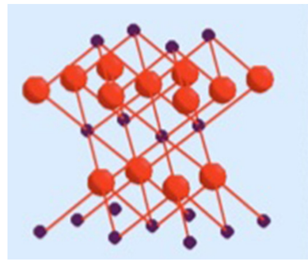
Vedmedenko *et al. J.Phys. D: Appl. Phys.* (2020)

Materials and Challenges

- Increasing ξ
- High resistivity (not compatible with low voltage devices)
- CMOS compatibility
- Air sensitivity
- Cost

Materials

Topological Insulators



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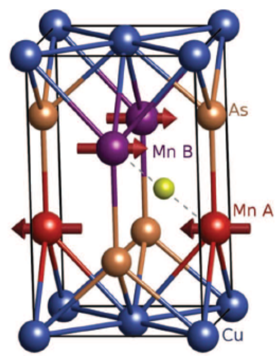

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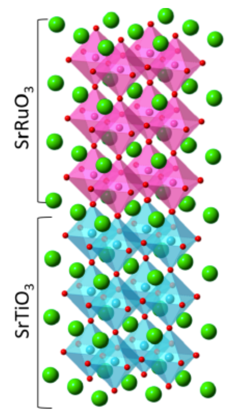

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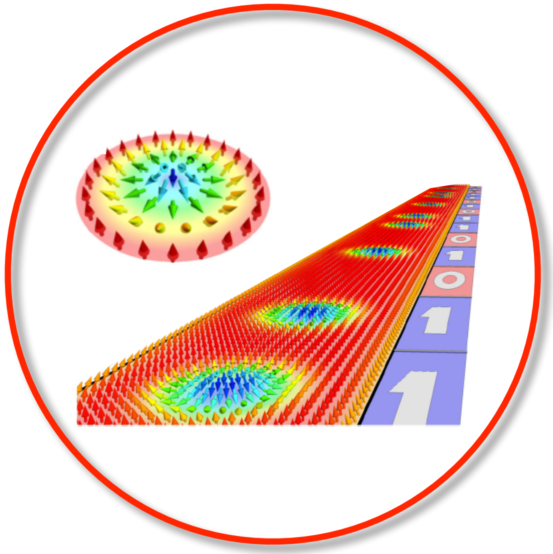
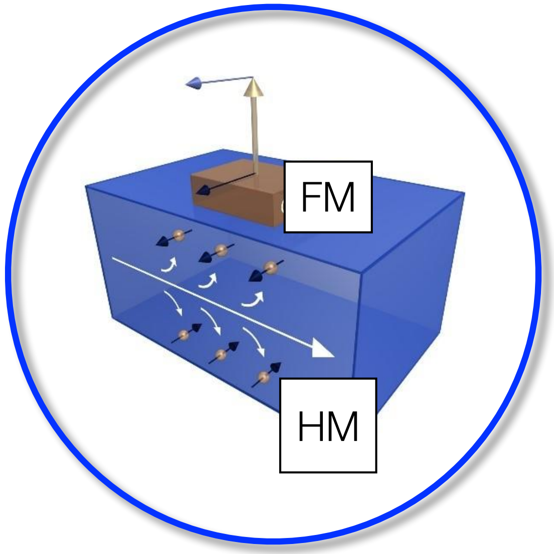


Non-volatile memory and current challenges



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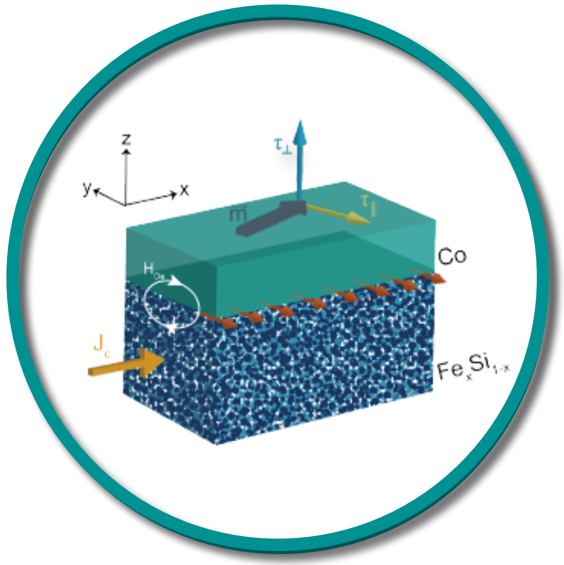

Using amorphous materials to create spin currents

Ferromagnets
Non-magnetic

Motivation

- Defect tolerant, low cost, CMOS compatible
- SHE, AHE, TI → topology in electronic structure, non-zero Berry curvature

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- Defect tolerant, low cost, CMOS compatible
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PRL **118,** 236402 (2017) PHYSICAL REVIEW LETTERS week ending 9 JUNE 2017

Topological Insulators in Amorphous Systems

Adhip Agarwala and Vijay B. Shenoy*
Department of Physics, Indian Institute of Science, Bangalore 560012, India
(Received 31 March 2017; published 8 June 2017)

PHYSICAL REVIEW LETTERS **123,** 076401 (2019)

Editors' Suggestion

Topological Amorphous Metals

Yan-Bin Yang,[1] Tao Qin,[2] Dong-Ling Deng,[1] L.-M. Duan,[1] and Yong Xu[1*]
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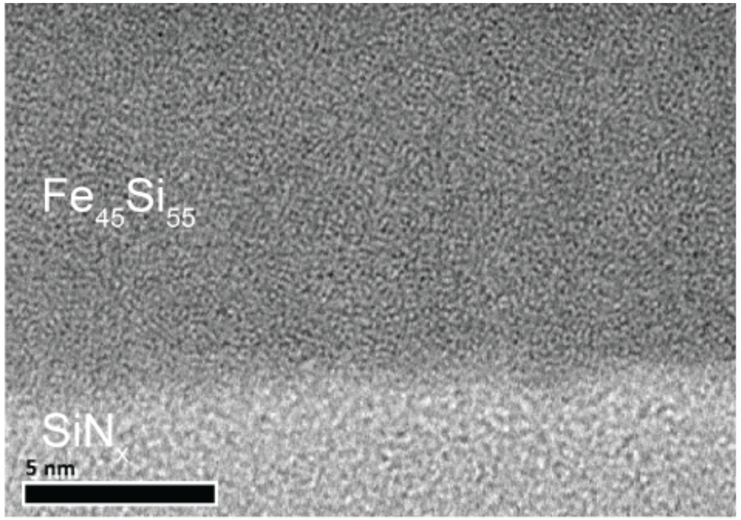
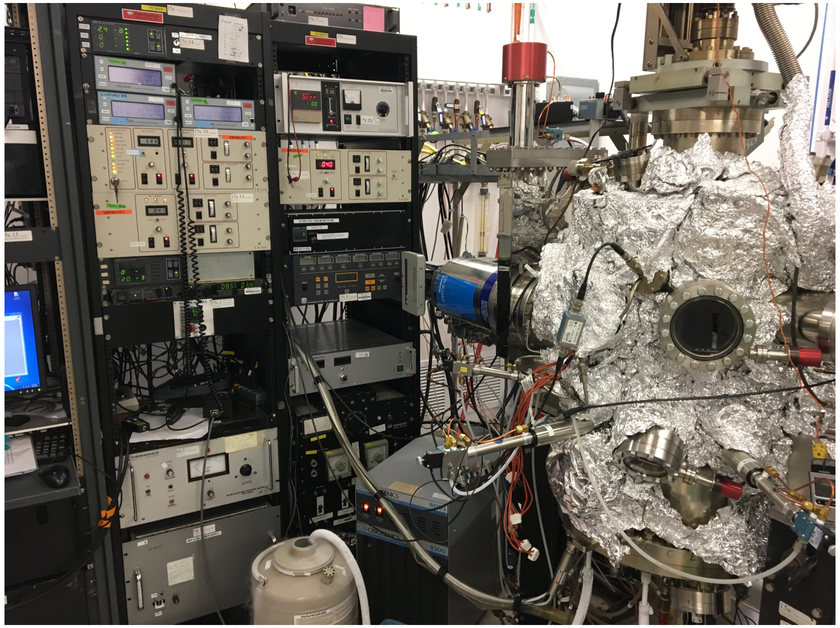
Thin Film Experimental Procedure

Amorphous Fe_xSi_{1-x}, Fe_xGe_{1-x}, $Fe_{1-y}Co_ySi_{1-x}$, Co_xSi_{1-x}, Co_xGe_{1-x} (x=0.43-0.72; y=0-0.3) thin films at room temperature on amorphous SiN_x substrates

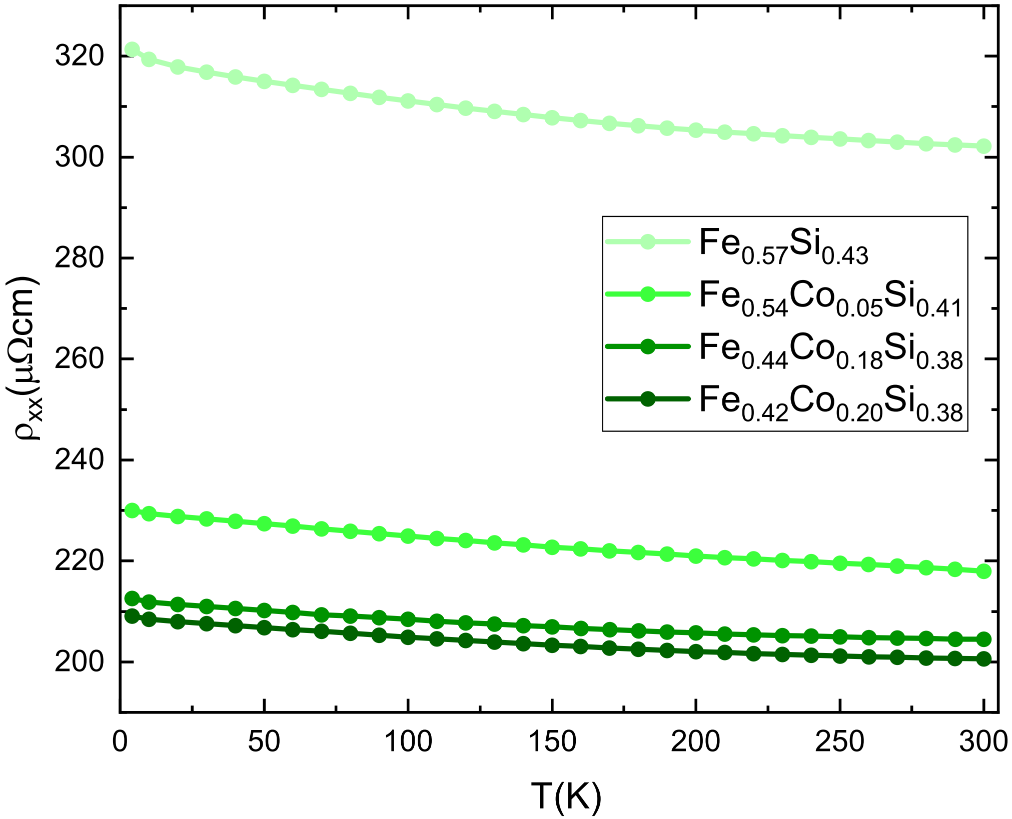




Characterization:
CEMS
XAFS
XAS/XMCD
SQUID magnetometry
HAXPES
PCAR
Electronic and magnetotransport

