UNIVERSITY OF DENVER

Thermal and Electrical Probes of Spin Effects in Antiferromagnets: a Revisitation and a New Idea?

Sam M. Bleser, Matthew R. Natale, Ryan M. Greening, M. J. Roos, Leo Hernandez, Xin Fan, and Barry L. Zink

UC DAVIS UNIVERSITY OF CALIFORNIA

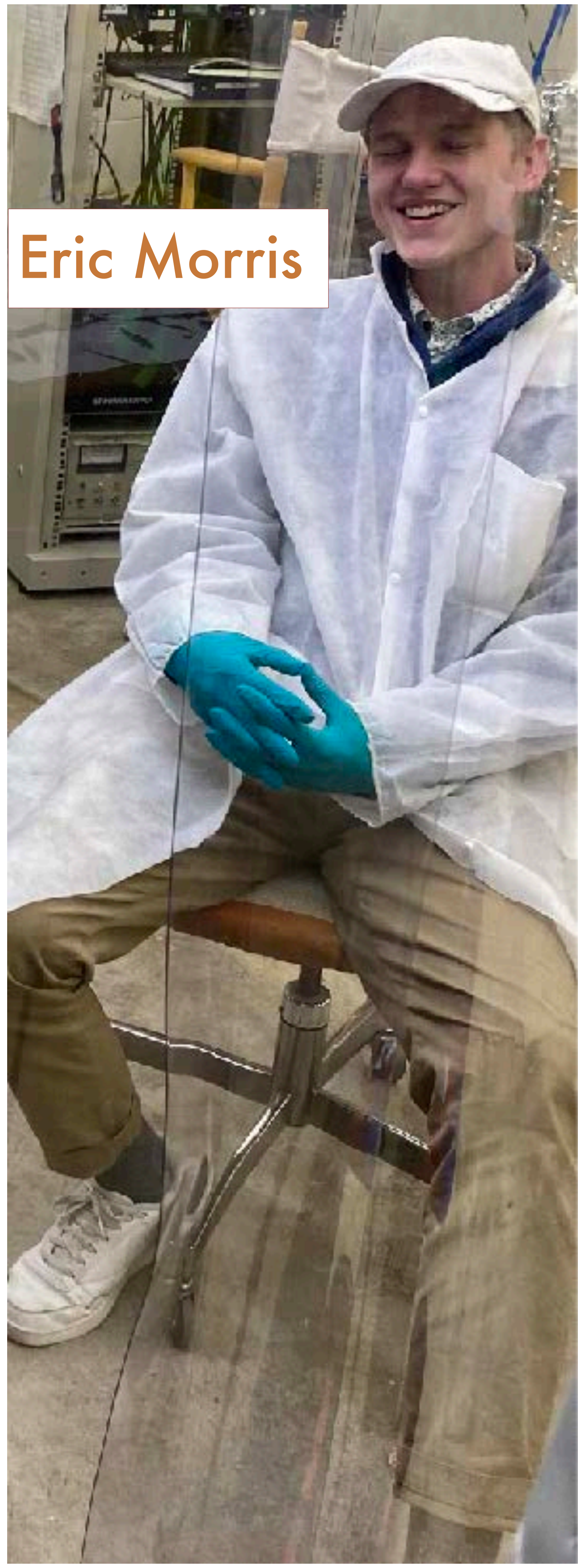
Dayne Sasaki, Ishmam Nihal, Yayoi Takamura

NSF
DMR-2004646
EECS-2116991

SPICE/SPIN+X seminar
Nov. 28, 2023
JGU/Mainz Uni. (virtual)

Zink Group

Ian Ellis (Not Pictured)



Matt, Leo, Sam all defending SOON

DMR-CMP,
EECS-EPMD

fabrication

U.S. DEPARTMENT OF ENERGY

Outline

- **Brief Advertisements**
  - "Thermal Spintronics: An Experimentalist's Guide" JMMM 2022,
  - Limit on long distance spin transport in a-Y-Fe-O JAP 2023
- **Spin currents, charge currents, conversion (NM, FM and AFM)**
  - A quick orientation
- **Spin-charge conversion in thermally evaporated chromium**
  - "Standard" LSSE: Significant spin conversion, large resistance, unexpected thickness dependence…
- **Temperature dependence of LSSE in evaporated and sputtered Cr**
  - Local Heating LSSE: correlation of larger VLSSE to (one of 2) suppressed ordering temperatures
- **First work on a low-field controllable compensated AF**
  - Hall MR shows dramatic effects that turn on below the Neel temperature in complex oxide bilayers.
- **Conclusions**

Brief Advertisements

Research article

Thermal effects in spintronic materials and devices: An experimentalist's guide

B.L. Zink

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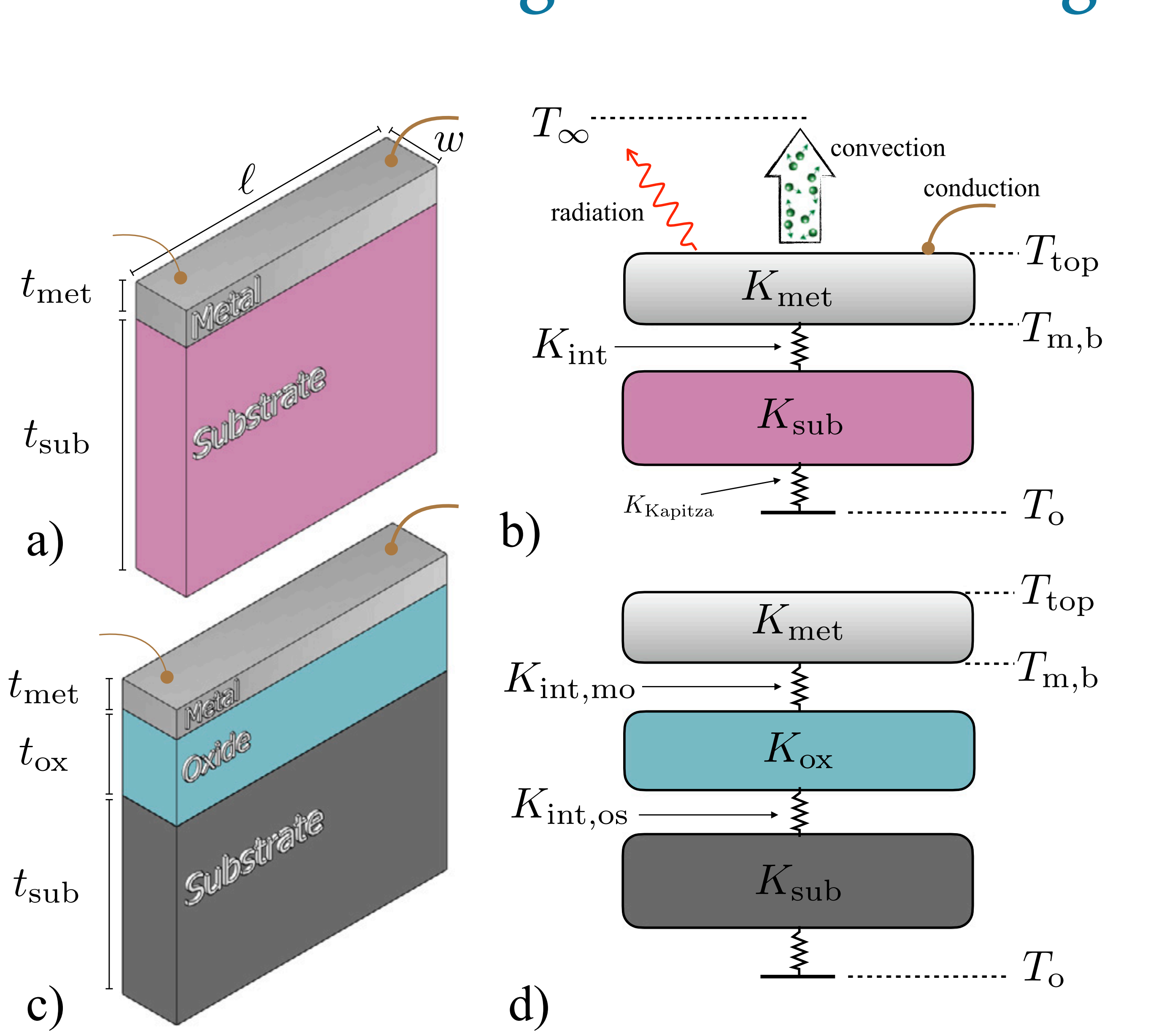
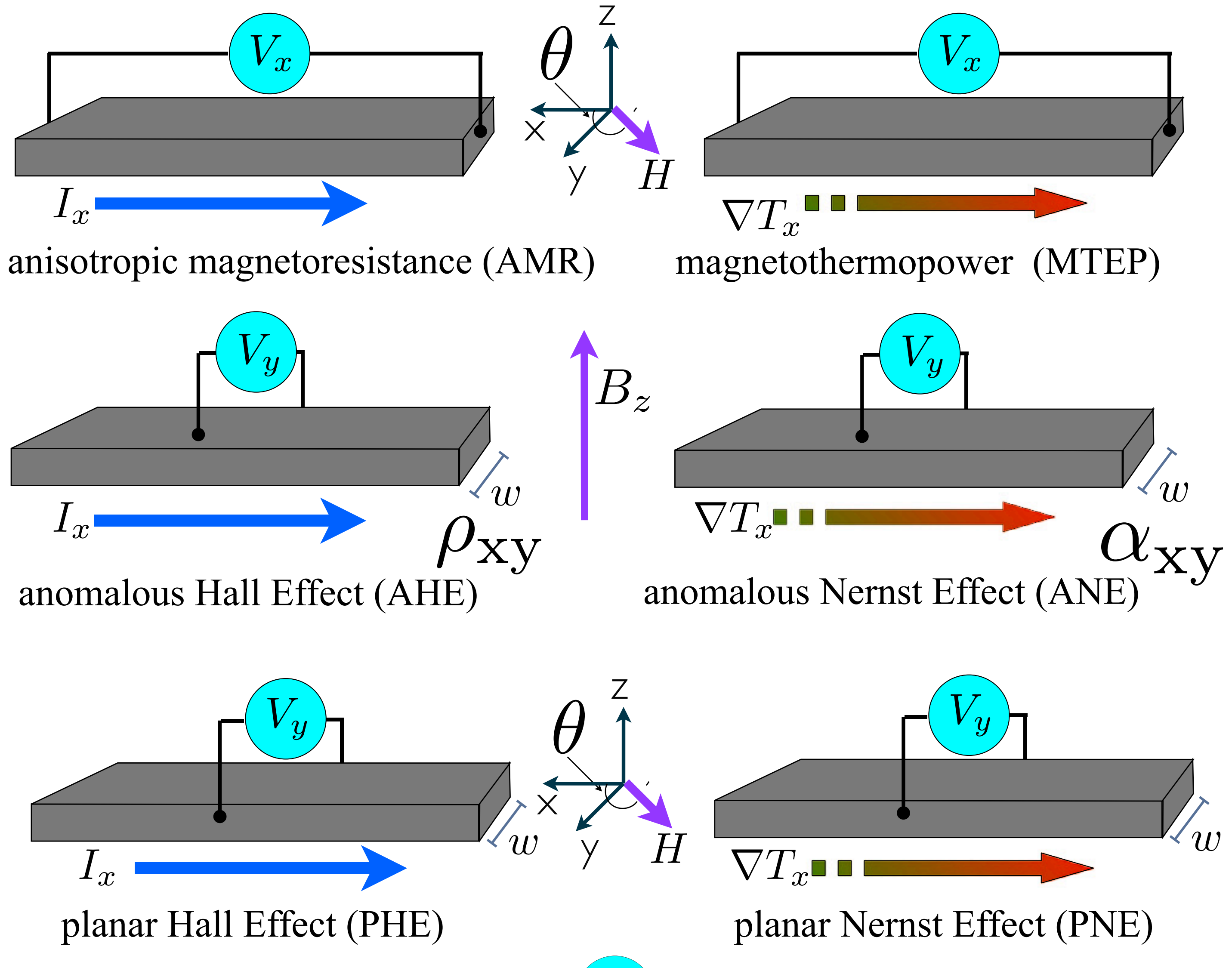
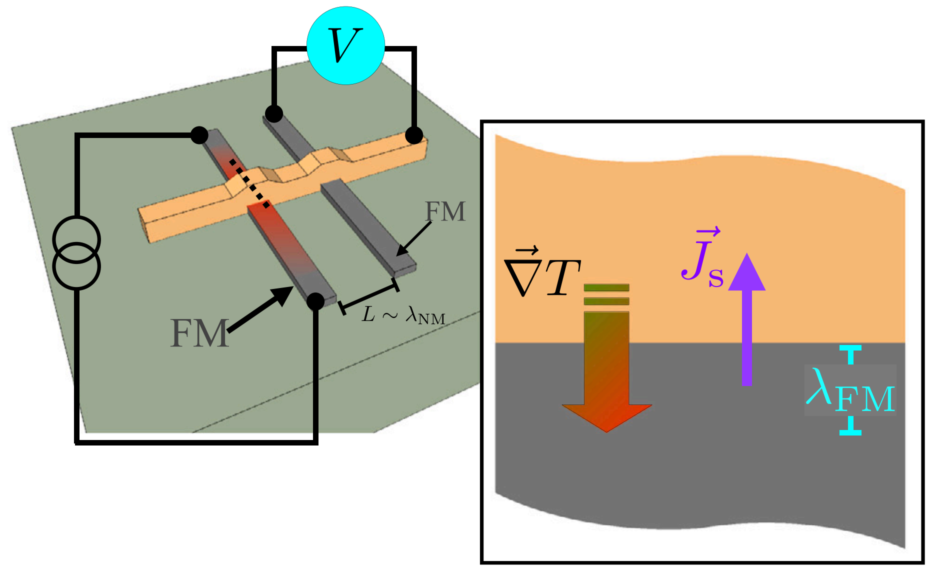
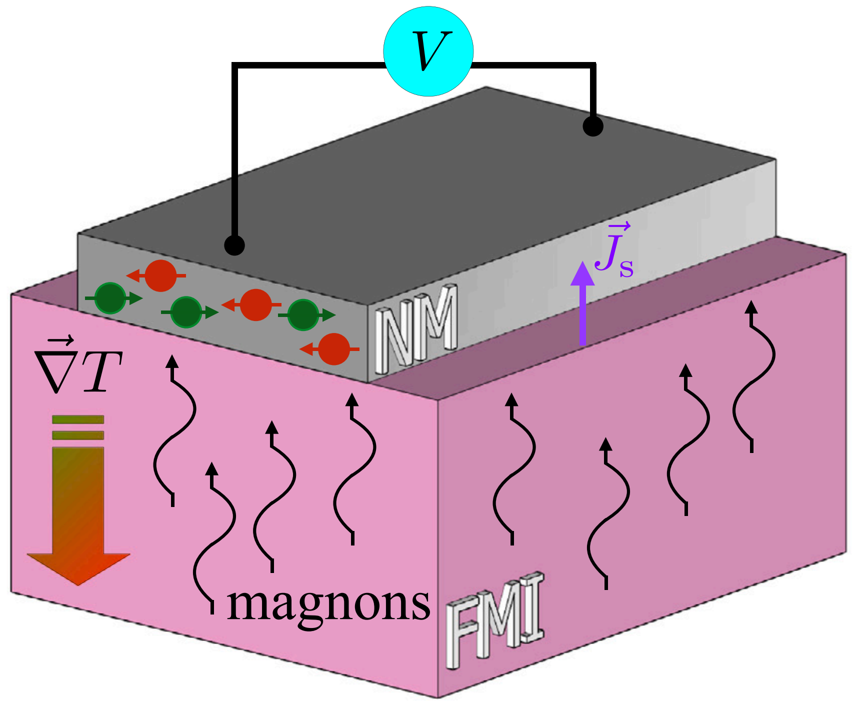
Journal of Magnetism and Magnetic Materials 564 (2022) 170120







spin-dependent Seebeck effect (SDSE)



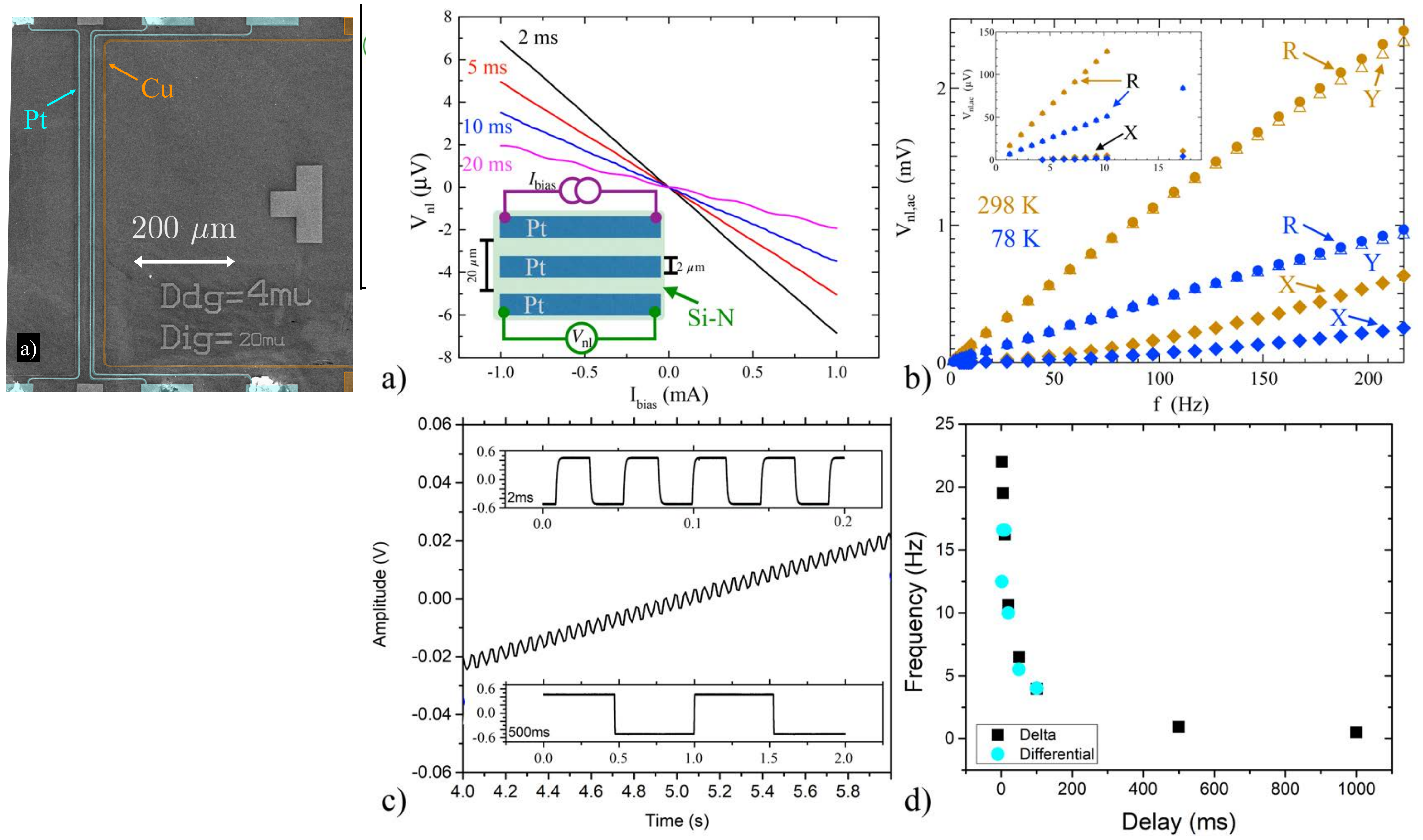
spin Seebeck effect (SSE)

Electrical, optical, and magnetic properties of amorphous yttrium iron oxide thin films and consequences for non-local resistance measurements

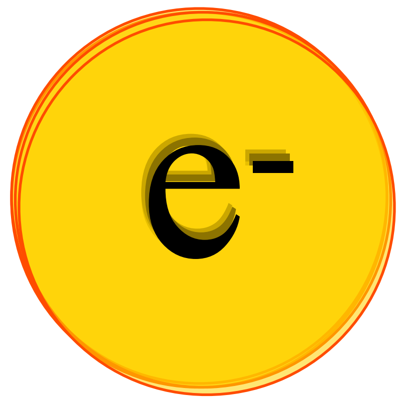
M. J. Roos,[1, a)] S. M. Bleser,[1, a)] L. Hernandez,[1, a)] G. M. Diederich,[1, 2, 3] M. E. Siemens,[1] M. Wu,[4] B. J. Kirby,[5] and B. L. Zink[1, b)]

Journal of Applied Physics **133** 223901 (2023)

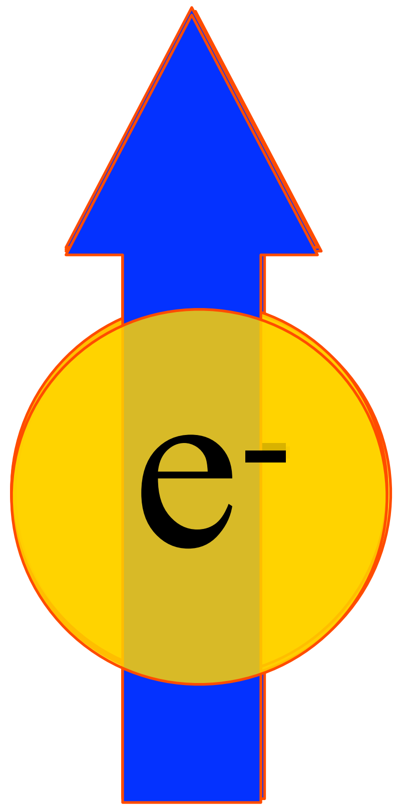
New experiments put a strong limit on long distance spin transport in disordered YIG, shows that these measurements are dominated by charge leakage, outlines pitfalls for non-local resistance when charge can flow.



Charge and Spin Transport



charge per unit time = (charge) current



"up" charges per unit time = spin polarized current

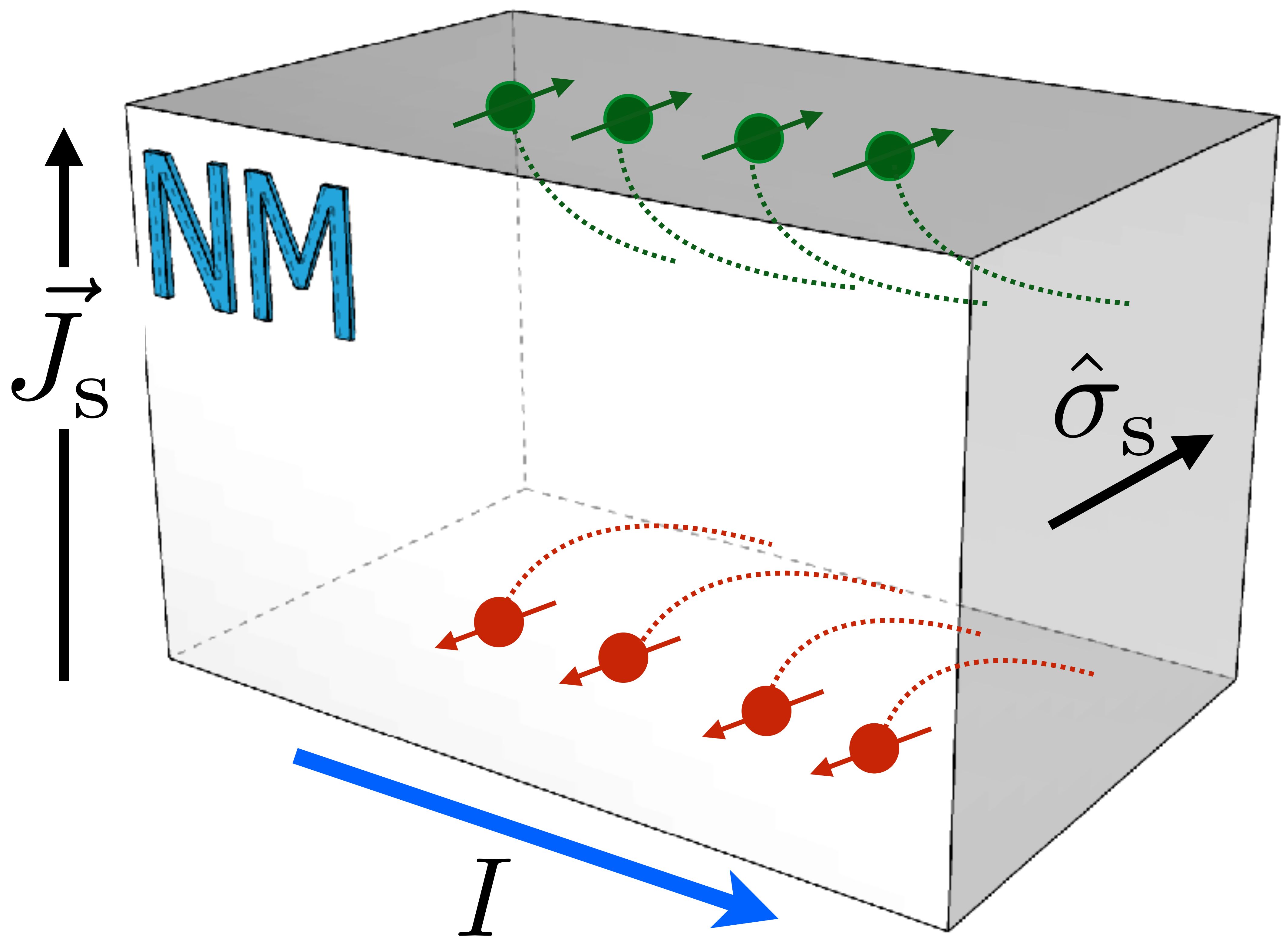
Takes work to move these charges in the electric field created by charge accumulation

Pure Spin Current

On average, no charge is moved.
Angular momentum transferred with no work?

How to generate a pure spin current?

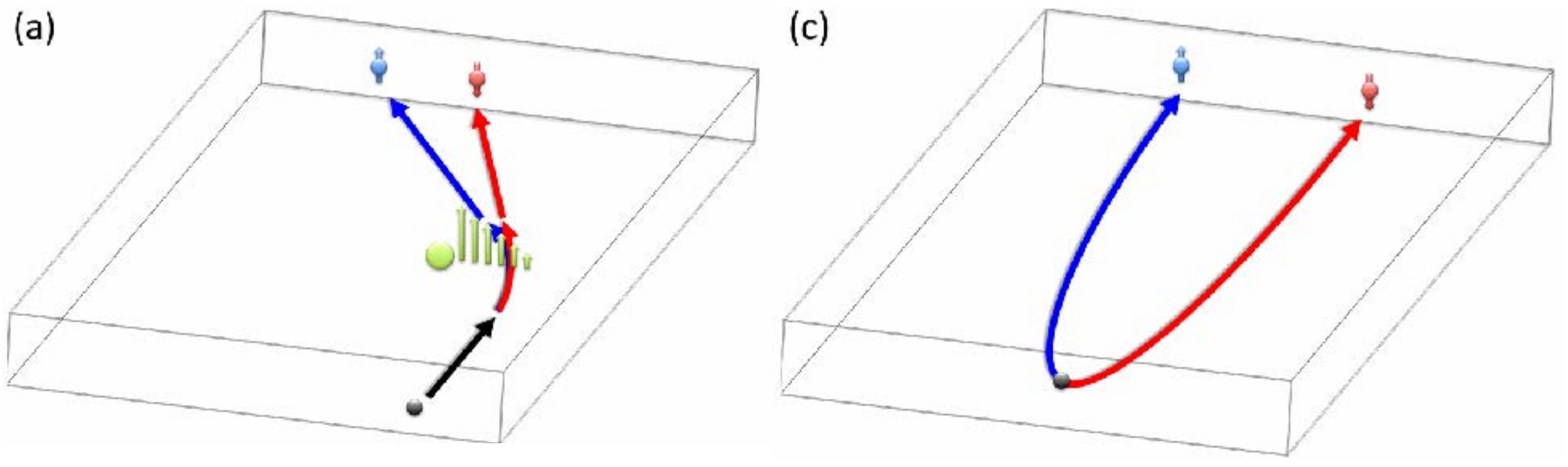
spin Hall effect (SHE)



M. I. D'yakonov and V. I. Perel', *Sov. Phys. JETP Lett.*, **13**, 467 (1971)

J. Hirsch, *PRL* **83** 1834 (1999)

spin-orbit coupling causes different transverse velocity for up and down spins



Platinum is (by far) the most commonly used SHE material

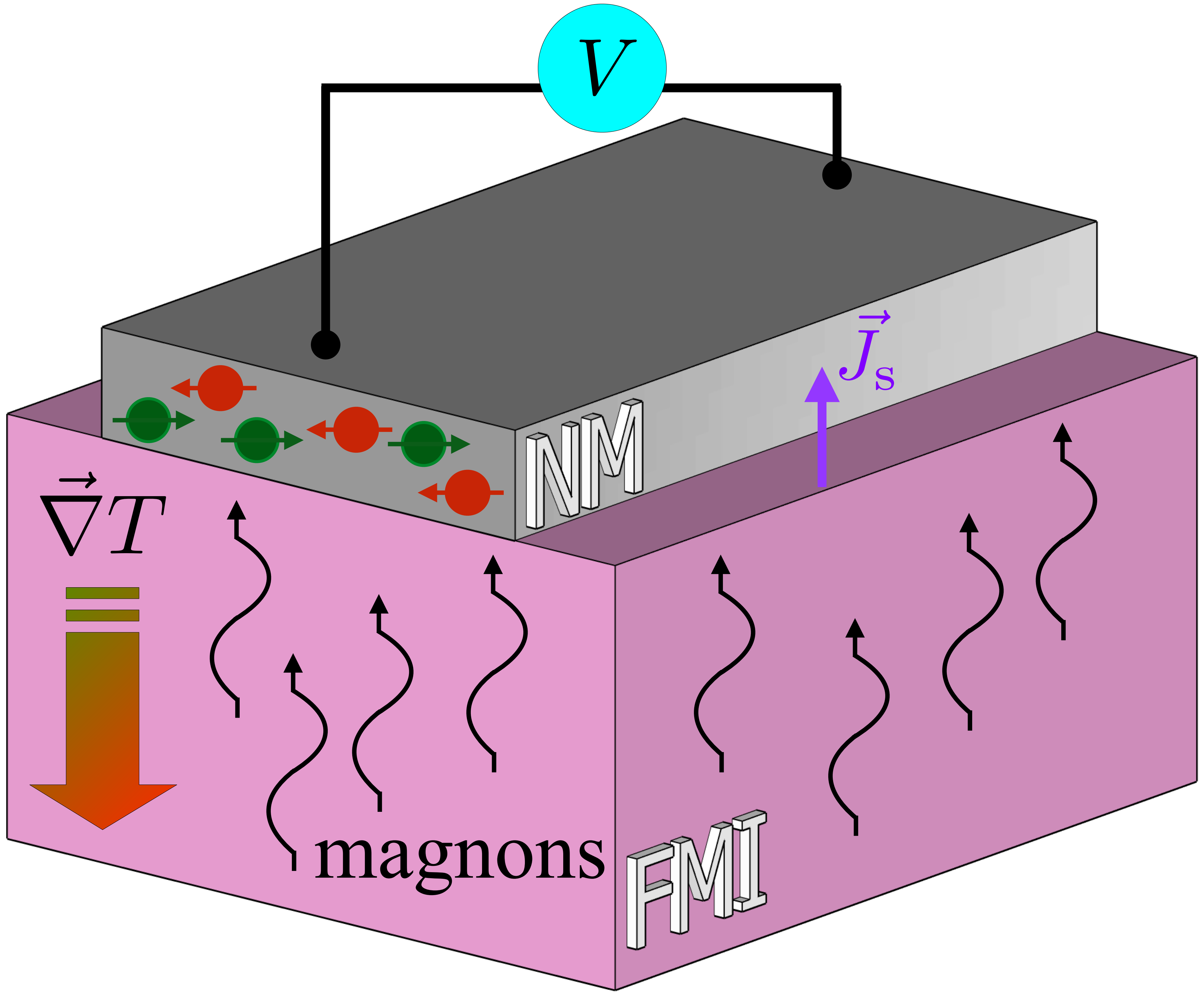
also works in reverse….

inverse spin Hall effect (ISHE)

Slnova, et al, RMP., Vol. 87 1213, 2015

A. Hoffmann, IEEE Trans. Mag., Vol. 49(10), 2013

How ELSE to generate a pure spin current?



spin Seebeck effect (SSE)

Thermal gradient applied to a ferromagnetic insulator drives a flow of magnons, which form a pure spin current

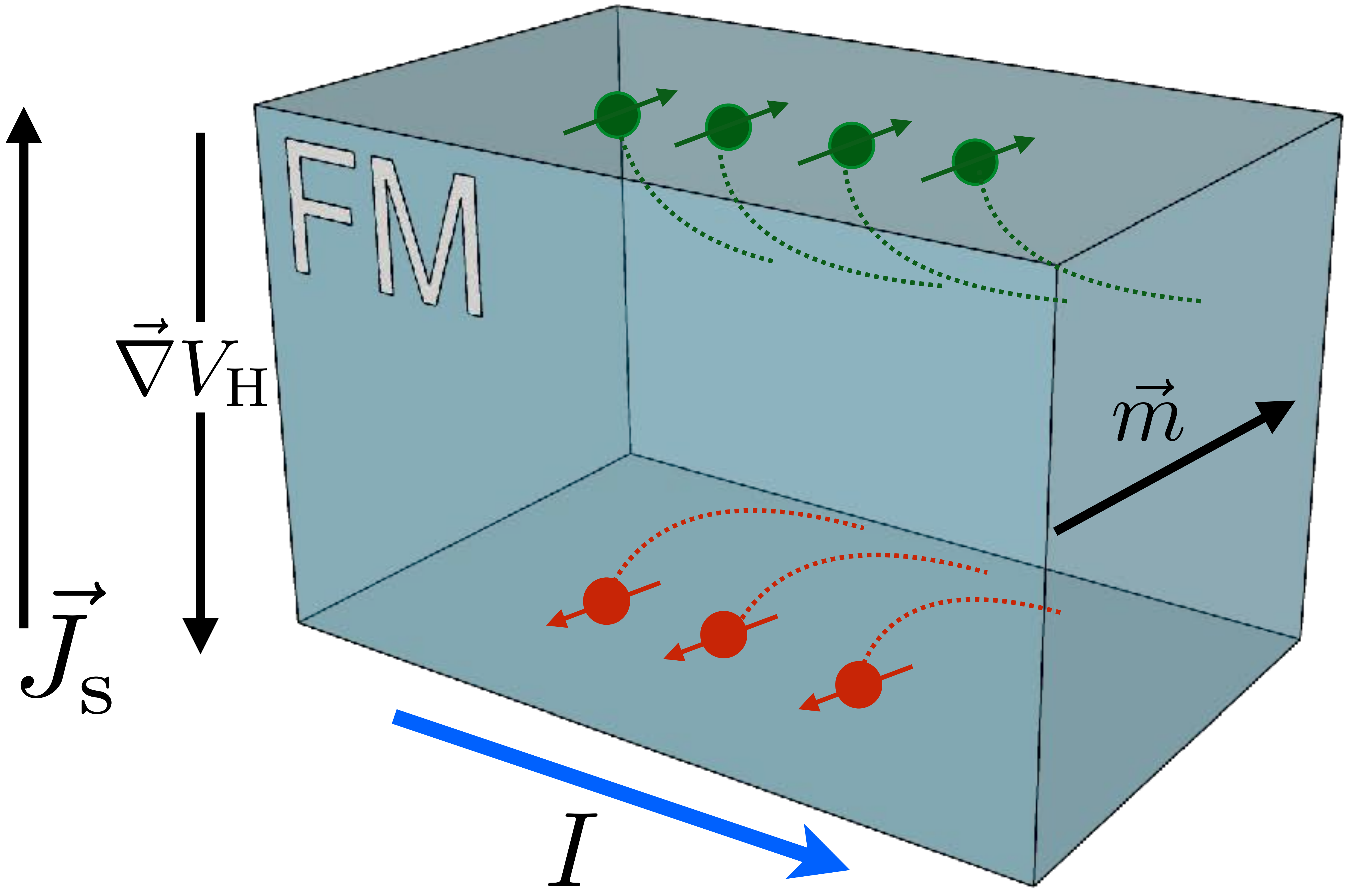
Note! Here detection is via the ISHE

This experiment can be used to probe either spin-charge conversion in the metal, or the magnetic properties of the material/interface

Uchida, et al., *APL* **97** 172505 (2010)

Spin-charge conversion with magnetic order

anomalous Hall effect (AHE)



inverse spin Hall effect (ISHE) also works

Miao, et al., *PRL* **111** 066602 (2013) ,…

What about ISHE in metallic antiferromagnets?

