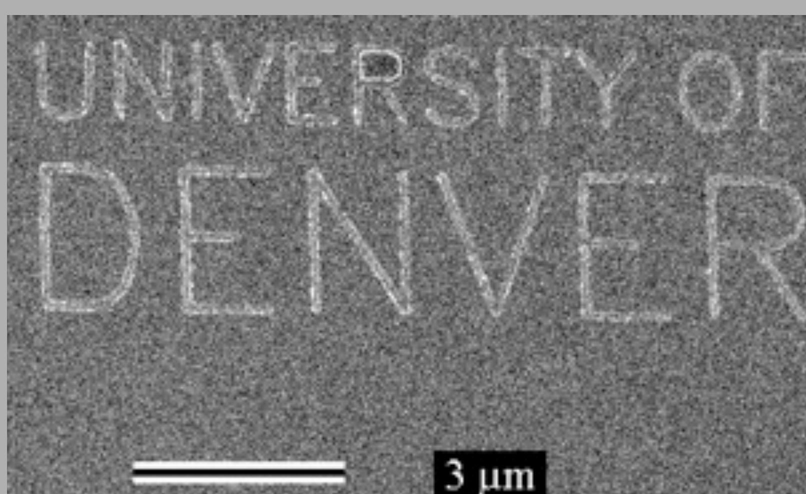
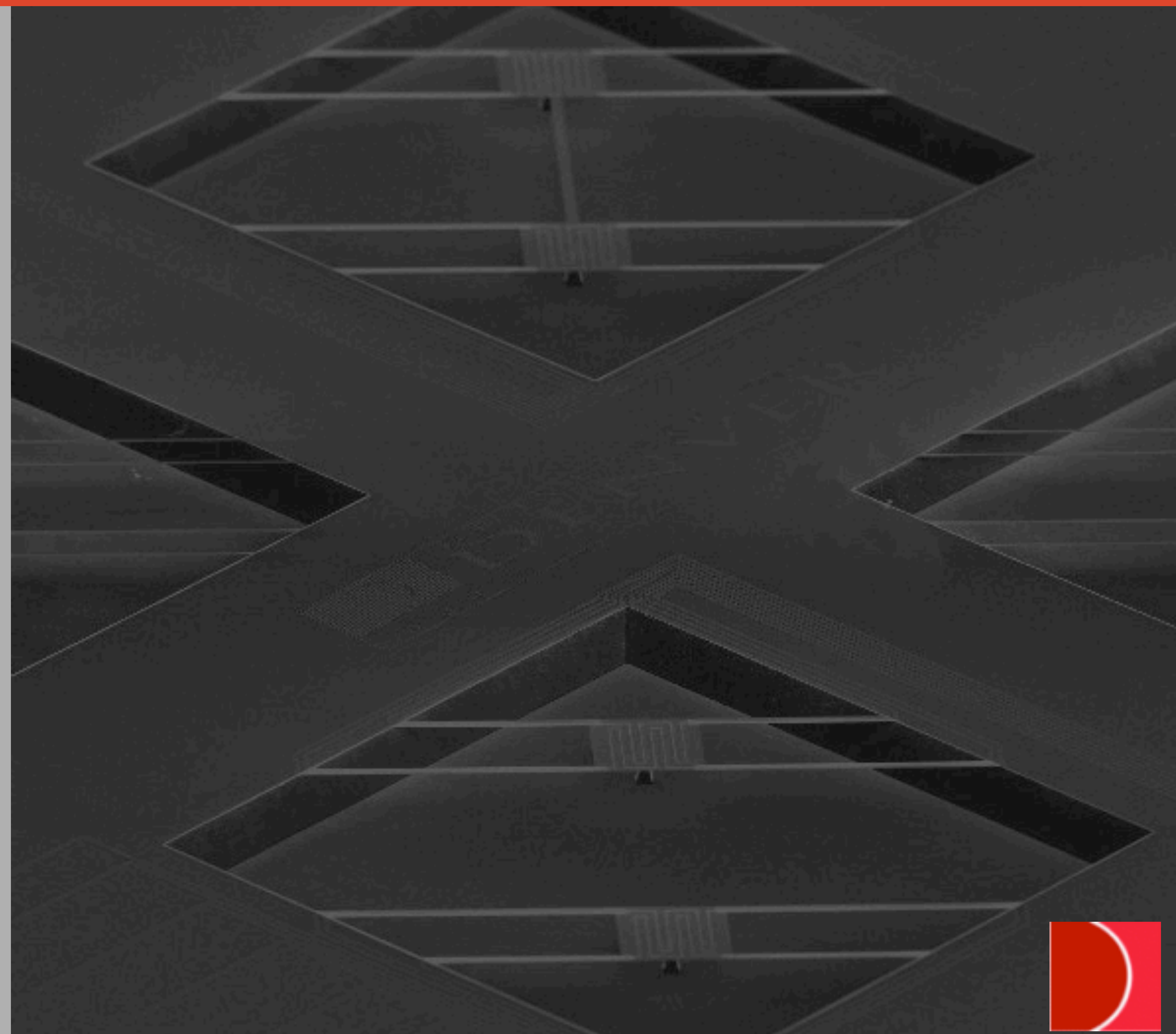
Thermoelectric Effects and Thermal Spin Currents in Magnetic Nanostructures

Barry L. Zink

Assistant Professor
Dept. of Physics & Astronomy
University of Denver
barry.zink@du.edu





Spin Caloritronics III
"*Experiments 2*" panel
May 13, 2011
Lorentz Center, Universiteit Leiden

Collaborators and Acknowledgments

DU Physics
Zink Research Group

- Post-Docs
  - Rob Horansky (also NIST)
- PhD Students
  - Azure Avery
  - Rubina Sultan (PhD Fall 2010)
  - Dain Bassett
  - Sarah Mason
- Undergrads
  - Di Di Wei
  - Joe Rauch
  - Gail Cotteril

- Matt Pufall

We Gratefully Acknowledge
Fabrication Advice and Assistance

- Jim Beall
- Dan Schmidt
- Gene Hilton
- Anna Fox

May 13, 2011

Less is different…

Modern processing tools allow manipulation of matter at length scales where transport phenomena are distinctly different from the bulk!