with F. Hellman UC Berkeley

Electronic Transport



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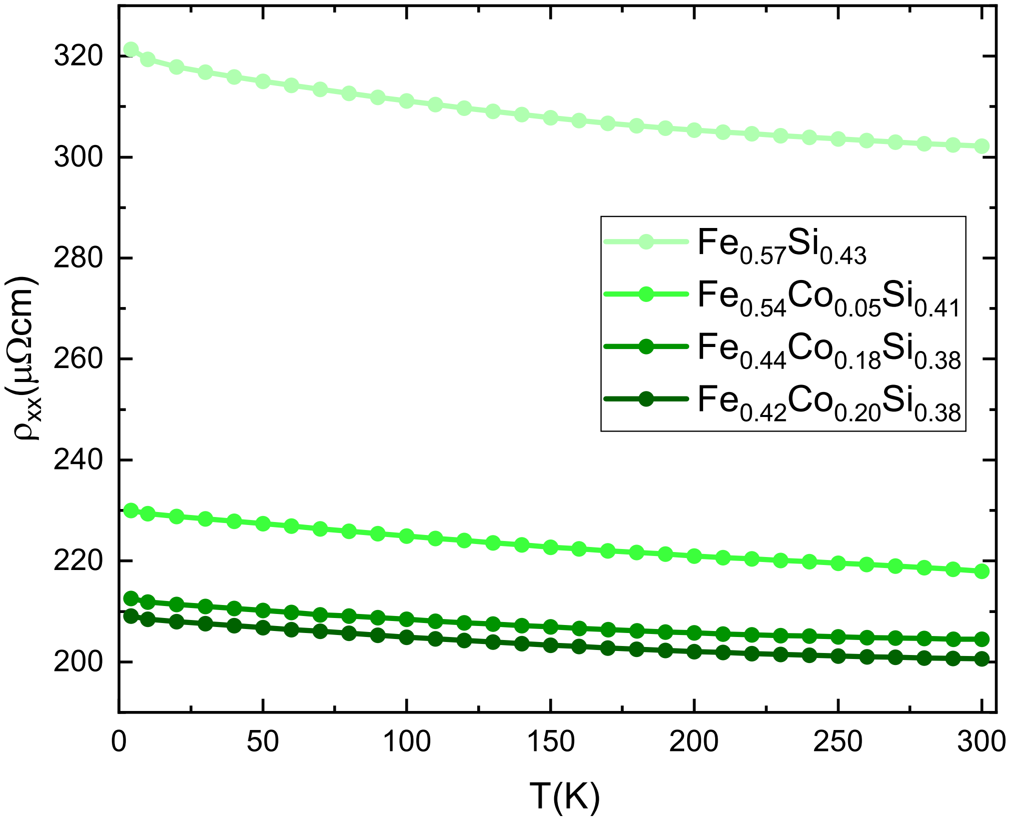
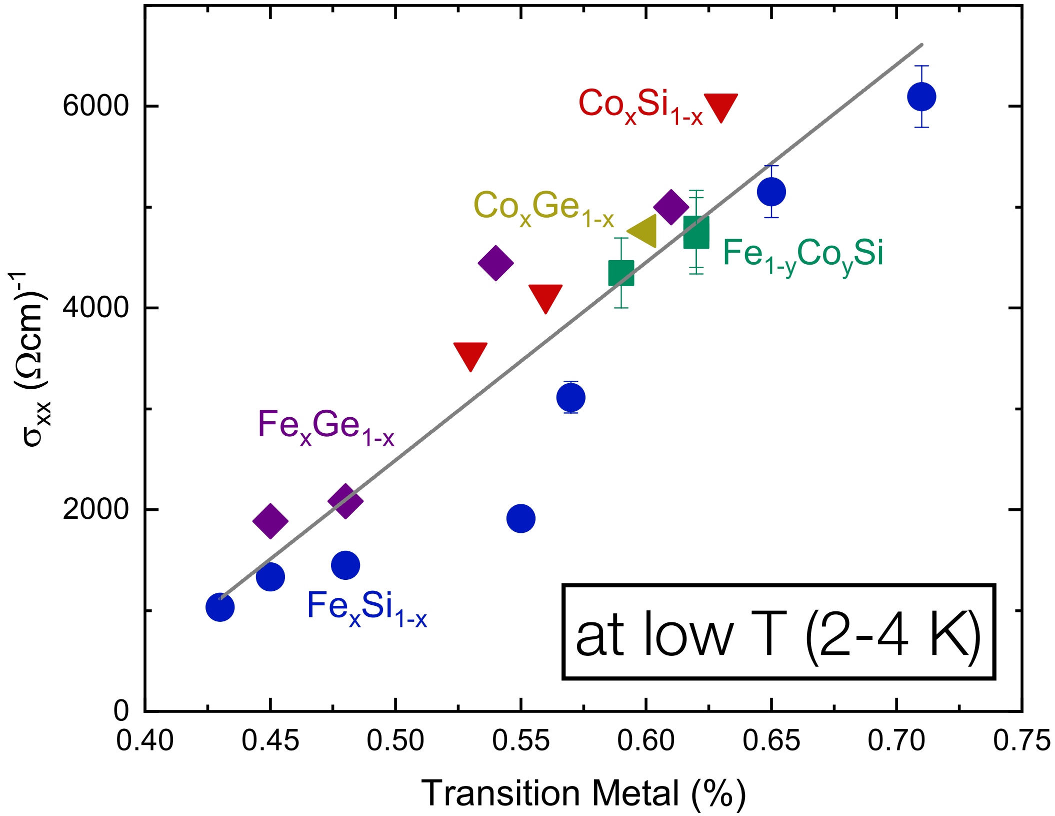
Electronic Transport





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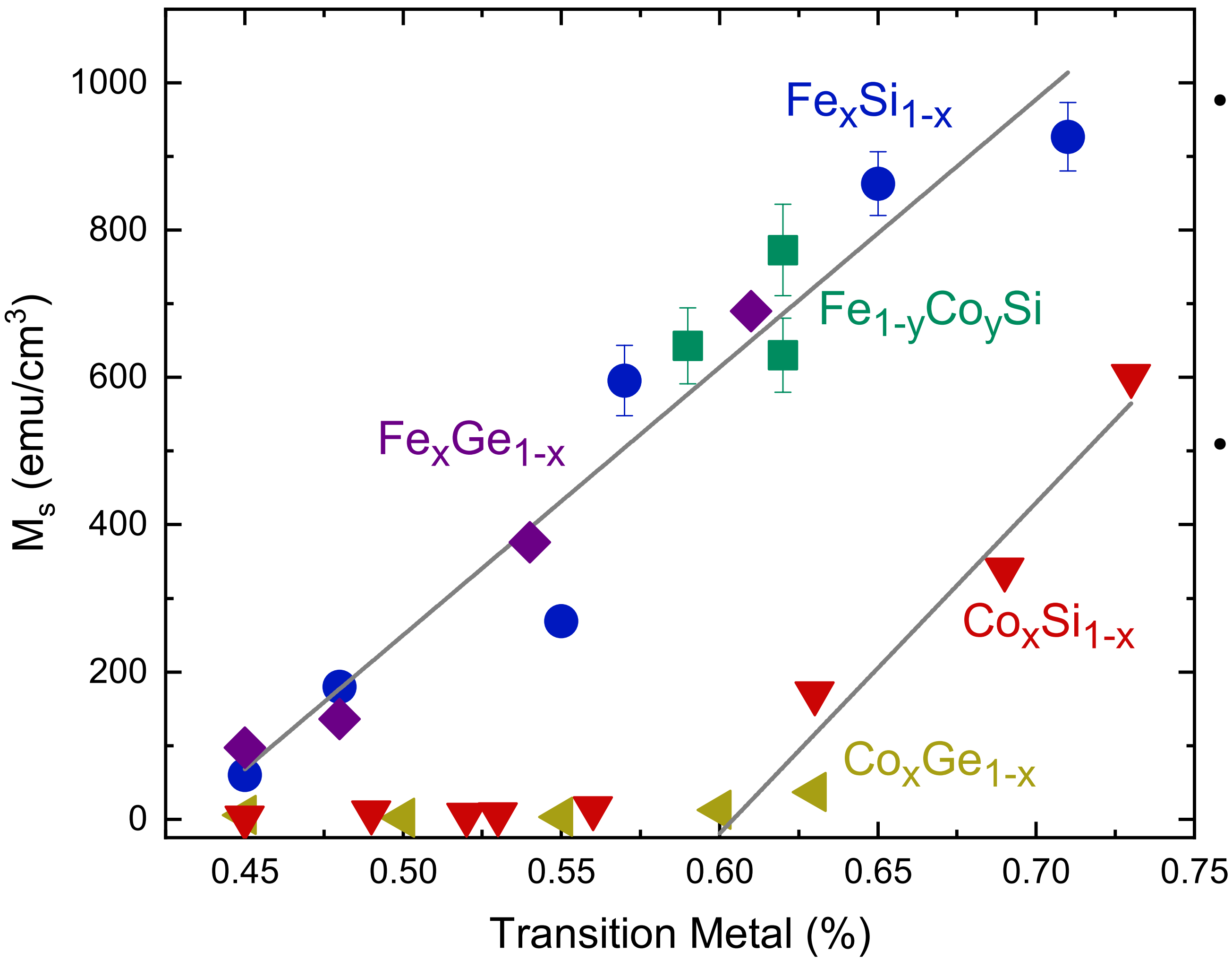
Saturation Magnetization



- For Fe-based and Co-based (>0.60) samples, FM at low T
- For Fe-based (>0.55), FM at RT

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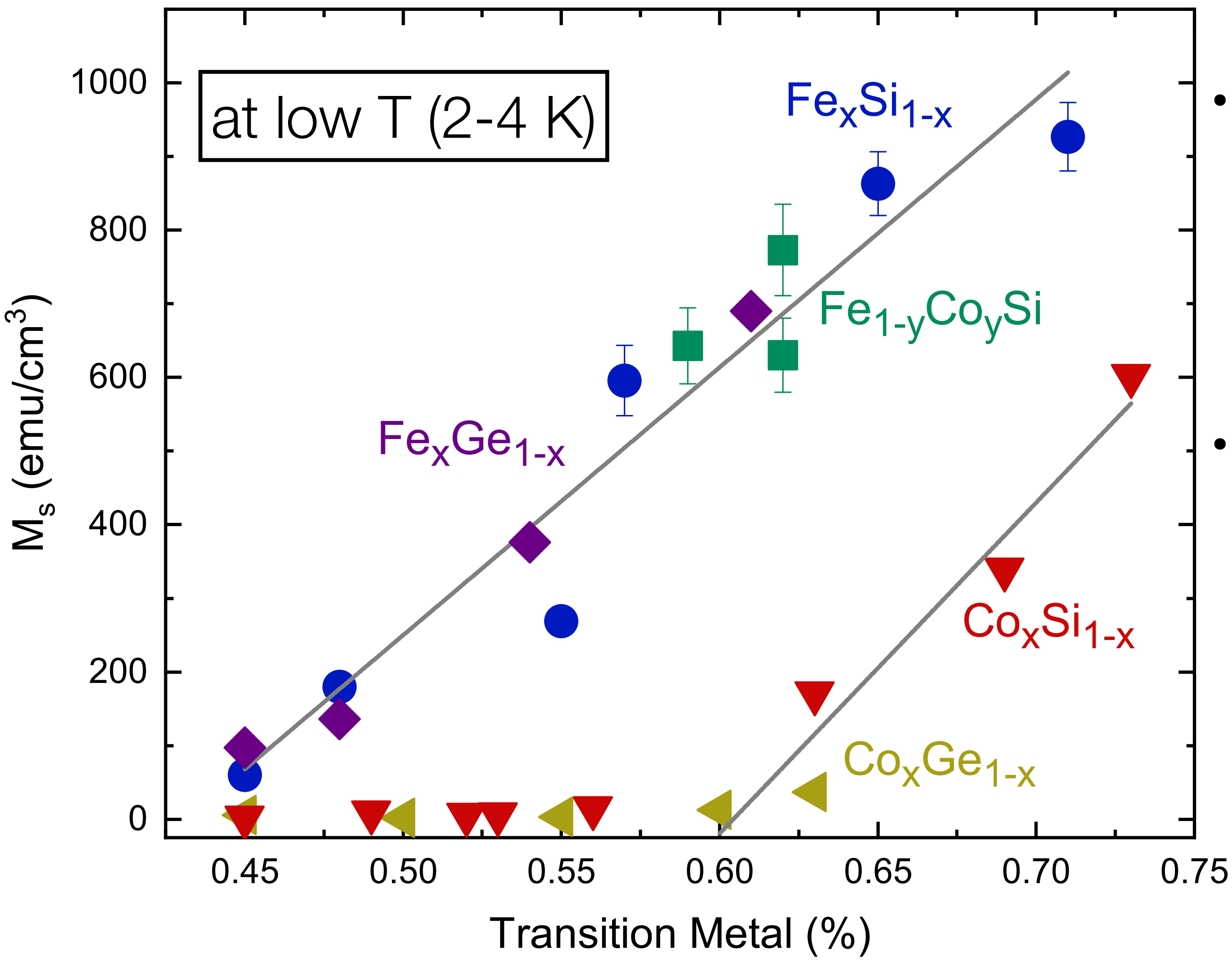

- For Fe-based and Co-based (>0.60) samples, FM at low T
- For Fe-based (>0.55), FM at RT