Views on ISHE in Cr

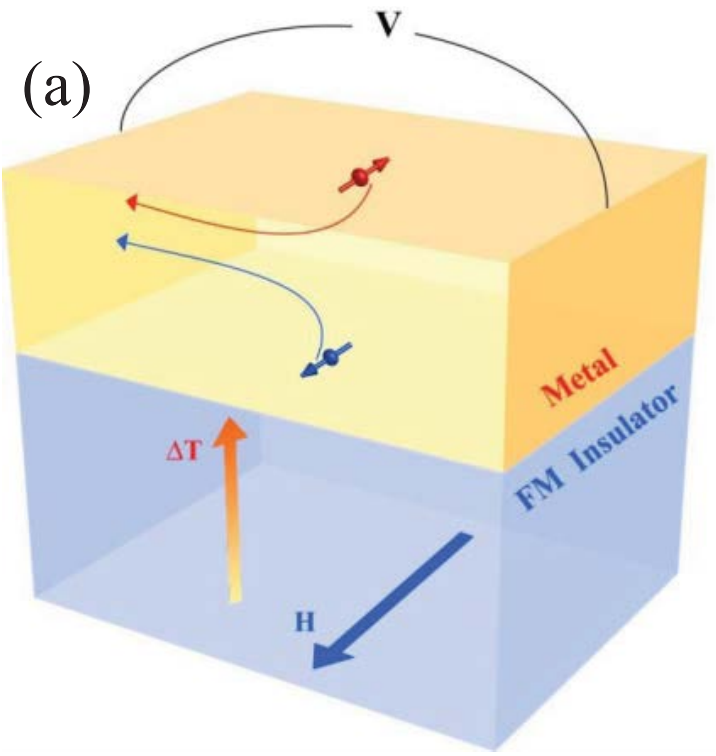
PHYSICAL REVIEW B **92**, 020418(R) (2015)

Inverse spin Hall effect in Cr: Independence of antiferromagnetic ordering

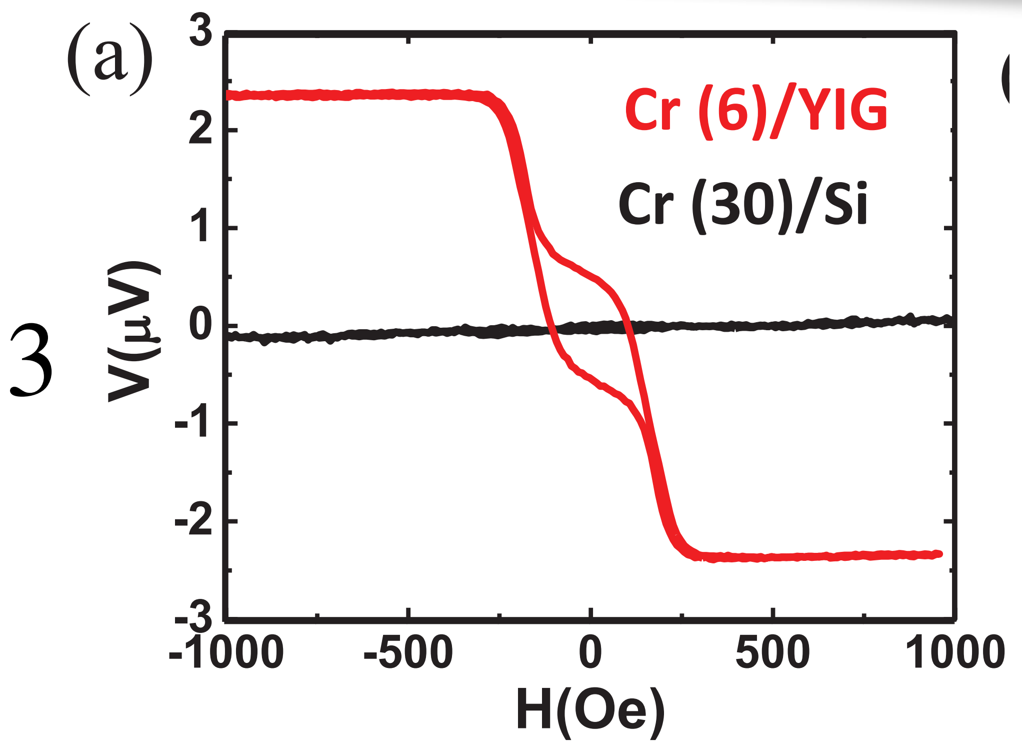
D. Qu,[1] S. Y. Huang,[1,2] and C. L. Chien[1,*]
[1]*Department of Physics and Astronomy, Johns Hopkins University, Baltimore, Maryland 21218, USA*
[2]*Department of Physics, National Taiwan University, Taipei 10617, Taiwan*
(Received 2 June 2015; published 29 July 2015)

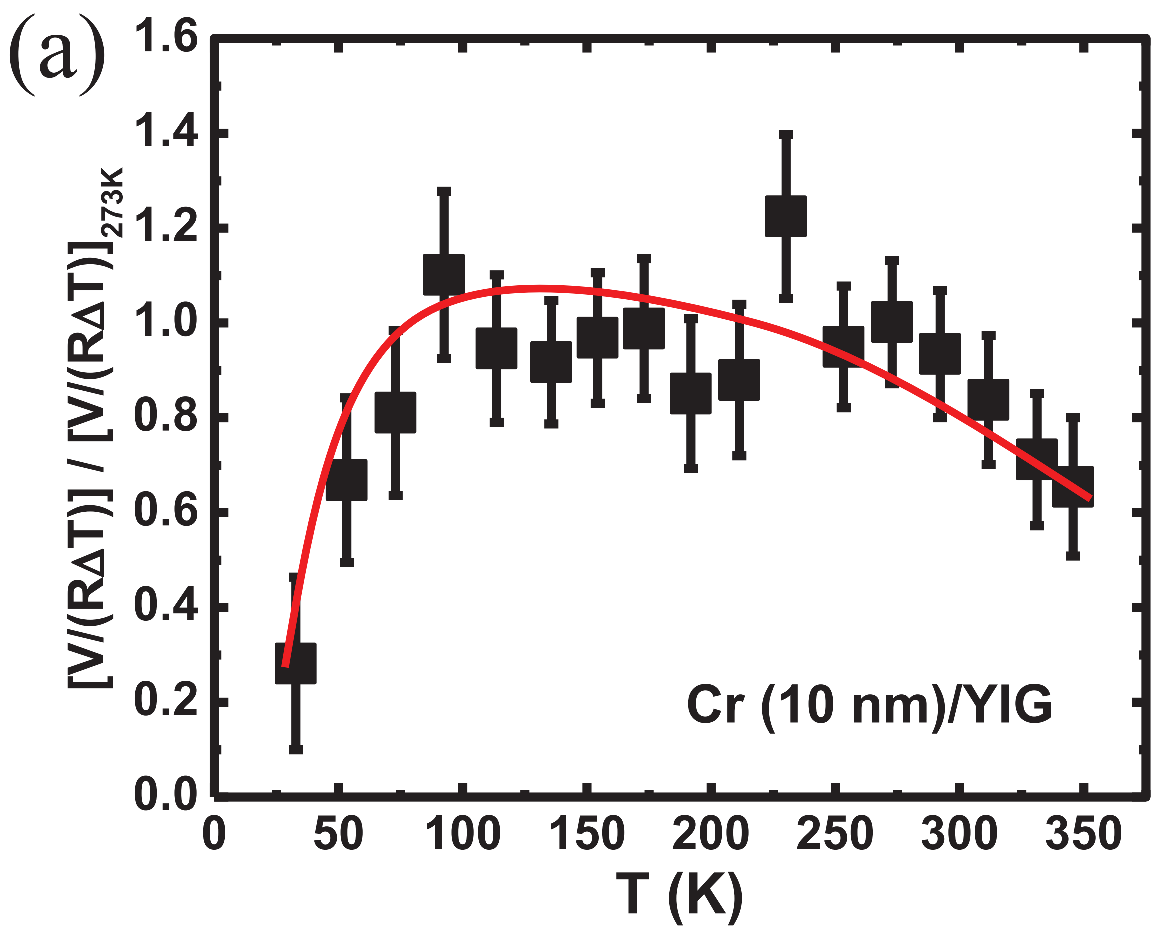
Sputtered Cr films Probed via longitudinal spin Seebeck effect (SSE)

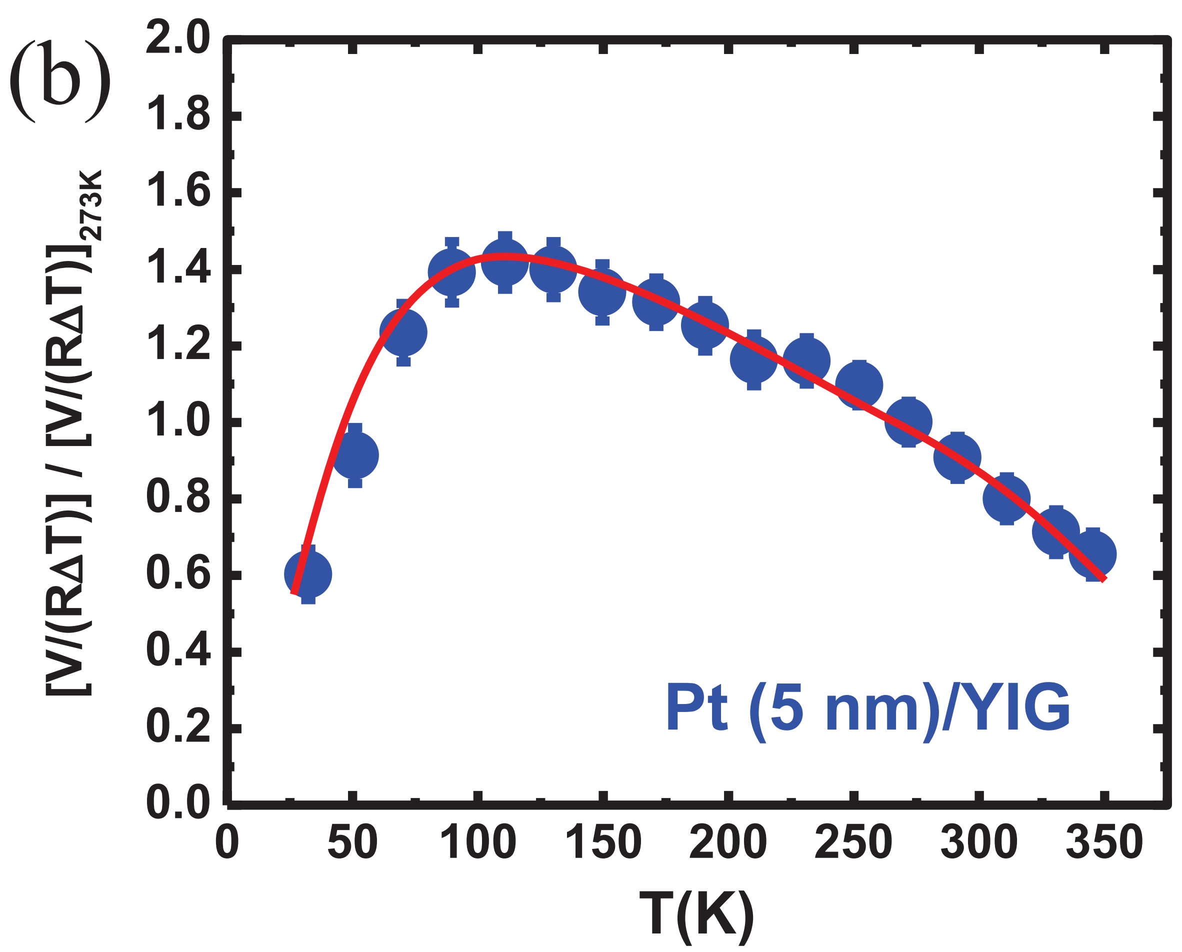
Negative SHA, no clear features near bulk Neel T, roughly 1/t dependence



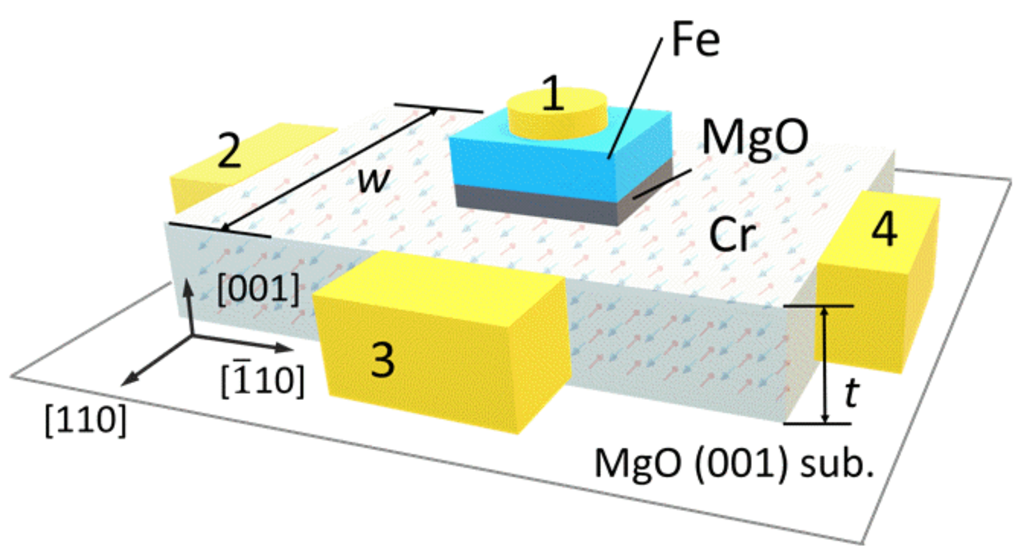
$$\frac{\theta_{\text{SHA,Cr}}}{\theta_{\text{SHA,Pt}}} \simeq 0.3$$

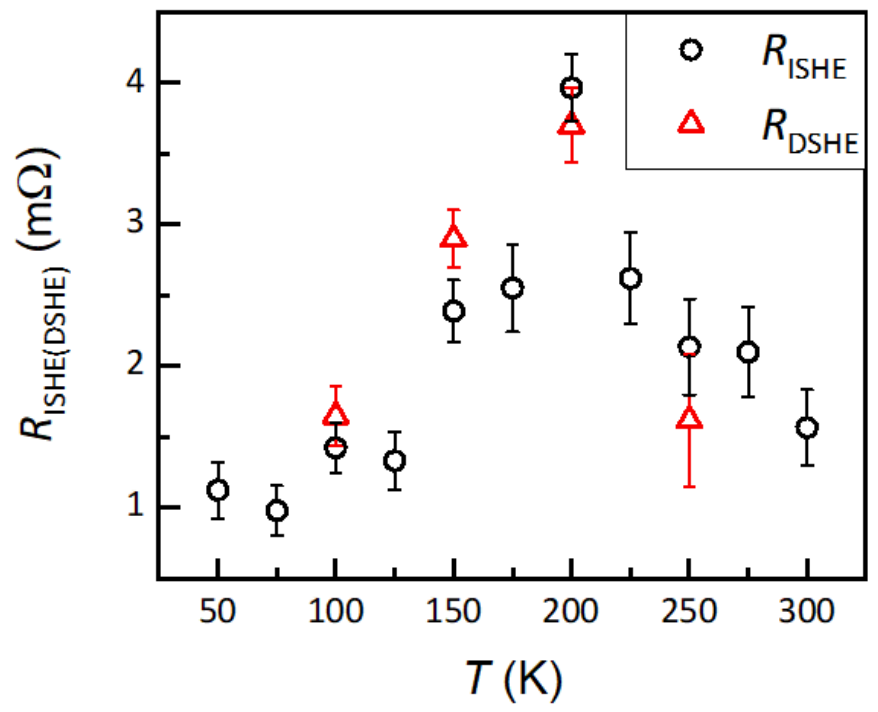






Fang, et al., arXiv 2304.13400 (2023)

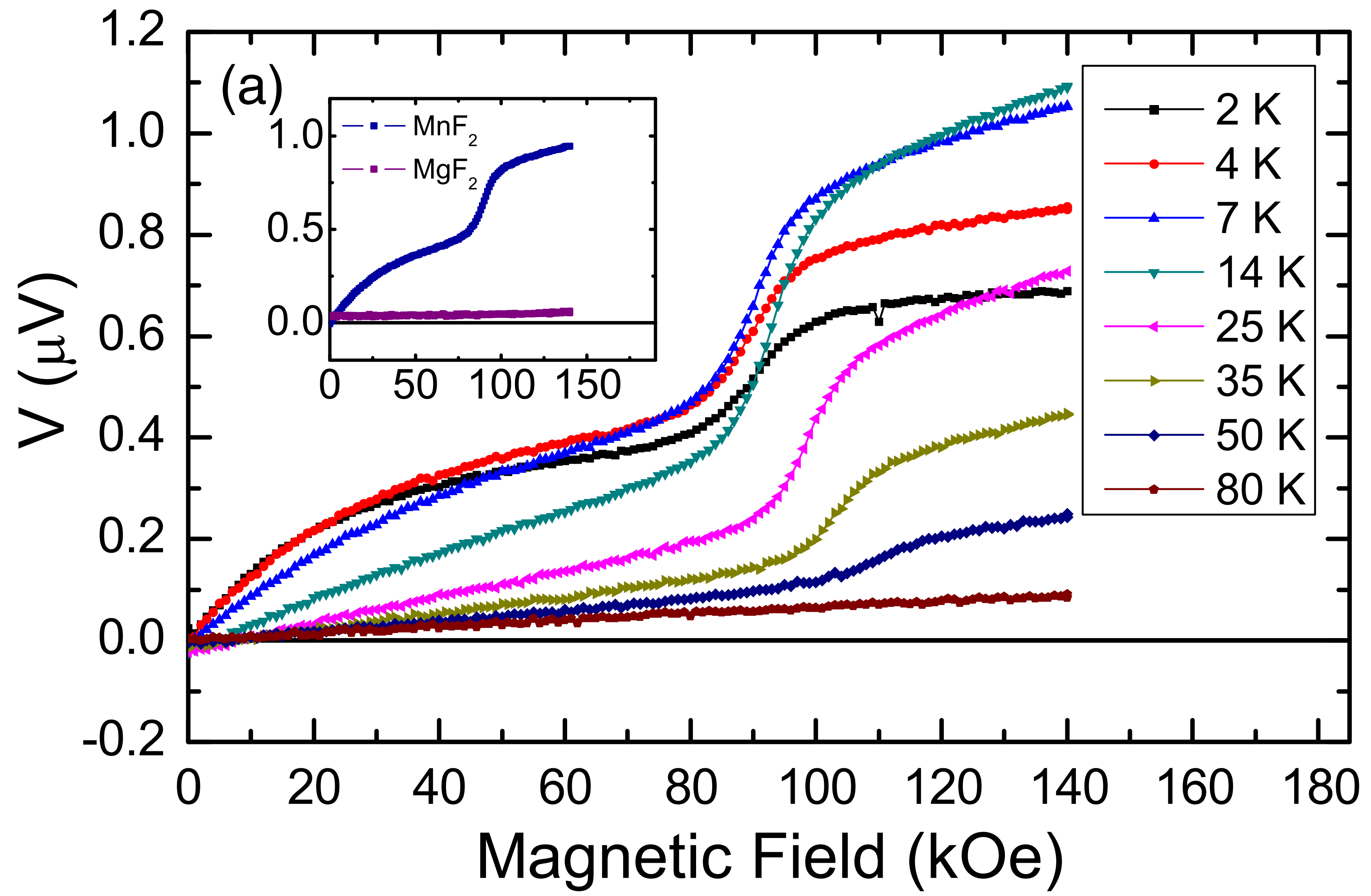




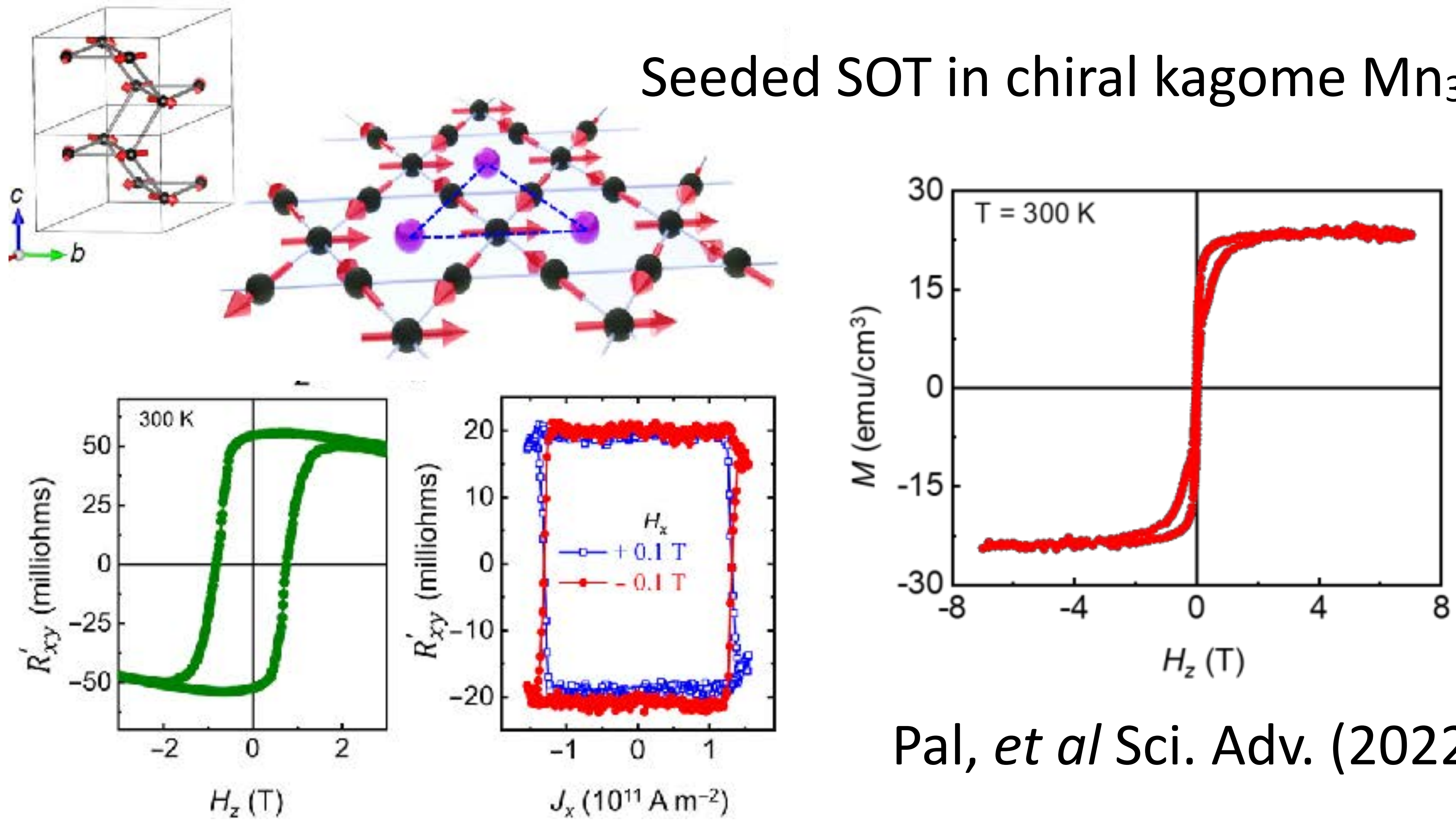
Peak near Neel temperature in a Cr/MgO/Fe MTJ spin current

Spin conversion and transport in antiferromagnets

Spin Seebeck Effect in MnF_2 Wu, *et al* PRL (2016)



Seeded SOT in chiral kagome Mn_3Sn



Pal, *et al* Sci. Adv. (2022)

Often have to engineer some moment to probe this physics

Non local transport in Fe_2O_3 Lebrun, *et al* Nature **561** 222 (2018)

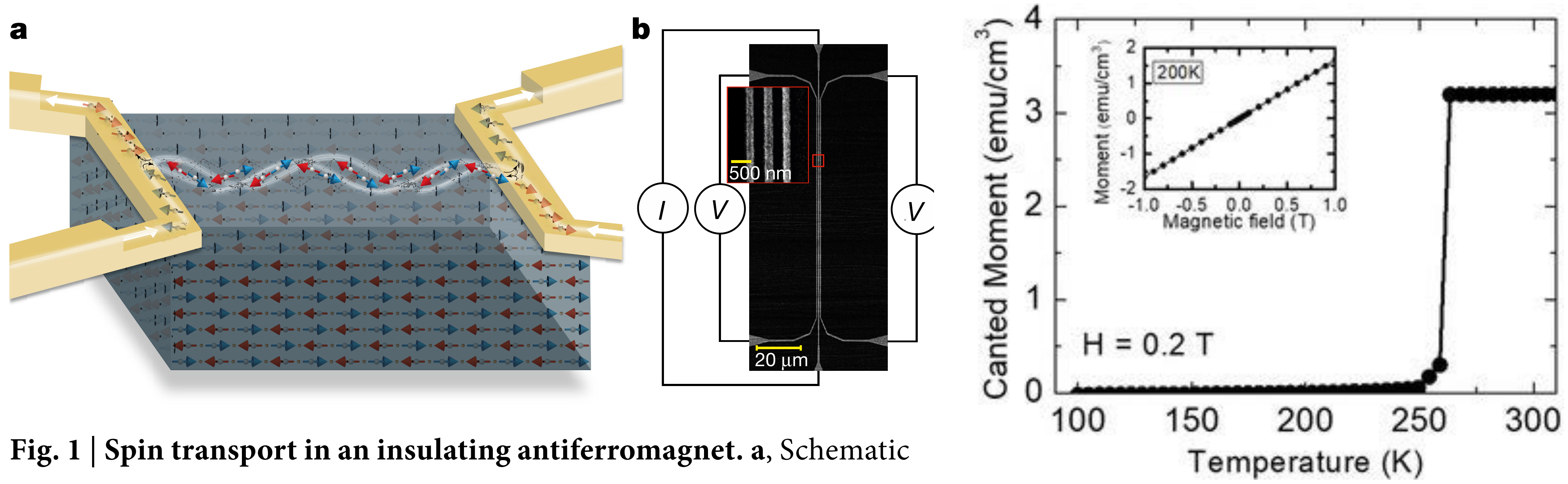
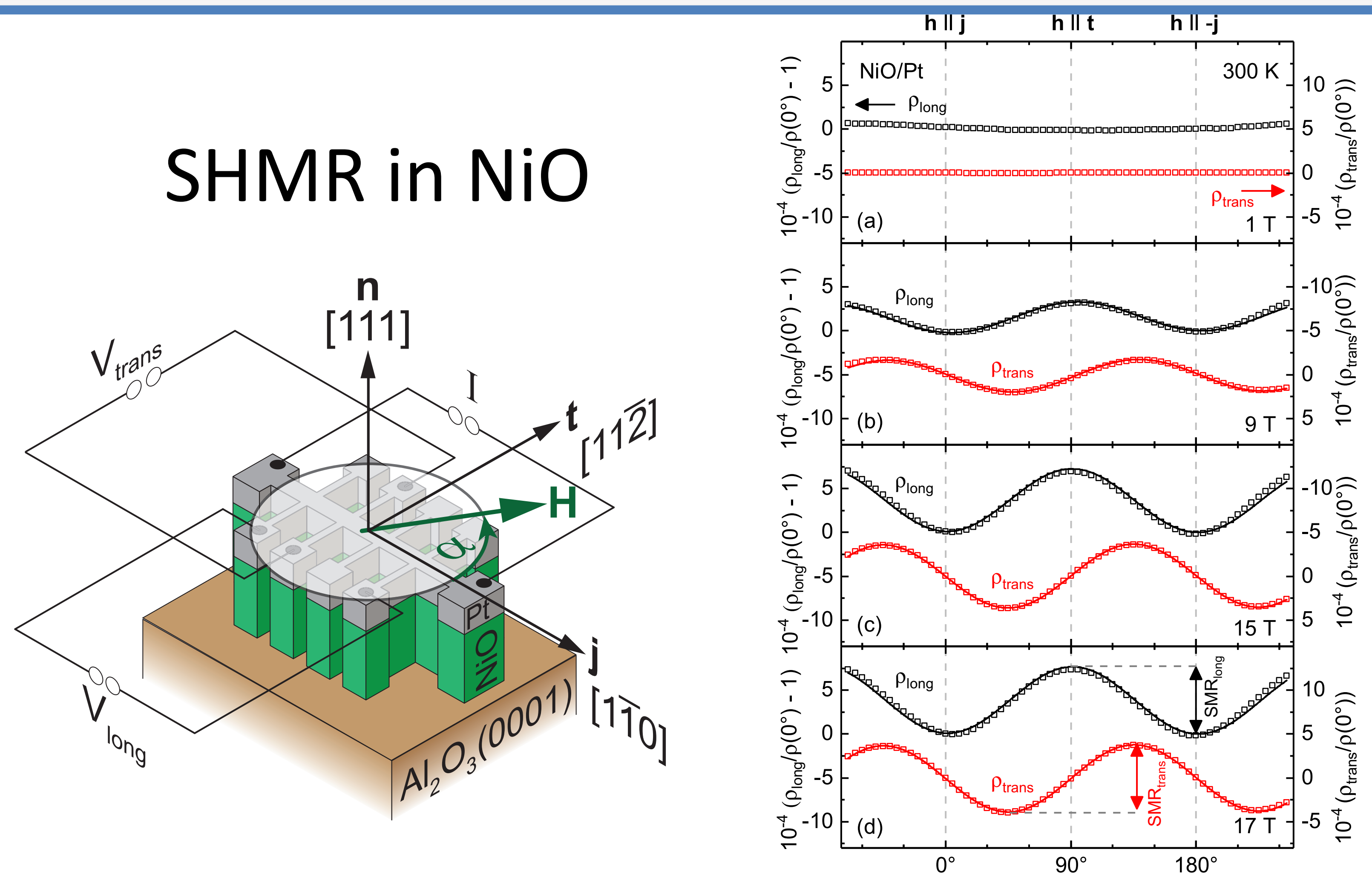


Fig. 1 | Spin transport in an insulating antiferromagnet. a, Schematic

SHMR in NiO



Fischer, *et al* PRB (2018)

Spin-charge conversion in thermally evaporated Cr

Journal of Applied Physics

Negative spin Hall angle and large spin-charge conversion in thermally evaporated chromium thin films

Cite as: J. Appl. Phys. **131**, 113904 (2022); https://doi.org/10.1063/5.0085352
Submitted: 15 January 2022 • Accepted: 27 February 2022 • Published Online: 18 March 2022