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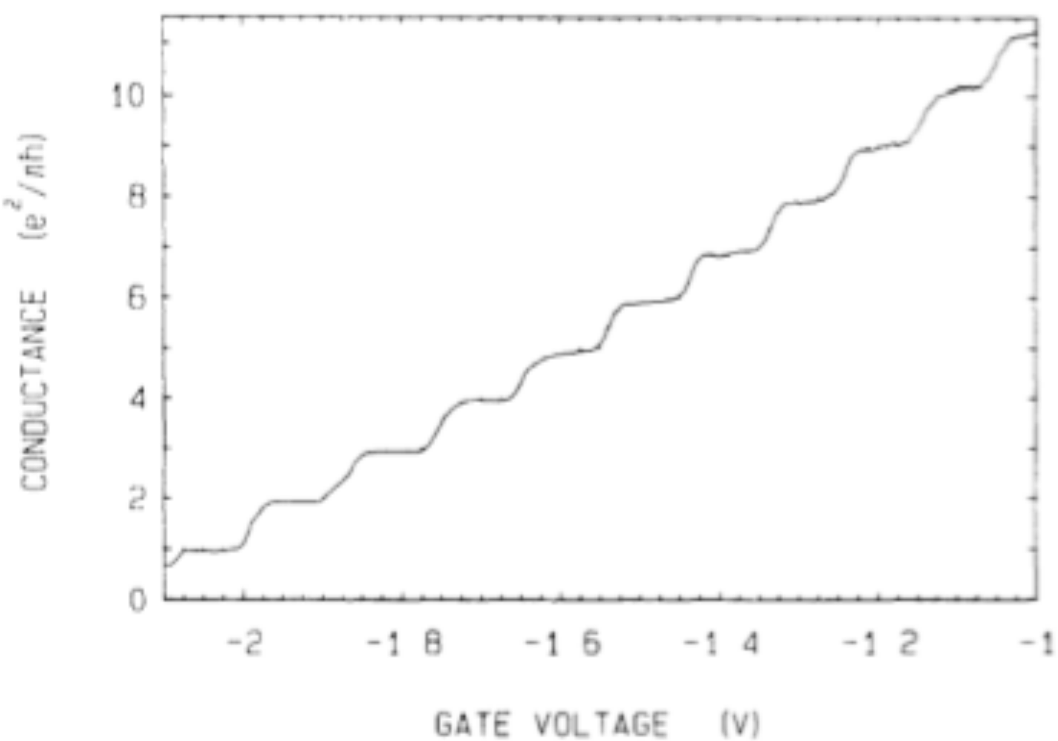

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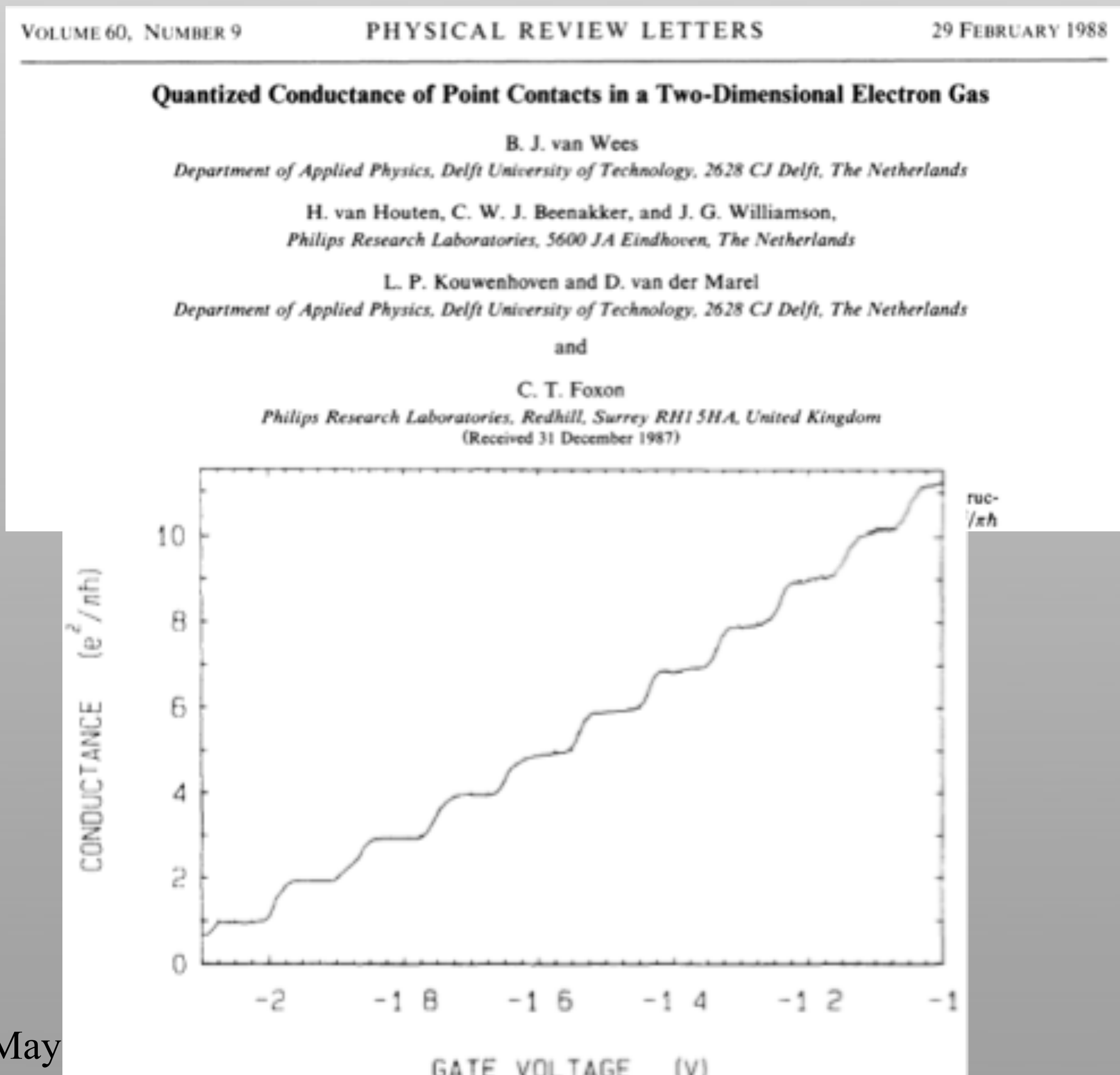

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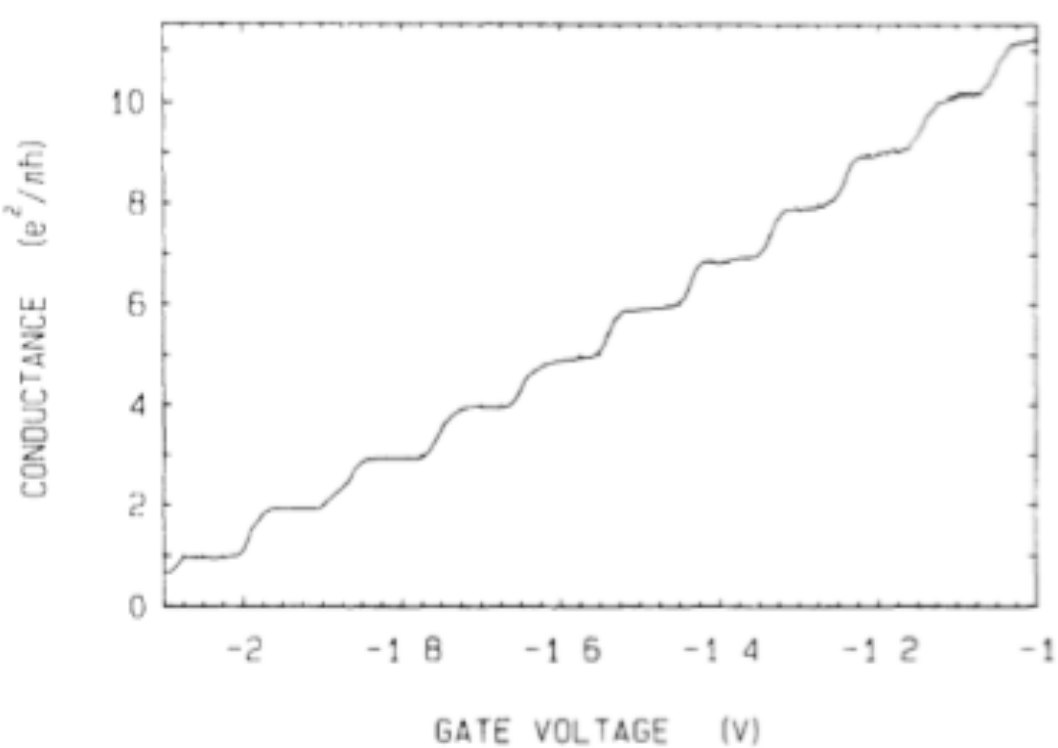