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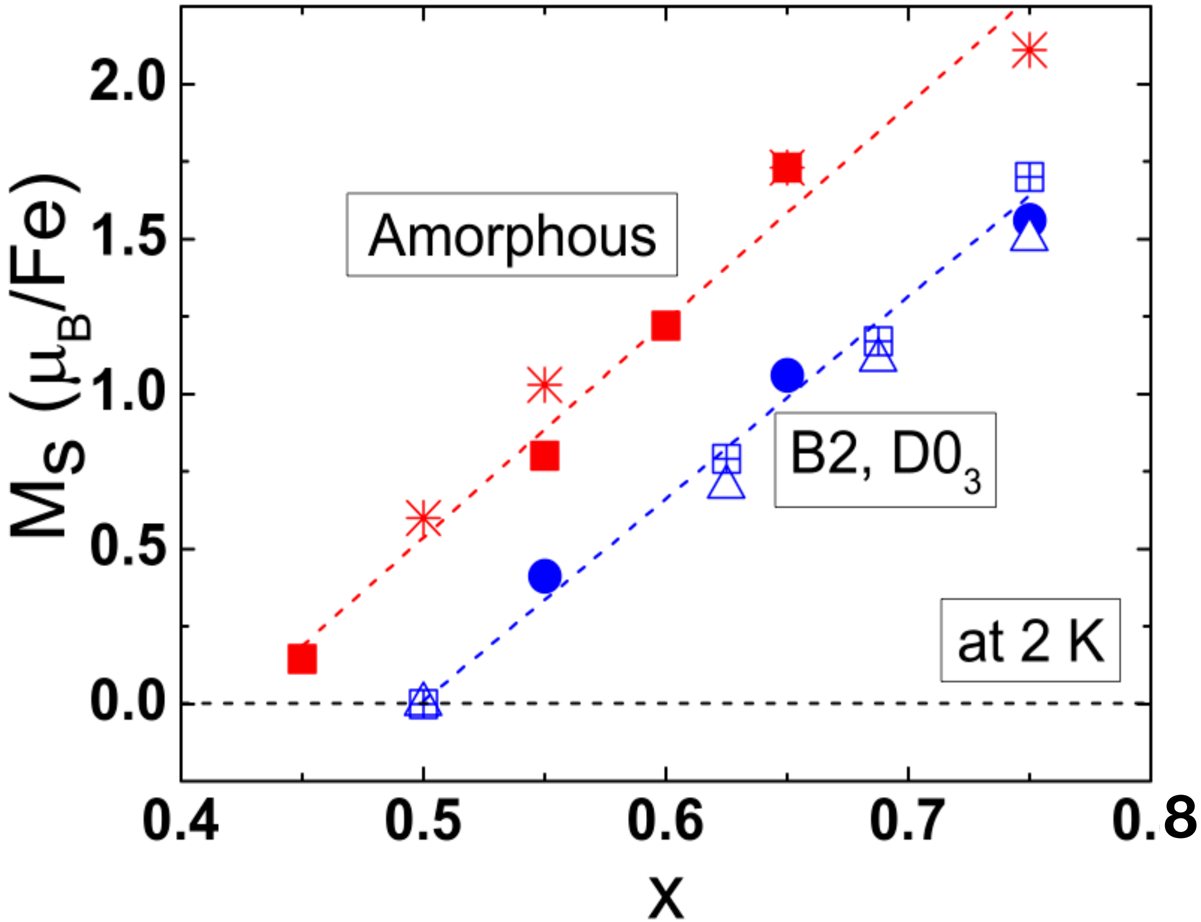
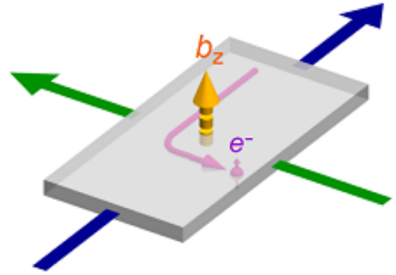
Magnetic Moment in Fe_xSi_{1-x} Thin Films

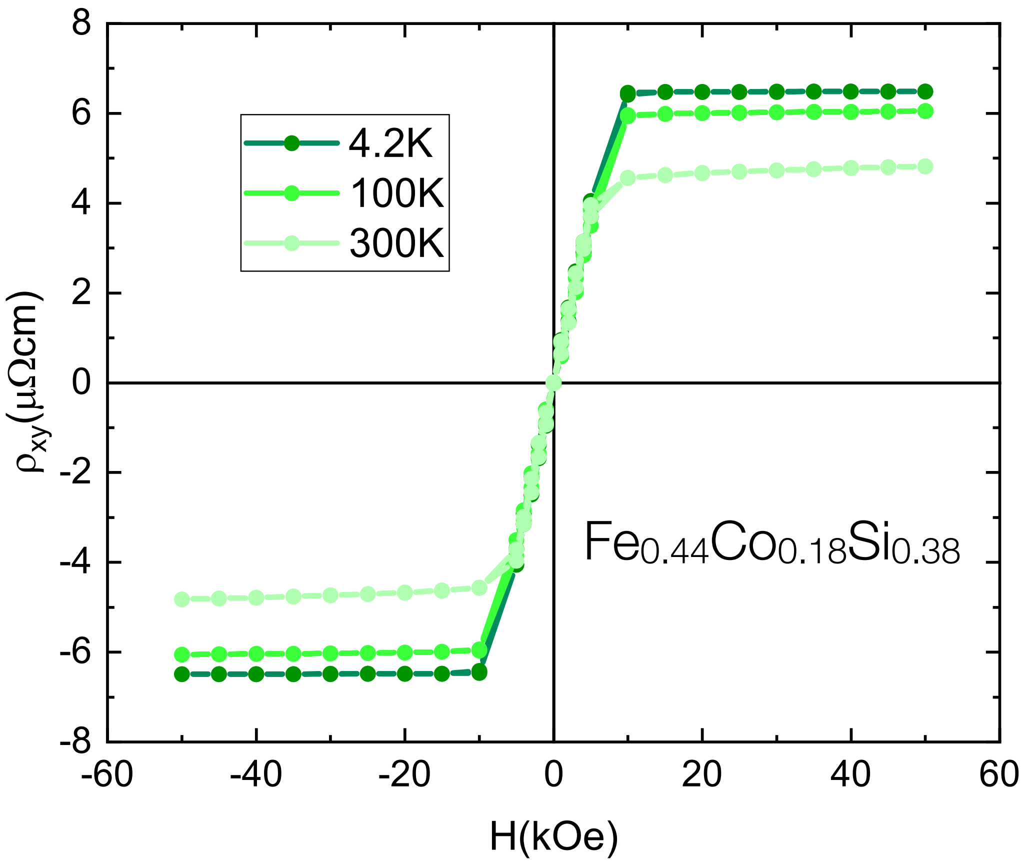
- Enhanced magnetic moment in amorphous films
- Reduction in Fe-Si first NN pairs → reduced p-d hybridization

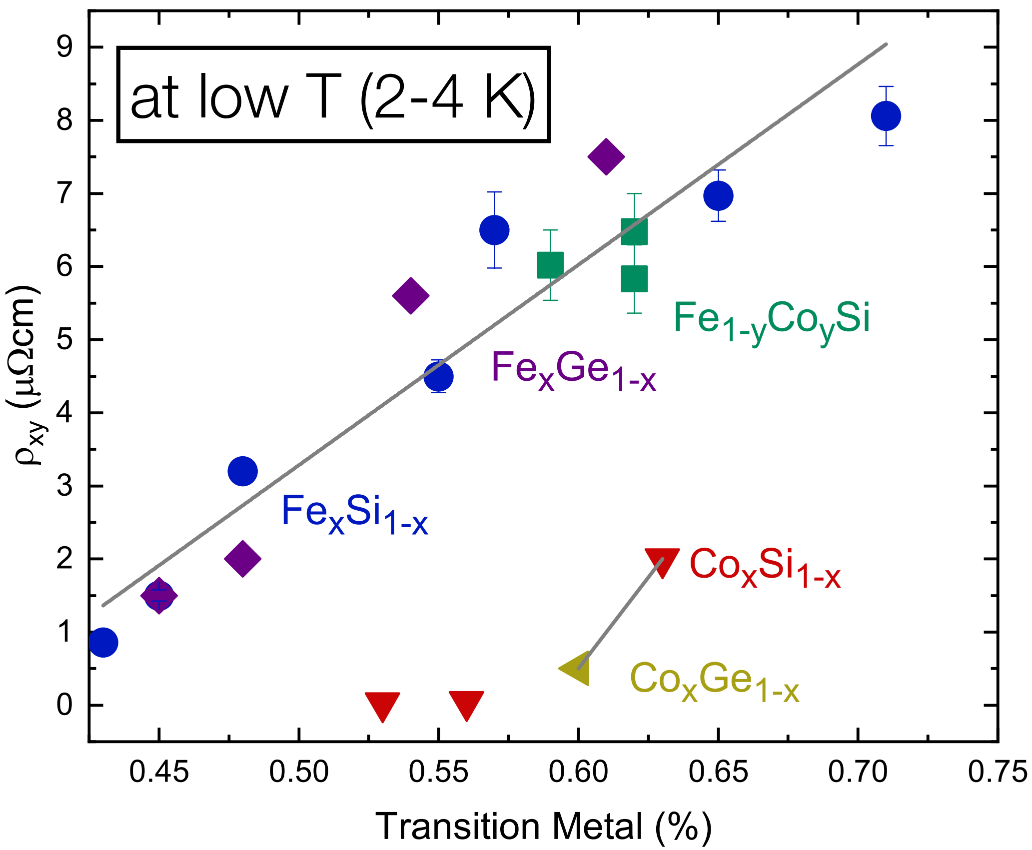


J. Karel et al. *Materials Research Express* (2014)

Anomalous Hall Effect



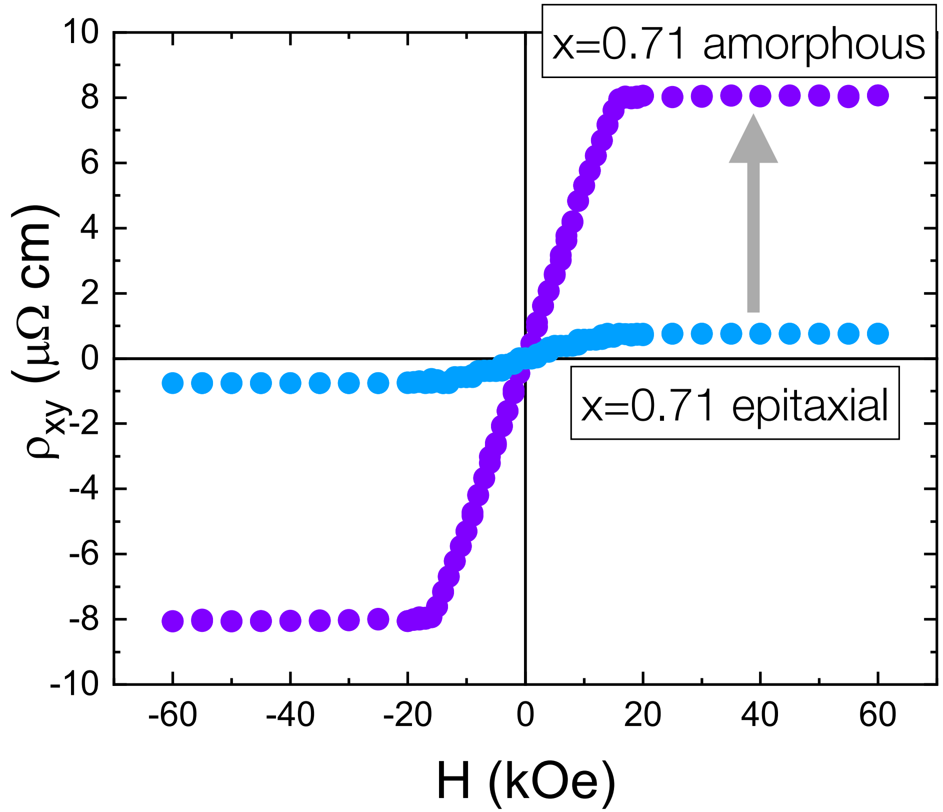




J. Karel *et al*. under review

Amorphous Materials with Large AHE

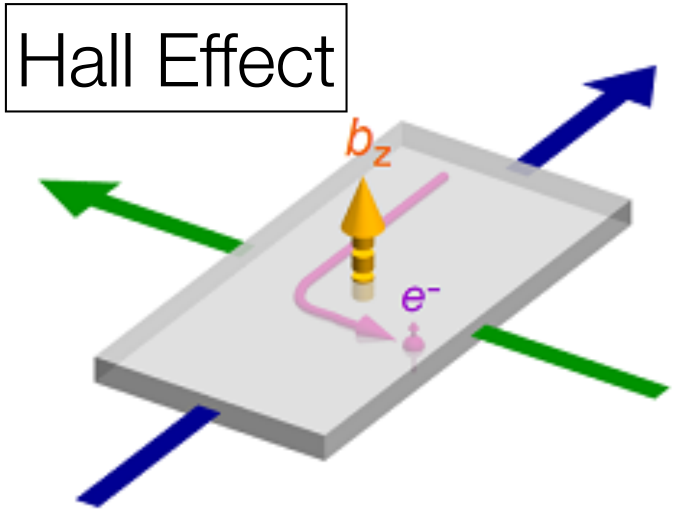
- Large AHE in amorphous Fe_xSi_{1-x} (x=0.43-0.71) in comparison to crystalline



J. Karel et al. *Europhys. Lett.* (2016)

The Anomalous Hall Effect

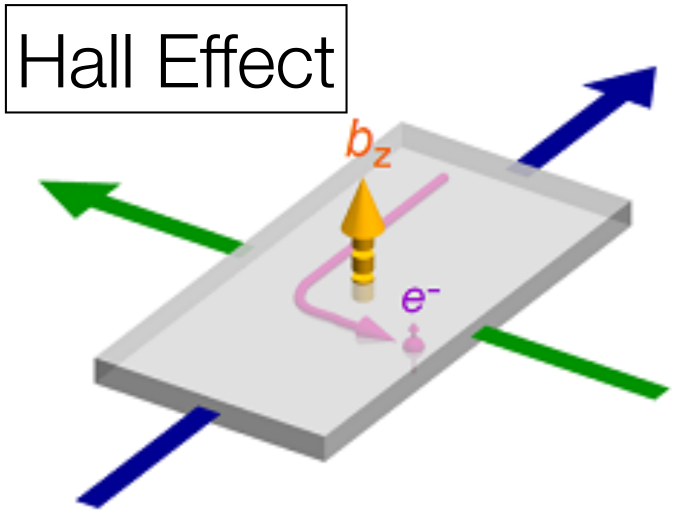
- Typically occurs in ferromagnets
- Extrinsic contribution
  - Skew-scattering
  - Side jump