S. M. Bleser, R. M. Greening, M. J. Roos, et al.

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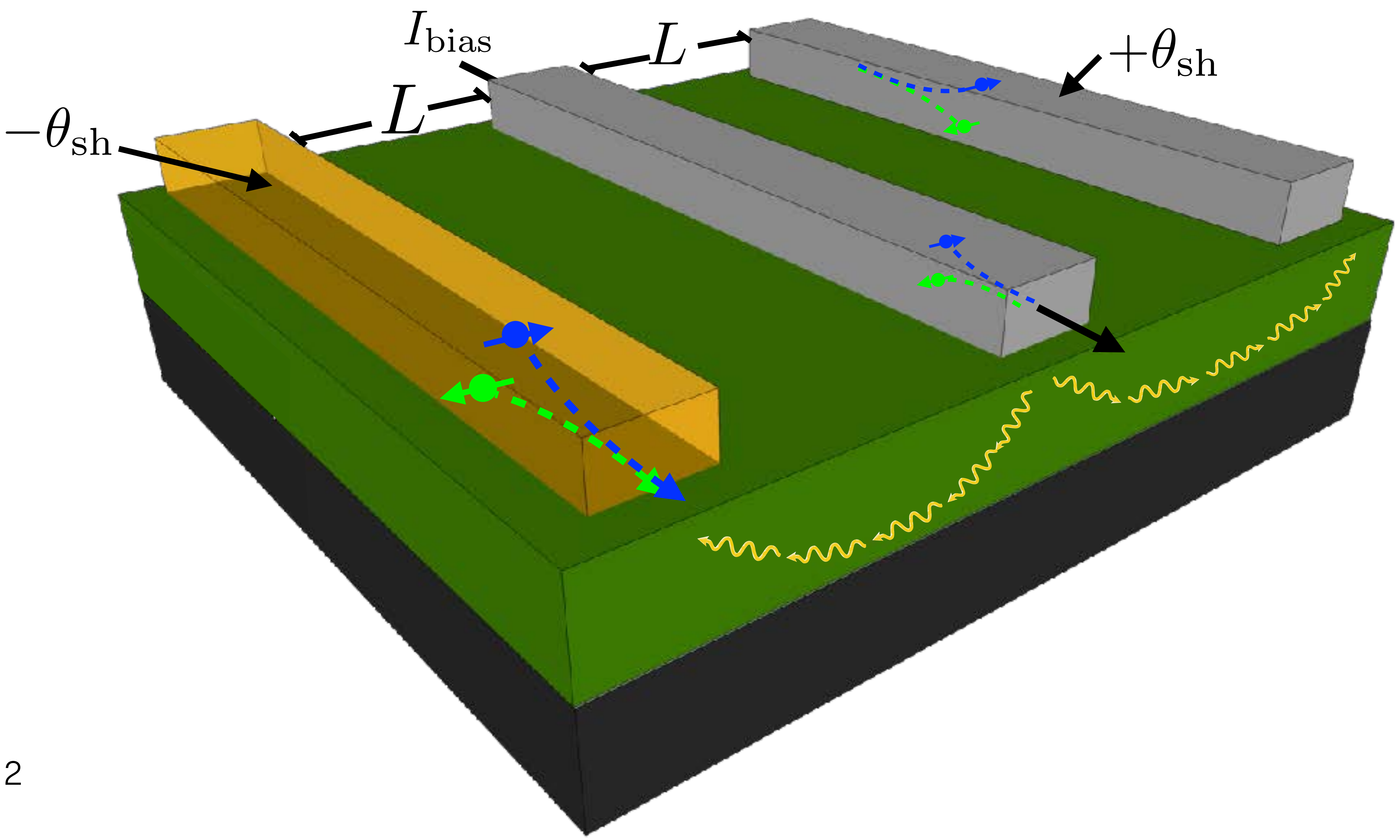
Pt is the most common metal (by far) in a wide range of spintronics devices

Would be nice to have a cheap, easy alternative (and/or complement with opposite spin Hall angle)

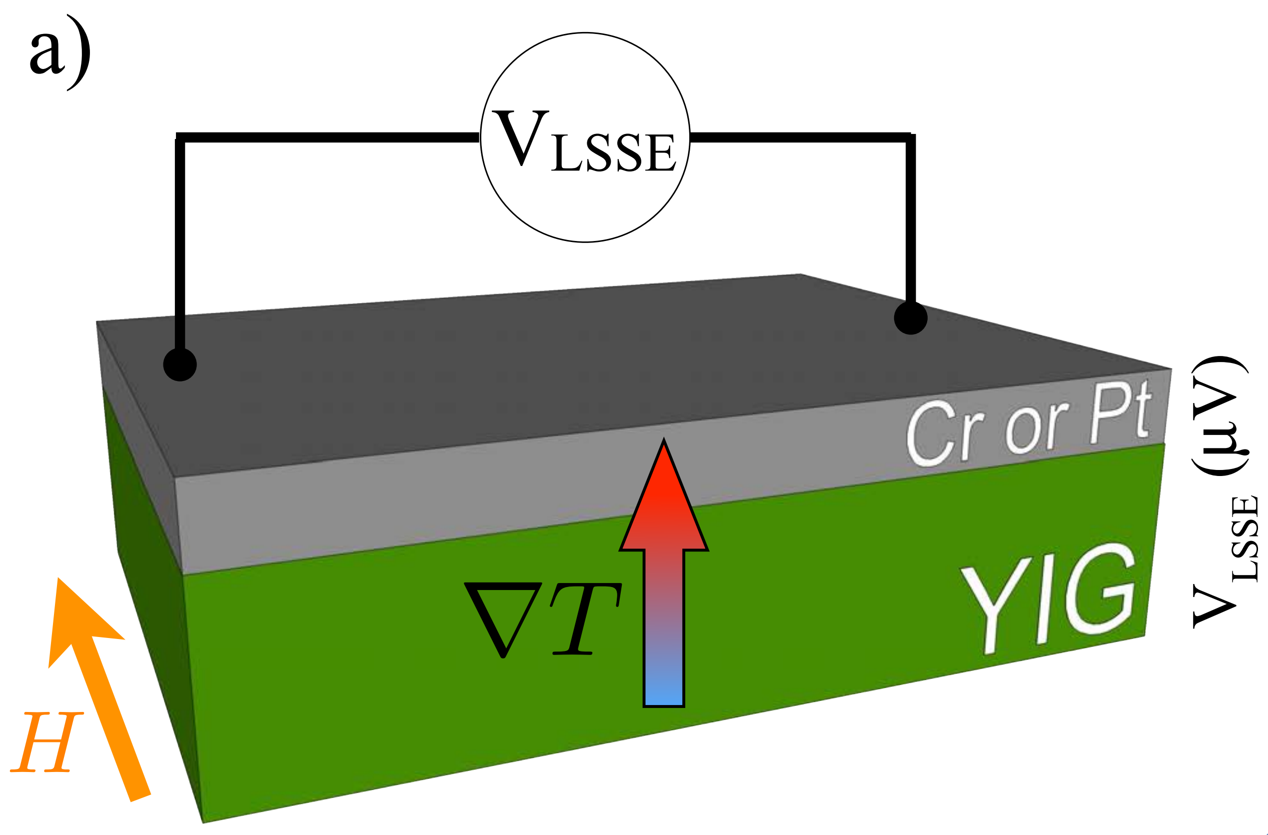


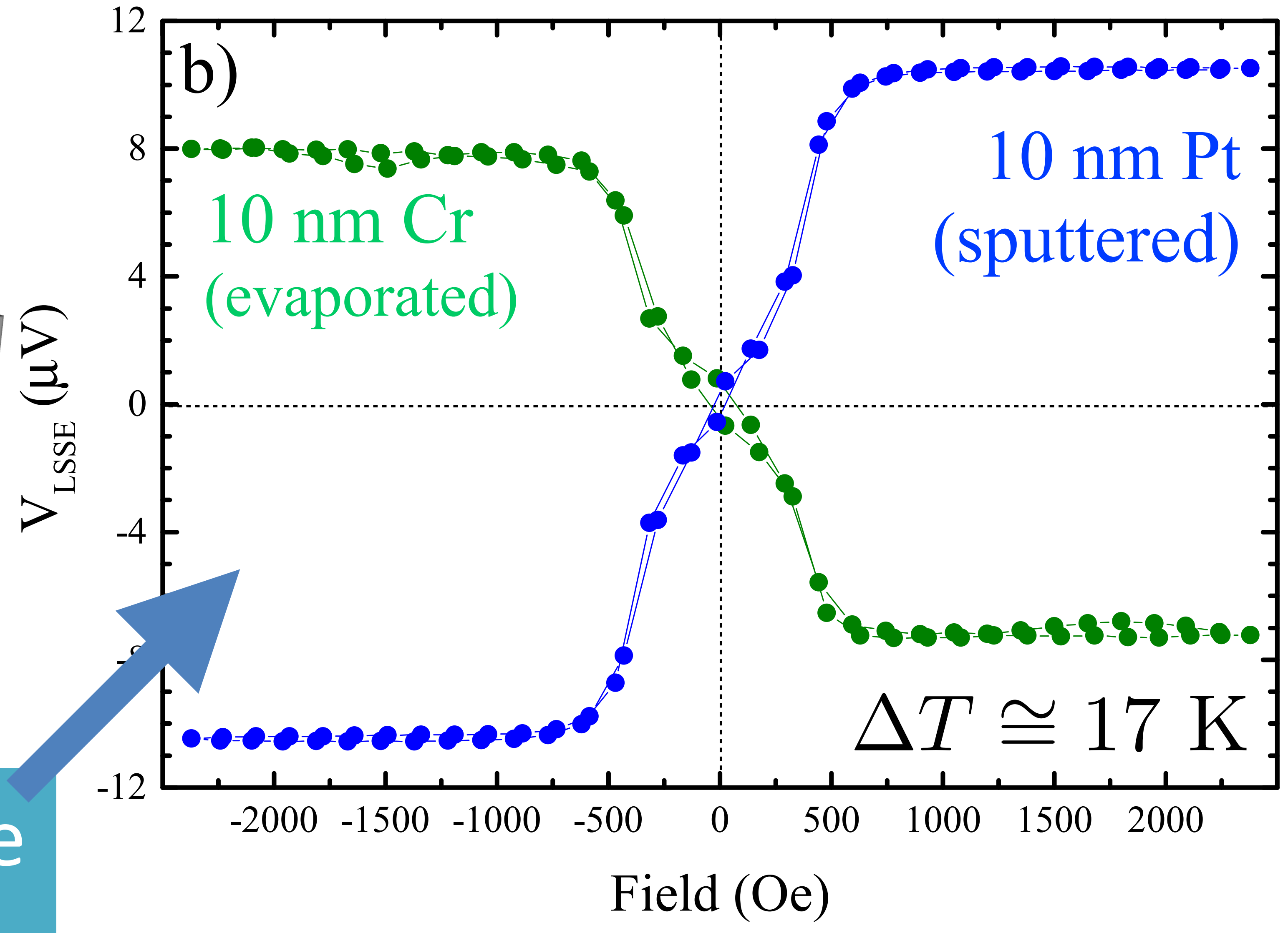
Help confirm spin transport in non-local (and other) experiments by showing opposite sign of voltage when SHA is opposite.

Spin-charge conversion in thermally evaporated Cr

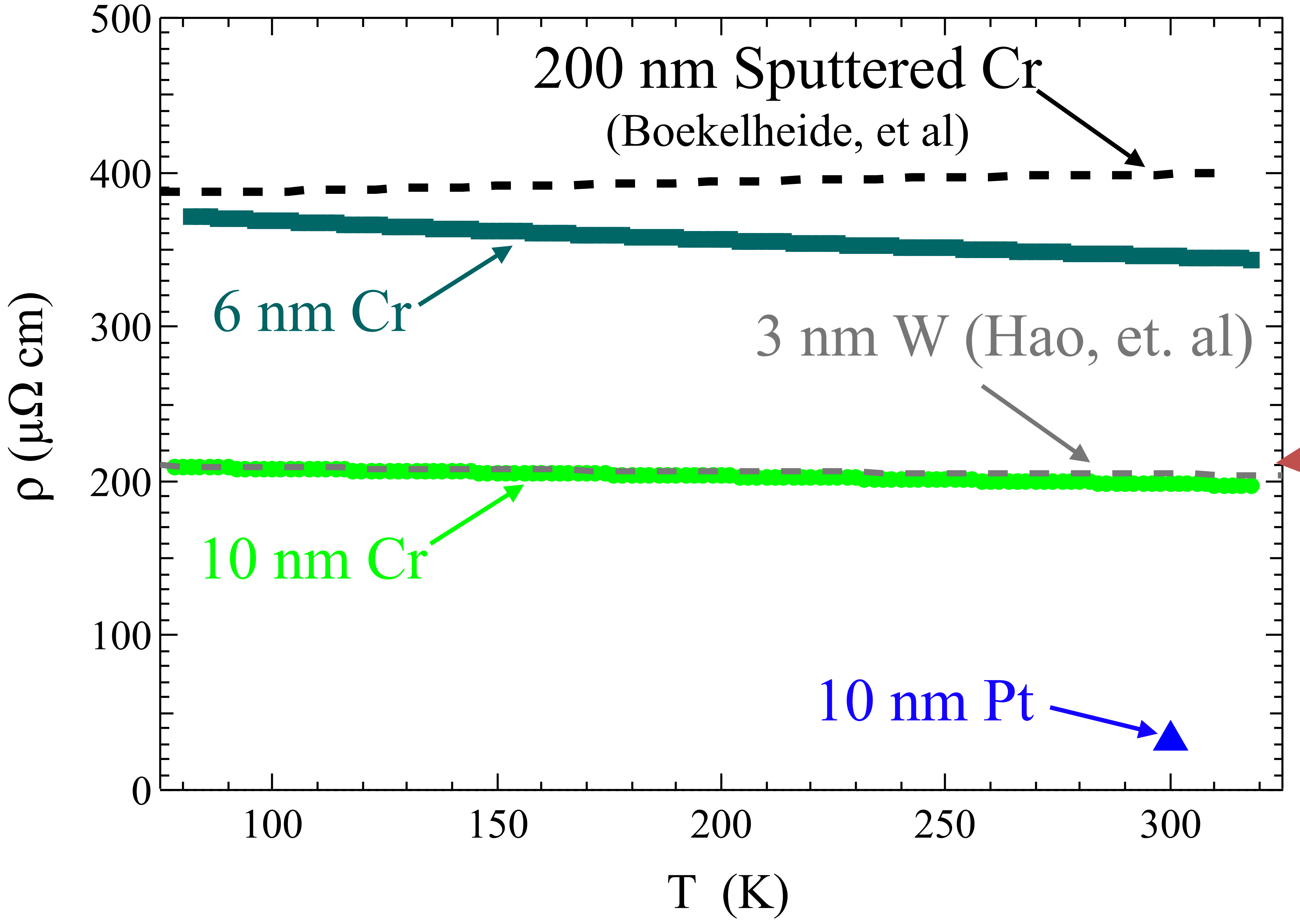
Thermally evaporated Cr (2-12 nm) in high vacuum onto polycrystalline YIG

Standard LSSE setup (external ∇T using blocks and Peltier heater/coolers)





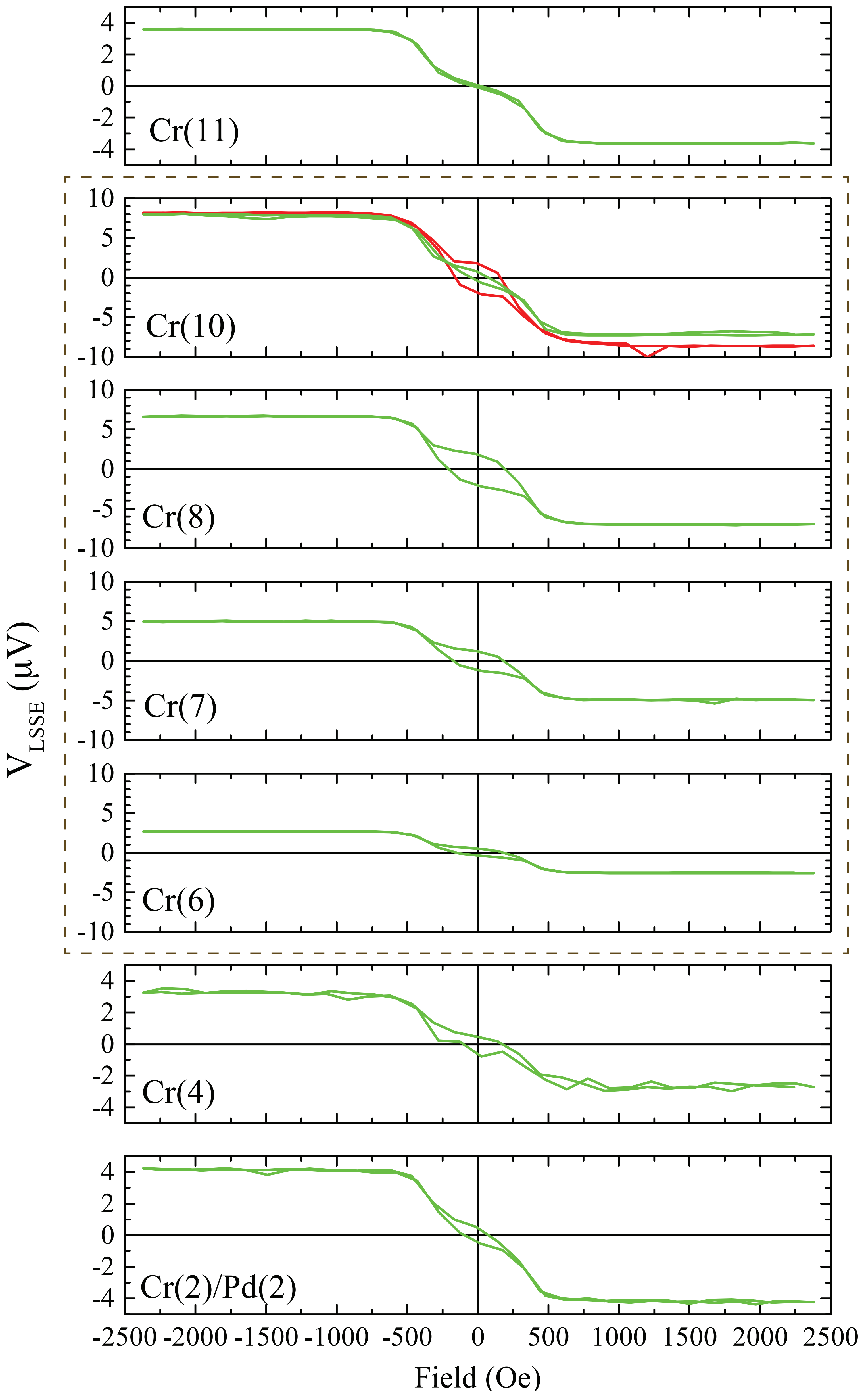
Comparison to Pt/YIG sample using same methods

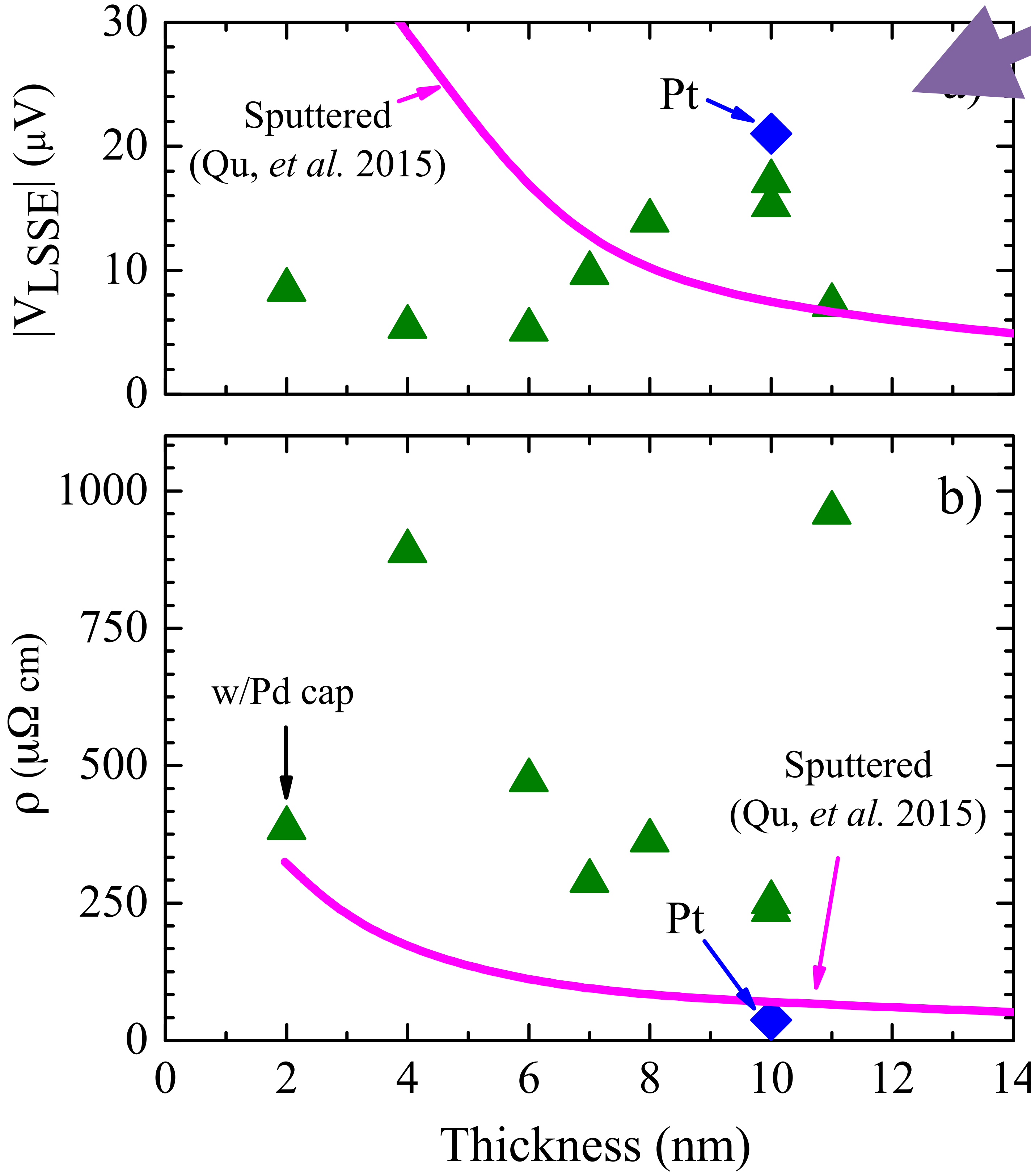


High film resistivity (not suprising for Cr) definitely playing a role

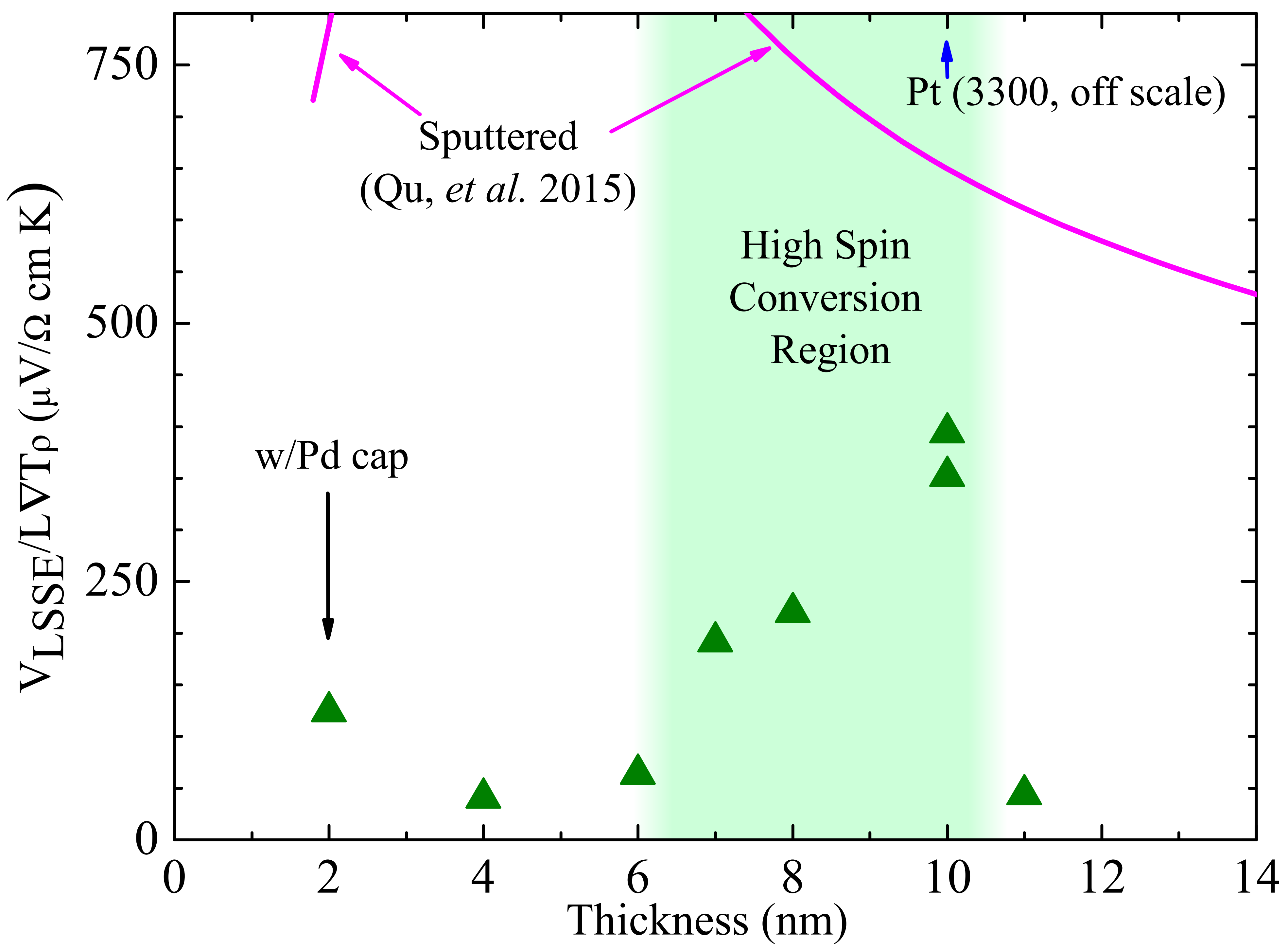
Bleser, Greening, Roos, Hernandez, Fan, BLZ JAP **131** 113904 (2022)

Spin-Charge conversion efficiency in thermally evaporated Cr





Large, useful total voltages (especially around 10 nm)

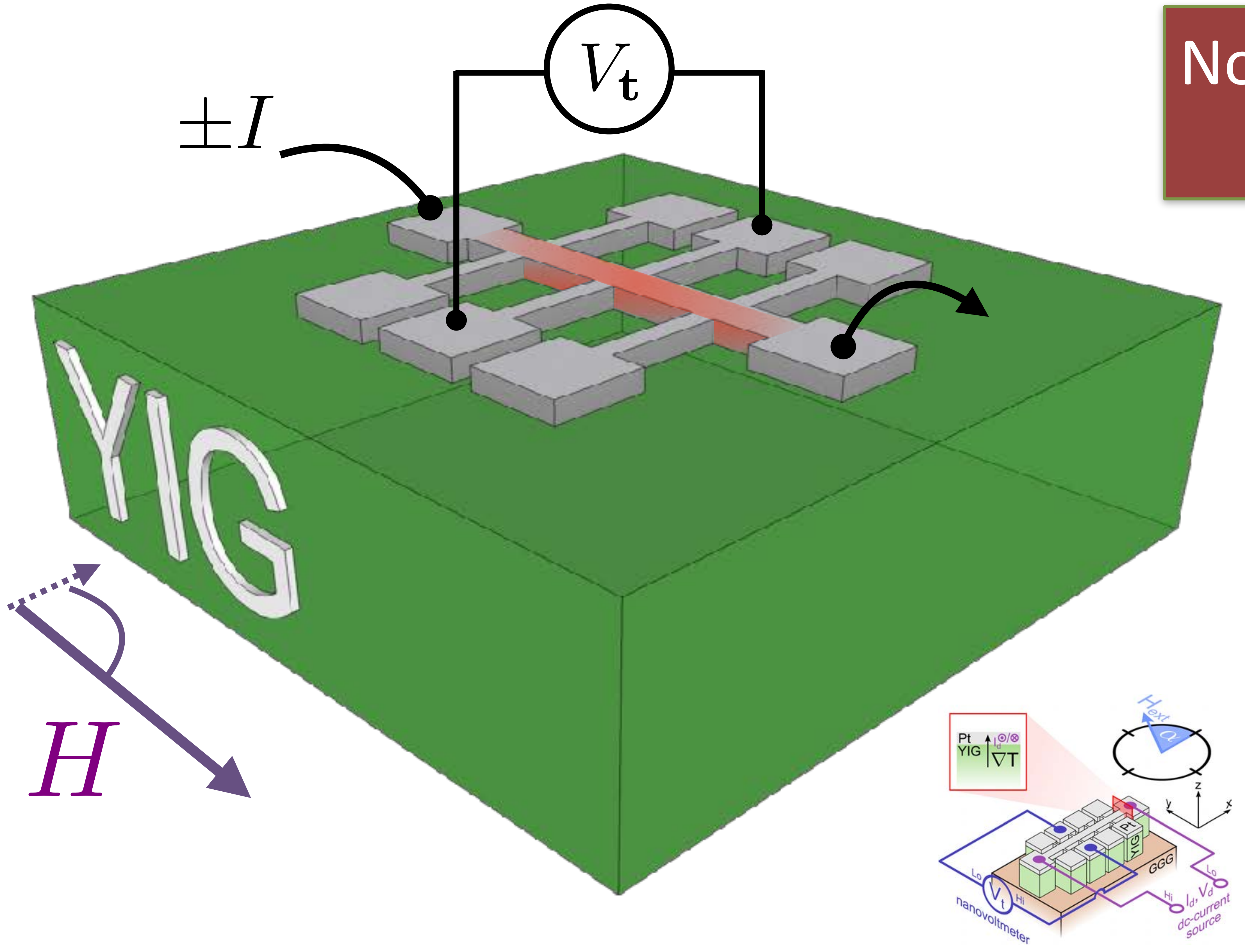


conversion efficiency about half of sputtered Cr

non-monotonic thickness dependence could indicate a role for strain-dependent spin density wave AF

Bleser, Greening, Roos, Hernandez, Fan, BLZ JAP **131** 113904 (2022)

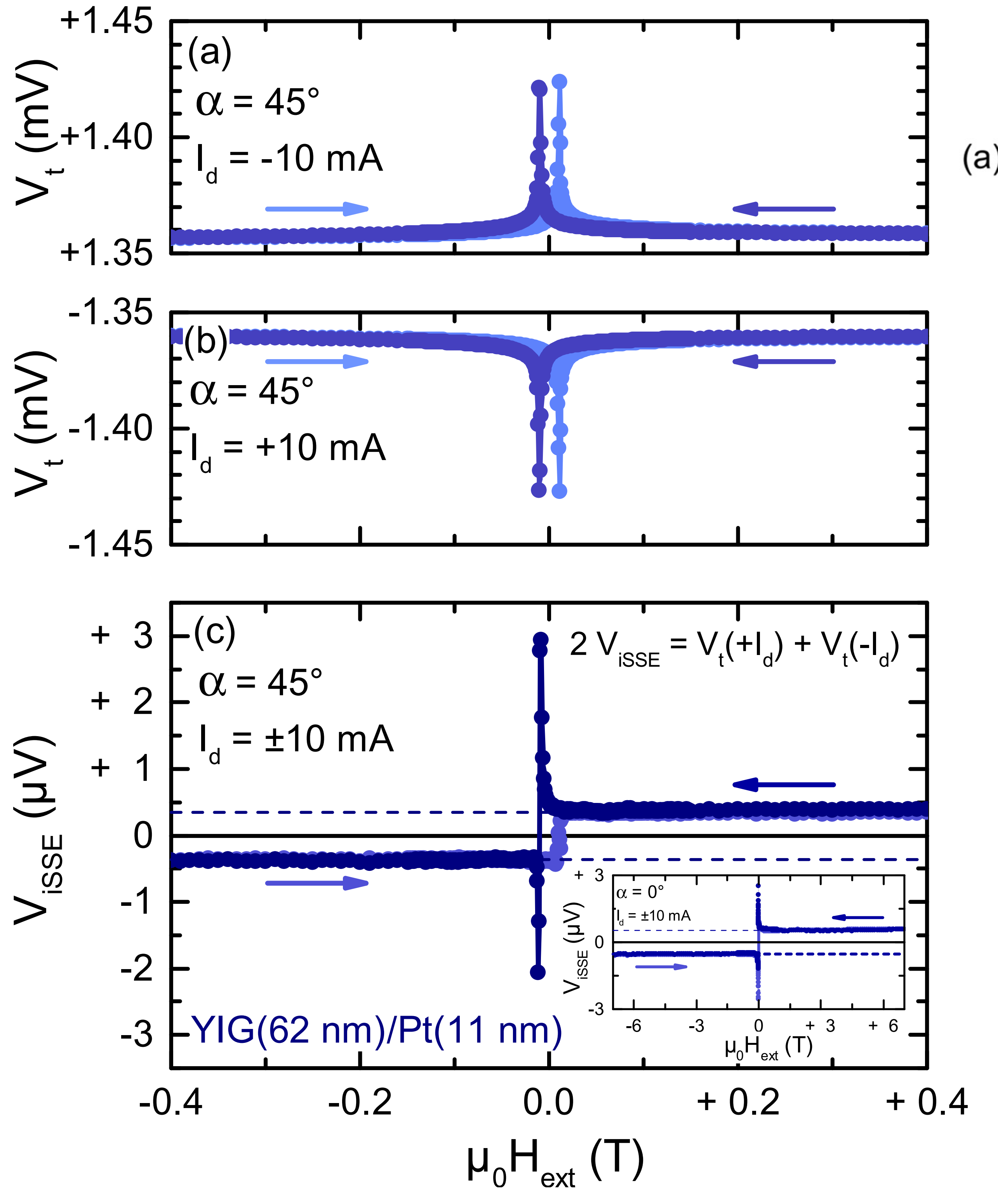
Temperature dependence of LSSE in evap Cr