NATURE | VOL 404 | 27 APRIL 2000 | www.nature.com

Measurement of the quantum of thermal conductance

K. Schwab*, E. A. Henriksen*, J. M. Worlock*† & M. L. Roukes*

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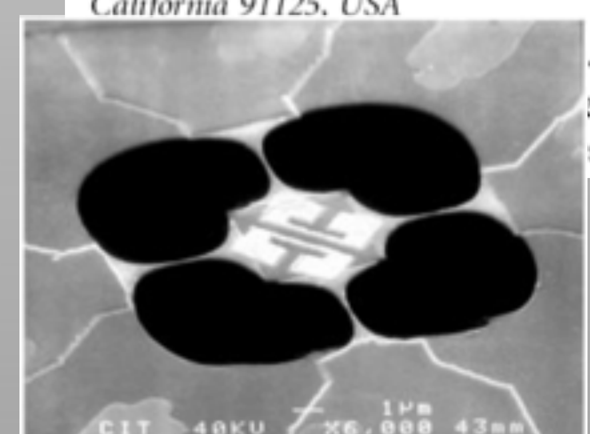

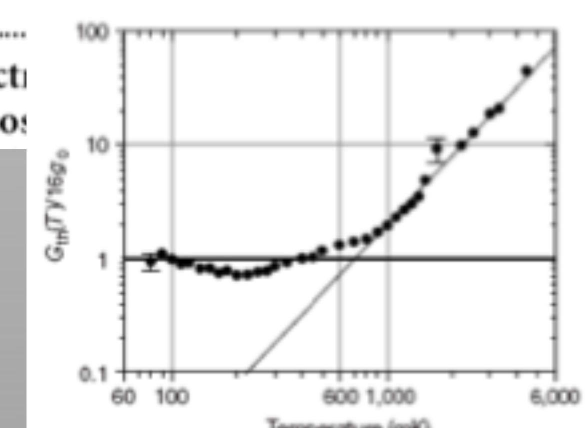

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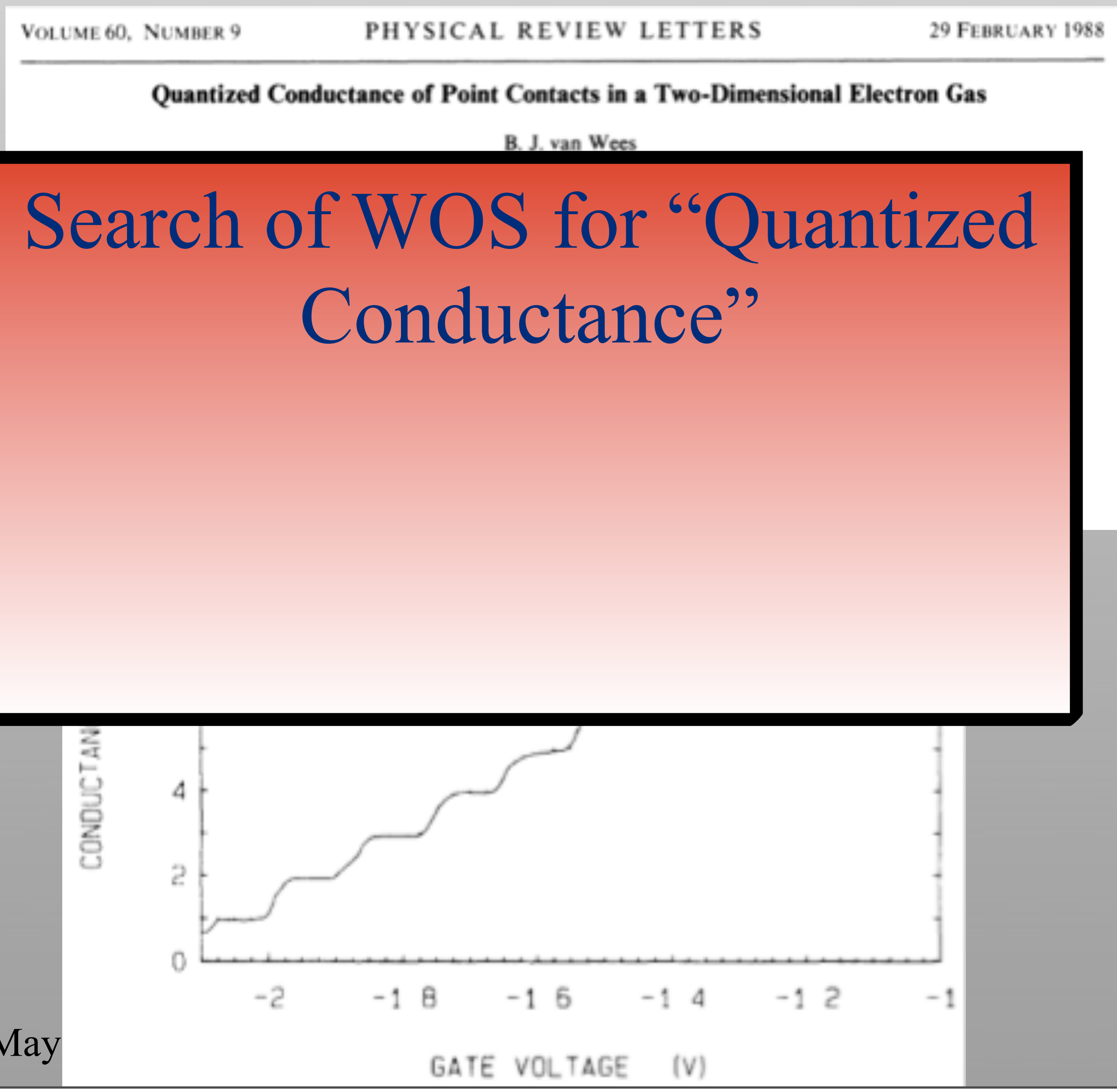
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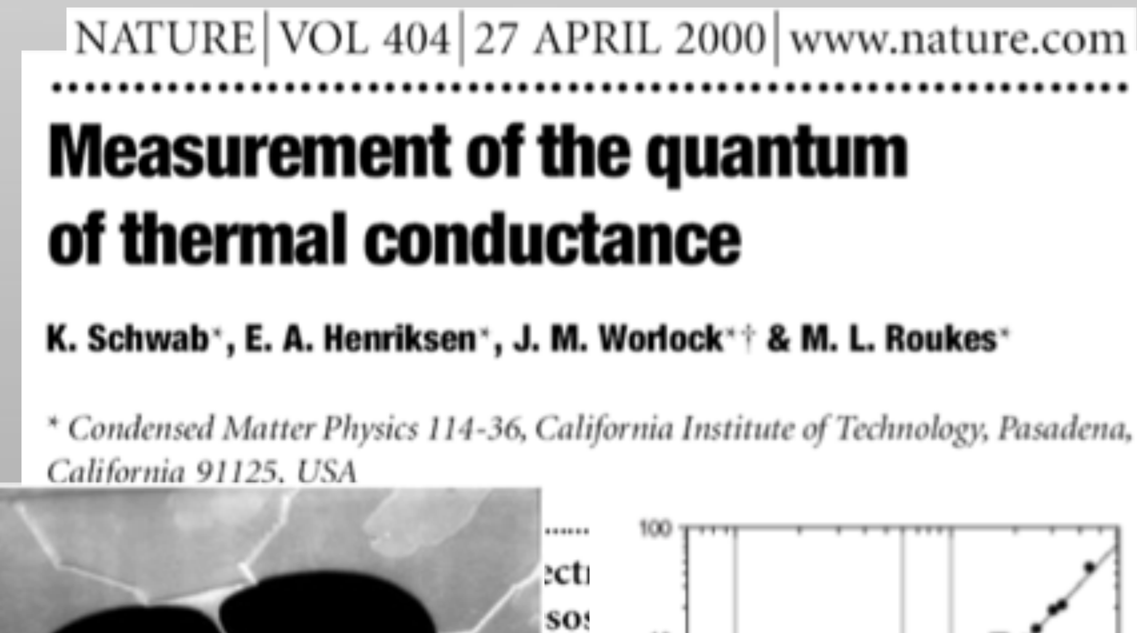
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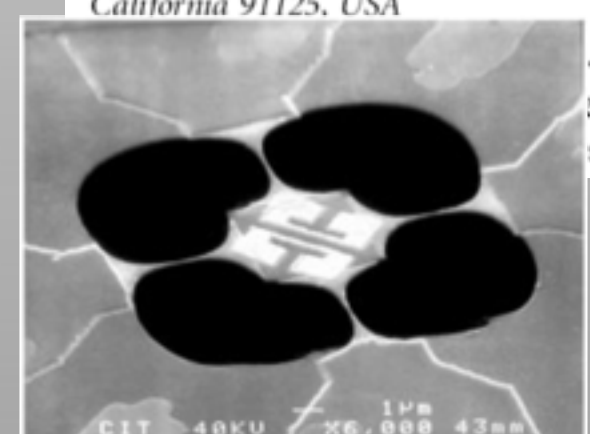