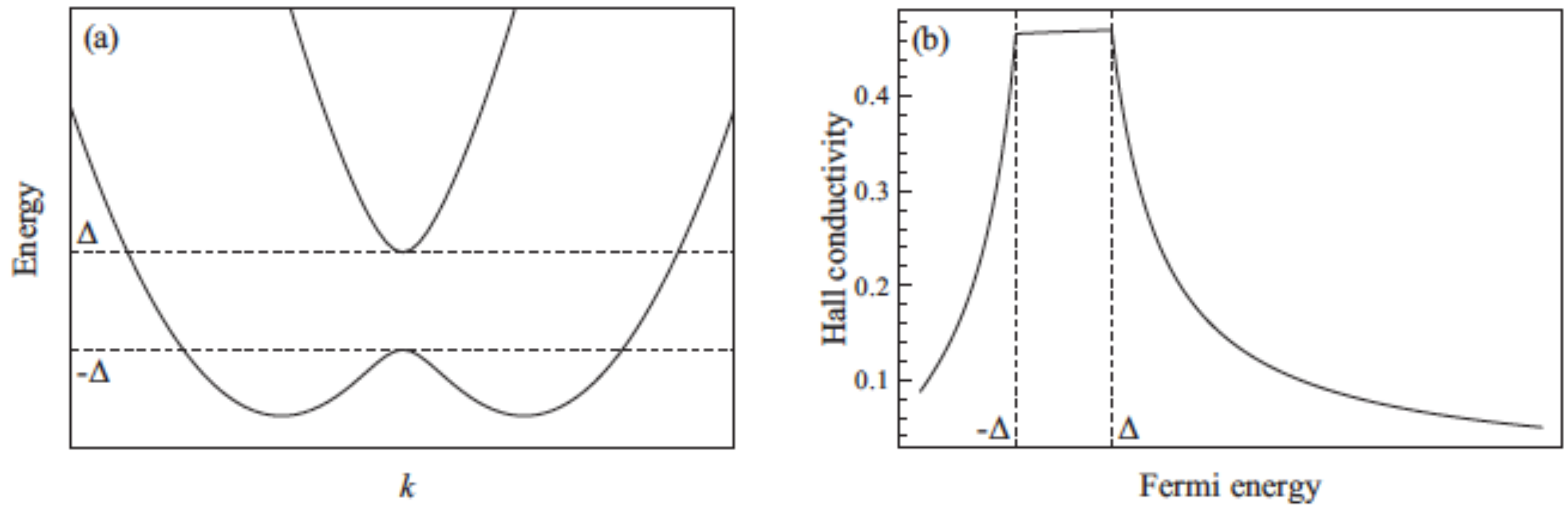


Xiao, Chang, Niu *Rev. Mod. Phys* (2010)
http://www.riken.jp/lab-www/cond-mat-theory/onoda/Pr2TM2O7.htm

The Anomalous Hall Effect

- Typically occurs in ferromagnets
- Extrinsic contribution
  - Skew-scattering
  - Side jump
- Intrinsic contribution (Berry curvature)
  - SOC opens gap
  - E_F near gap, Hall conductivity enhanced





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Unified Scaling of the AHE in Ferromagnets

σ_{xy} $(\Omega\text{-cm})^{-1}$

σ_{xx} $(\Omega\text{-cm})^{-1}$

$\sigma_{xy}=\rho_{xy}/\rho_{xx}^2$

S. Onoda et. al. *PRL.* 2006)
N. Nagaosa et al., *Rev. Mod. Phys.*(2010)

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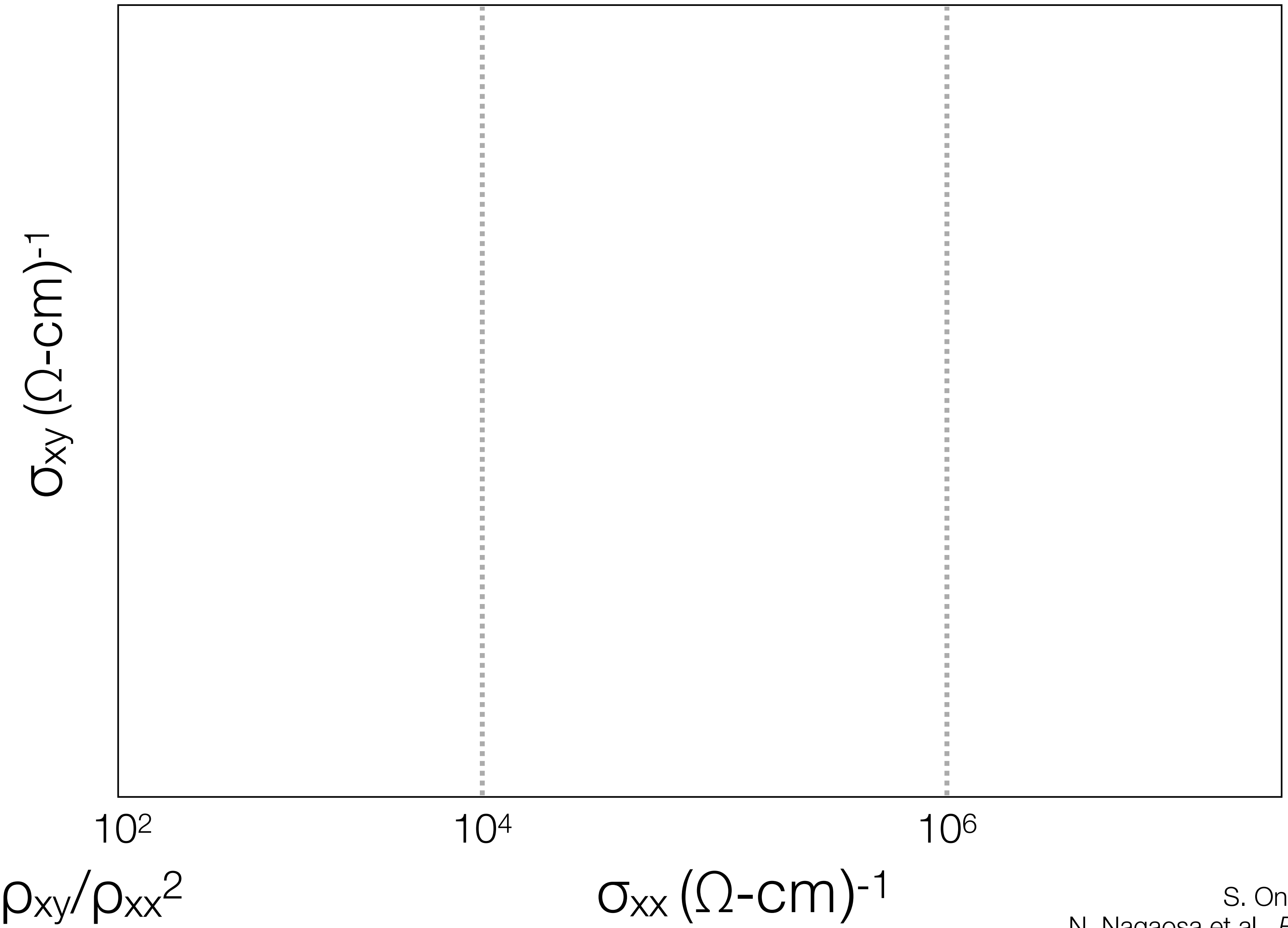

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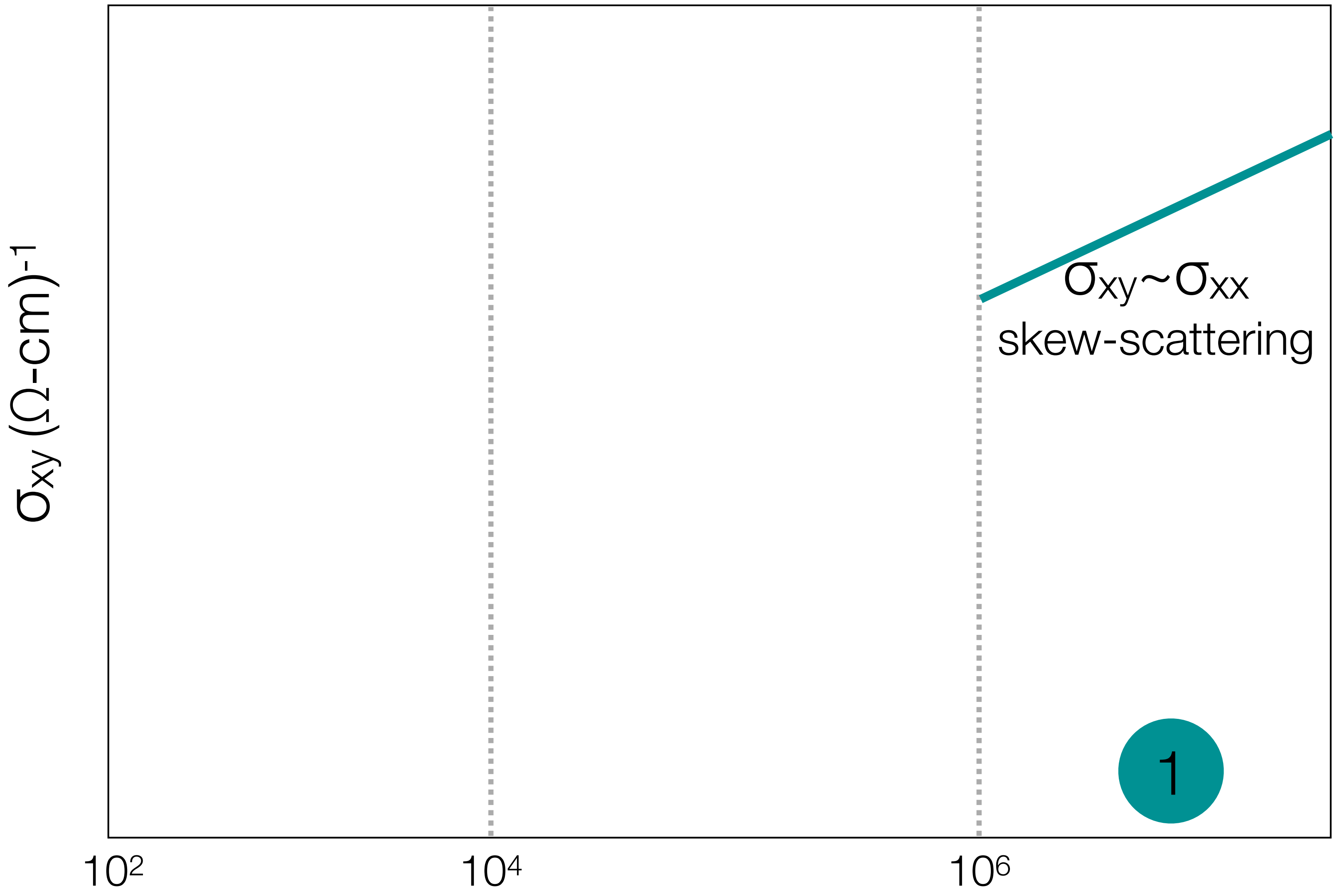

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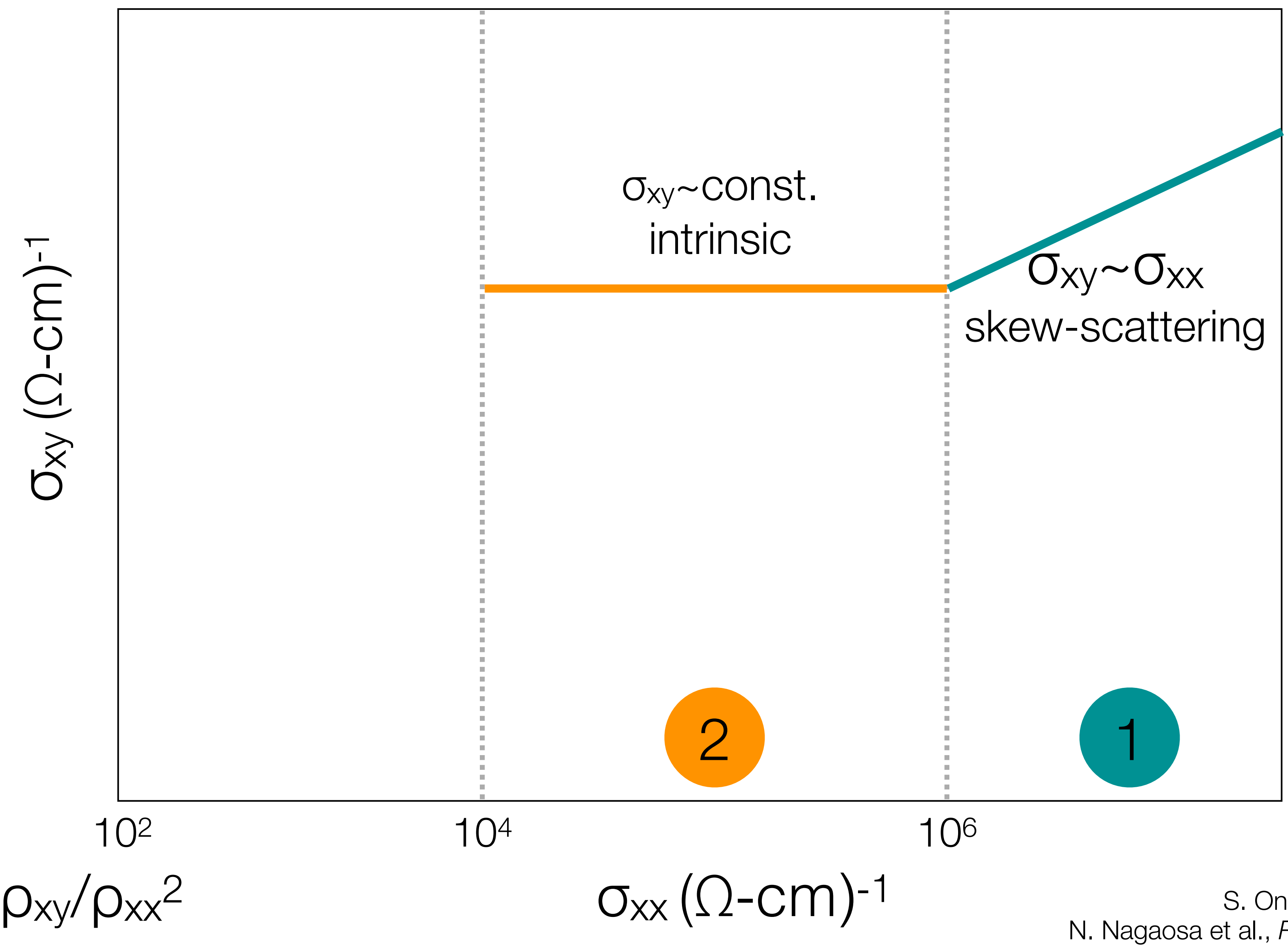