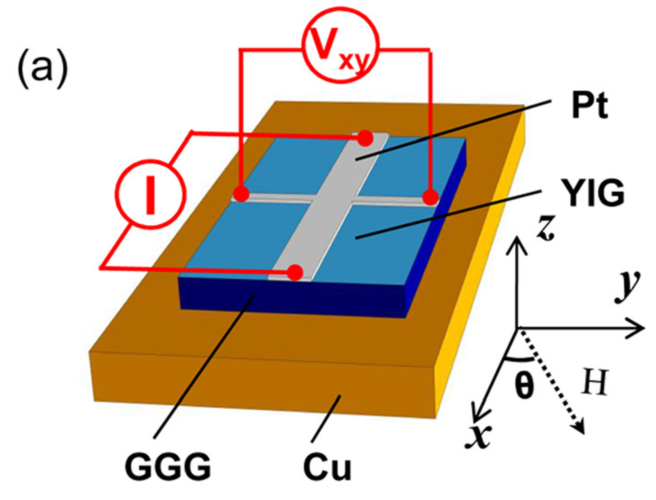


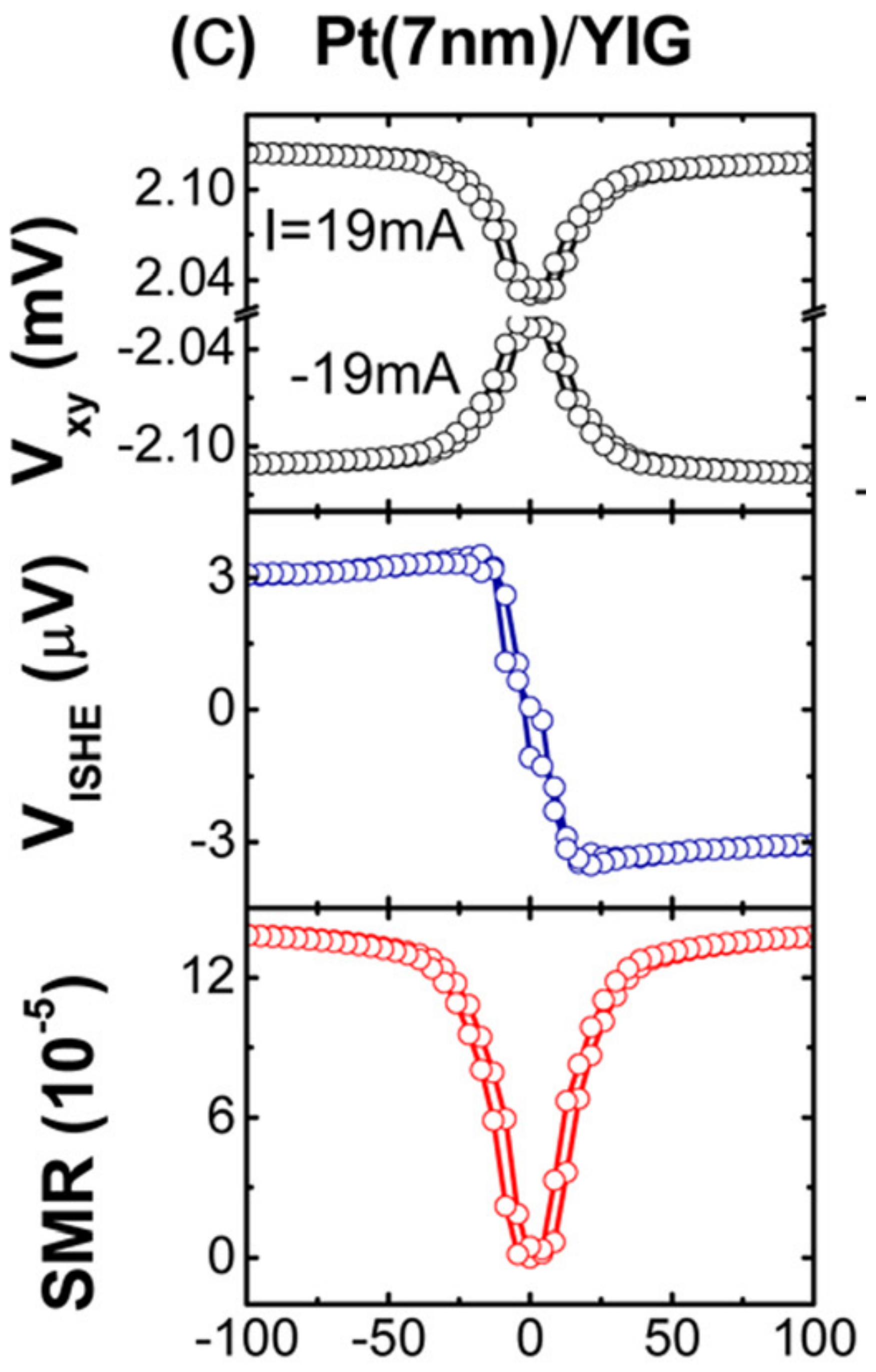
Now using local heating LSSE via patterned Hall bars on polycrystalline YIG

$$V_{\mathbf{LSSE}} = \frac{V_{xy}(I^+) + V_{xy}(I^-)}{2} \qquad V_{\mathbf{SHMR}} = \frac{V_{xy}(I^+) - V_{xy}(I^-)}{2}$$

Compare Pt, Cr, and Cu films





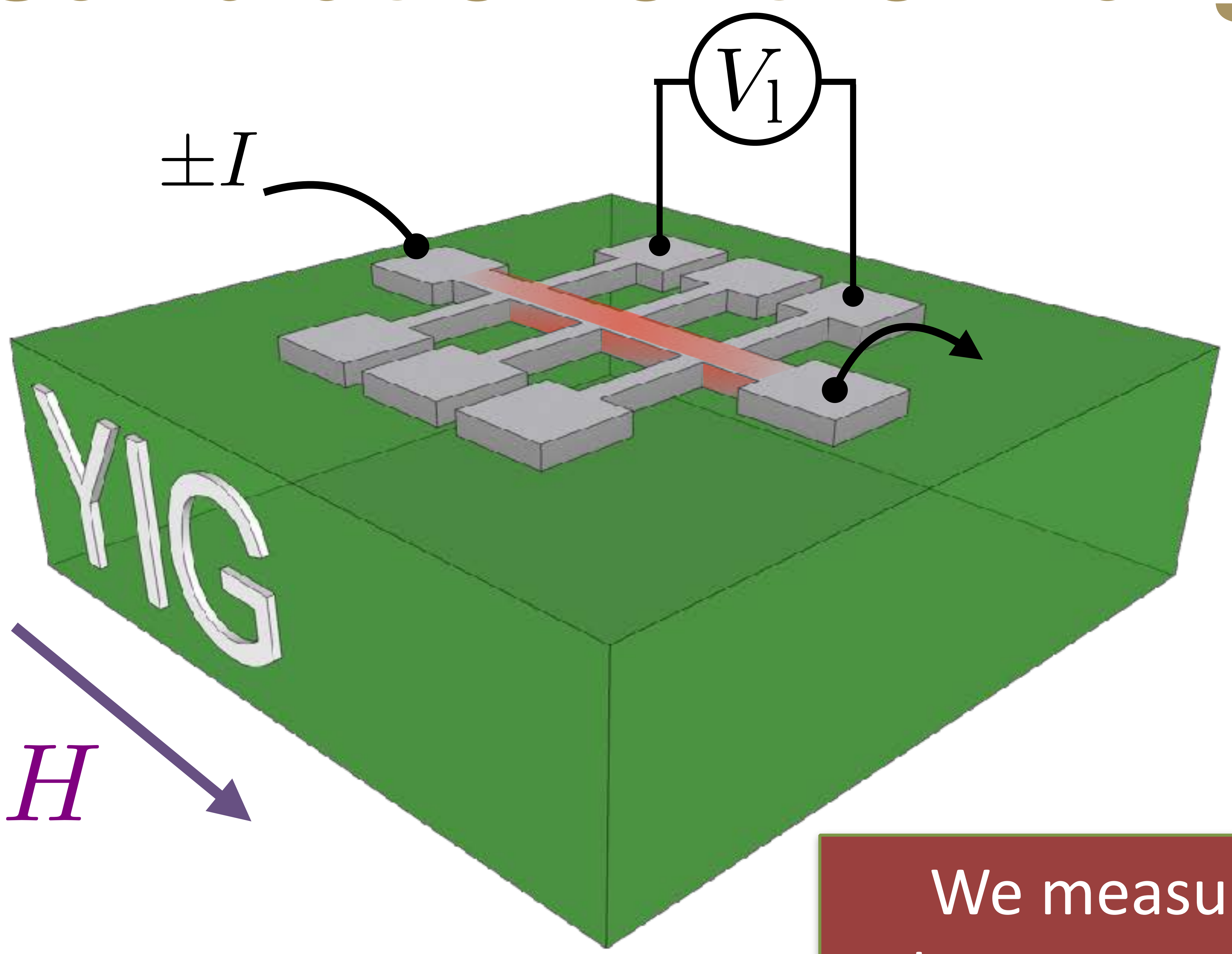


Similar on epi YIG:

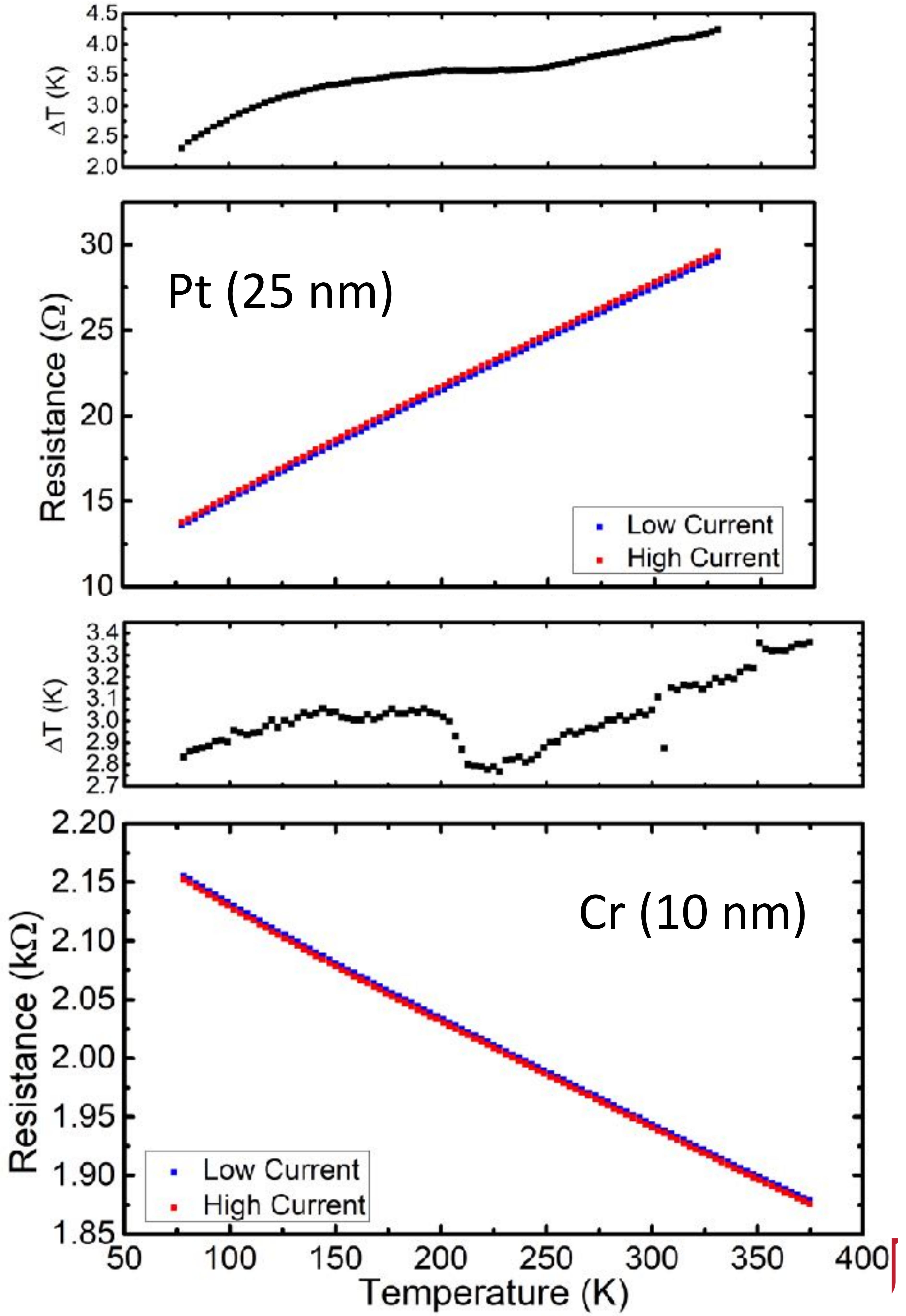
Schreier, *et al* APL **103** 242404 (2013)

Wang, et al APL **105** 182403 (2014)

Calibration of thermal gradient

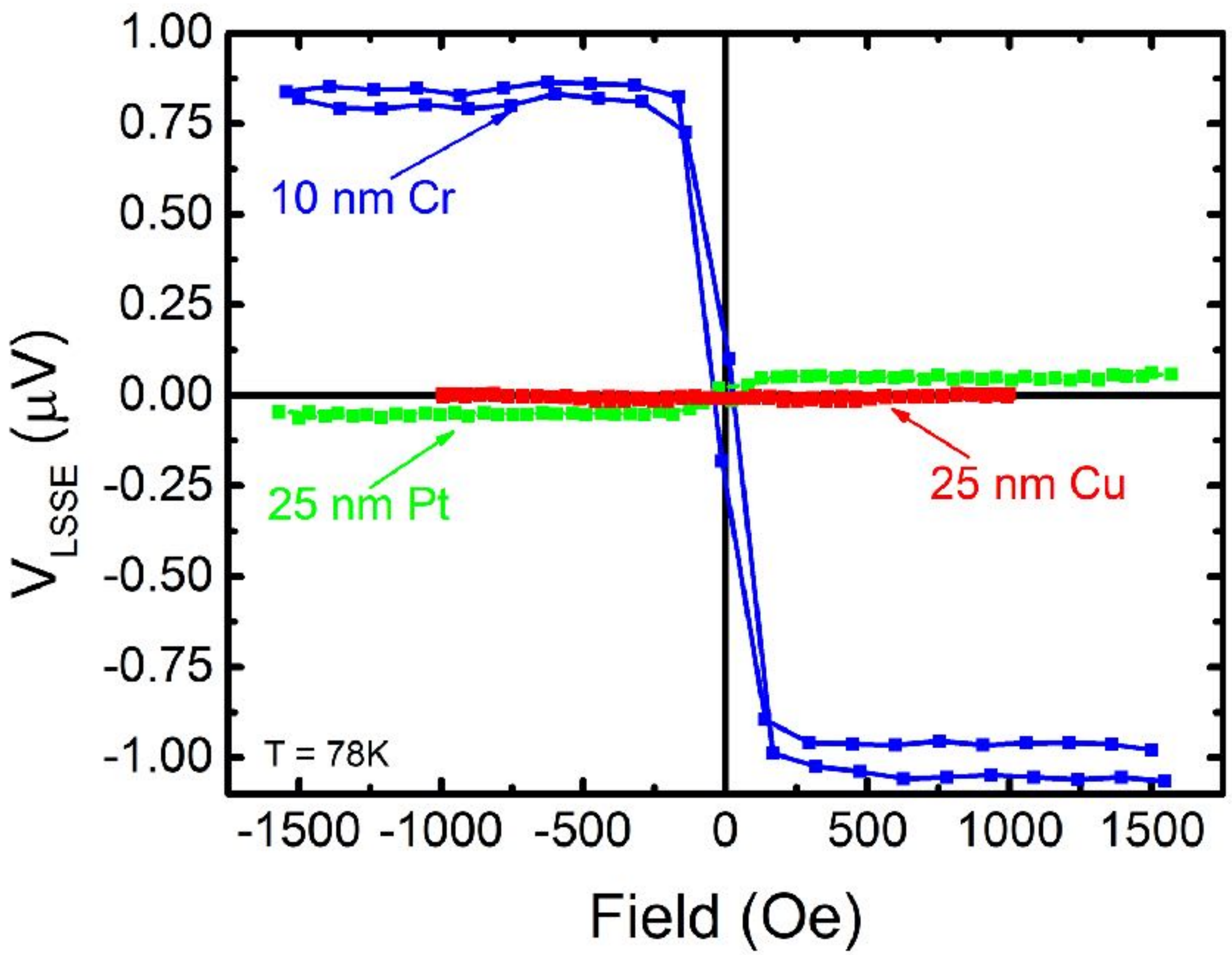


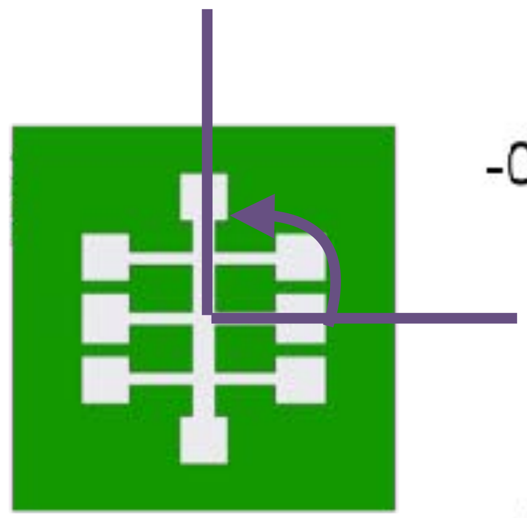
We measure longitudinal voltage at a series of current to determine the thermal gradient generated

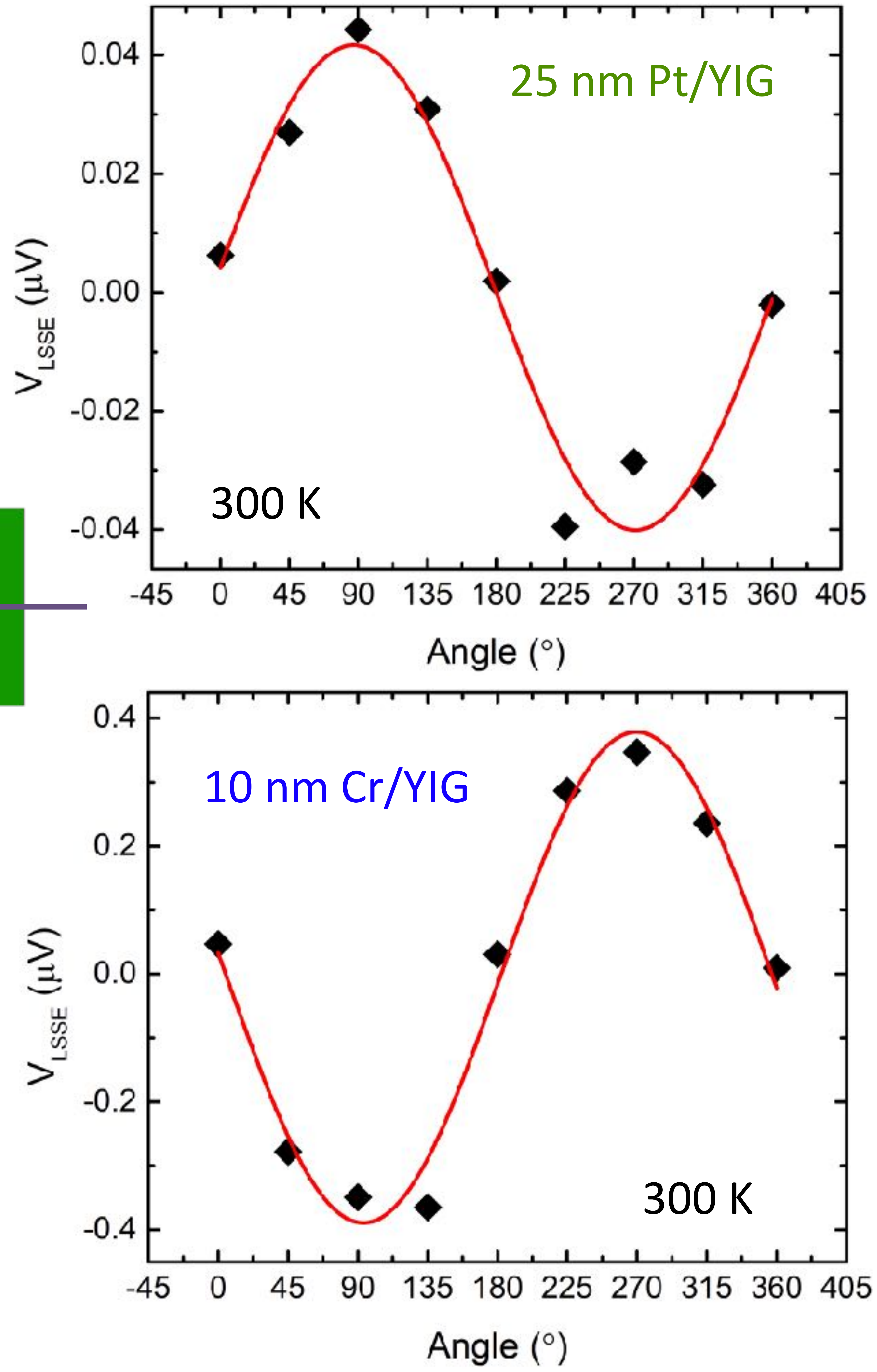


Bleser, Natale, Greening, Fan, Zink *in preparation*

Comparison of Cr/YIG and Pt/YIG







Raw LSSE voltage

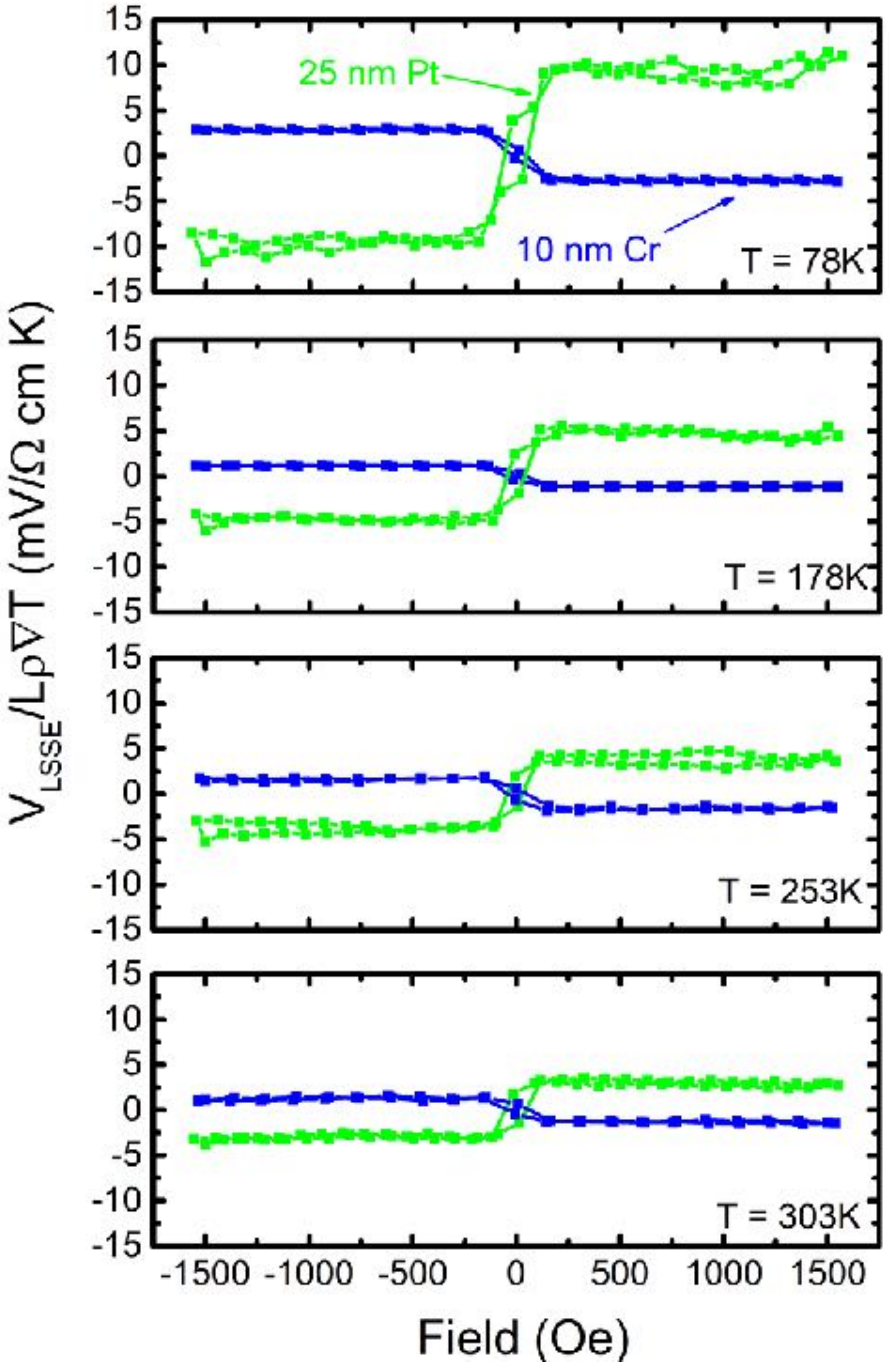
Large R in Cr gives somewhat larger heating, less shunting, is very nice for this technique

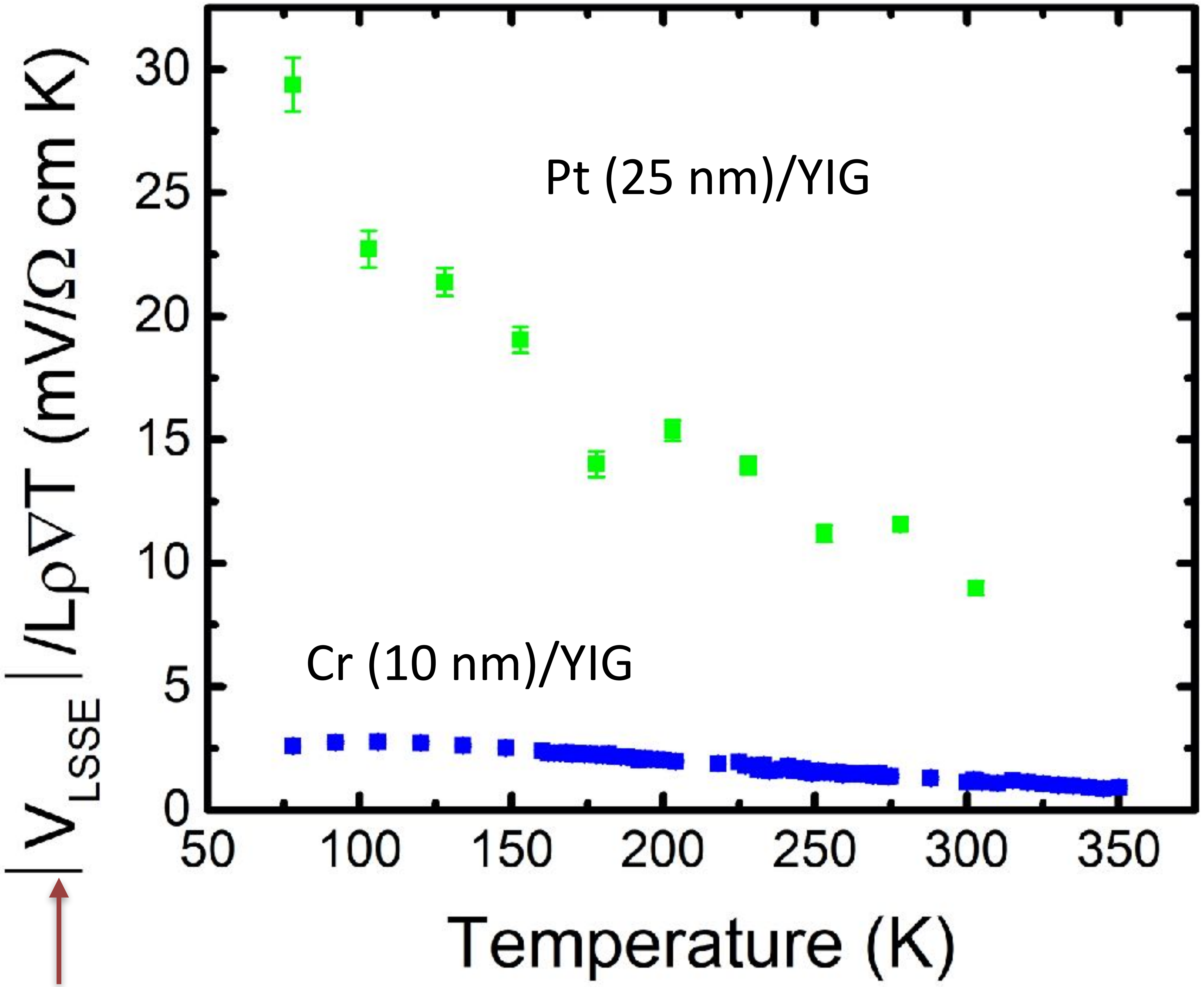
Bleser, Natale, Greening, Fan, Zink *in preparation*

Temperature dep, Cr/YIG vs Pt/YIG

$$V_{\text{LSSE}} = 2(CL\nabla T)(\rho\theta_{\text{sh}})\frac{\lambda_{\text{sf}}}{t}\tanh\left(\frac{t}{2\lambda_{\text{sf}}}\right)$$

$$\frac{V_{\text{LSSE}}}{L\nabla T\rho} = 2(C\theta_{\text{sh}})\frac{\lambda_{\text{sf}}}{t}\tanh\left(\frac{t}{2\lambda_{\text{sf}}}\right)$$

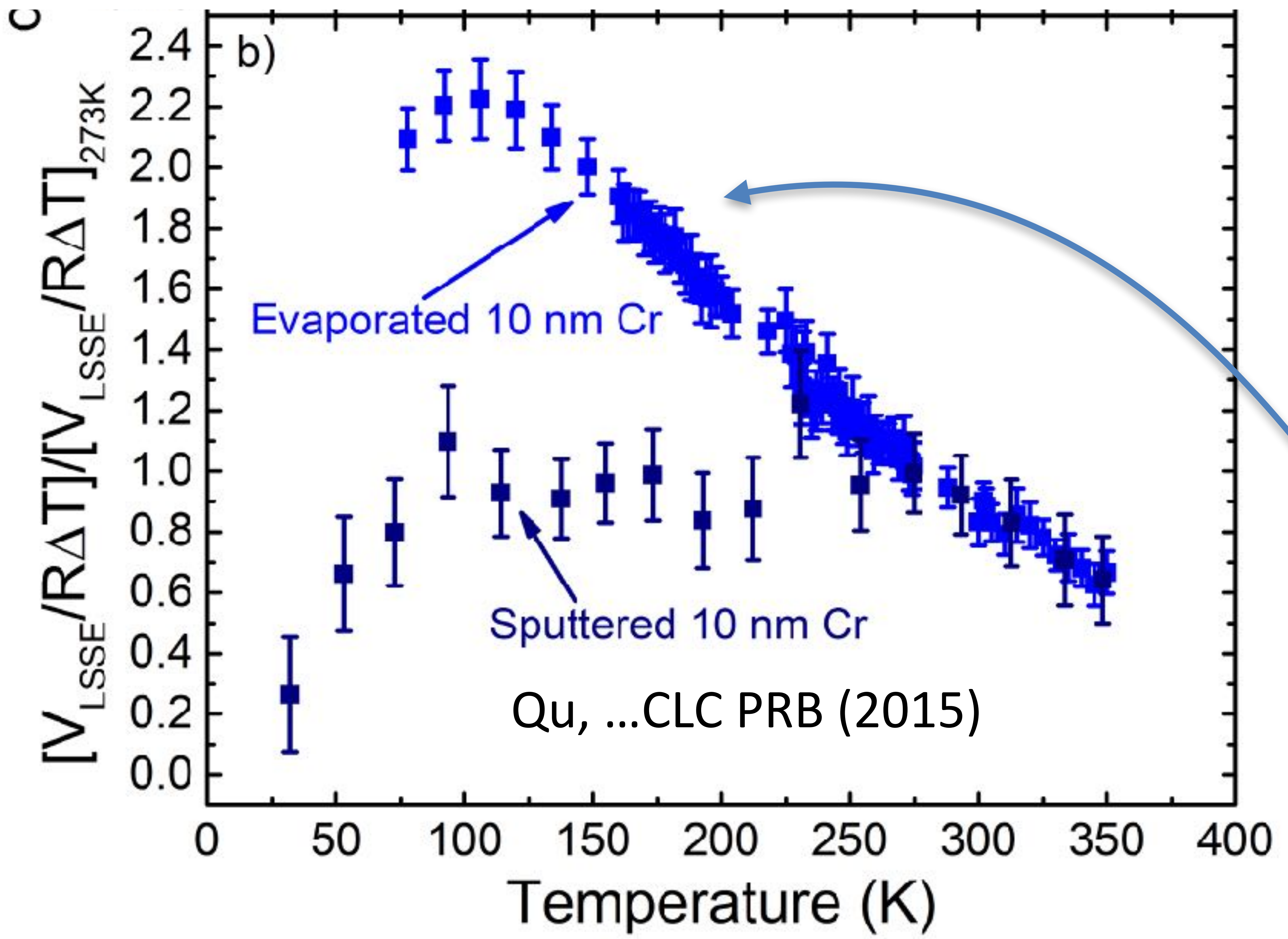




spin conversion efficiency

Comparison of Cr/YIG T-dependence

dR/dT features indicate TWO potential Neel temperatures in 10 nm evaporated Cr



AFM in Cr is driven by spin density waves. These can be commensurate (CSDW) or incommensurate (ICSDW)