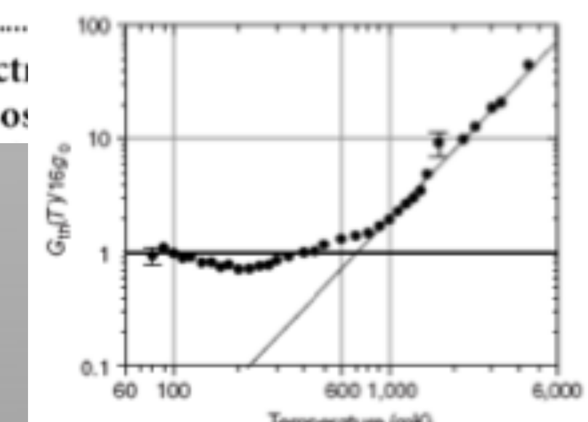

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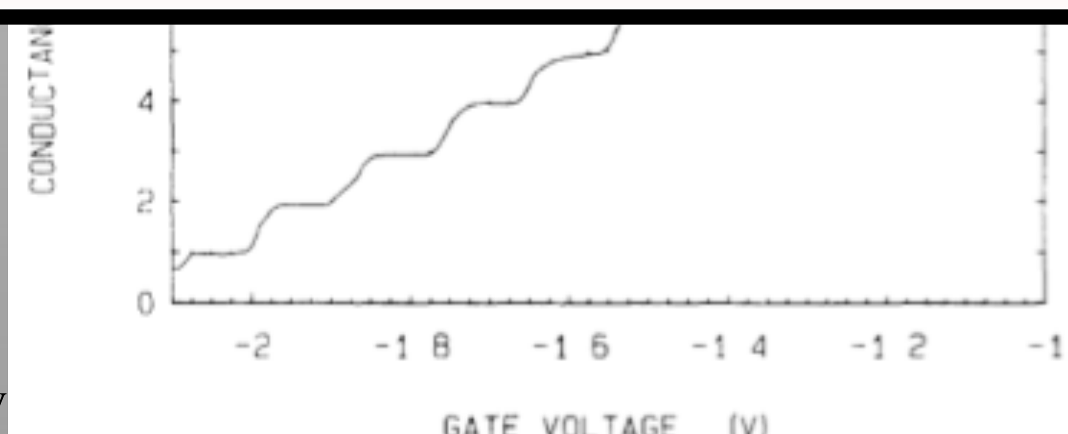


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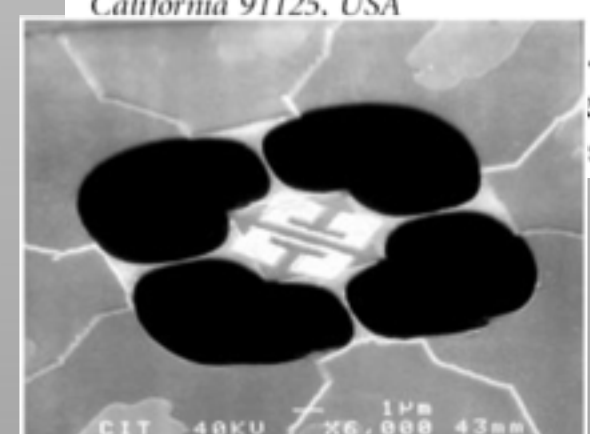