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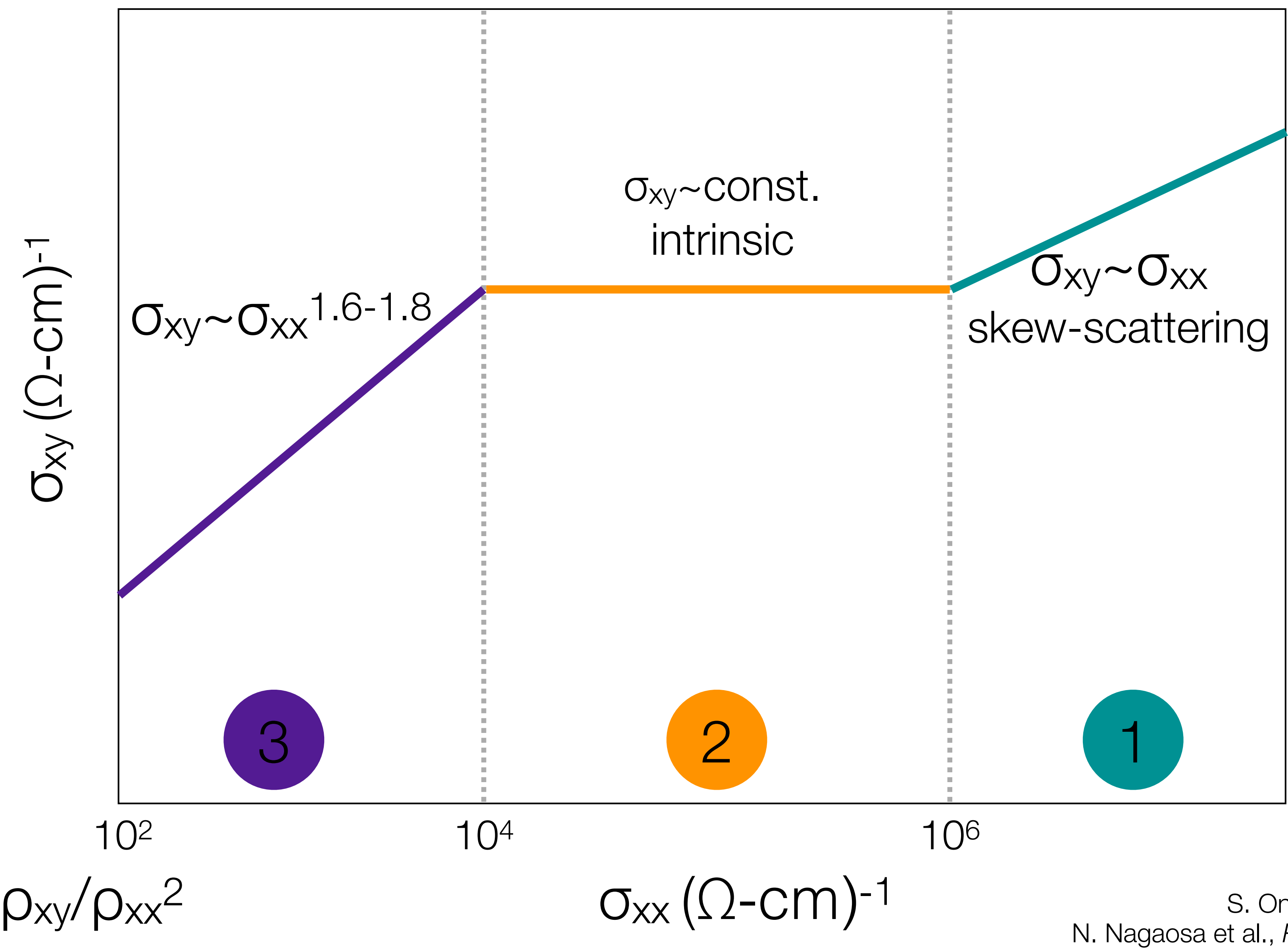

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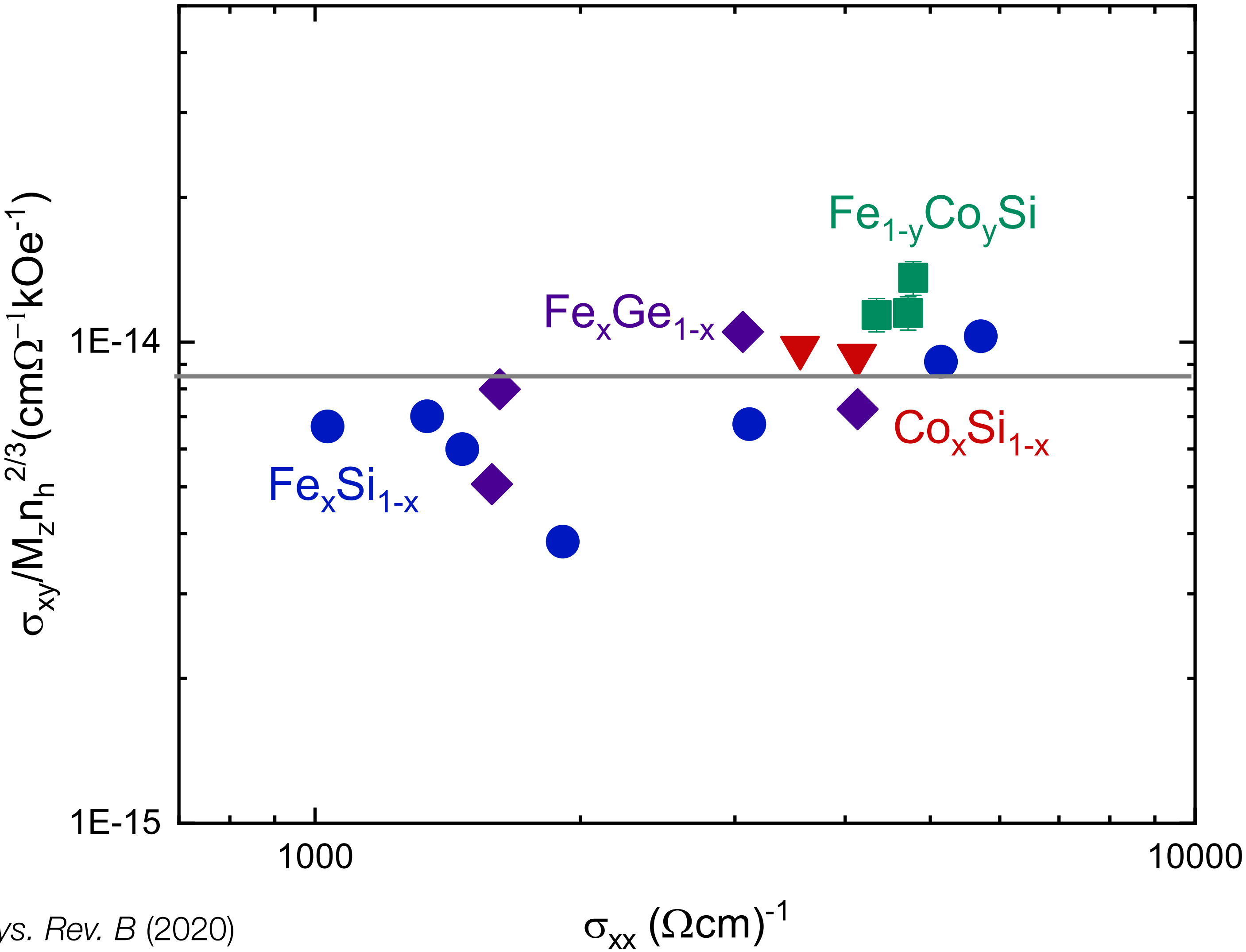
Scaling of the AHE



S. Bouma *et al. Phys. Rev. B* (2020)
J. Karel et al. *Europhys. Lett.* (2016)
J. Karel *et al*. under review

Intrinsic AHE

- Independent of σ_{xx} → Berry phase
- Indication of role of local structure

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Locality of the anomalous Hall conductivity

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[2]*Dipartimento di Fisica, Università di Trieste, 34127 Trieste, Italy*

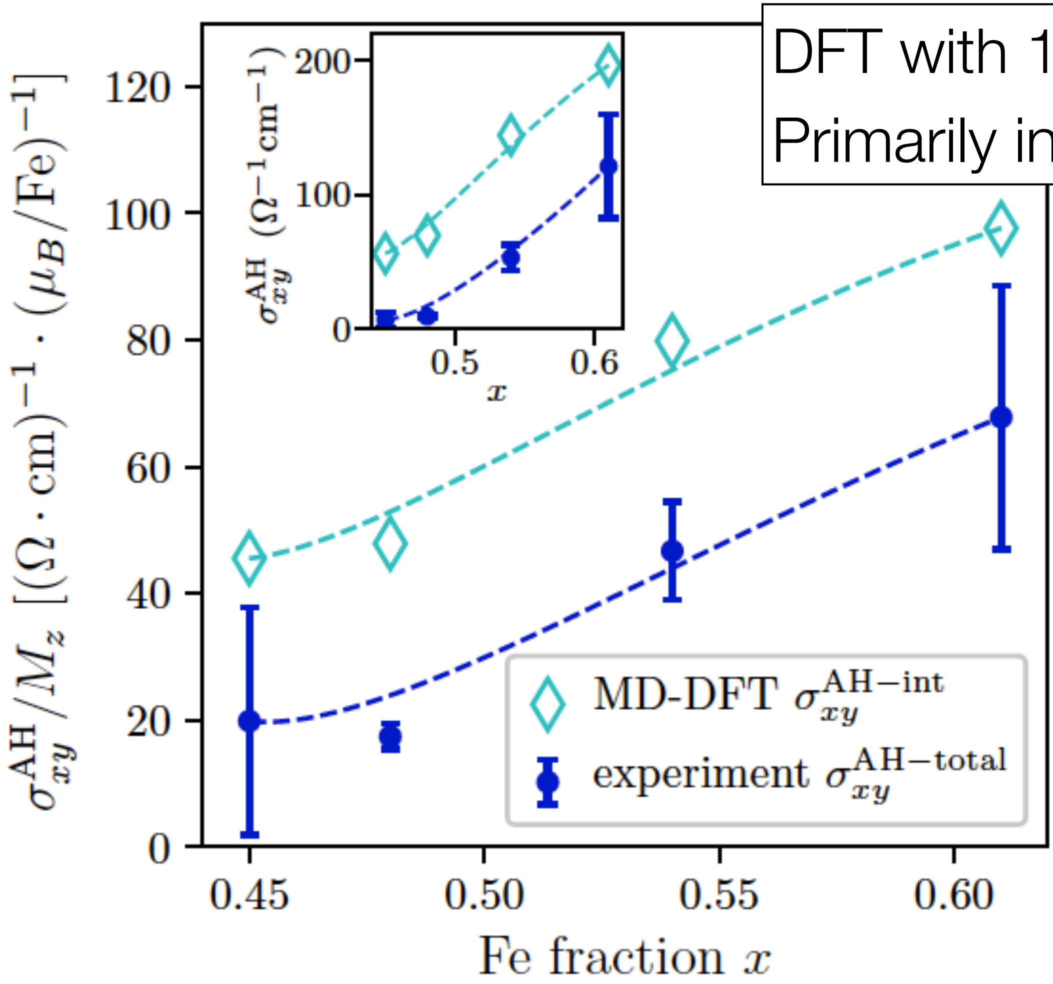
[3]*Consiglio Nazionale delle Ricerche (CNR), Istituto Officina dei Materiali (IOM) DEMOCRITOS, 34136 Trieste, Italy*

[4]*Donostia International Physics Center, 20018 San Sebastián, Spain*

(Received 23 December 2016; published 31 March 2017)

Intrinsic AHC is local property of the electronic ground state and can be evaluated for samples where the concept of reciprocal space doesn't make any sense