In bulk: ⟶ $\mathbf{ICSDW}\ T_{\mathrm{n}} = 305\ \mathrm{K}$

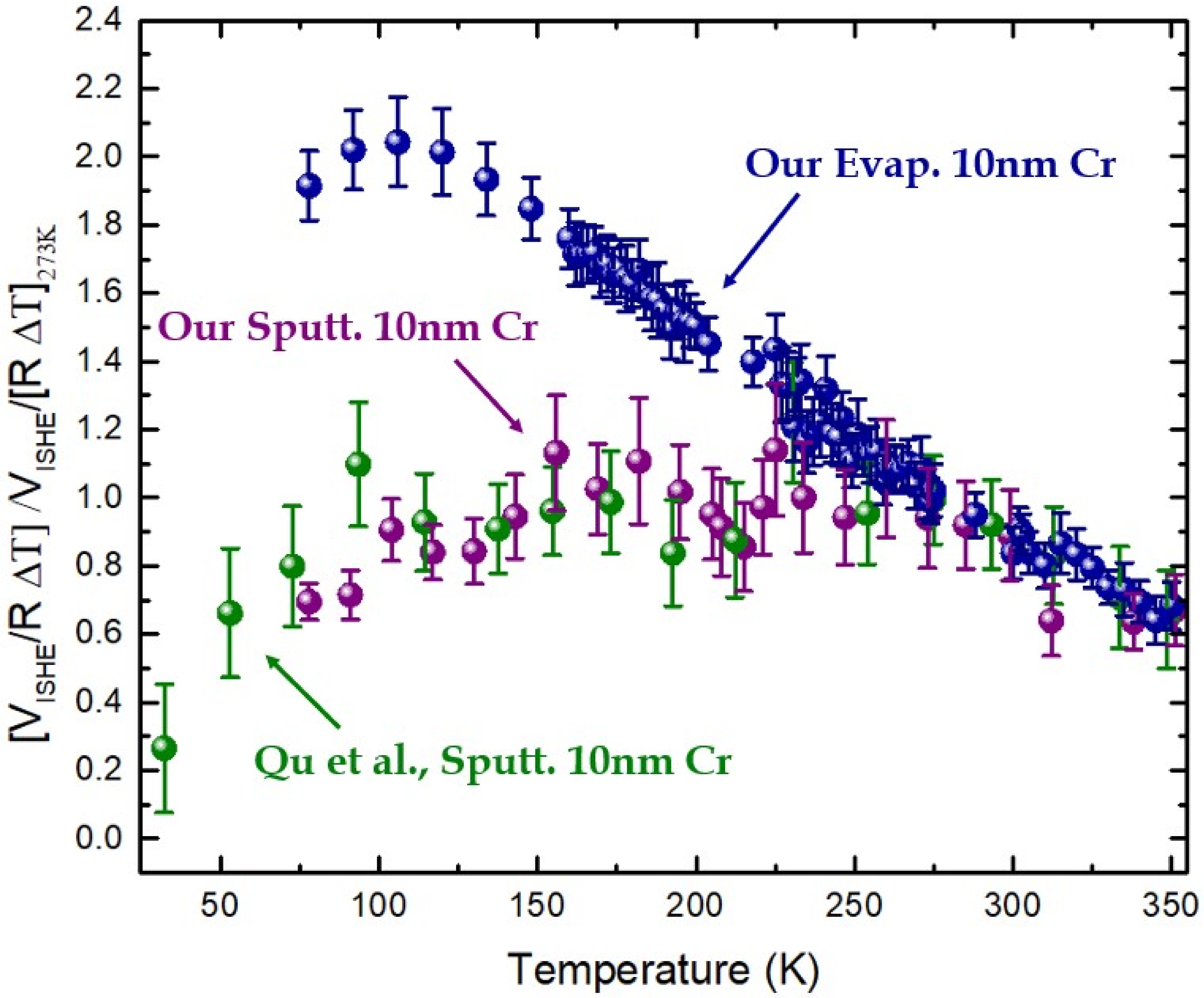
Strain in films can drive the CSDW → $\mathbf{CSDW}\ T_{\mathrm{n}} = 425\ \mathrm{K}$

Films can also end up in a mixed state, and size effects can reduce both temperatures

Quite different T dependence in evaporated Cr below the ~200 K ordering, where all Cr has become AF

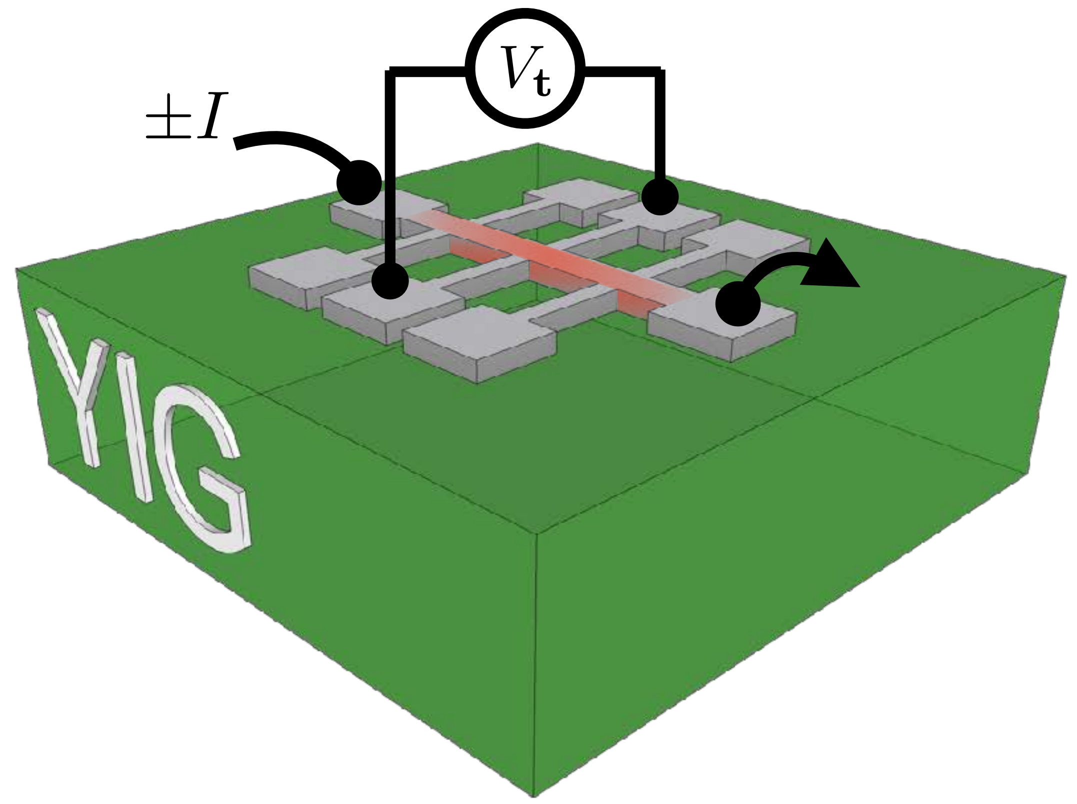
Bleser, Natale, Greening, Fan, Zink *in preparation*

Latest updates…



We have recently completed the same local LSSE experiment on 10 nm sputtered Cr.

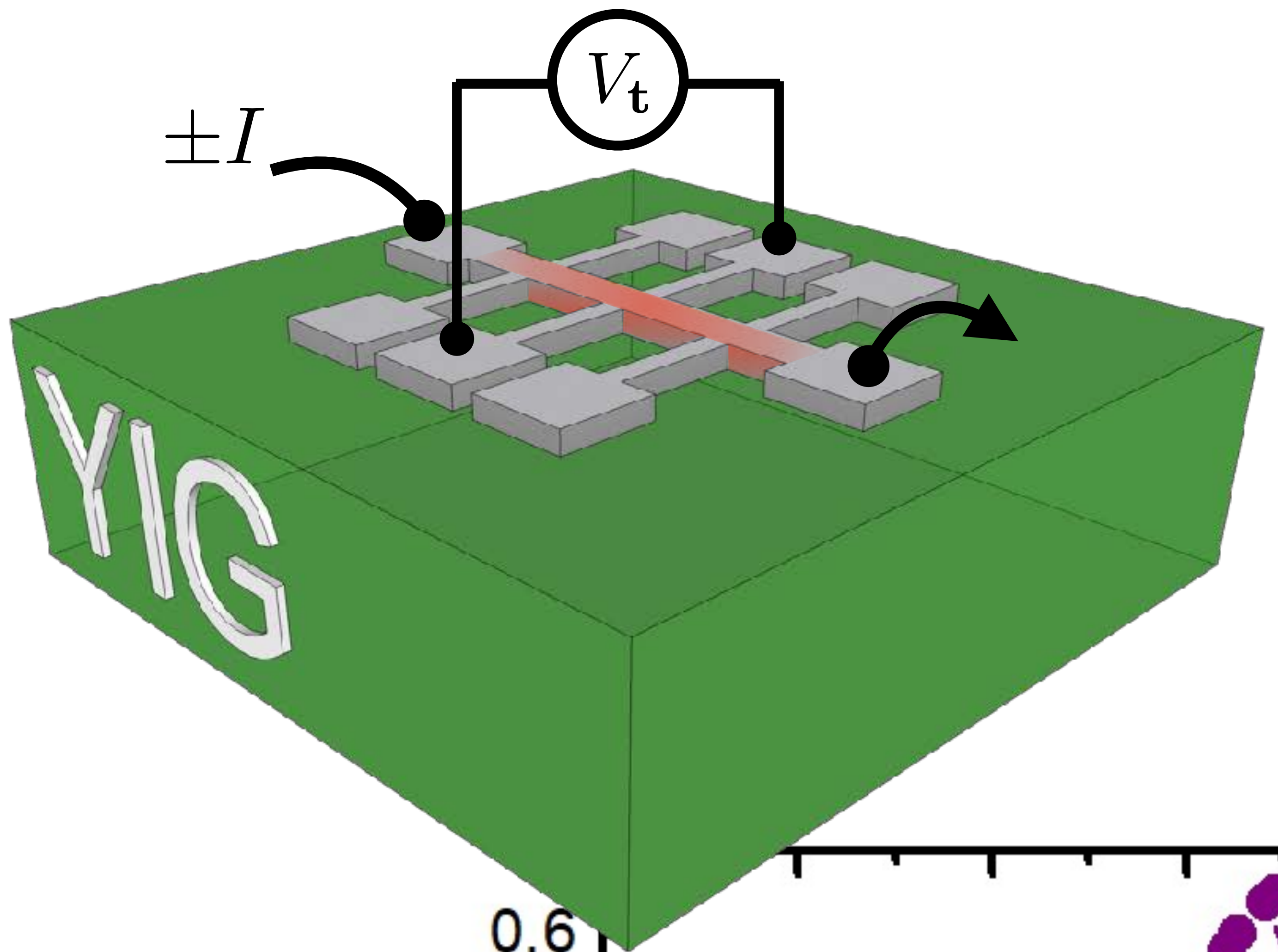
(only one high T feature in dR/dT)



Excellent agreement between our sputtered Cr LSSE efficiency is further evidence that the mixed SDW state plays a role in spin conversion in Cr thin films

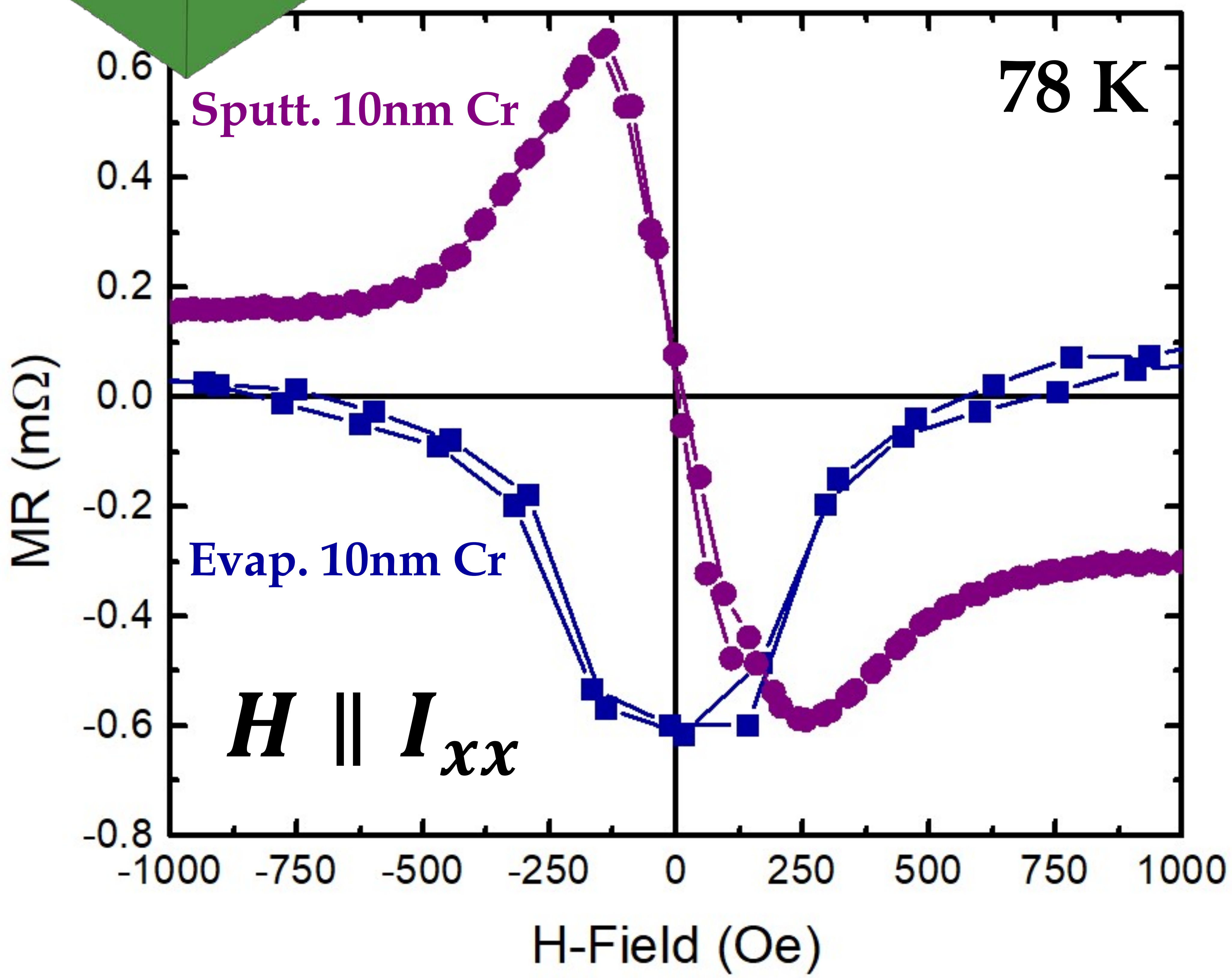
Bleser, Natale, Greening, Fan, Zink *in preparation*

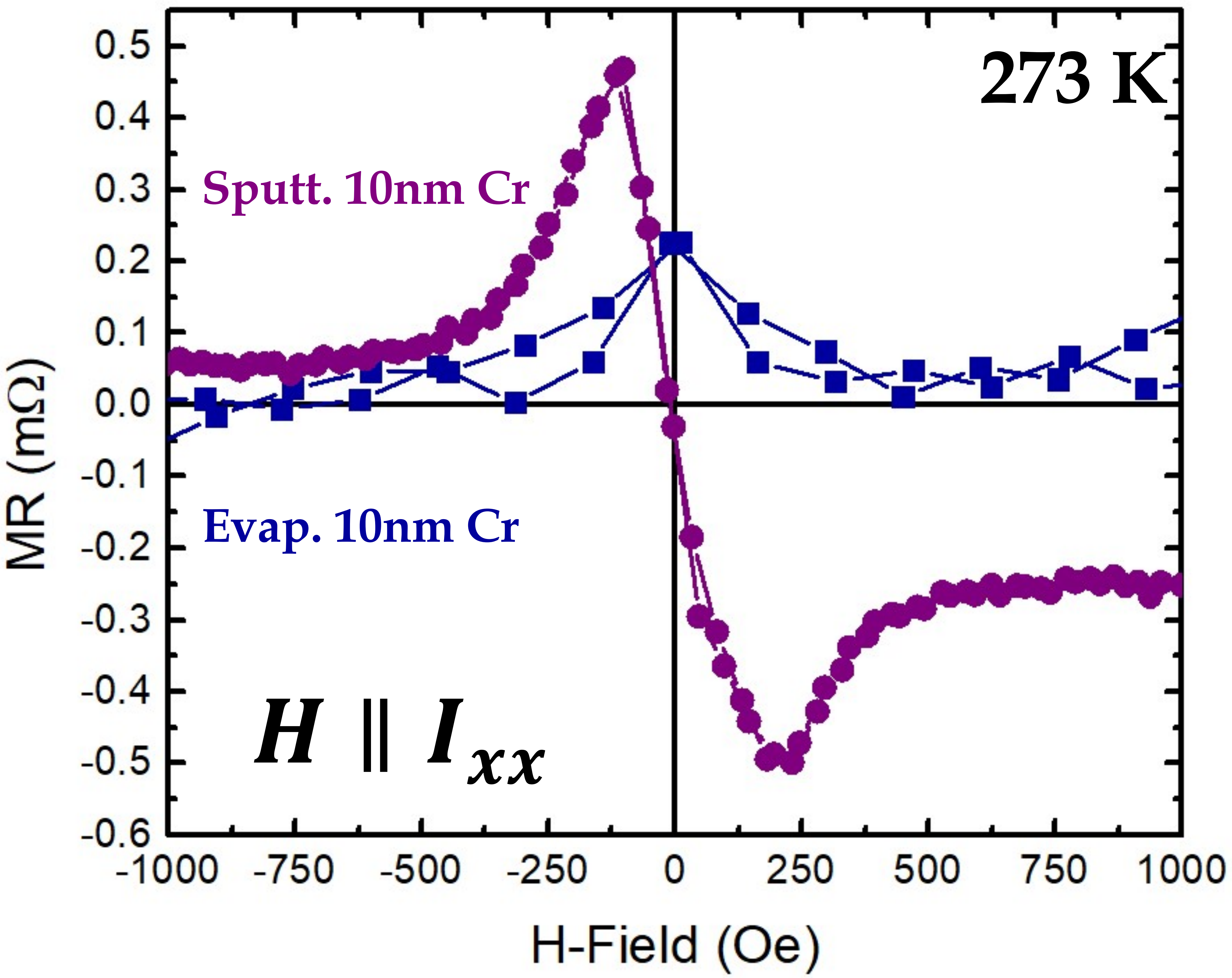
Brief look at SMR in Cr/YIG



$$V_{MR} = \frac{V(I^+) - V(I^-)}{2}$$

Here evaporated Cr gives signals with expected symmetry, while something…else is happening in sputtered Cr….



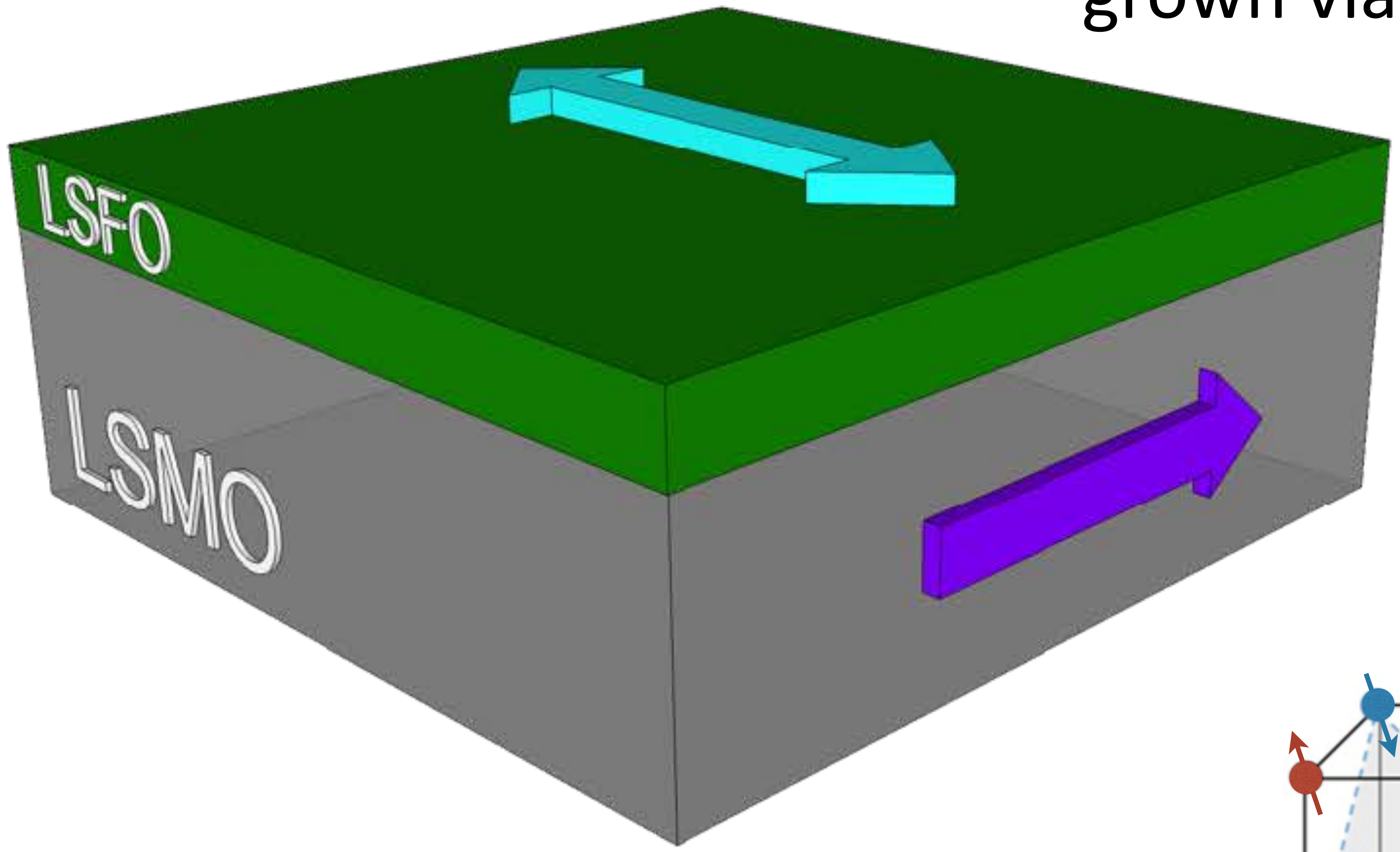


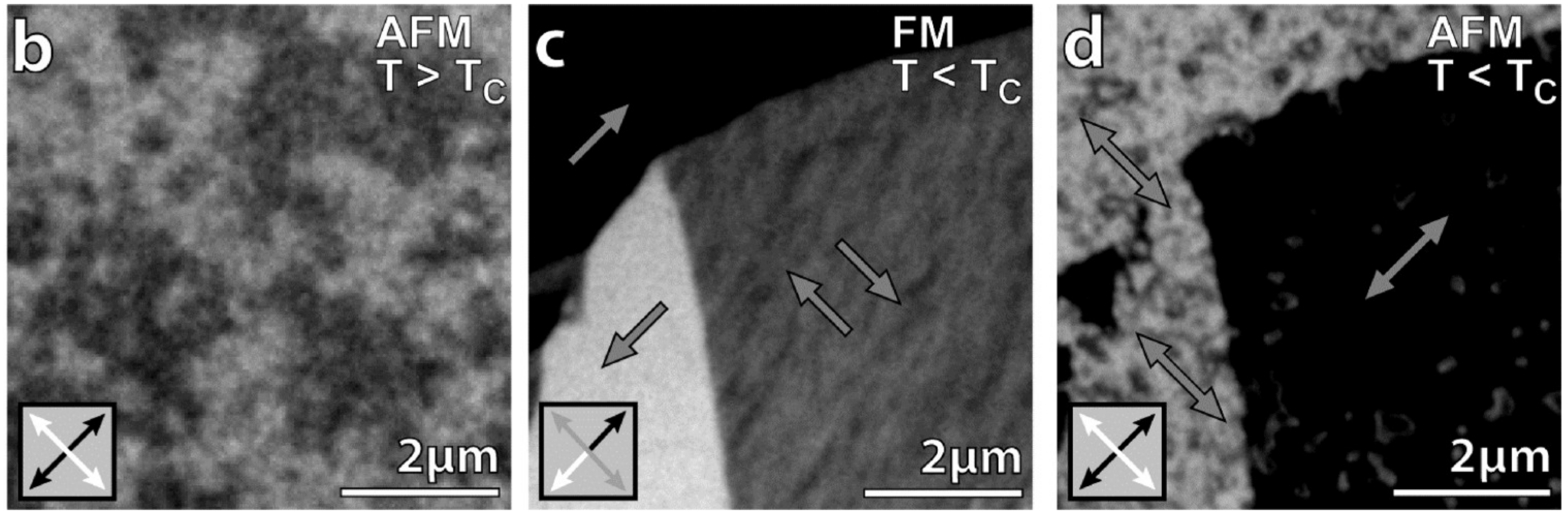
Low-field controllable AFM/FM bilayers

高村 TAKAMURA GROUP

UCDAVIS UNIVERSITY OF CALIFORNIA

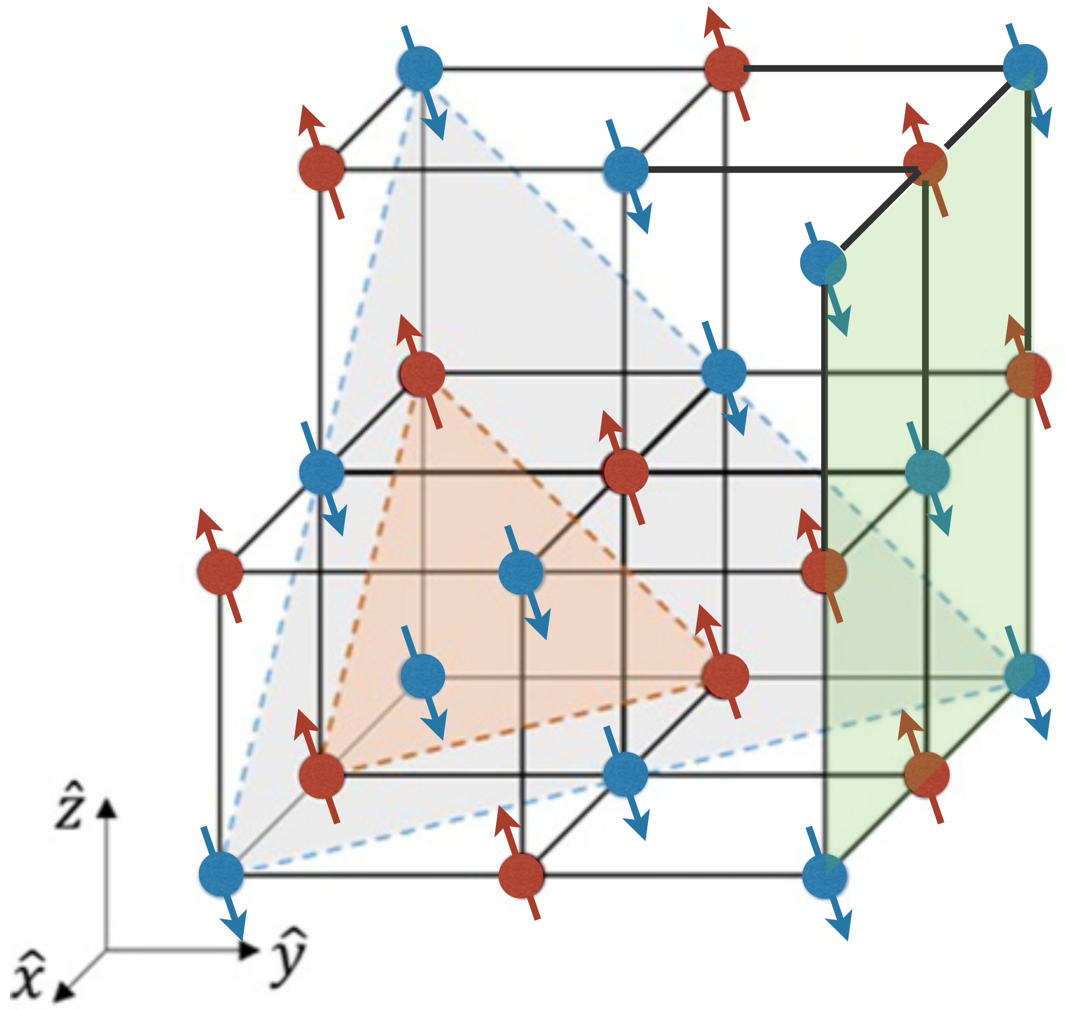
"spin flop" coupled (100)
$La_{1-x}Sr_xFeO_3/La_{1-x}Sr_xMnO_3$
Perovskite bilayers
grown via PLD

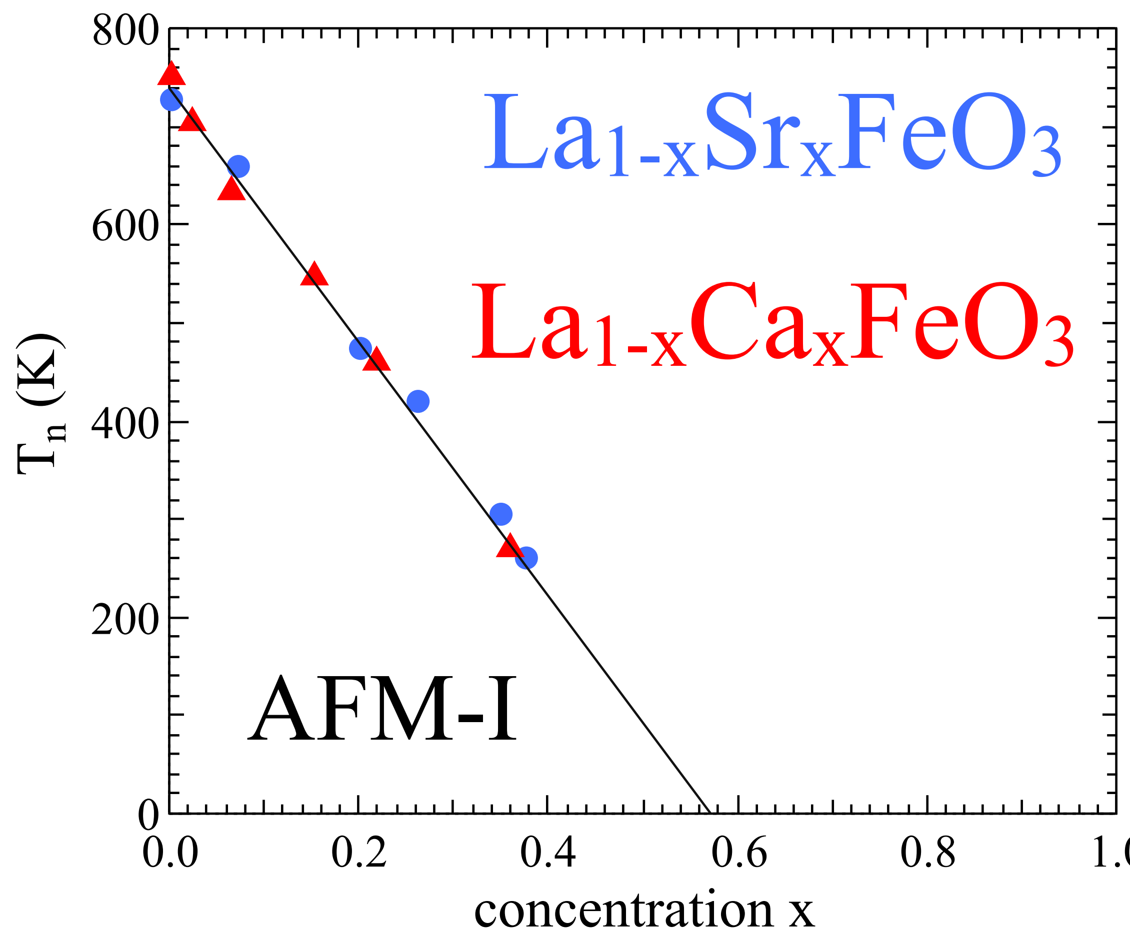


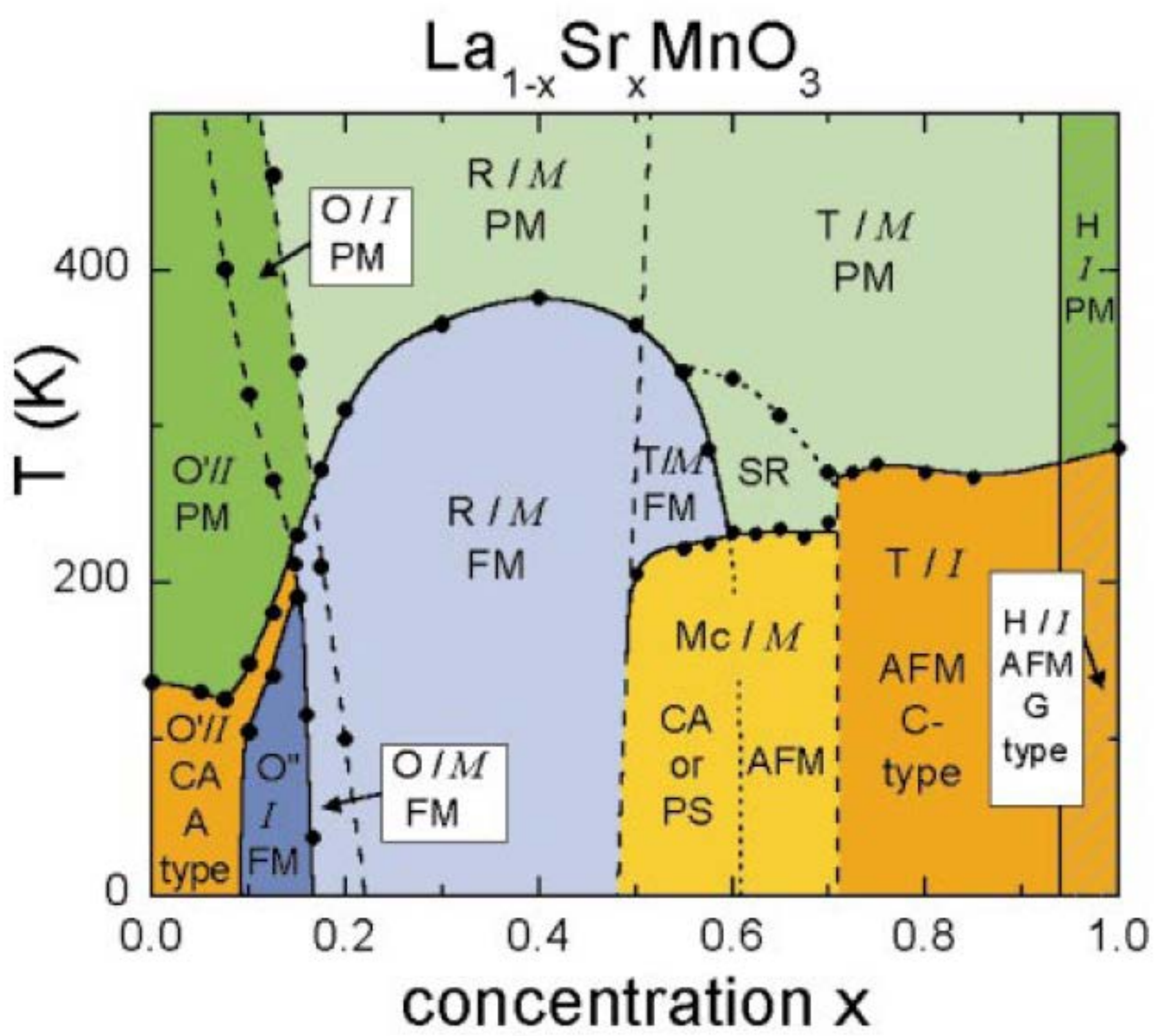


Folven…Y. Takamura et al. *Nano Lett* **12** 2386 (2012)