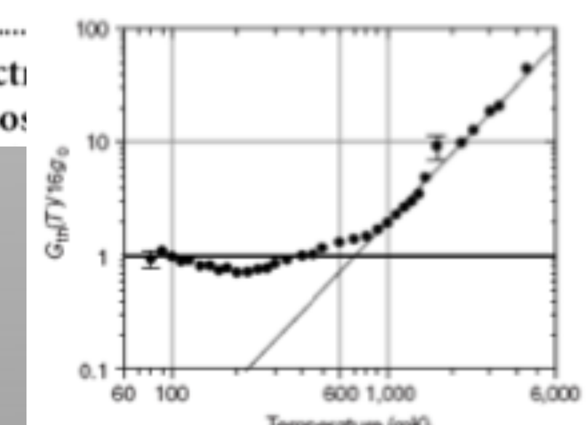

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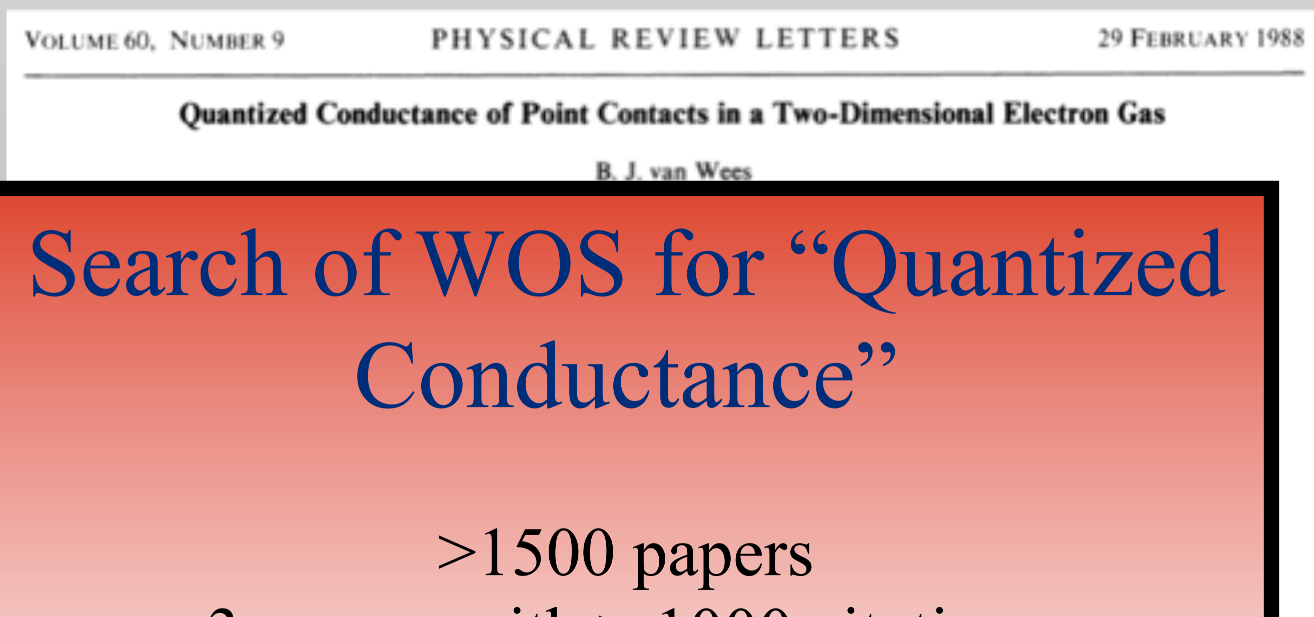
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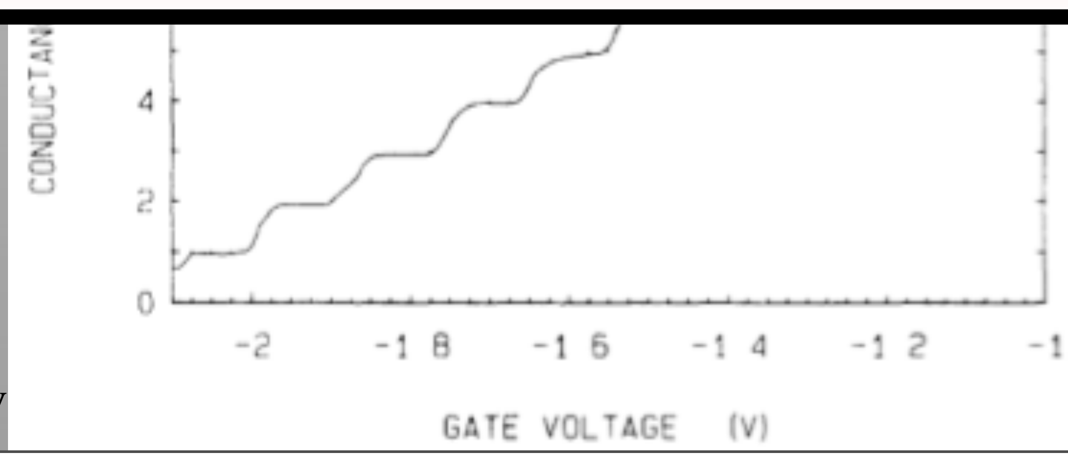


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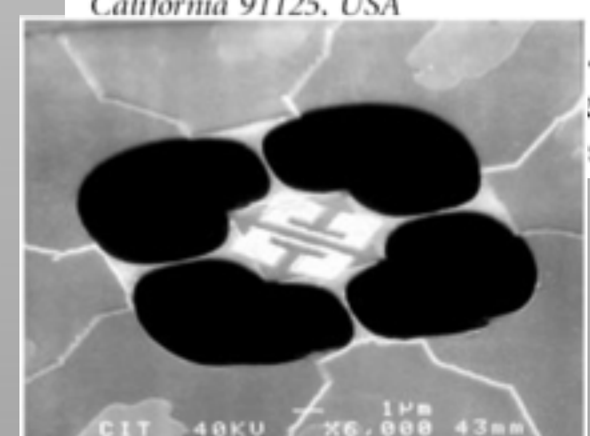

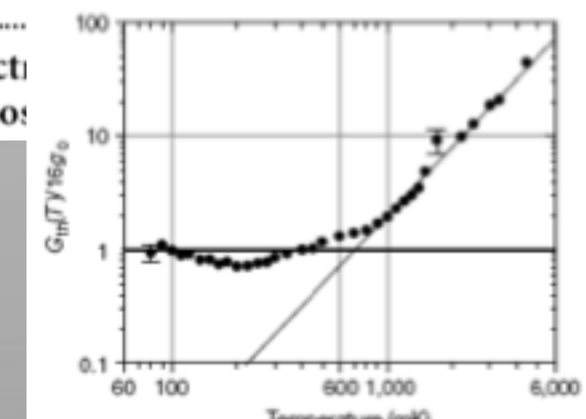

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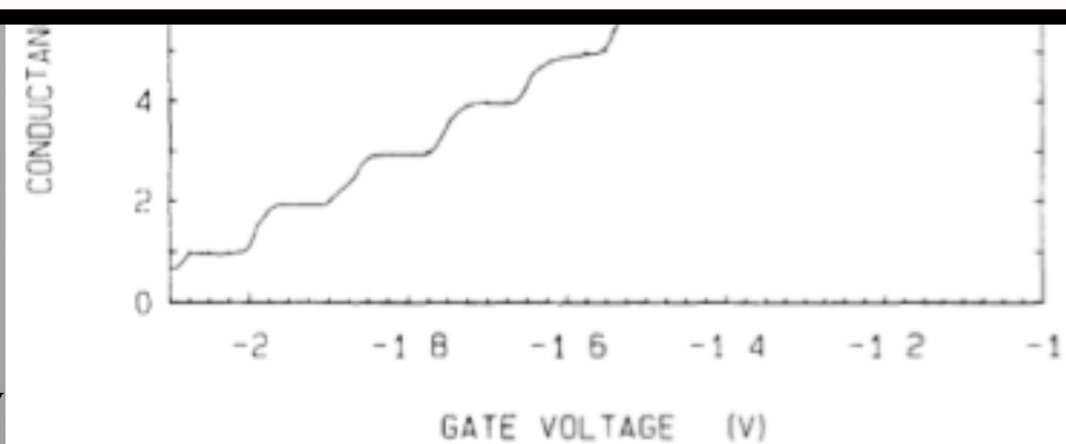