Intrinsic Hall Conductivity in Amorphous Fe_xGe_{1-x} and Fe_xSi_{1-x}



DFT with 128 atom supercell
Primarily intrinsic contribution

Bouma *et al. Phys. Rev. B* (2020)

with R.Q. Wu UC Irvine

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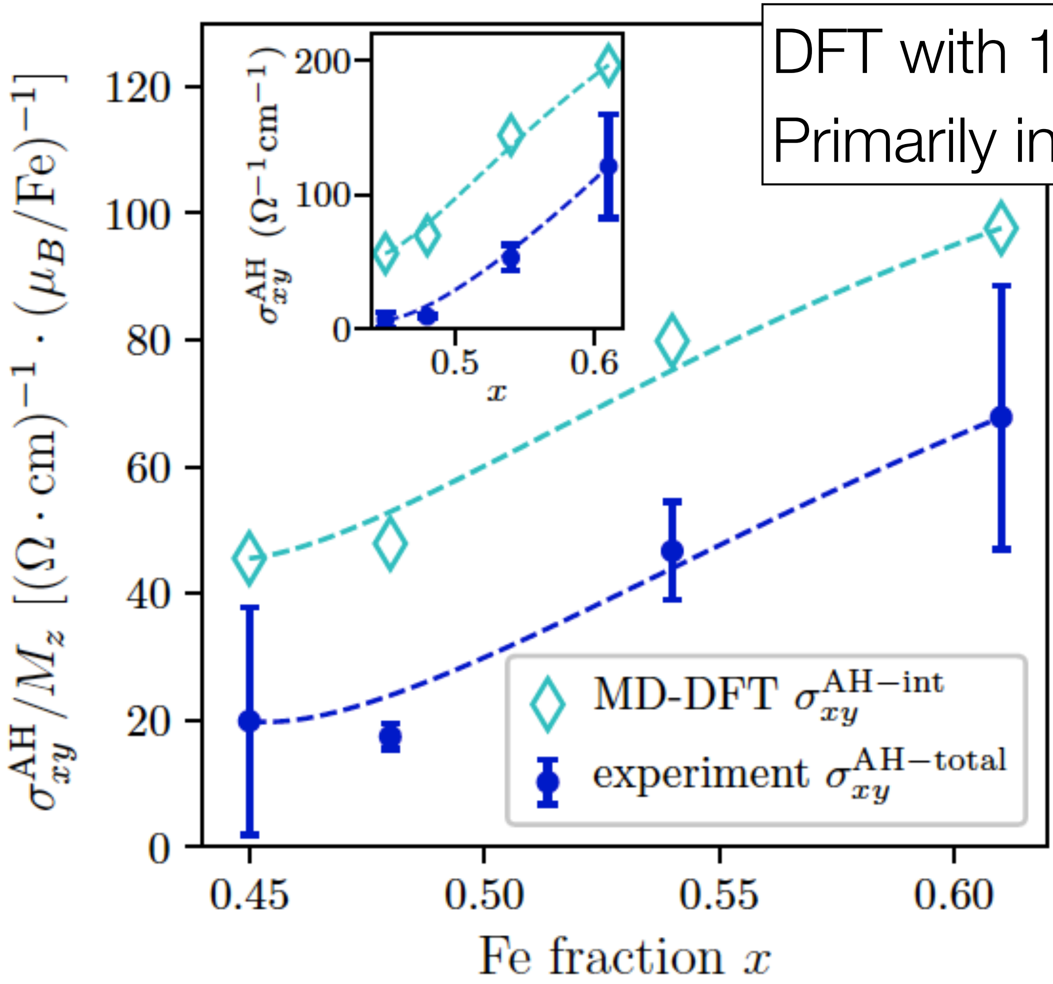


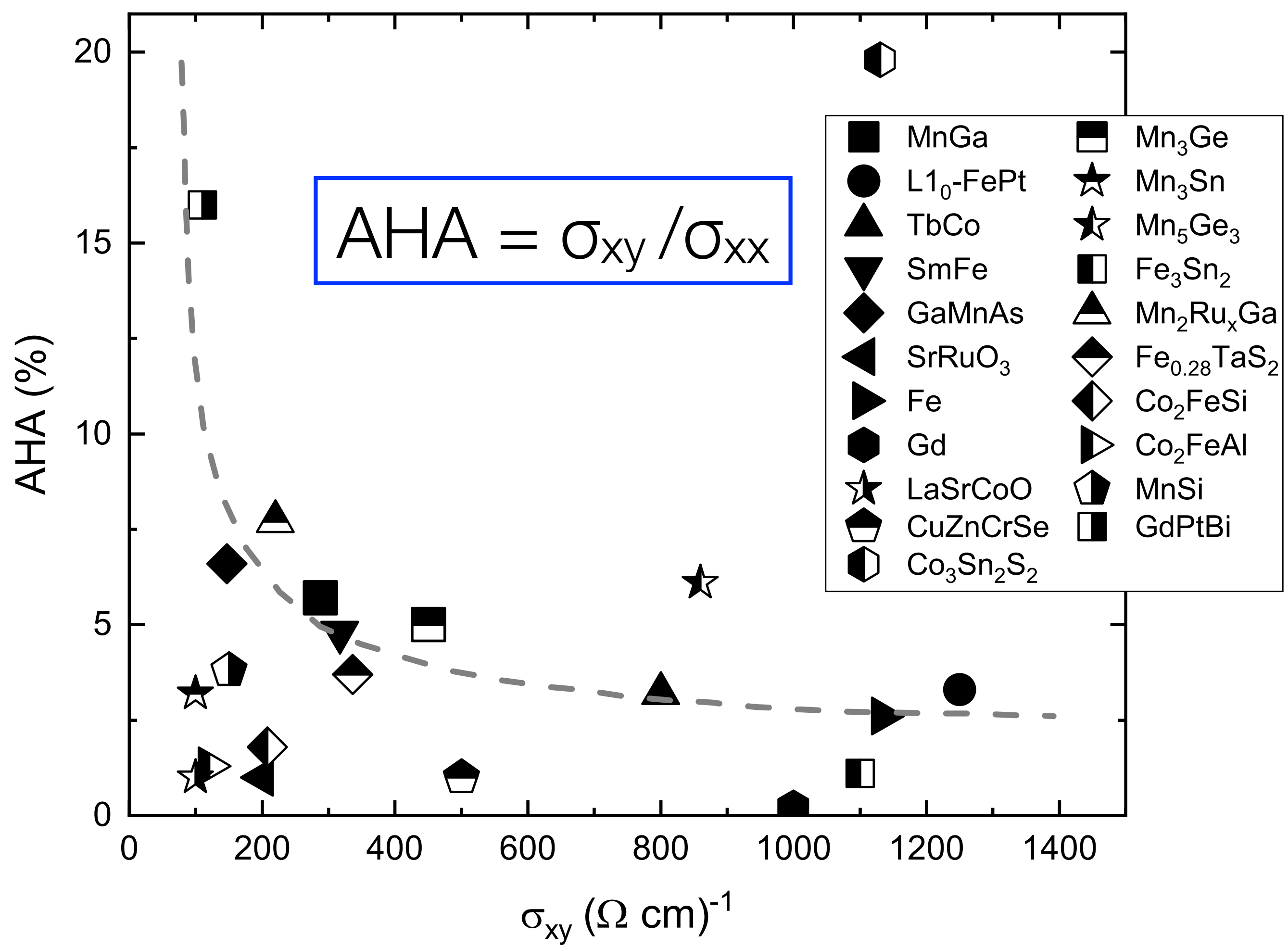
DFT with 128 atom supercell
Primarily intrinsic contribution

- Calculated amorphous Fe_xSi_{1-x} x=0.50: σ_{xy} (intrinsic) = 28 $(\Omega\text{-cm})^{-1}$
- Experimental result: x=0.55 σ_{xy} = 17 $(\Omega\text{-cm})^{-1}$ and x=0.57 σ_{xy} = 43 $(\Omega\text{-cm})^{-1}$

Bouma *et al. Phys. Rev. B* (2020)

with R.Q. Wu UC Irvine

Anomalous Hall Angle - Crystalline Materials

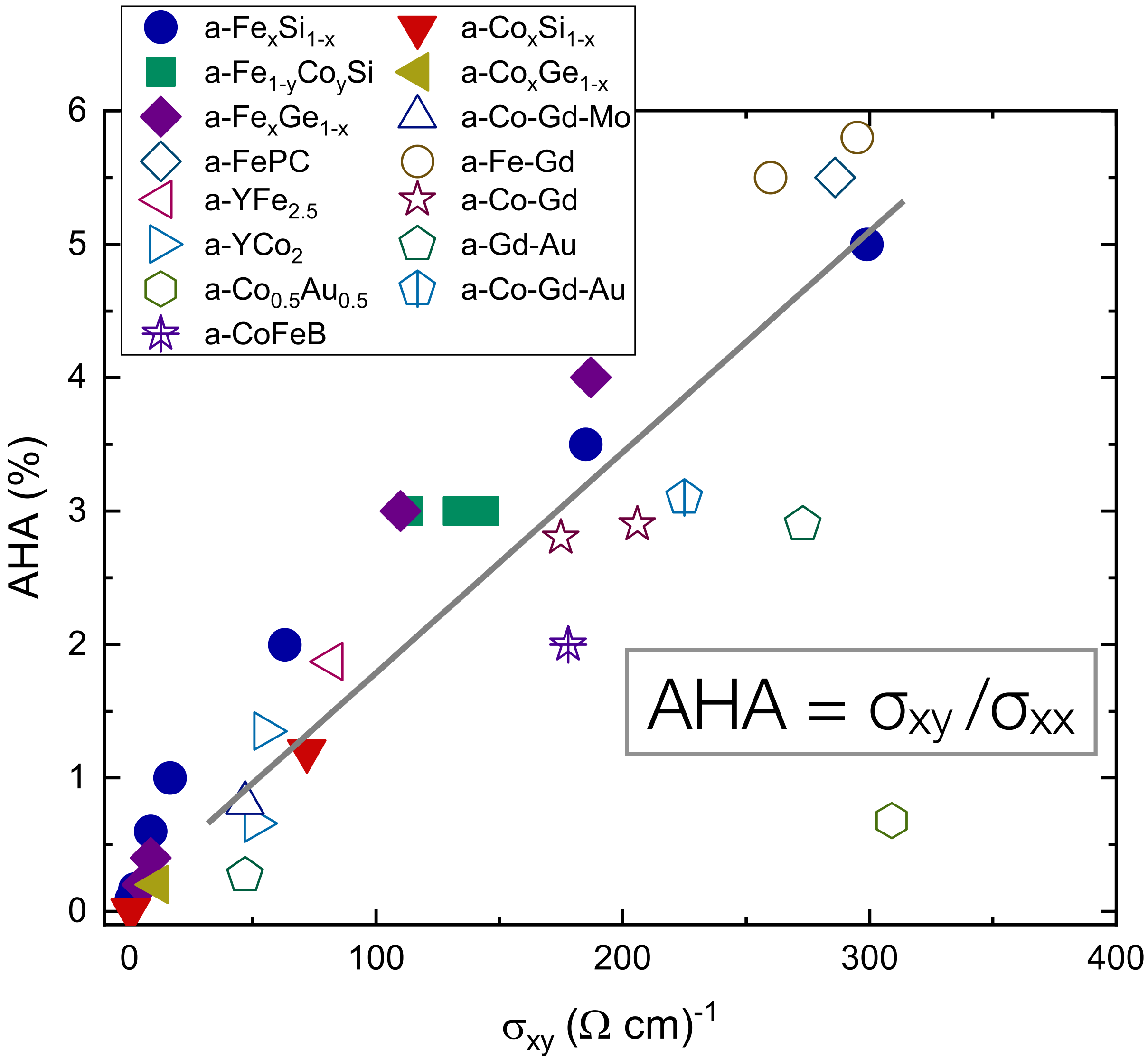


J. Karel *et al*. under review

E. Liu *et al*. *Nature Physics* (2018)

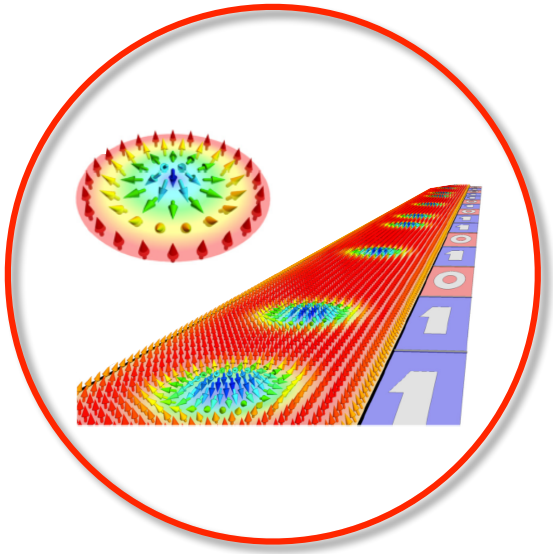
Anomalous Hall Angle - Amorphous Materials

- AHA as large as 5%
- Driven by intrinsic mechanism
- Potential to increase further by increasing σ_{xy}