Opportunity to control Neel vector with low field



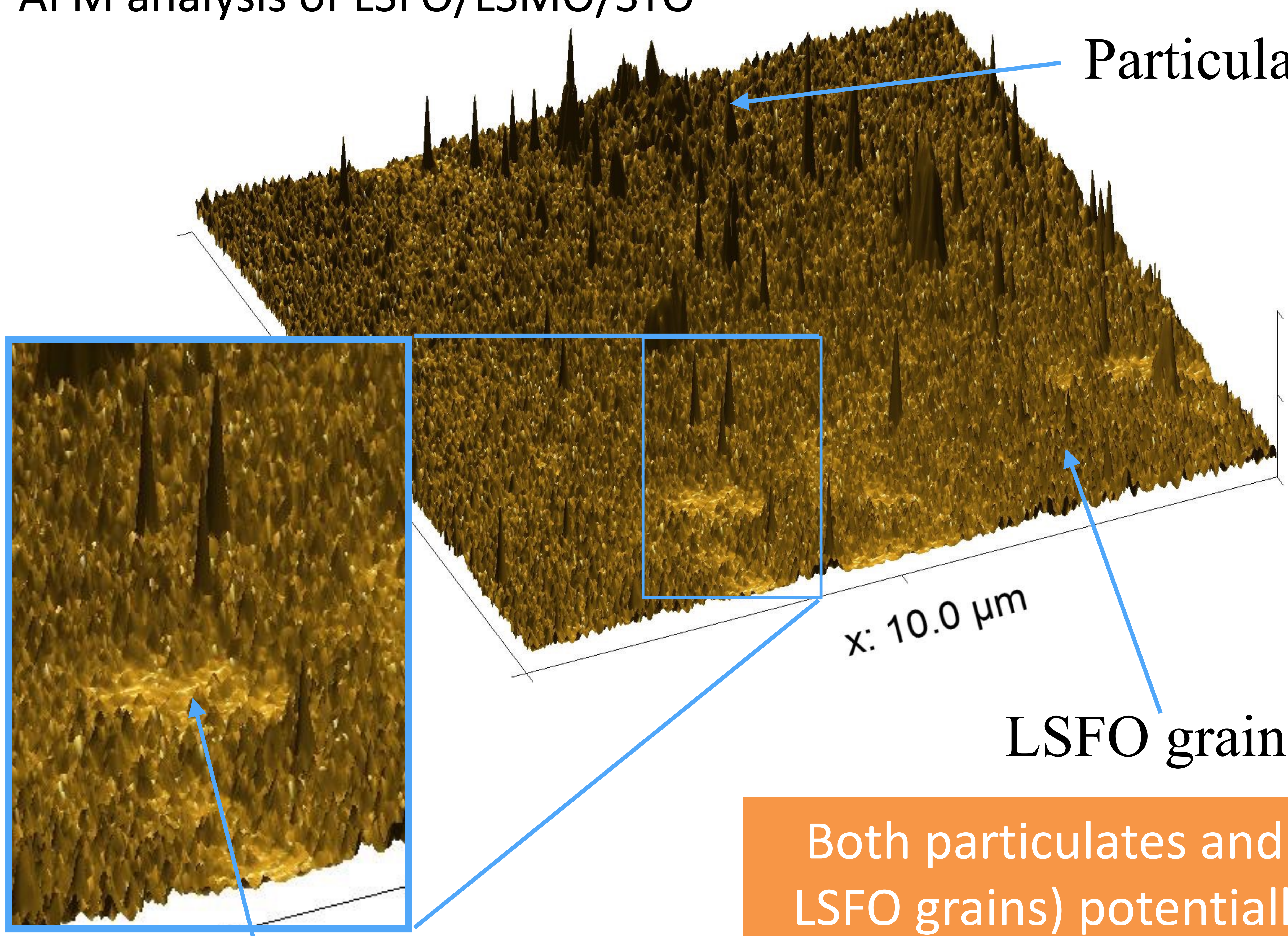


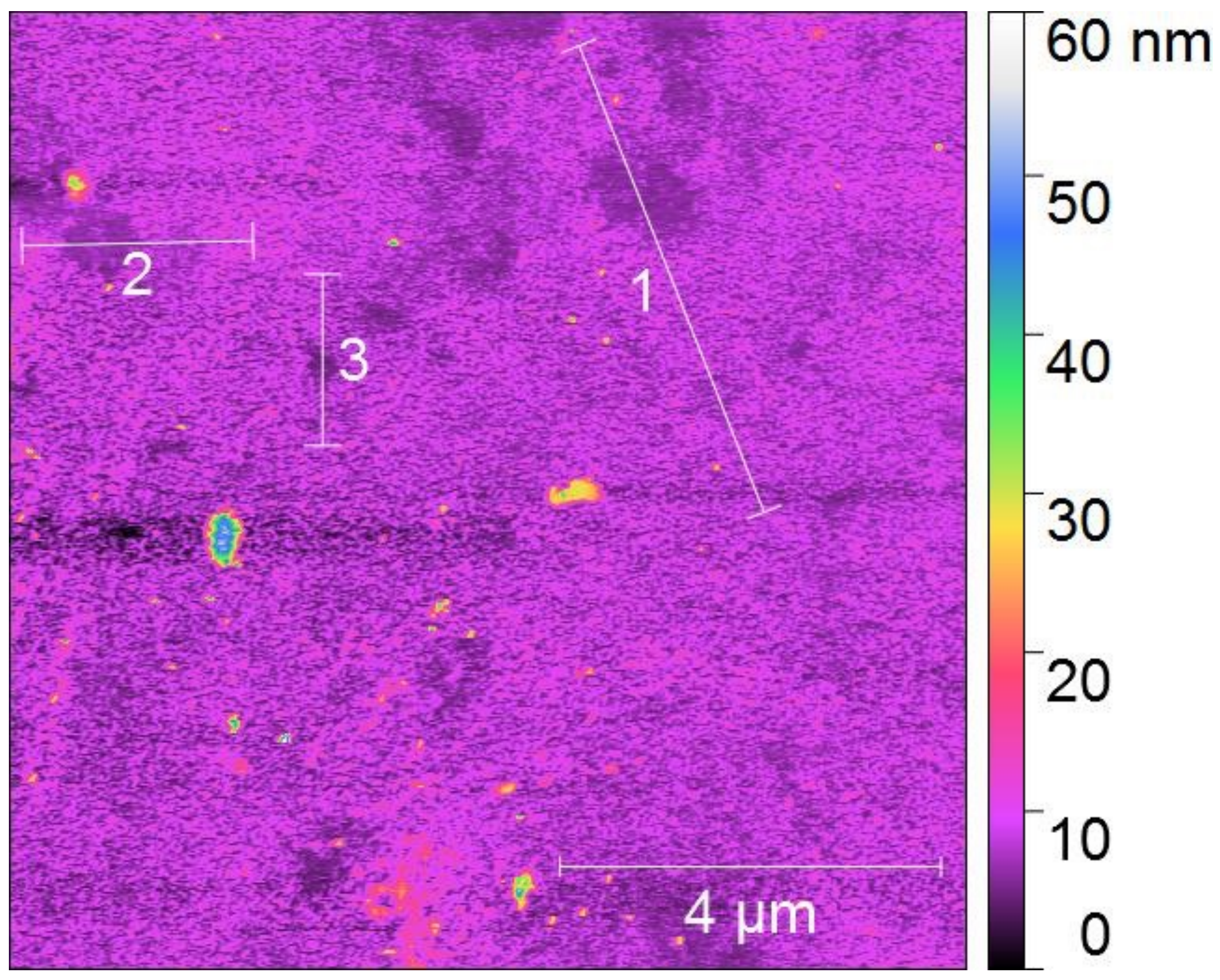


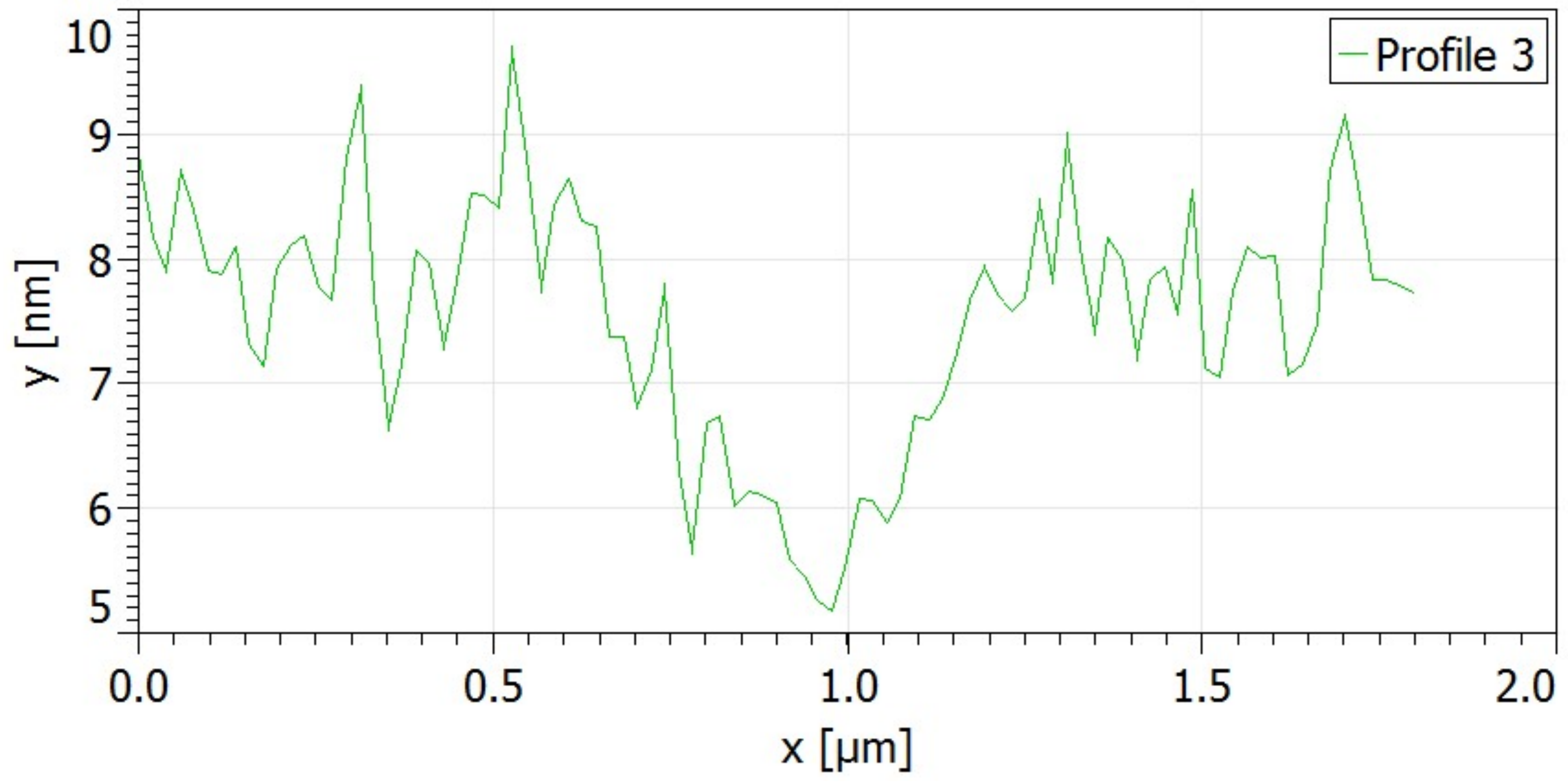
Materials Challenges for transport measurements

"Spin-flop" arrangement typically achieved at x=0.3, thin LSFO (~3 nm)

AFM analysis of LSFO/LSMO/STO







Both particulates and pits (likely missing LSFO grains) potentially allow conduction directly to LSMO

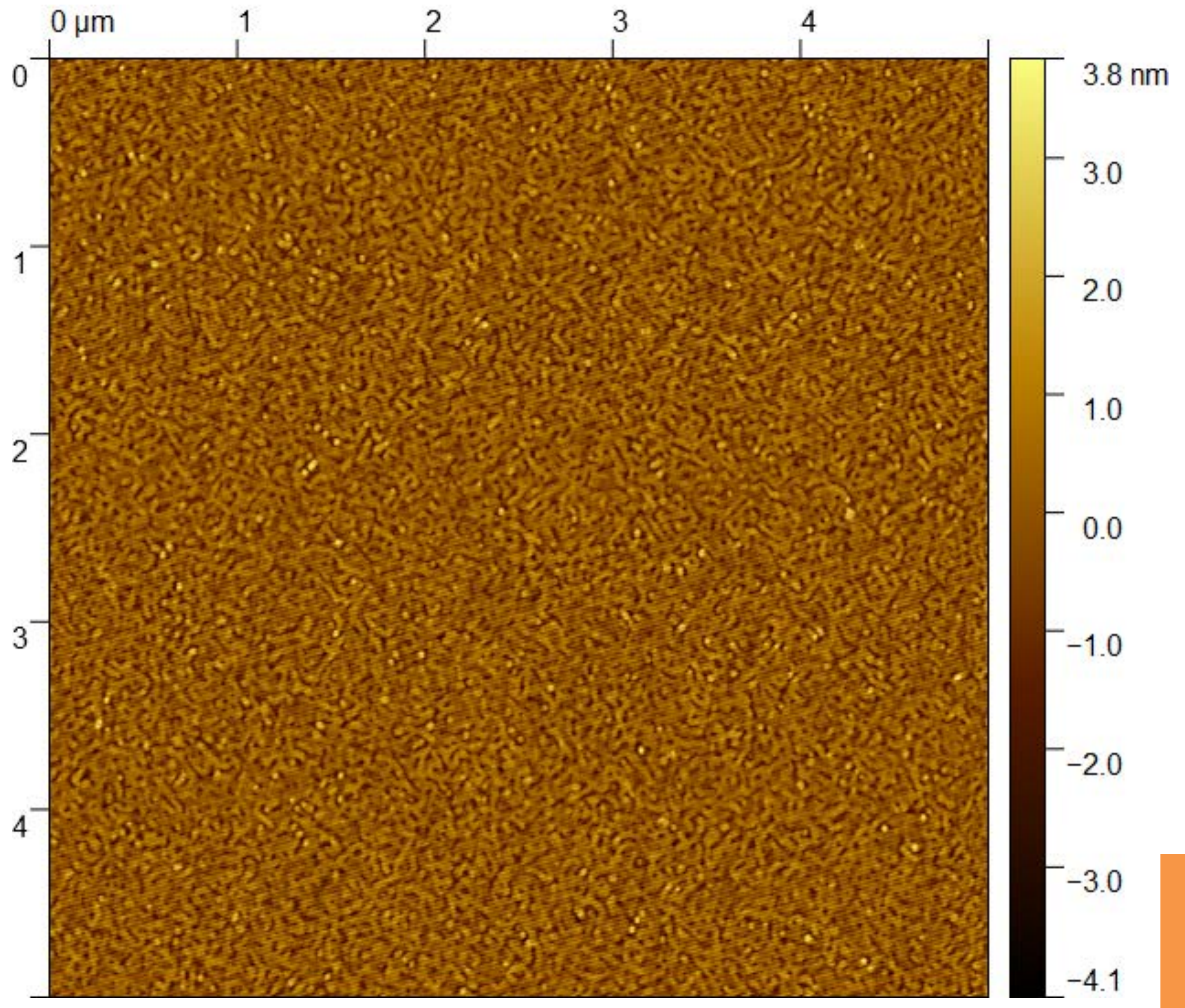
Ideally we would love the LSFO to be a true insulator, but this is NOT really the case….

Solutions?

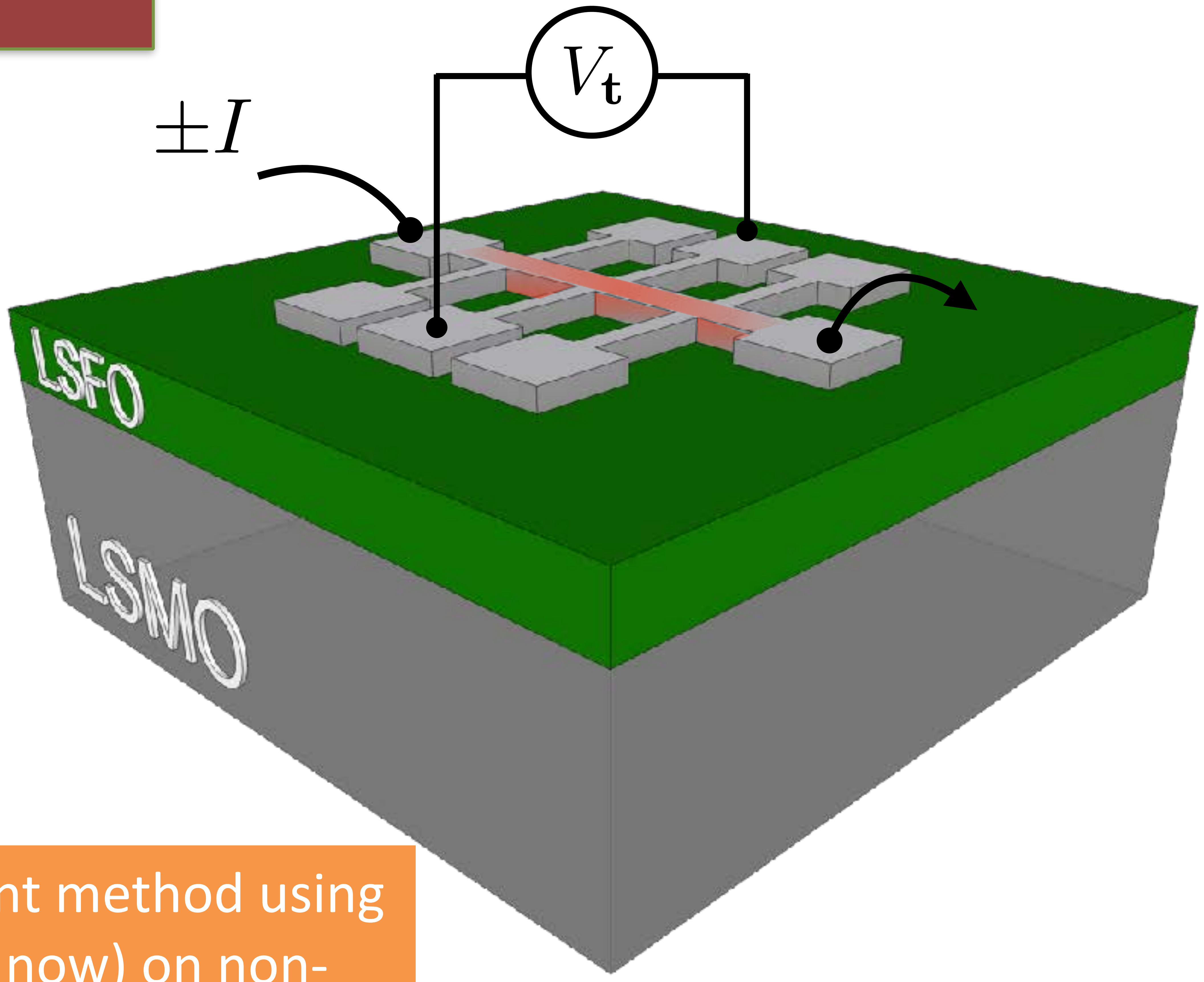
WARNING! Ongoing Research

Takamura group has now achieved "spin-flop" arrangement with x=0.5 LSFO, allows a thicker AFMI layer

30 u.c.(~11.76 nm) LSFO (50% Sr)// 90 u.c. (~35 nm) LSMO // LSAT



Maximum particle height = 3.833 nm
Maximum pit depth = at least 4.109 nm



Explore using dc current method using Hall bars. Focus (for now) on non-thermal part, probes SHMR

Reminder of SHMR in AFMI

PHYSICAL REVIEW B **97**, 014417 (2018)

Spin Hall magnetoresistance in antiferromagnet/heavy-metal heterostructures

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[5]*Center for Transport and Devices of Emergent Materials, Technische Universität Dresden, 01062 Dresden, Germany*
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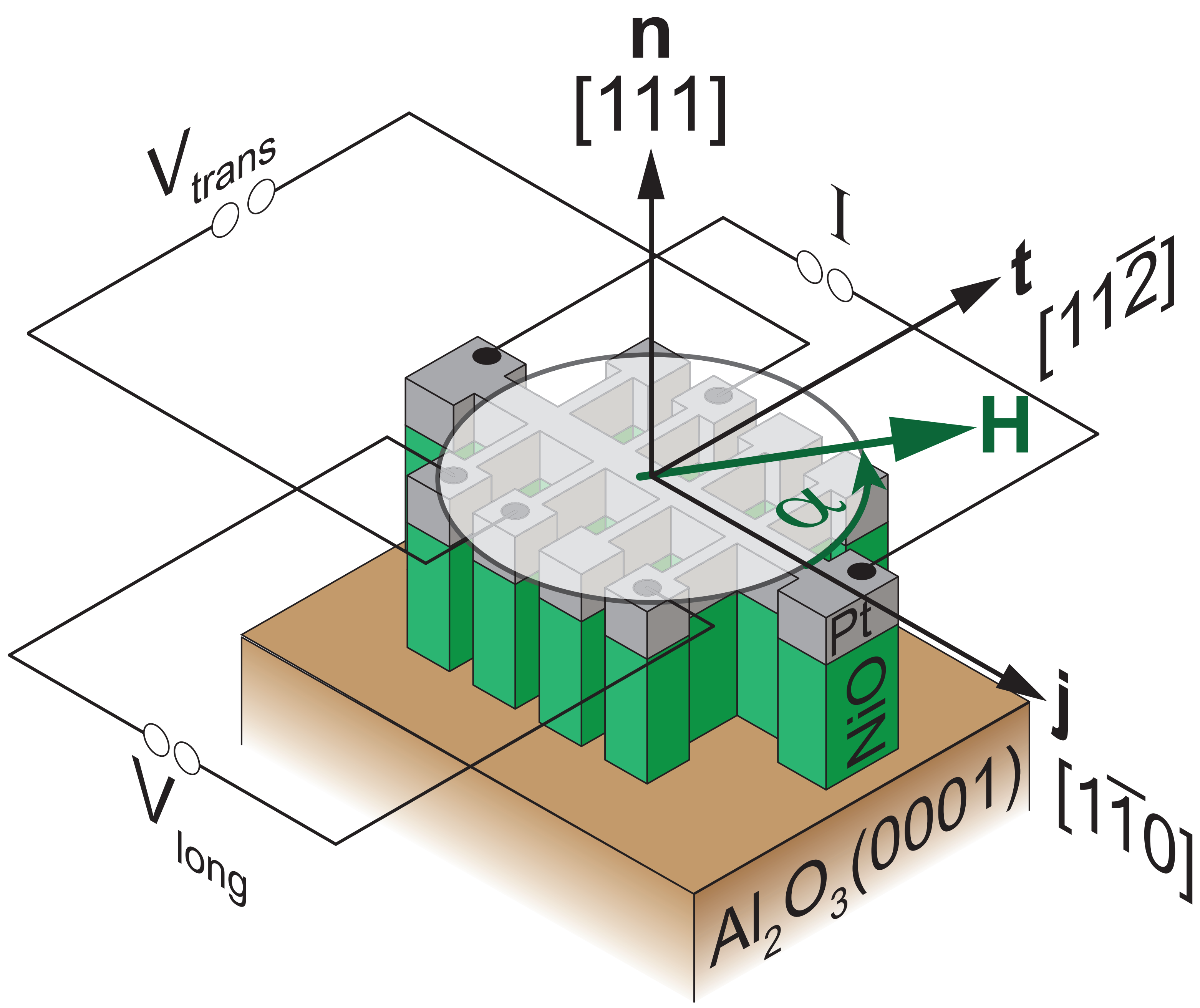
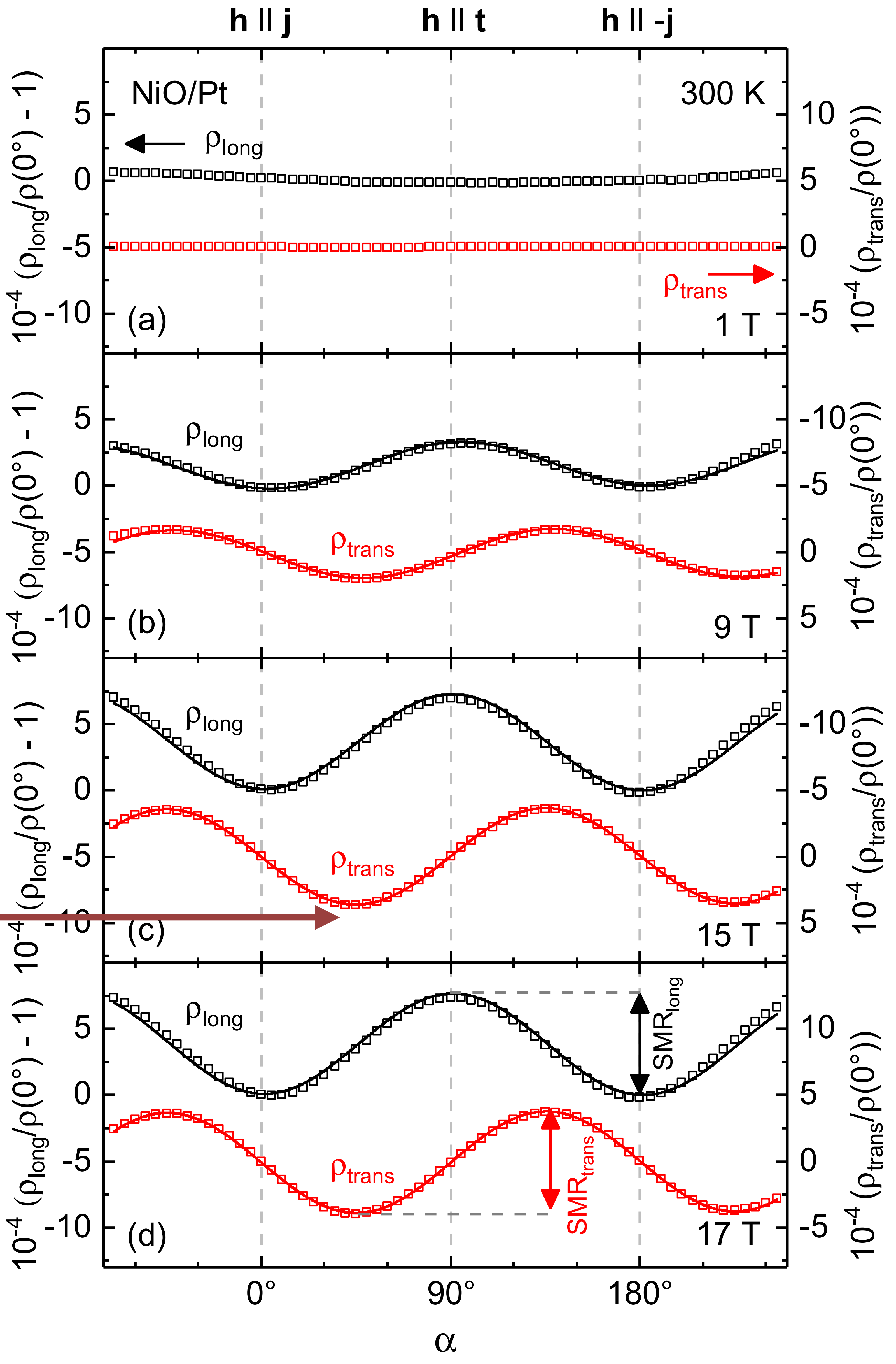
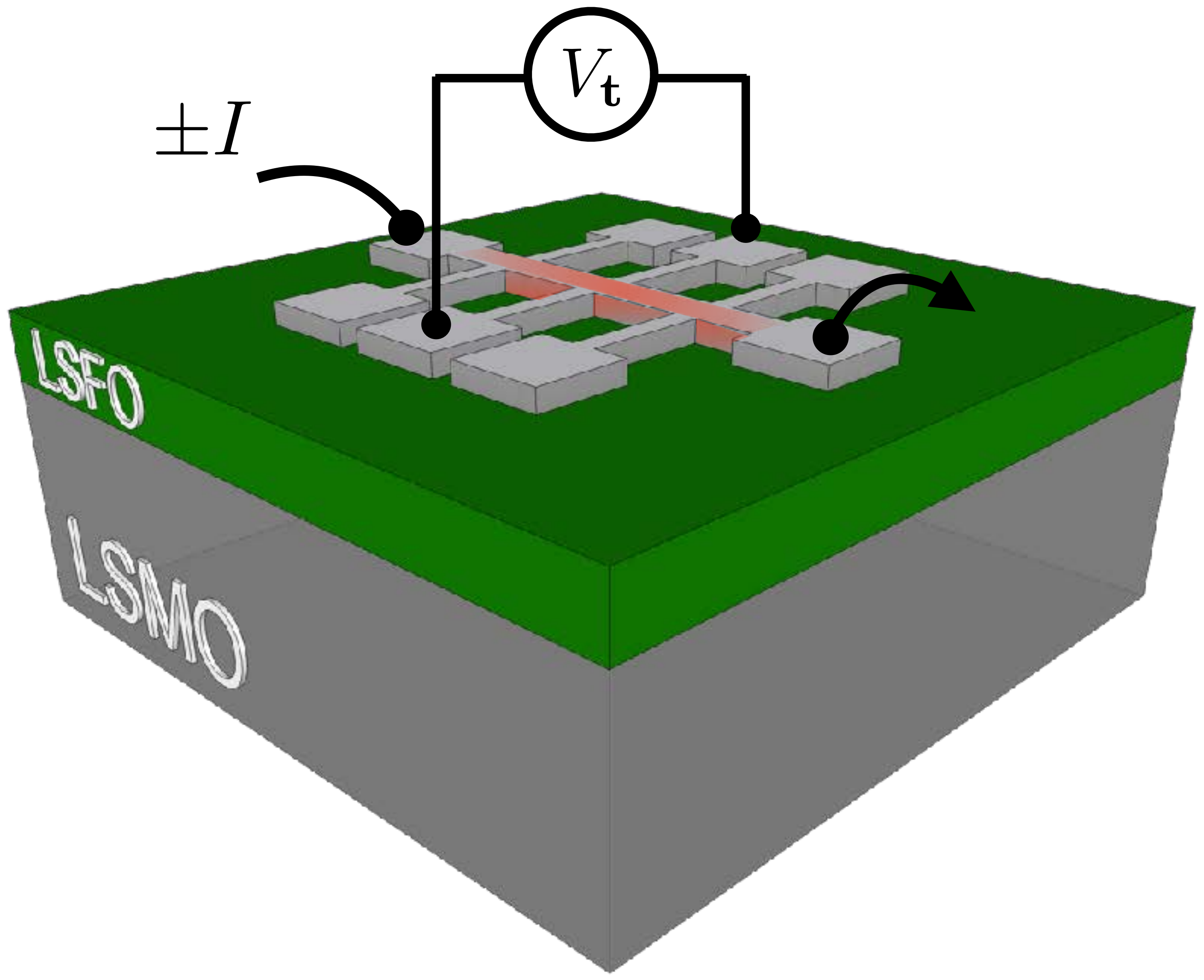


Largest effects in transverse voltage at 45 degree angles…



First results

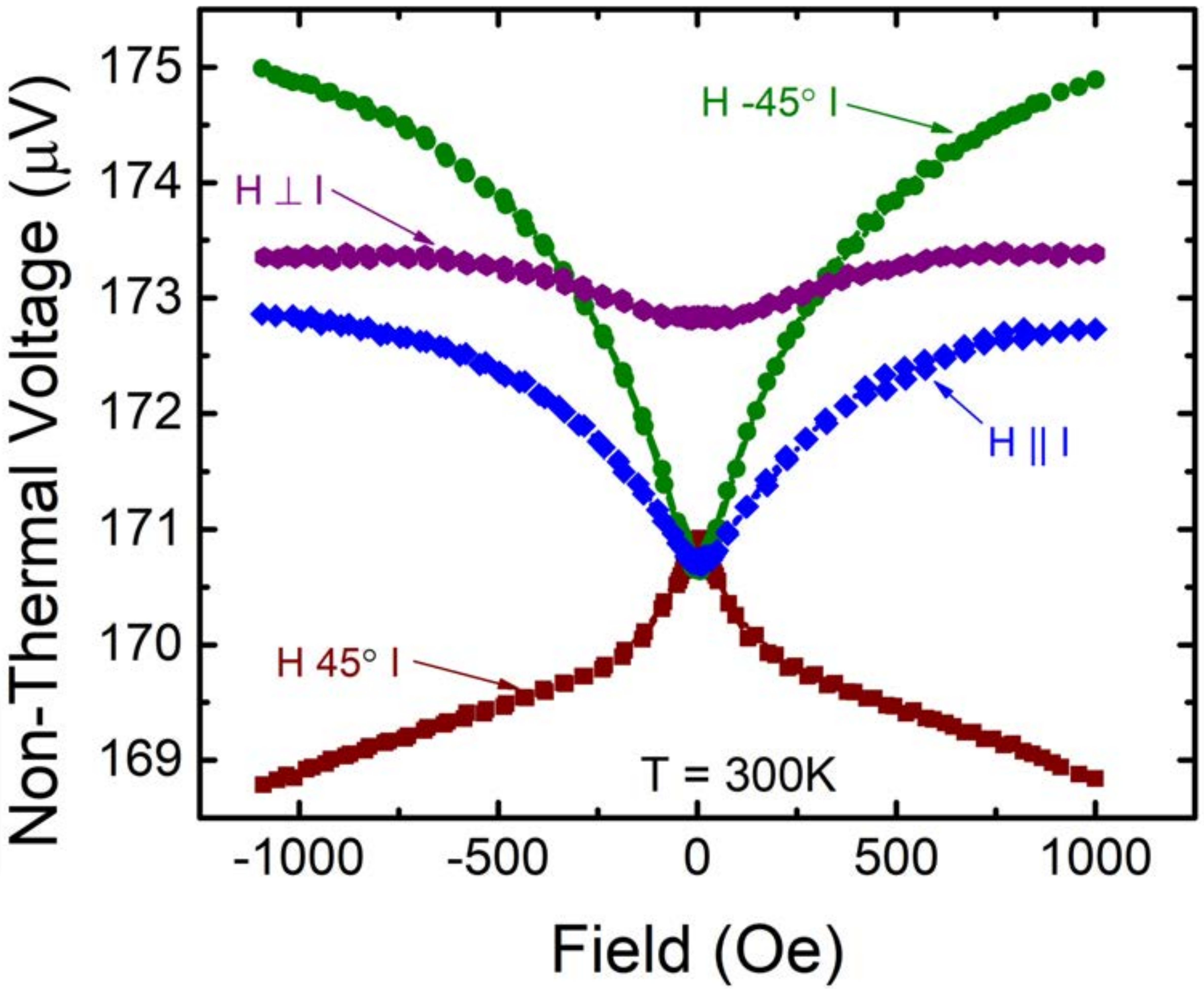
WARNING! Ongoing Research



Pt Hall Bar on LSFO/LSMO, I=+/- 500 microamps

Clear low field magnetoresistance, is the AFM playing a role?