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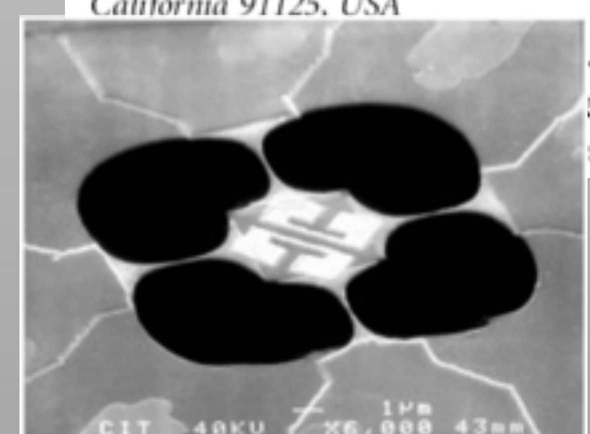

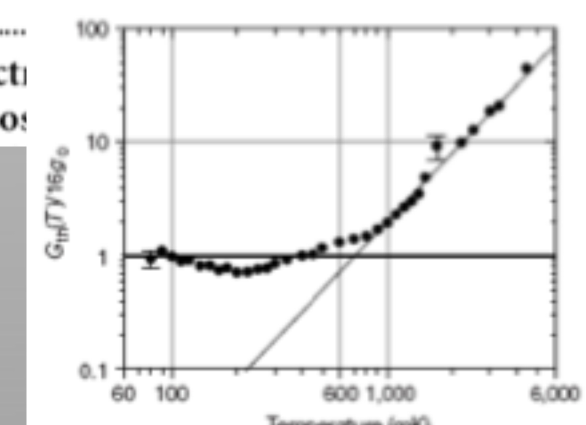

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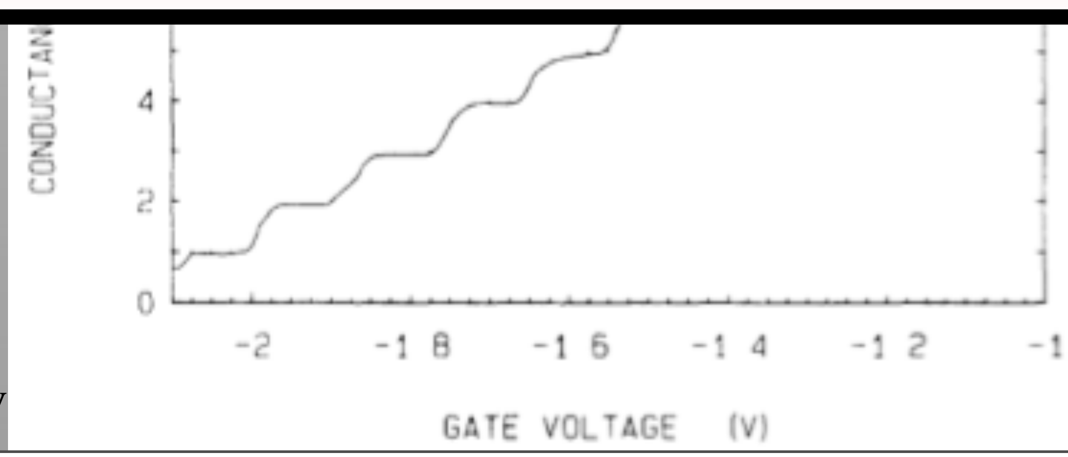

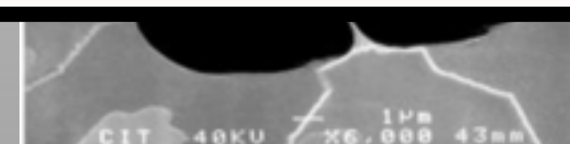

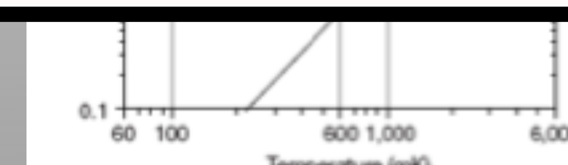

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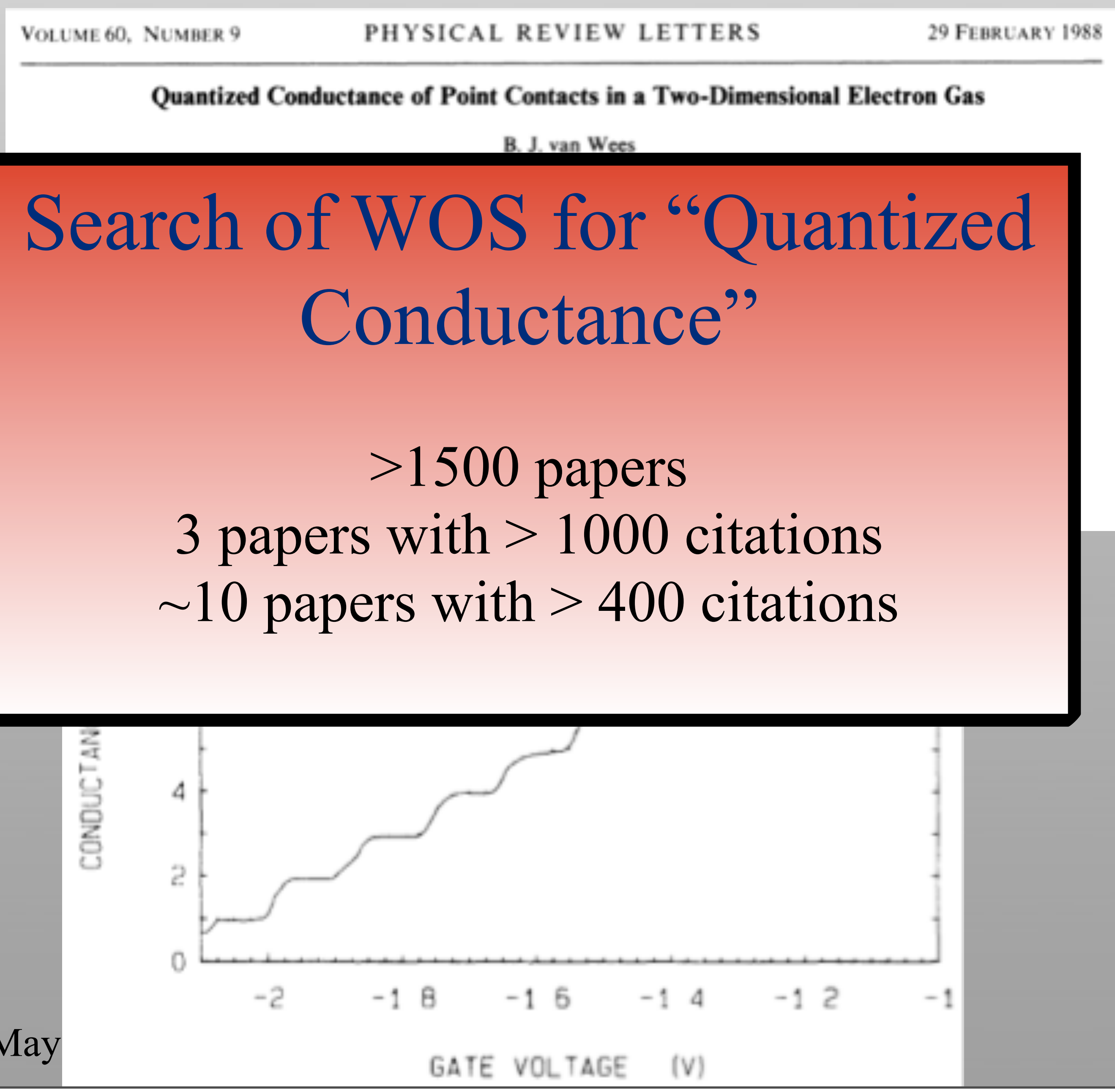
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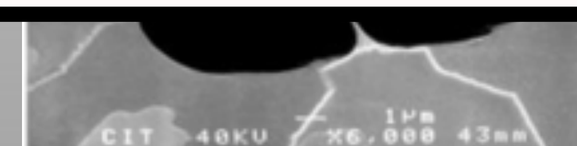