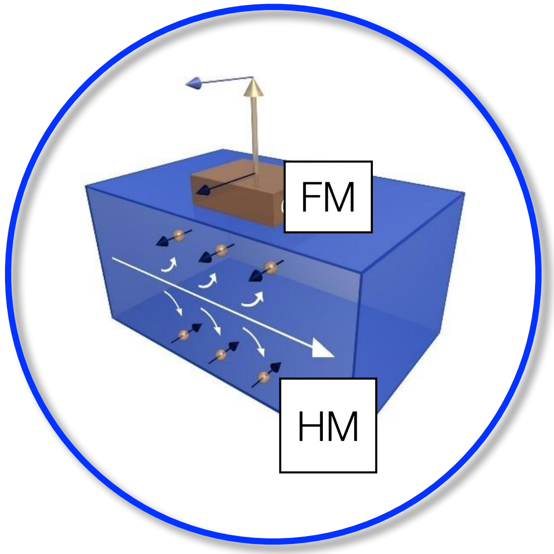


J. Karel *et al*. under review

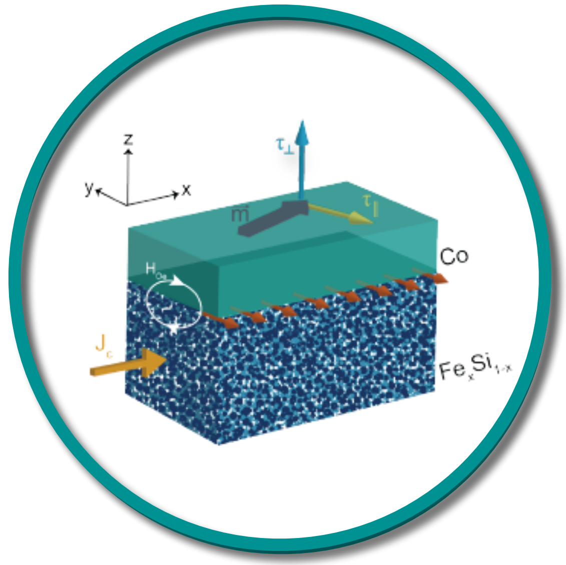
Outline



Non-volatile memory
and current
challenges



Methods for spin
current generation

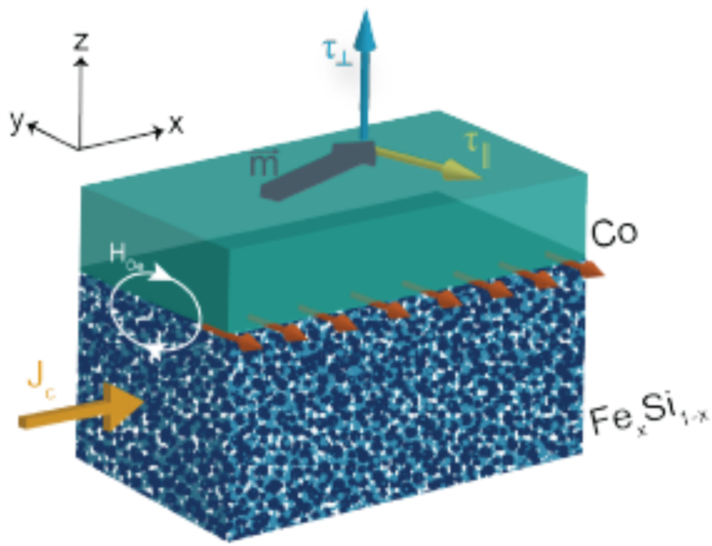


Using amorphous materials
to create spin currents

Ferromagnets
Non-magnetic

Spin Orbit Torques Generated by Amorphous Fe_xSi_{1-x} Thin Films

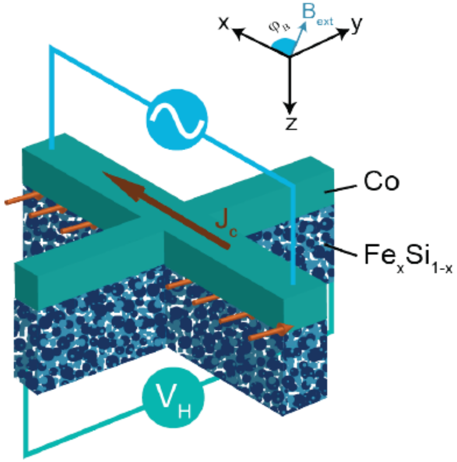
- Harmonic Hall and spin torque FMR measurements at room temperature
- Amorphous Fe_xSi_{1-x} ($x=0.40$, 0.45); paramagnetic at room temperature
- Extract spin orbit torque efficiency, ξ



C.-H. Hsu, J. Karel, *et al.* arXiv:2006.07786v1

with S. Salahuddin UC Berkeley

Harmonic Hall Measurements



Spin Physics in Semiconductors, Springer (2017)

C.-H. Hsu, J. Karel, *et al.* arXiv:2006.07786v1

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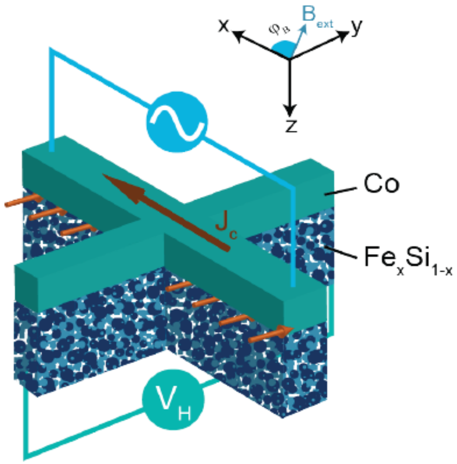

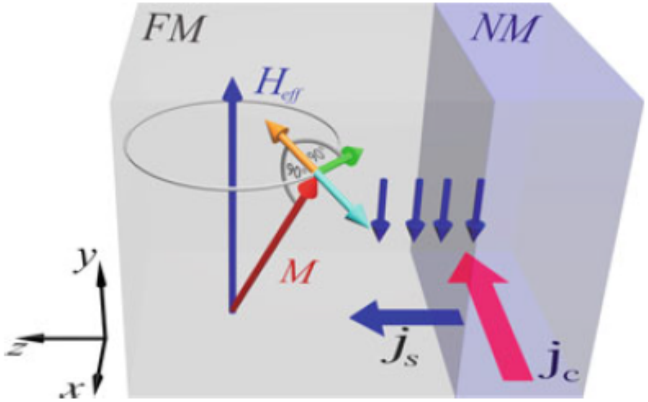

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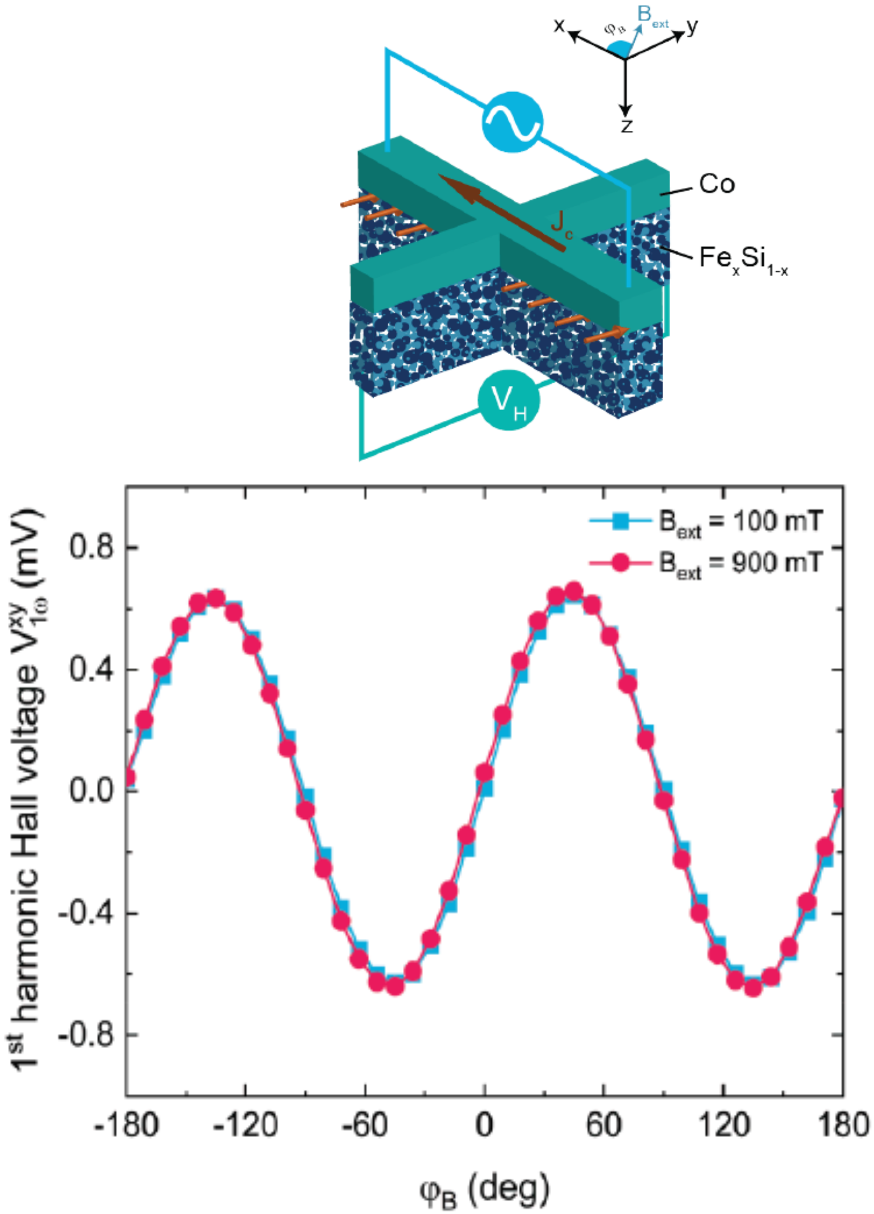