LSFO (~12 nm)//LSMO (~35 nm) // LSAT



$\hat{n} \perp \hat{\sigma}$

$\hat{n} \parallel \hat{\sigma}$

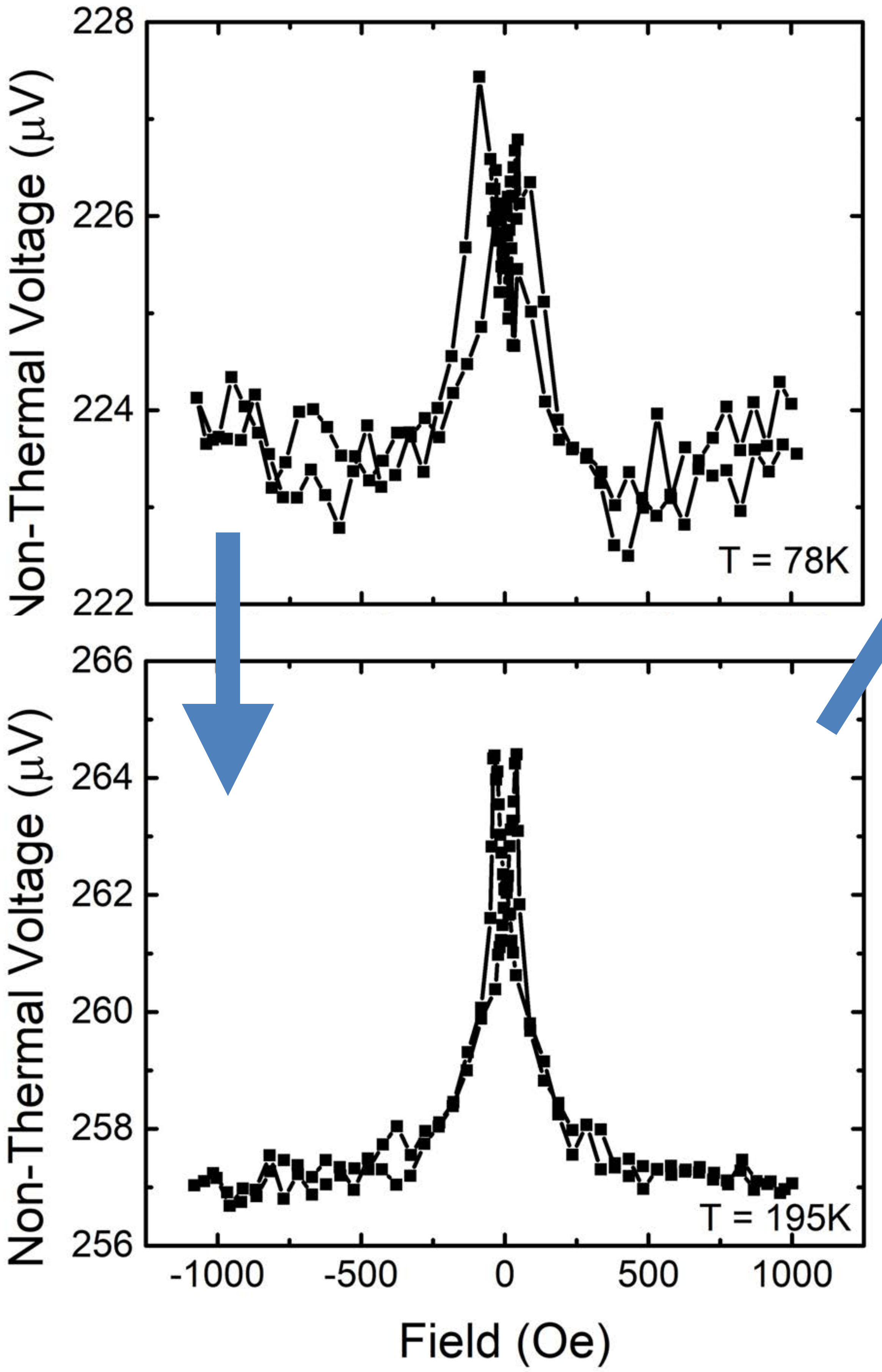
Pattern in V_{trans} vs angle roughly consistent with that seen at large field in NiO

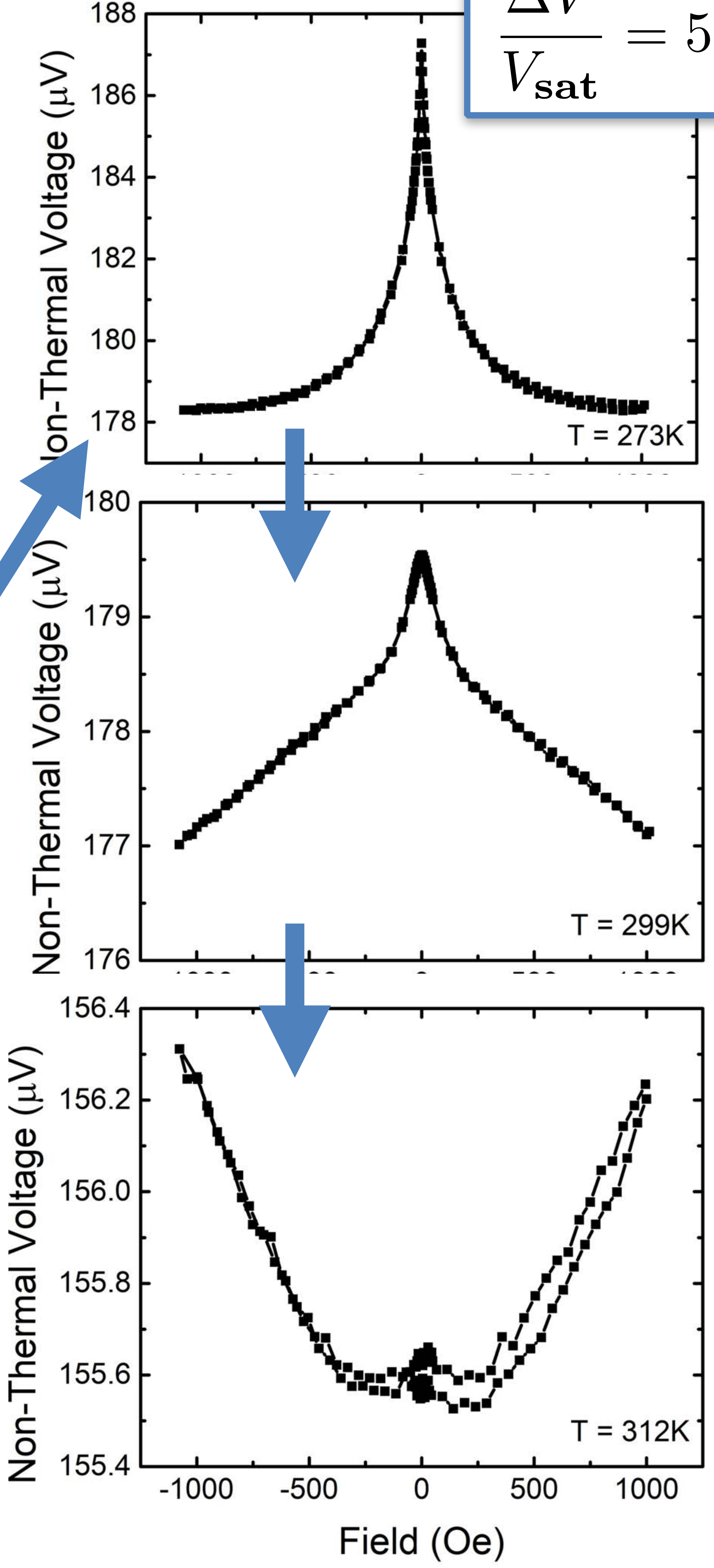
Vs. T @ 45°

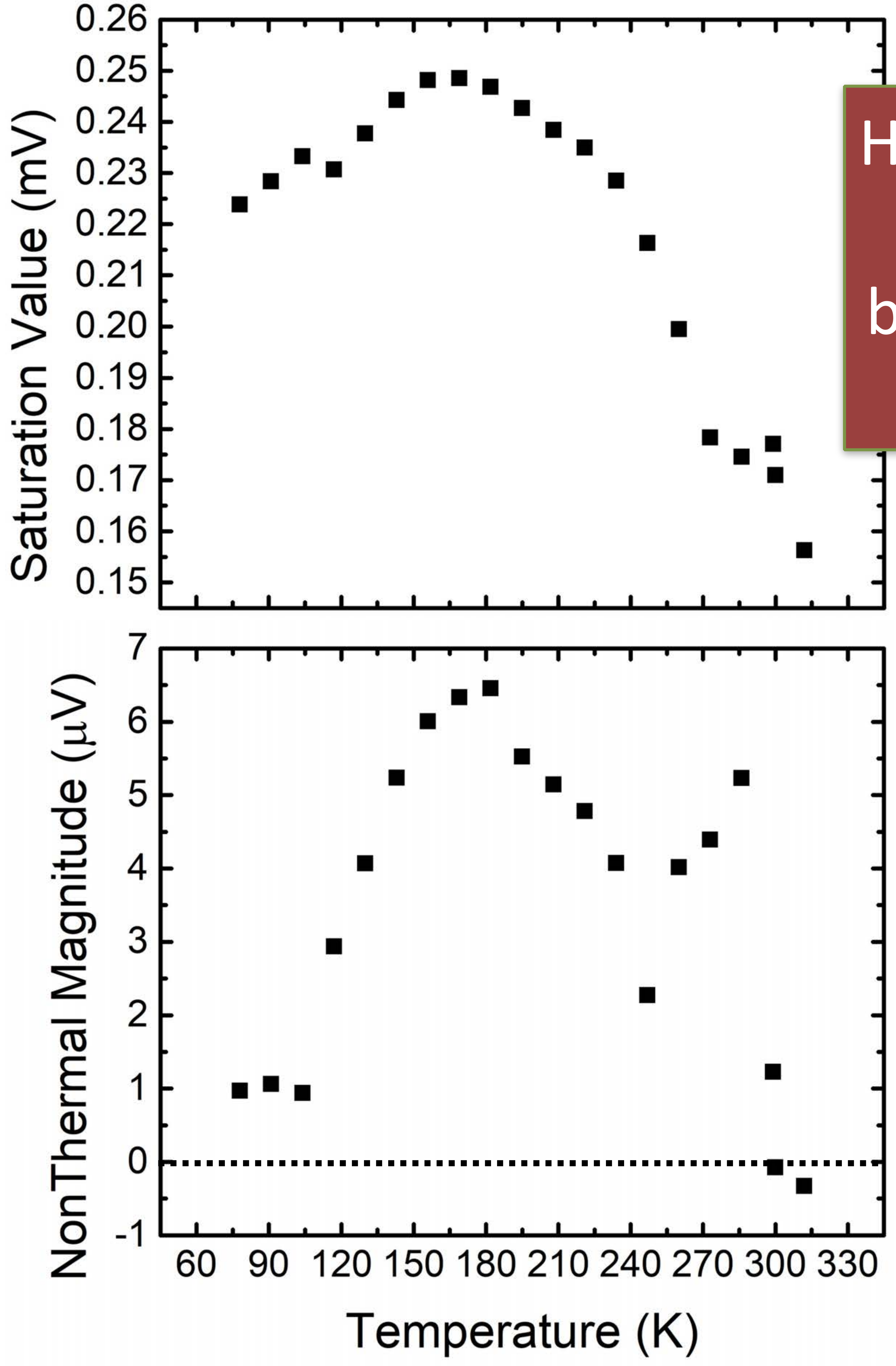
WARNING! Ongoing Research

$$\frac{\Delta V}{V_{\text{sat}}} = 5 \times 10^{-2}$$

LSFO (~12 nm)//LSMO (~35 nm) // LSAT







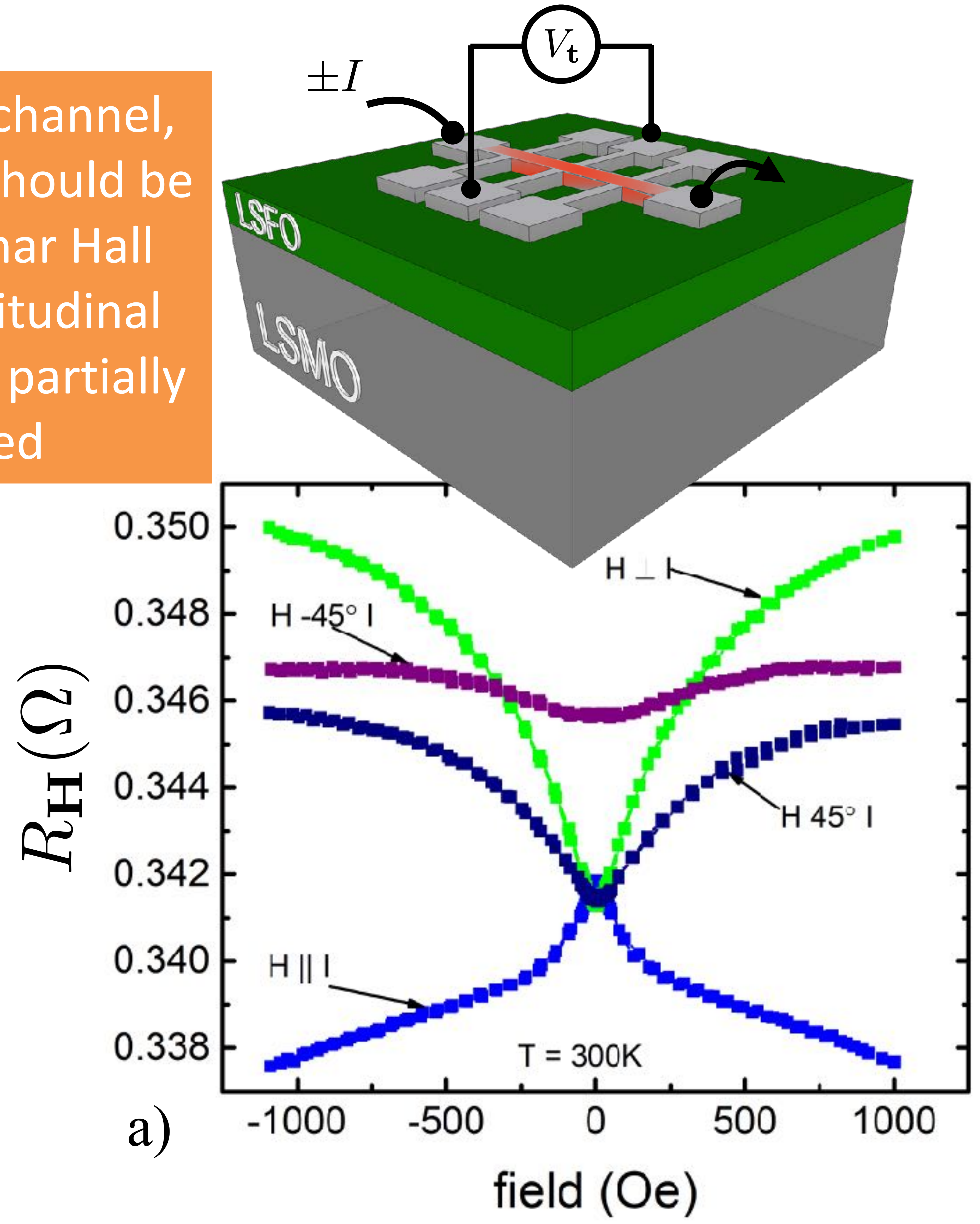
Have not yet done magnetometry, but T_n likely 300 K or below?

LARGE MR (100x larger than NiO at a 17 T)
Almost certainly indicates that LSMO effects contribute

Compare Pt Hall bars with no current channel

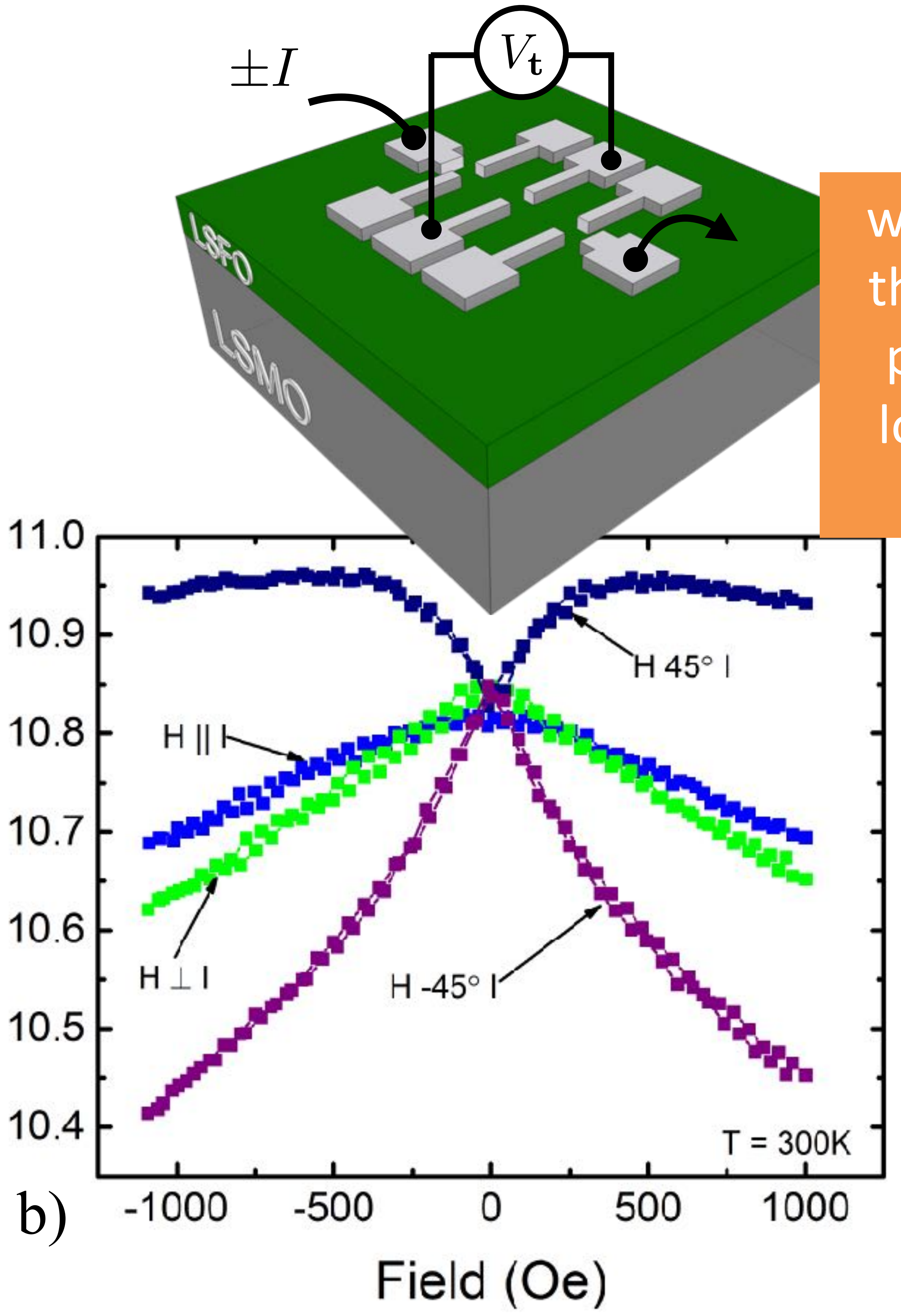
WARNING! Ongoing Research

with the Pt channel, spin effects should be larger, planar Hall effect, longitudinal MR in LSMO partially shunted



a)

with no Pt channel, this geometry tests planar Hall effect, longitudinal MR in LSMO

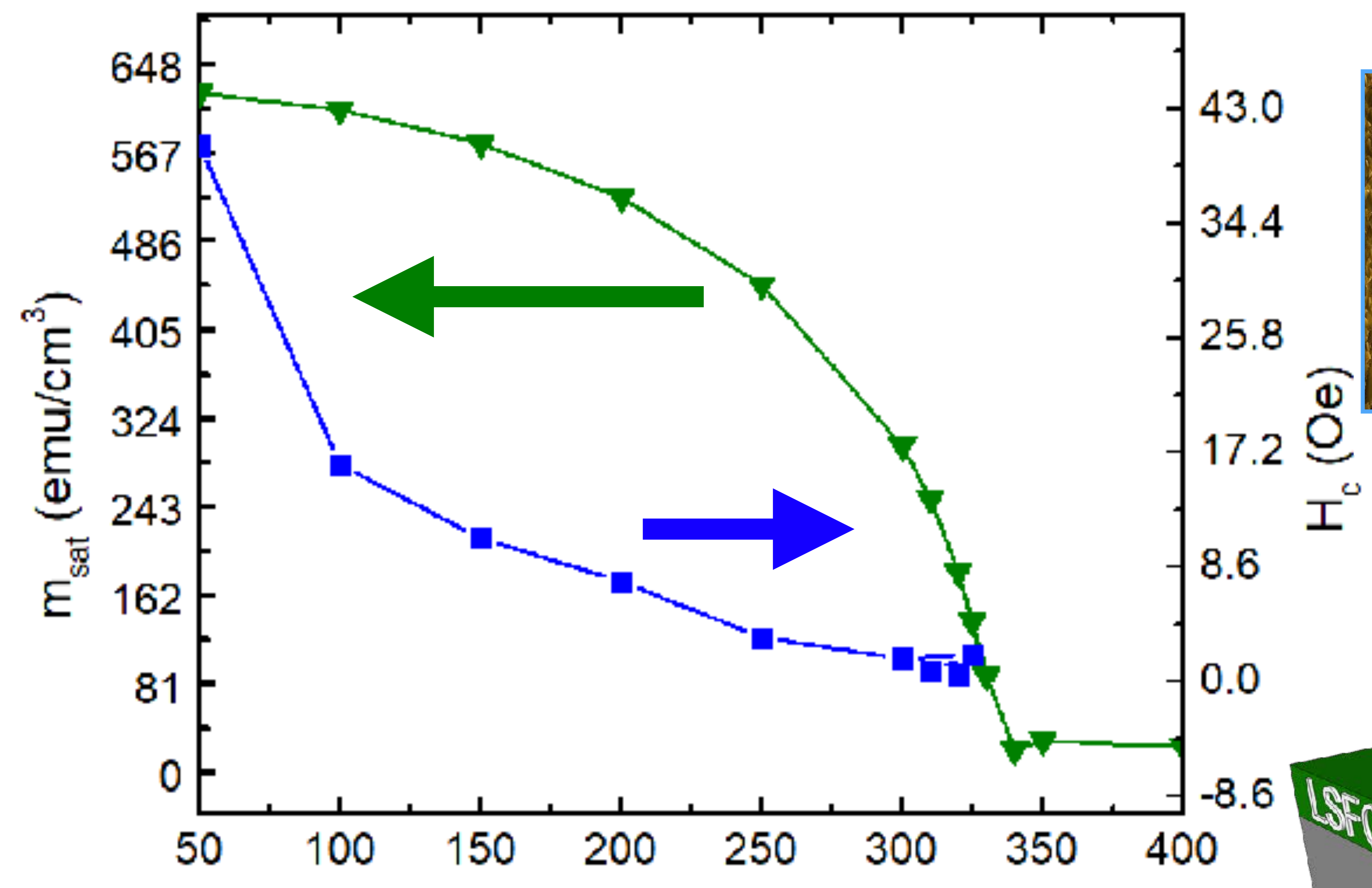


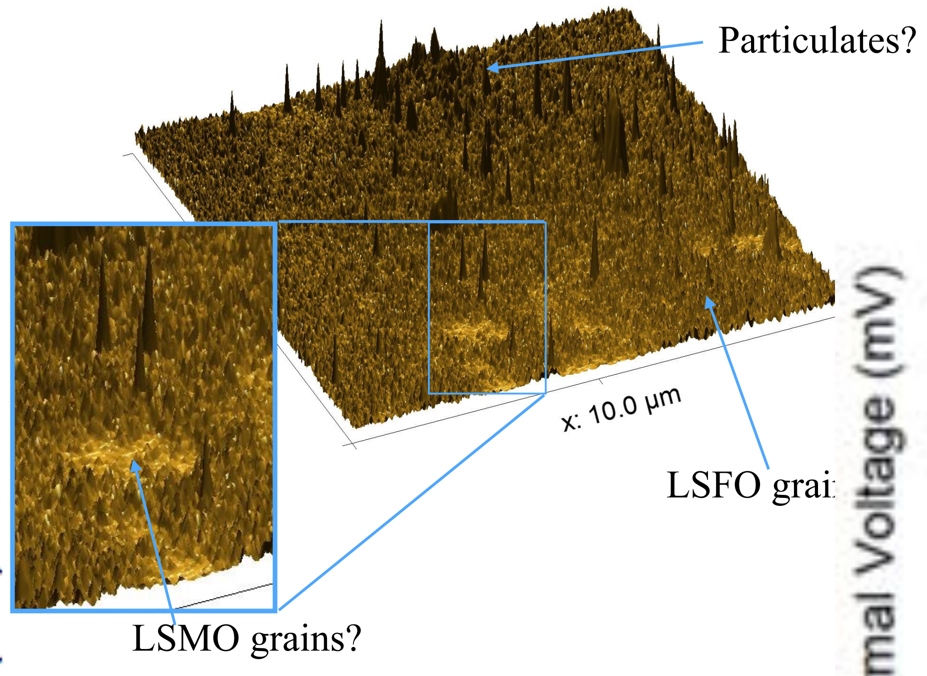
b)

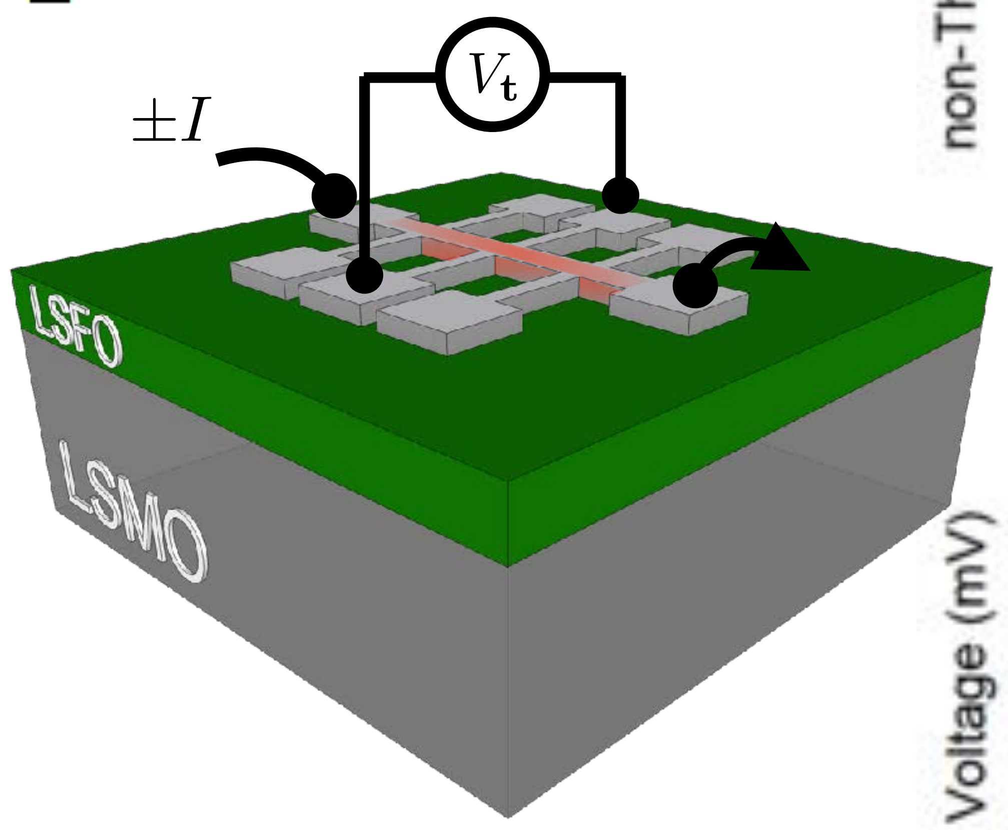
Total change of symmetry of the signals when Pt current channel is absent

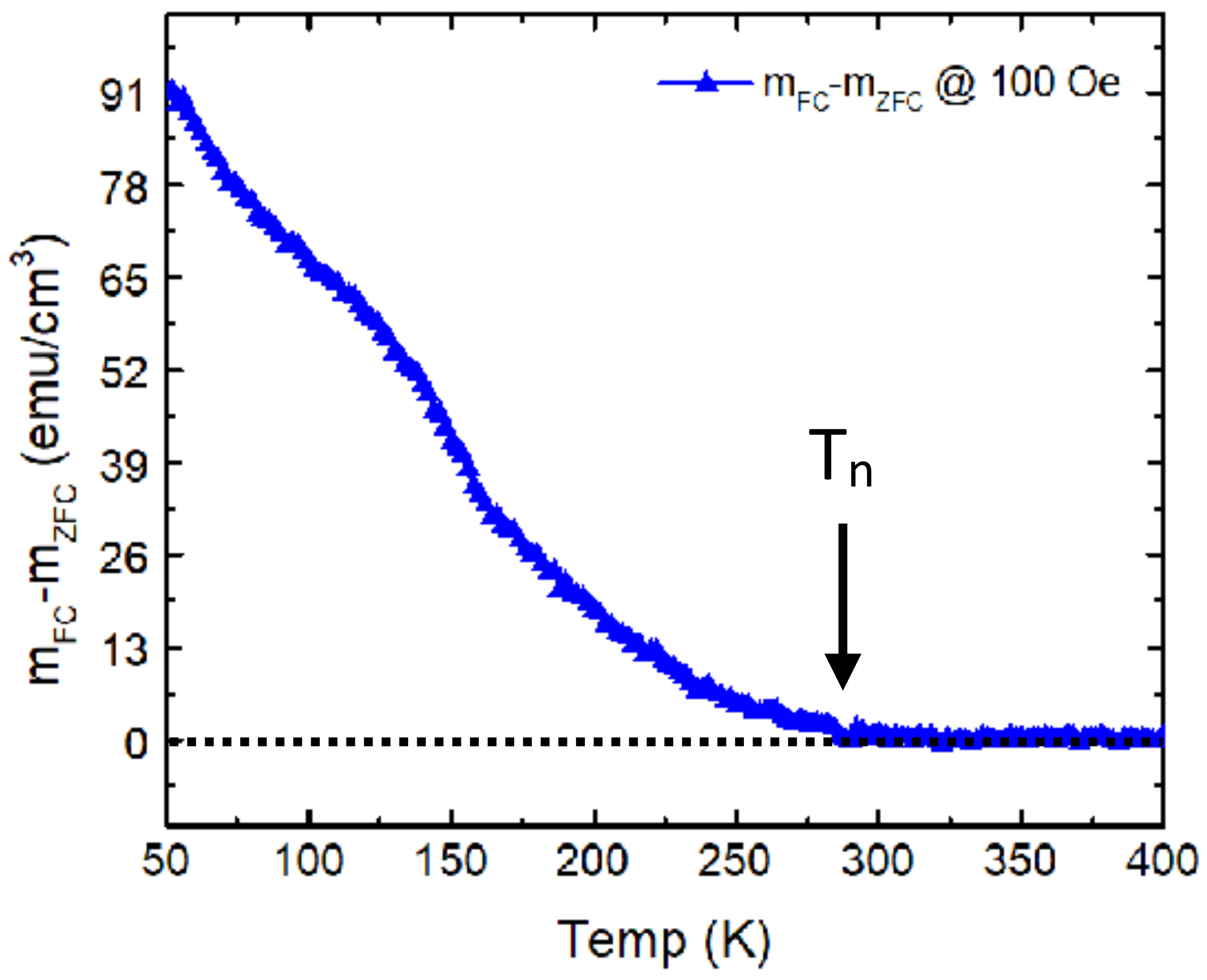
Even with pinholes, SHMR “knows” about AFM