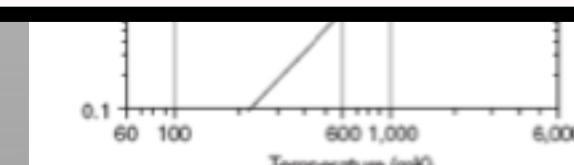

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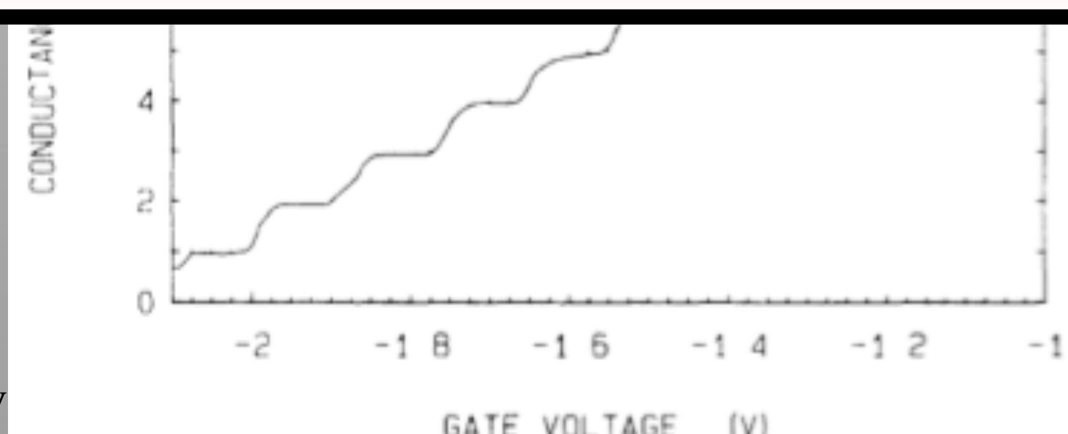

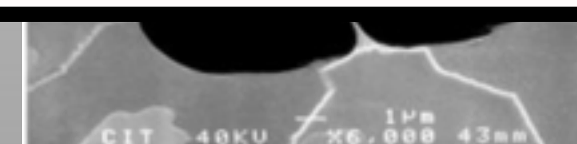

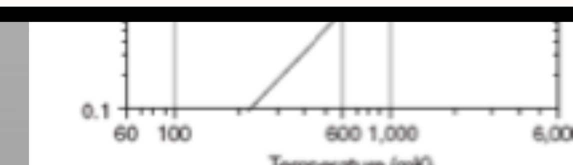

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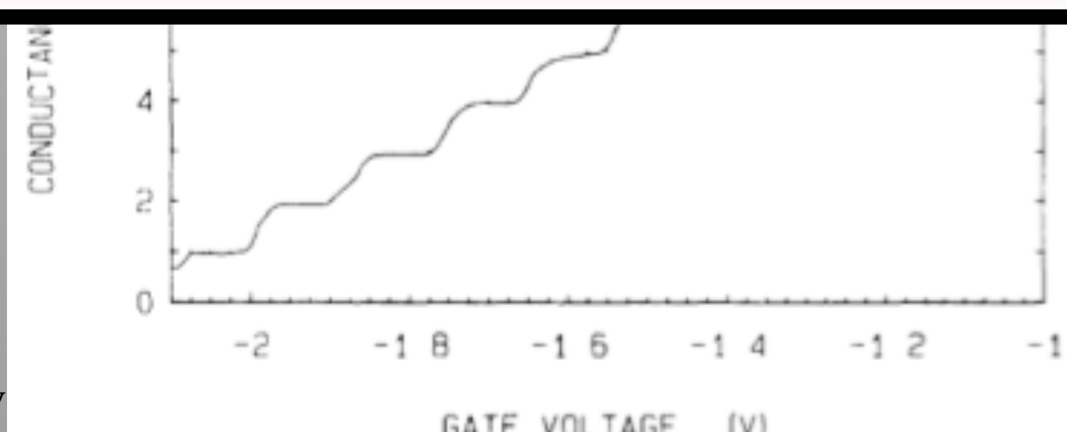

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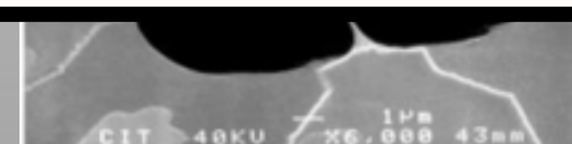