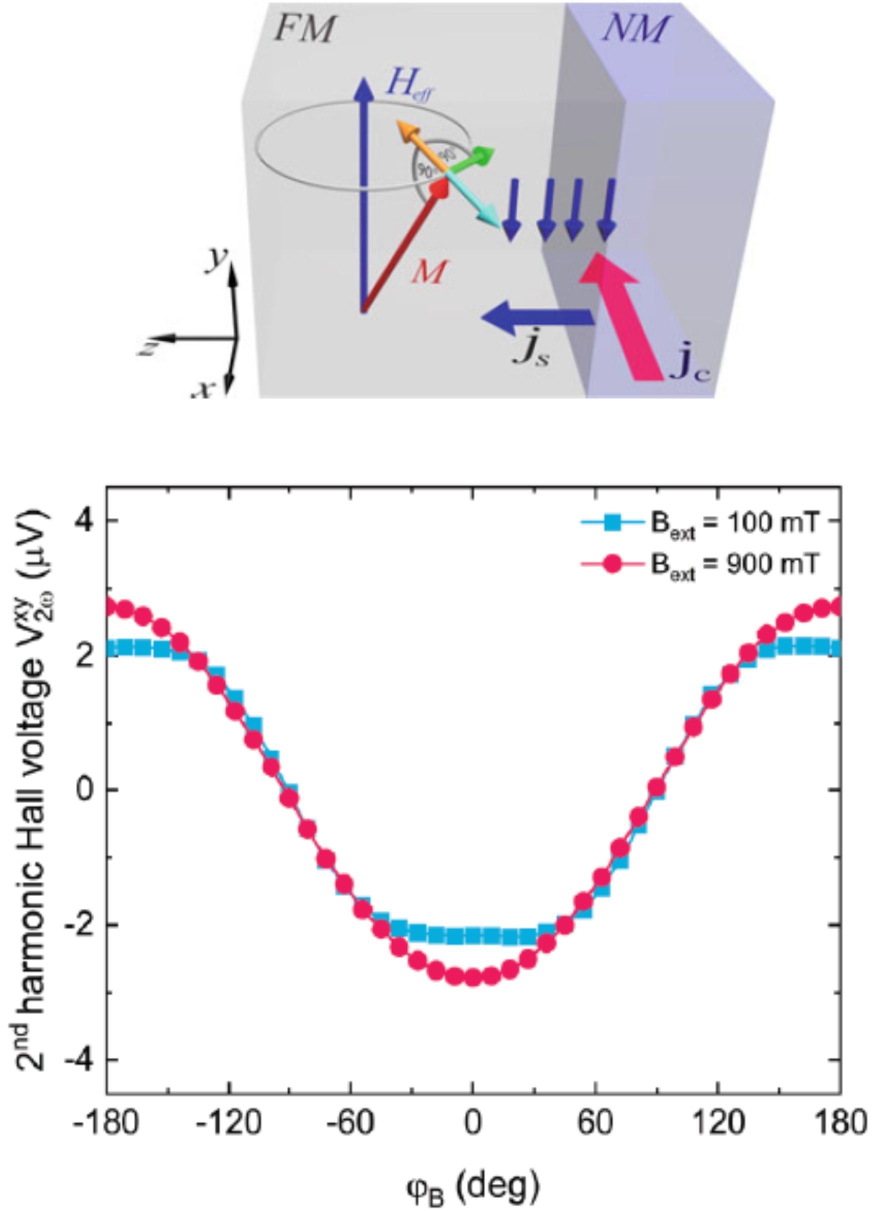

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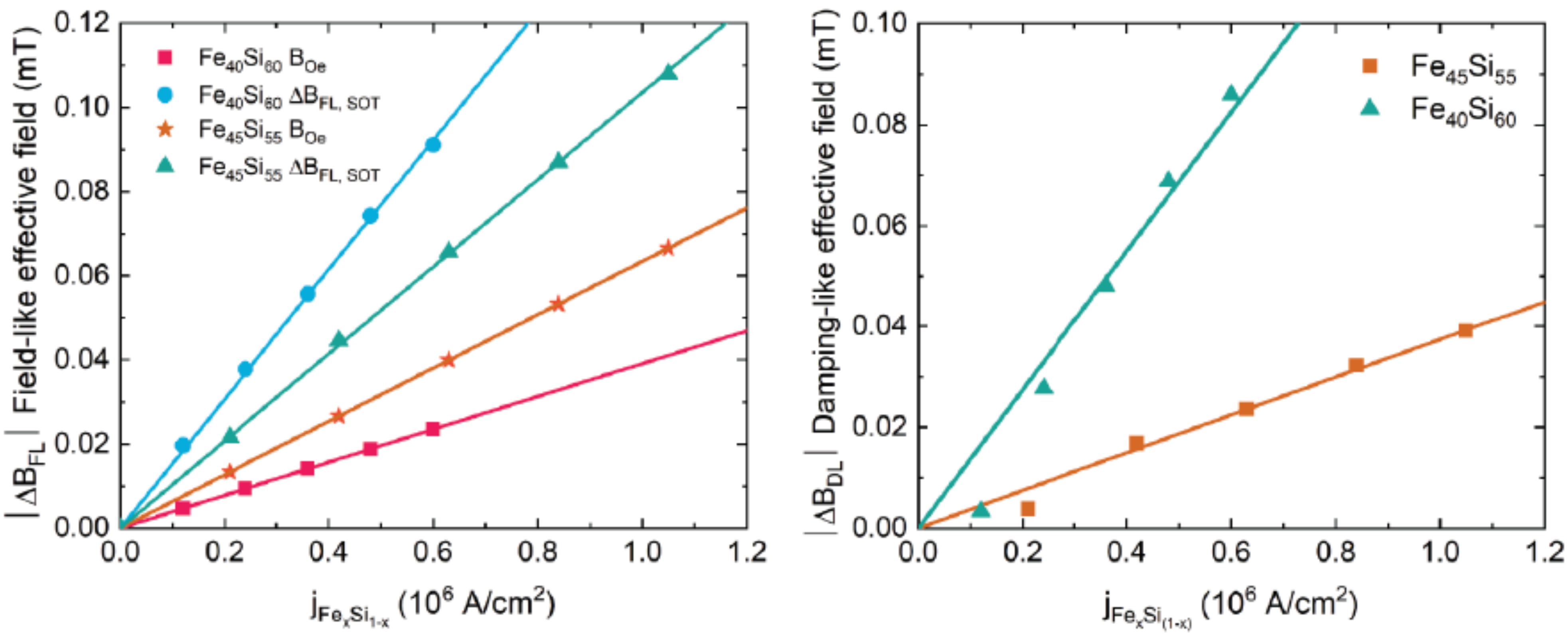
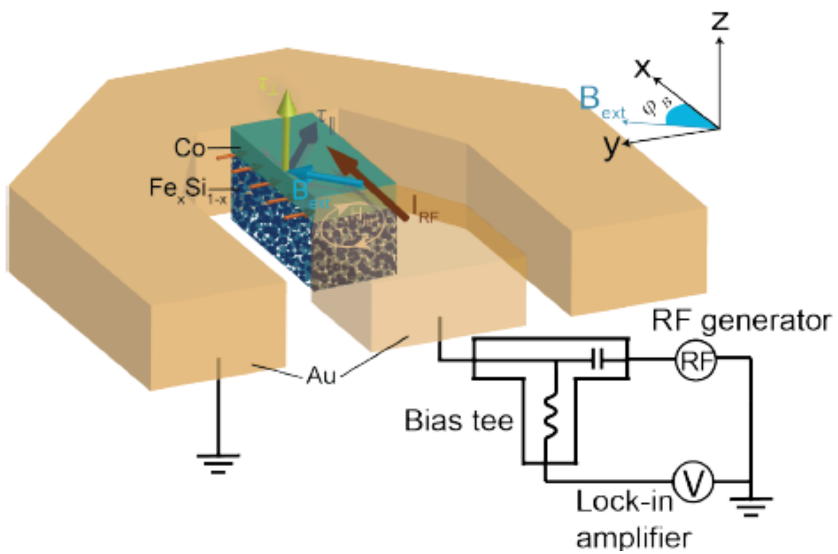
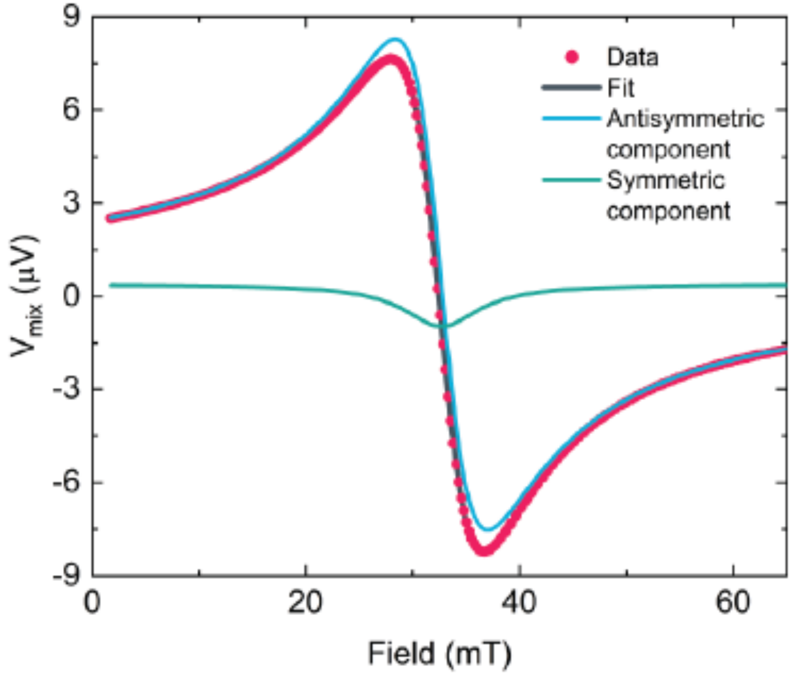


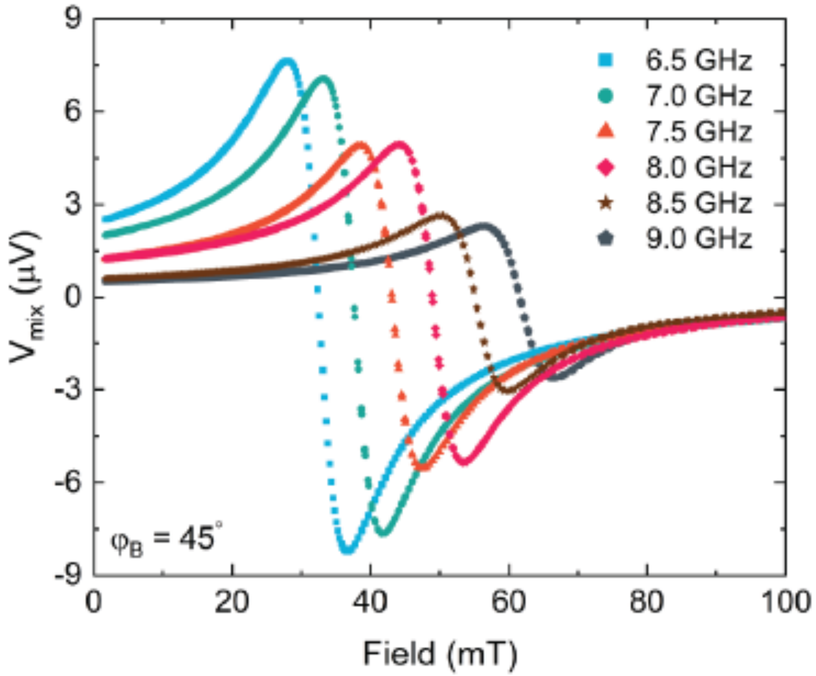
x=0.40 ξ =11.92%
x=0.45 ξ =3.98%

C.-H. Hsu, J. Karel, *et al.* arXiv:2006.07786v1

Spin-Torque Ferromagnetic Resonance





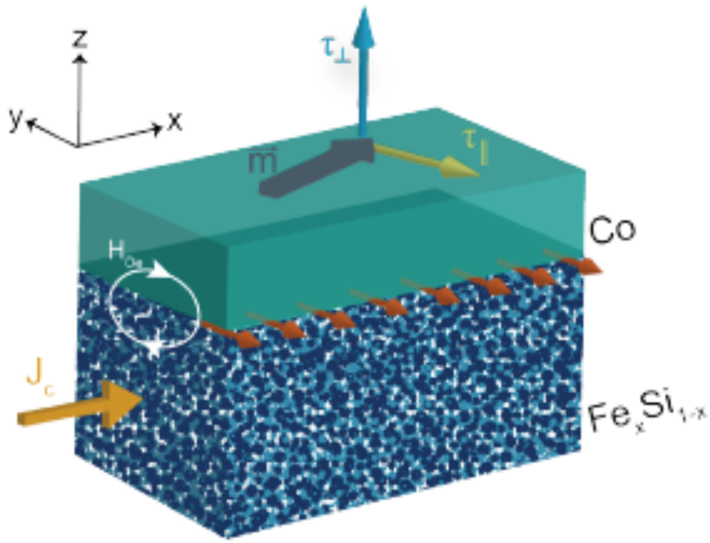


x=0.40 ξ =4.32%
x=0.45 ξ =2.56%

C.-H. Hsu, J. Karel, *et al.* arXiv:2006.07786v1

SOT Measurement Summary

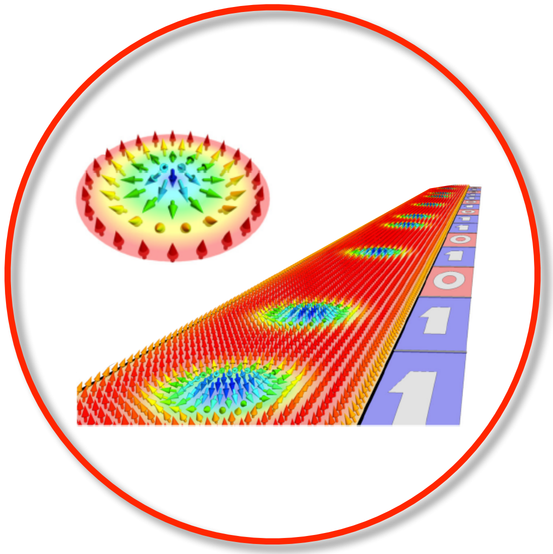
- Amorphous Fe_xSi_{1-x} exhibits SOT, ξ ~3-12%
  - Crystalline p-type Si ξ ~0.01%
  - Pt ξ ~8%
- Need to understand more about origin of large SOT

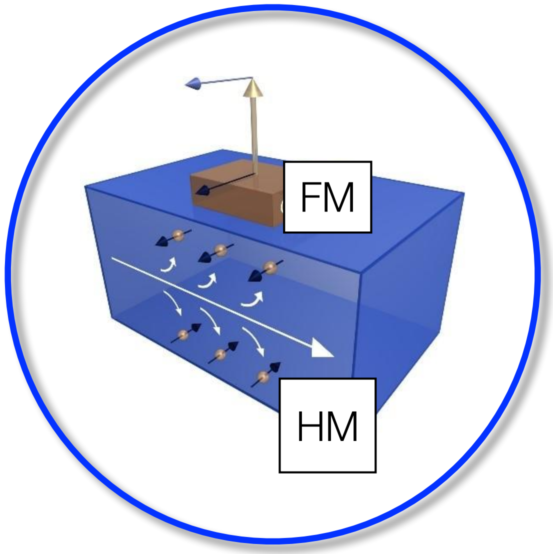


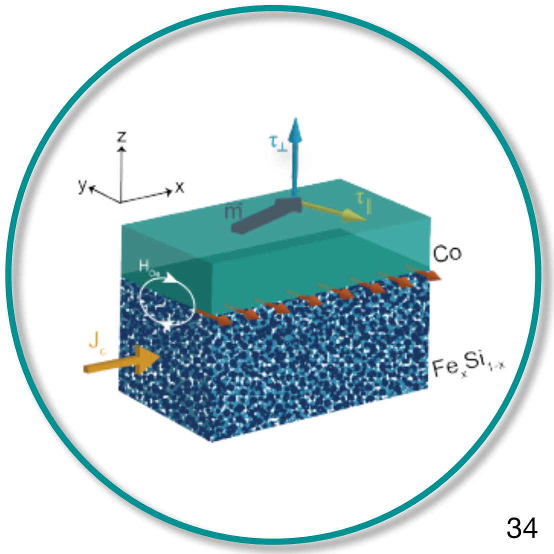
C.-H. Hsu, J. Karel, *et al.* arXiv:2006.07786v1

Concluding Remarks and Future Work

- Efficient spin current generation critical to numerous low-power data storage and logic devices
- AHA greater than or equal to crystalline materials
- Spin orbit torque efficiencies ~ Pt
- Potential to further improve
  - Amorphous Bi_2Te_3







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FLEET
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MONASH University

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