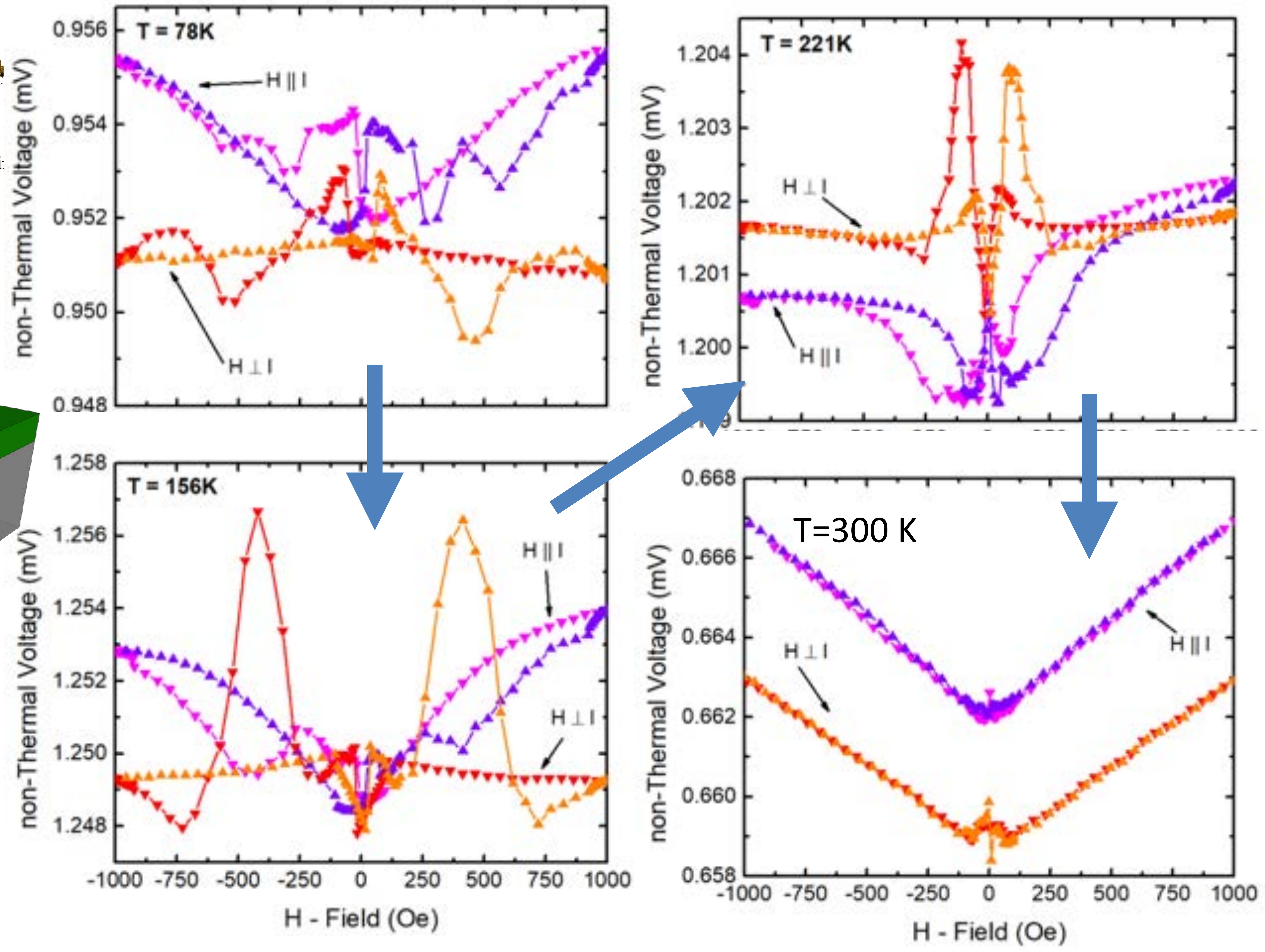
LSFO (~3 nm)//LSMO (~10 nm) // STO







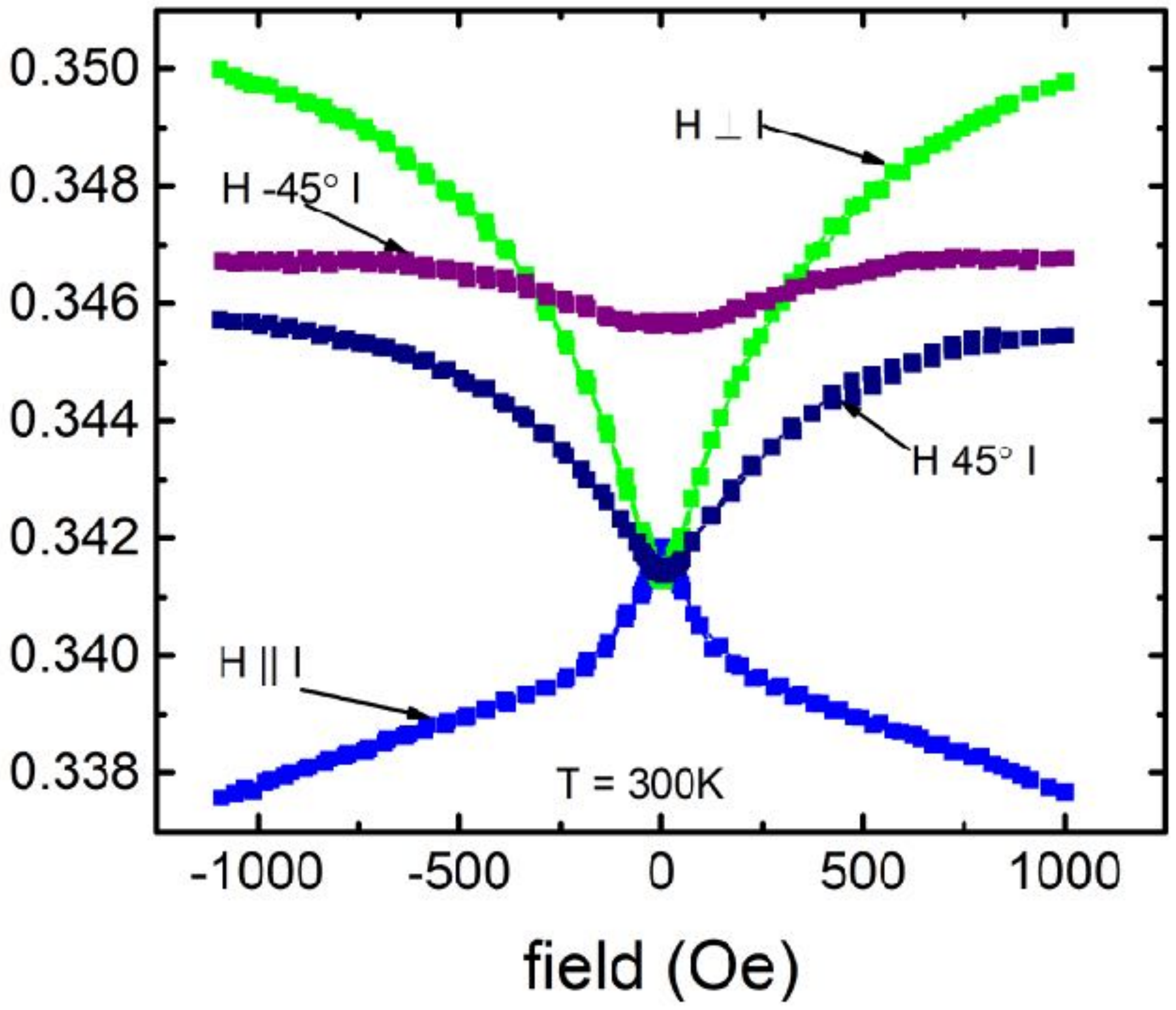


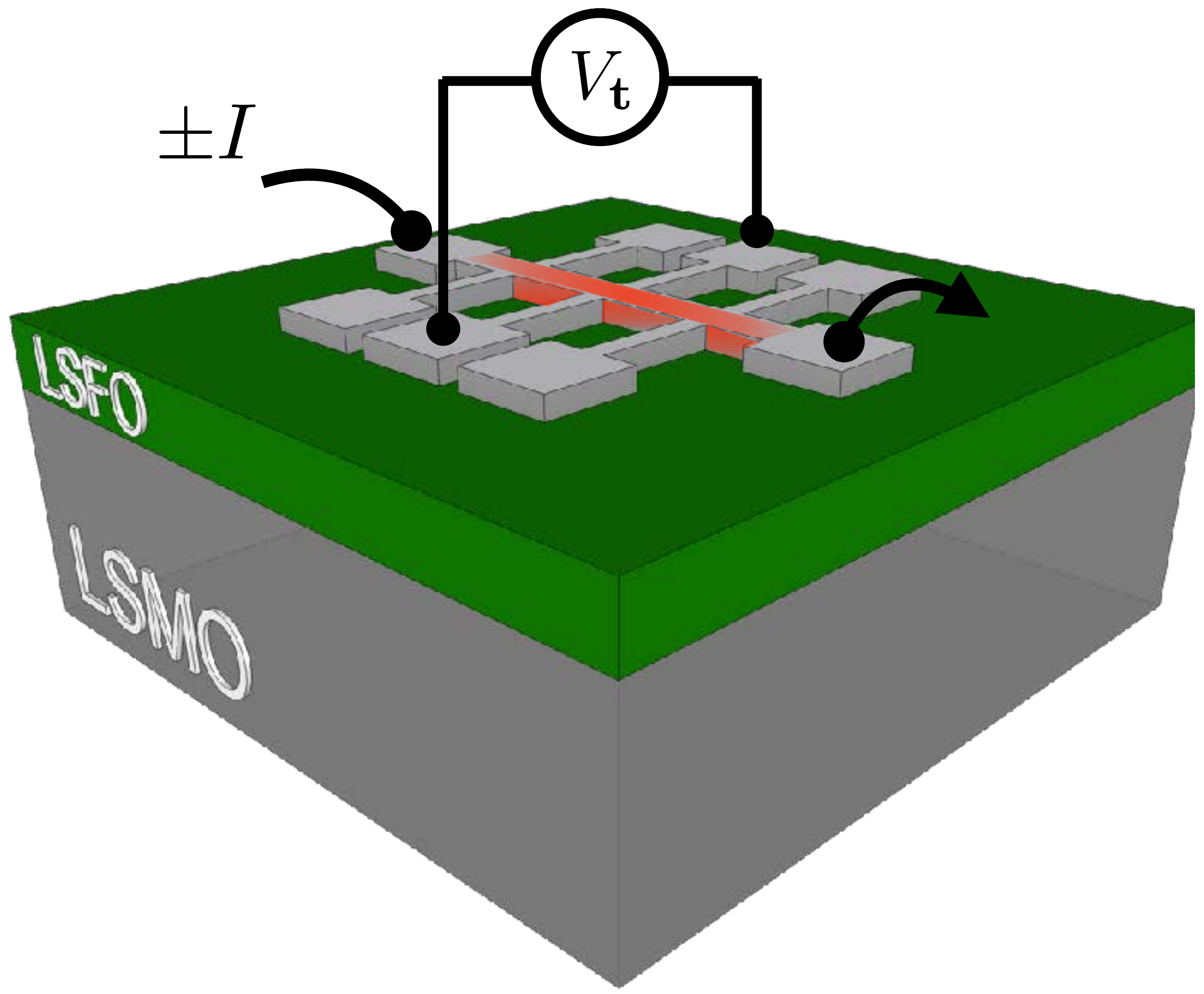


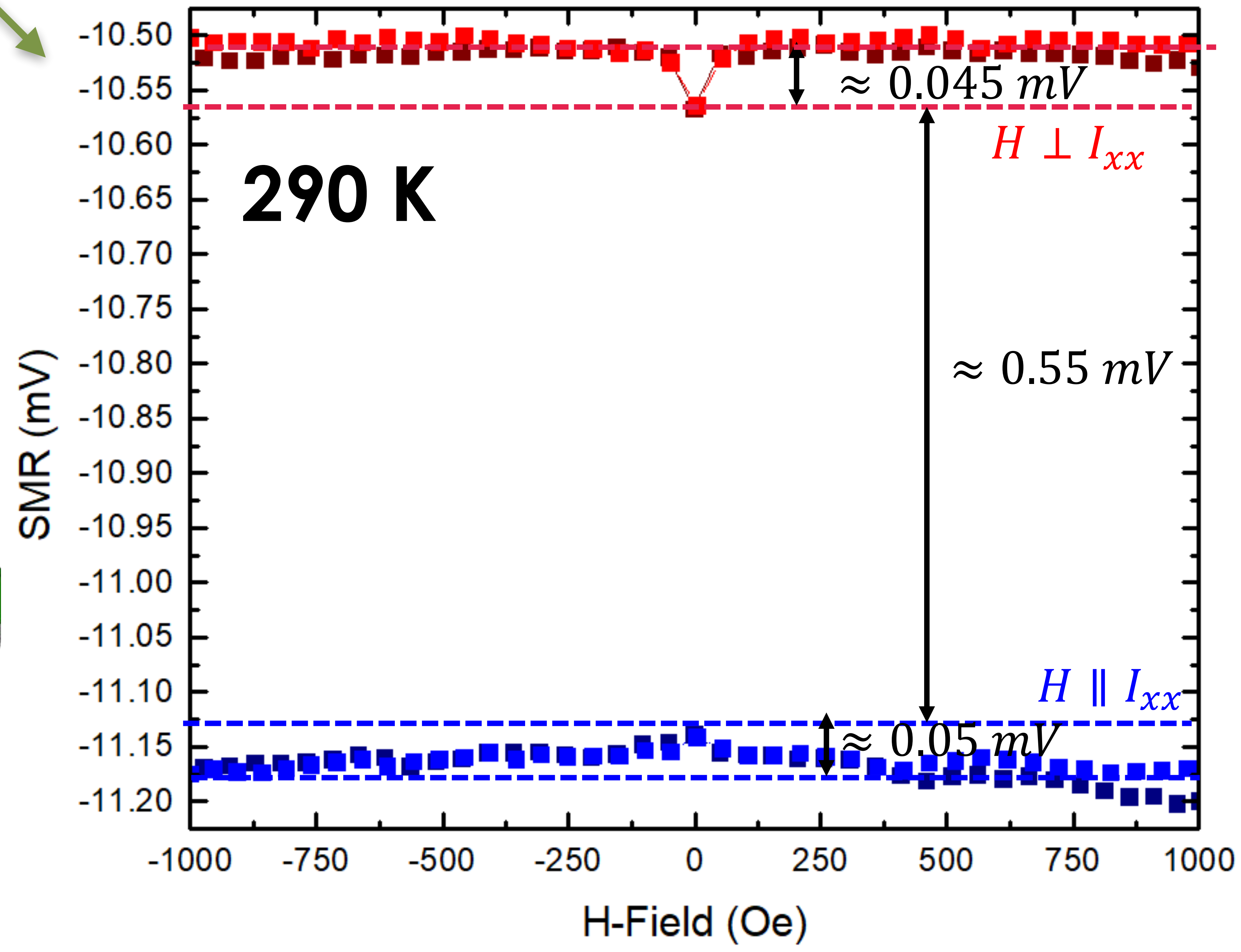
Dramatic shift in size and shape of SHMR voltage vs. H at T_n=300 K

Finally, back to the case of Cr

Pt Hall bar   Cr Hall bar





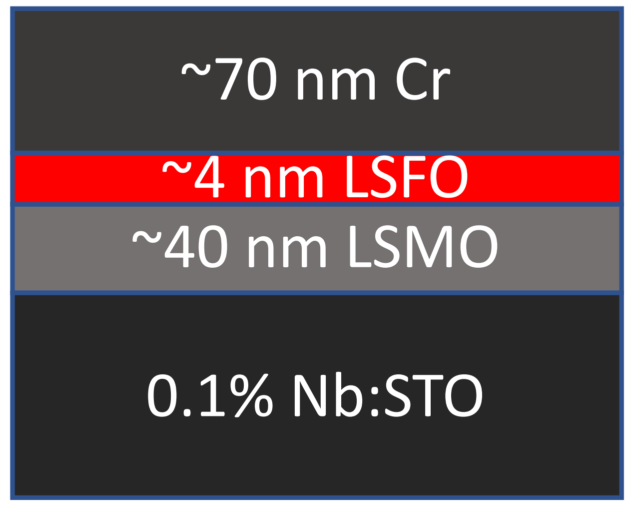


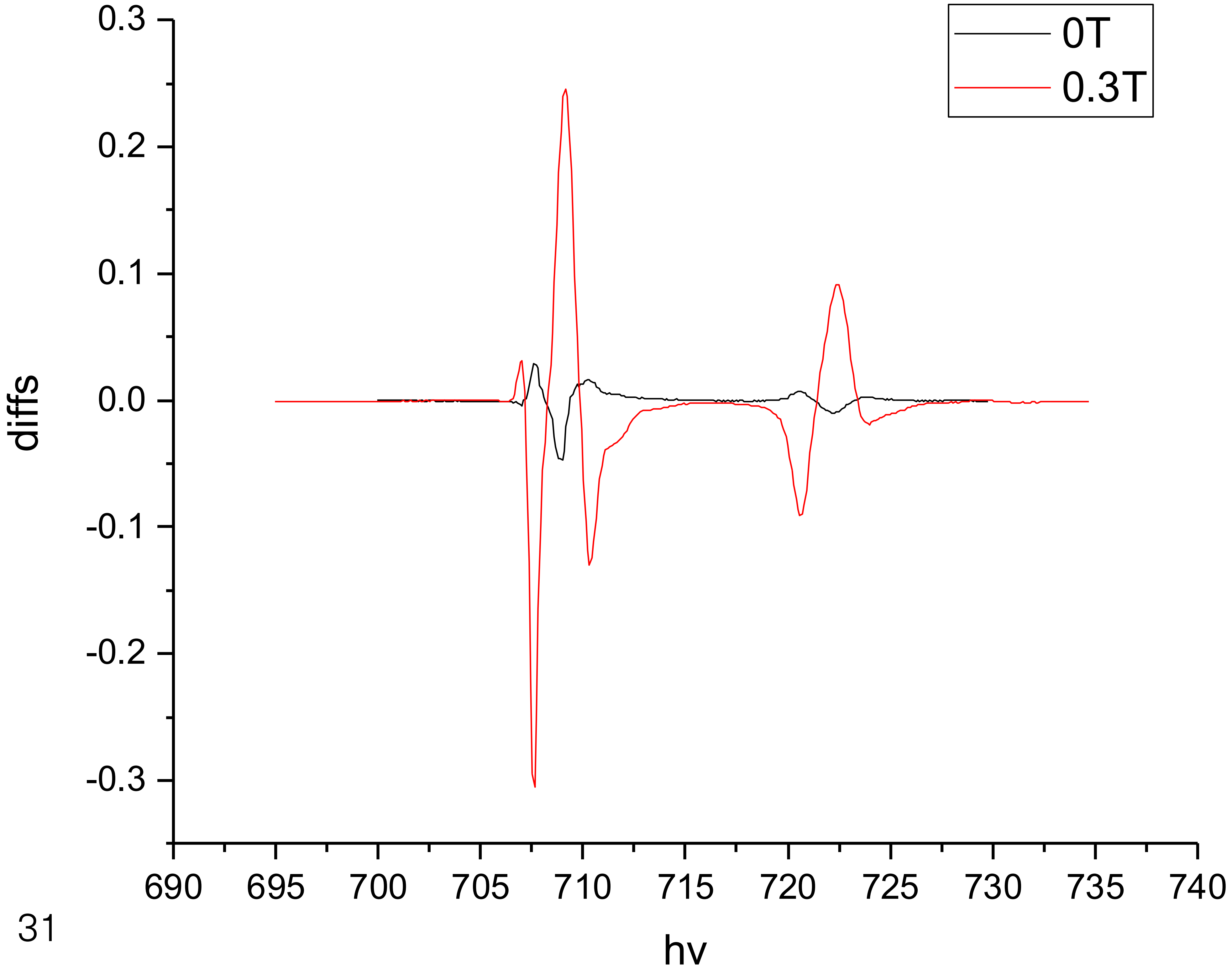
Larger baseline voltage consistent with less shunting from Cr, as expected, but almost no change with applied field?

Cr/LSFO XPEEM: Unfortunate interactions…

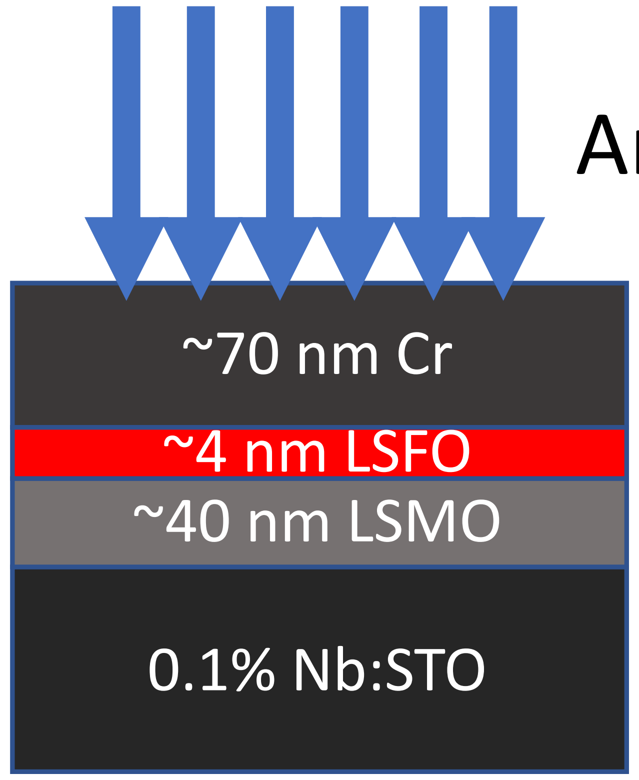
Fe XMLD Comparison

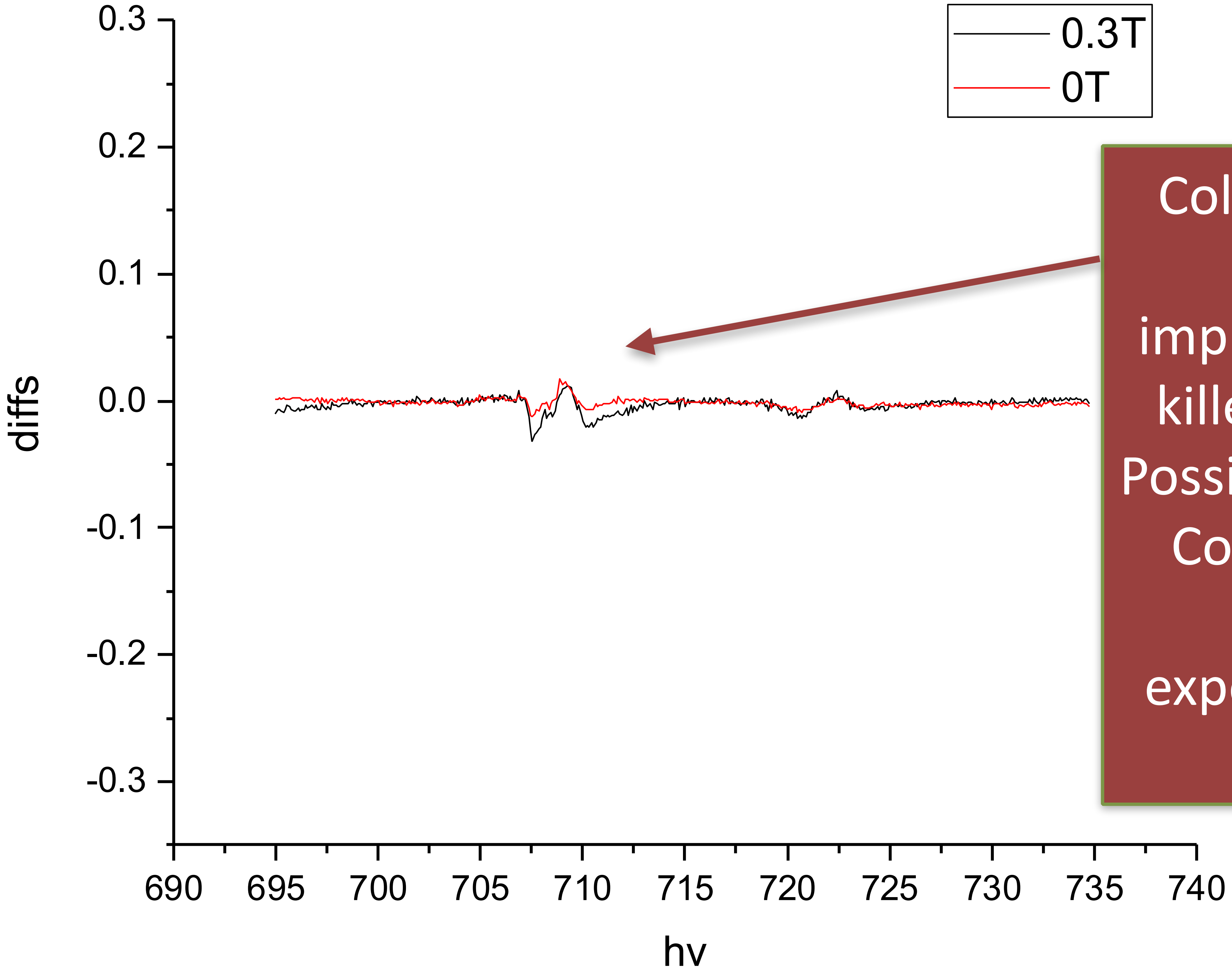
Bilayer + Cr





Ar+ (50 keV, 1e15/cm2)

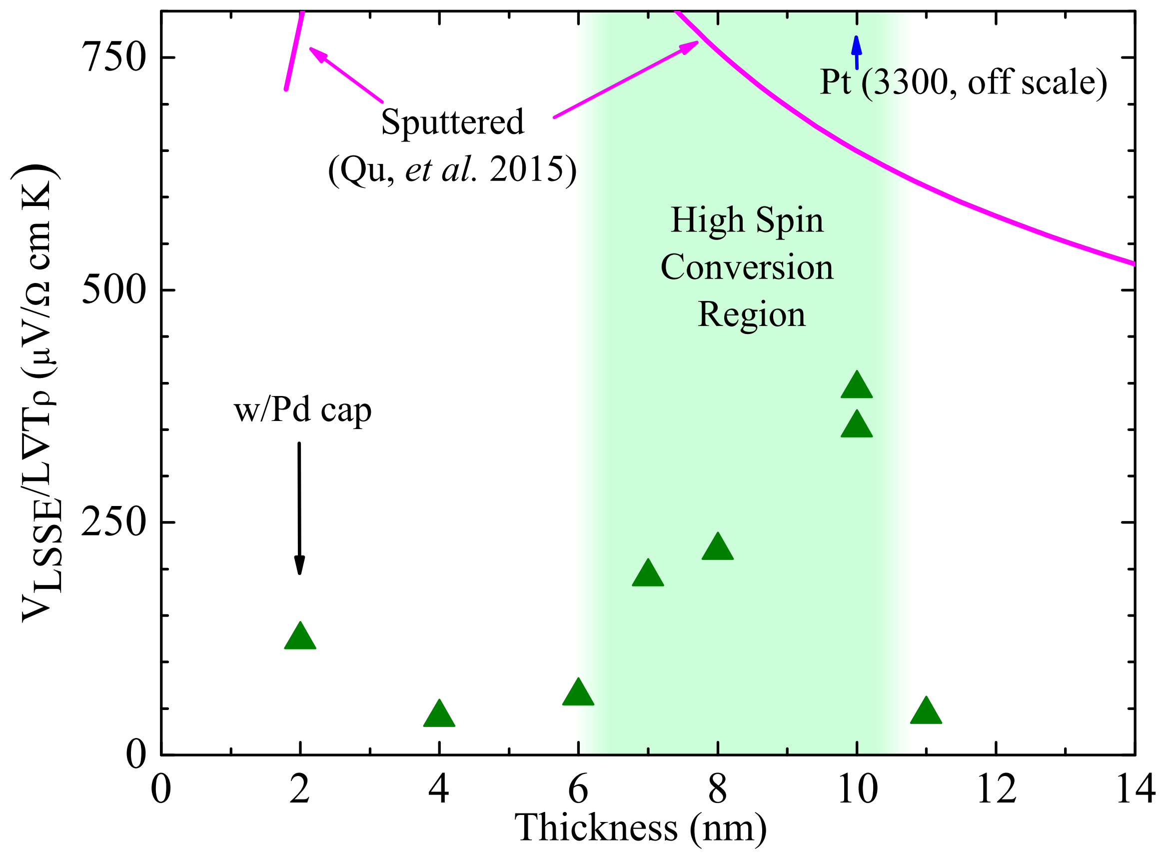


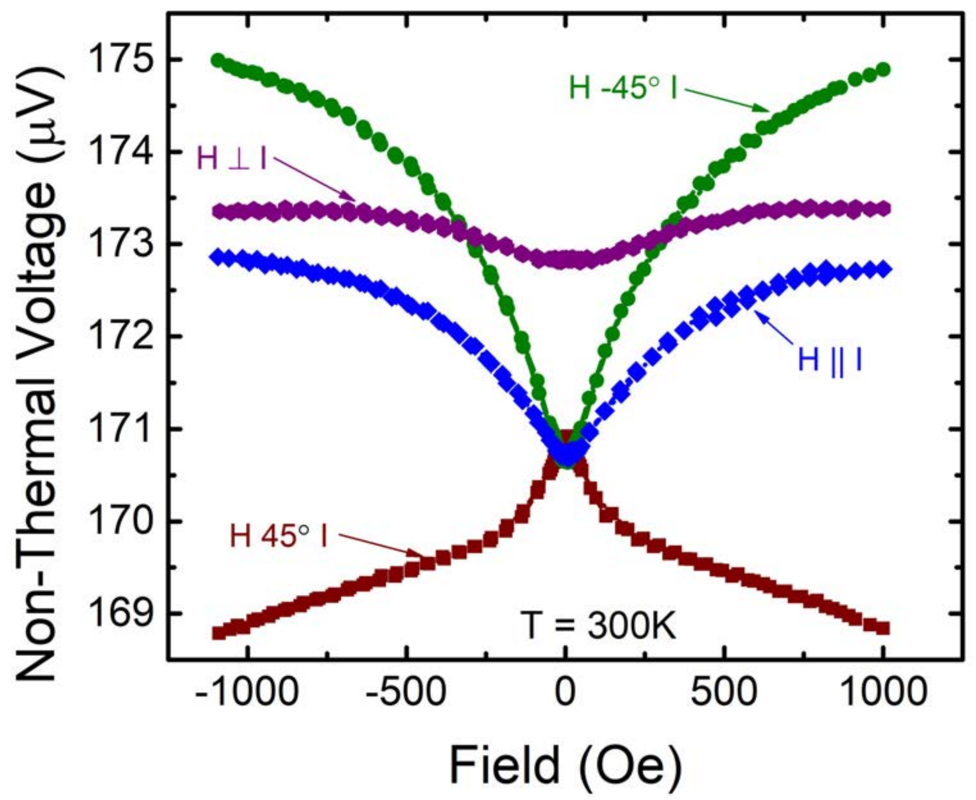


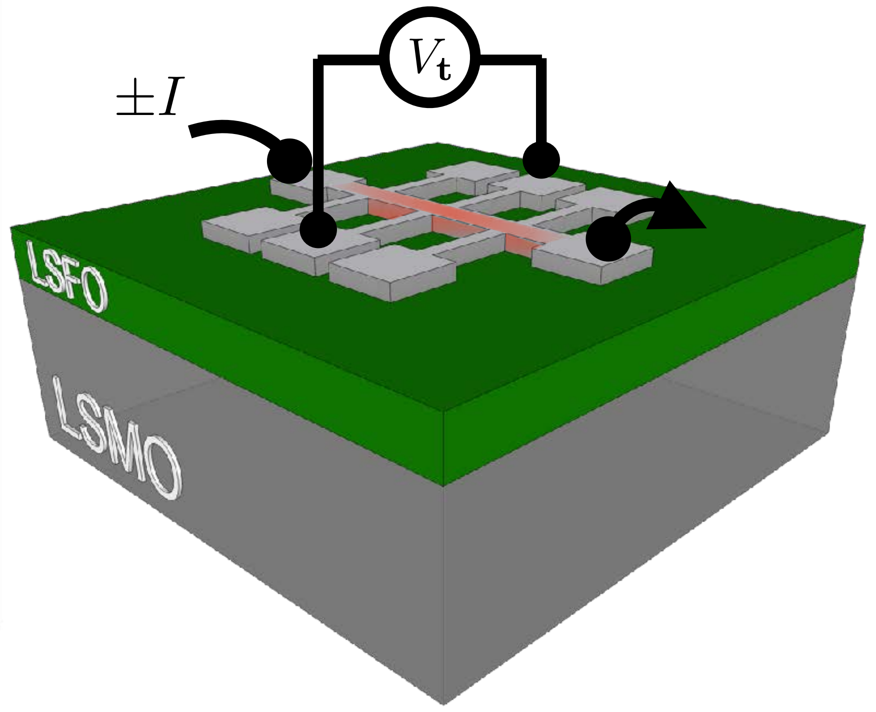
Collapse of Fe XMLD signal indicates that ion implantation in the THICK Cr killed the AFM in the LSFO. Possible cause is Cr + Heating. Could mean our Cr/LSFO/ LSMO microheater experiments probe the case of NO AFM

Conclusions

- Large (enough), thickness dependent spin conversion efficiency in evaporated Cr thin films
  – Bleser, et al. JAP **131** 113904 (2022)
- Temperature dependence in local heating LSSE in evaporated Cr suggests a possible role for AFM order?
  – Bleser, et al. in preparation
- Exchange coupled Perovskite Oxide AFM/FM bilayers are promising for controllable antiferromagnetic spintronics
  – More data coming soon…







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