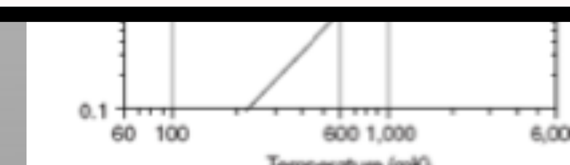

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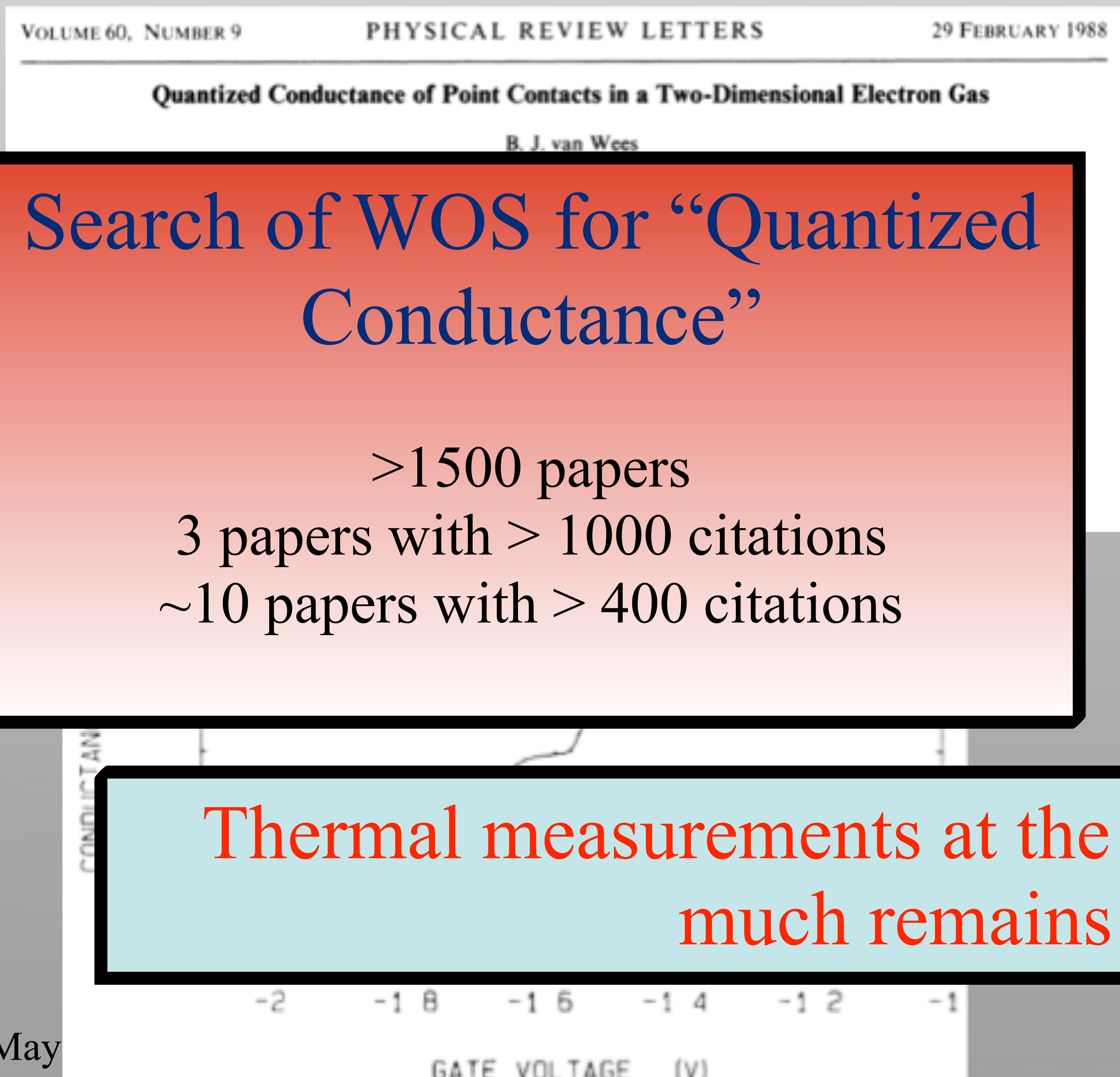
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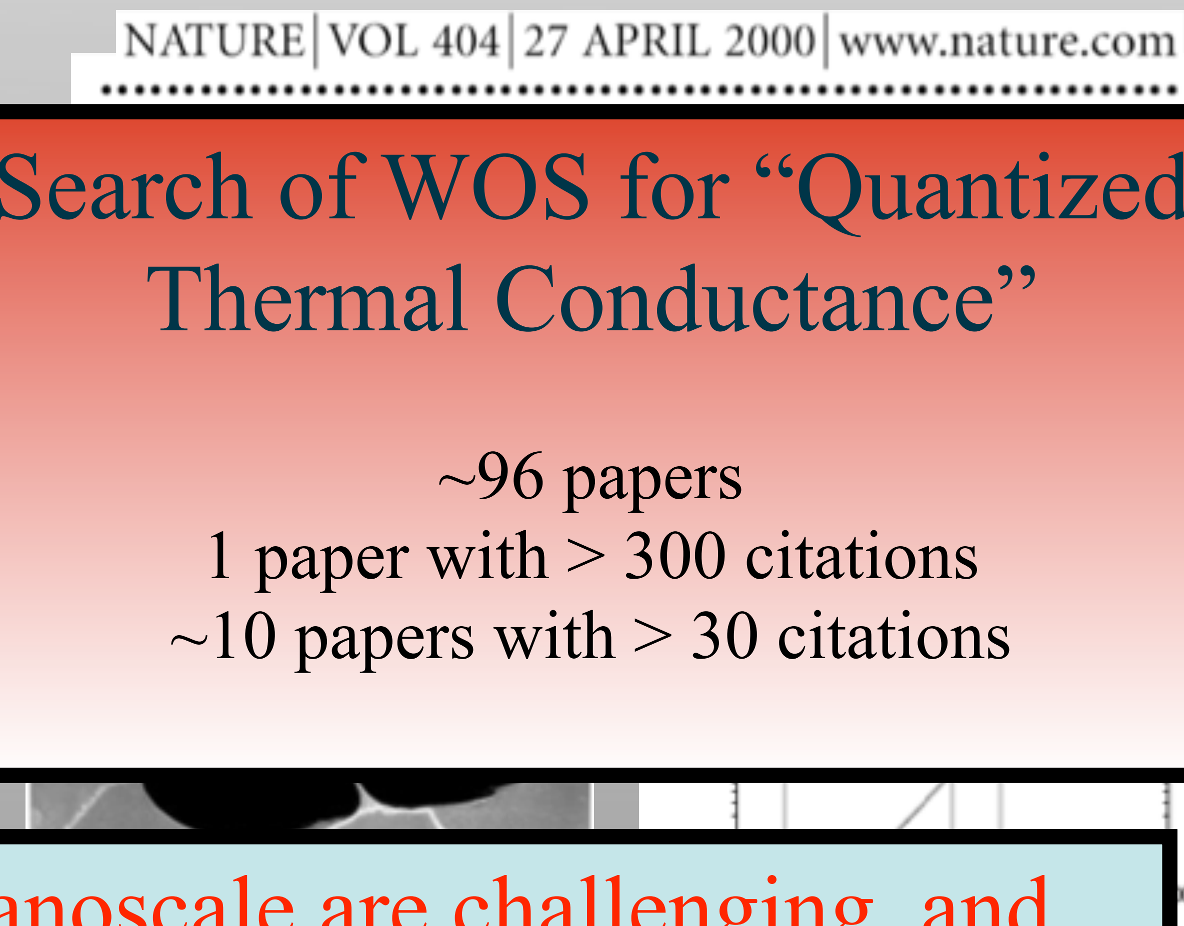
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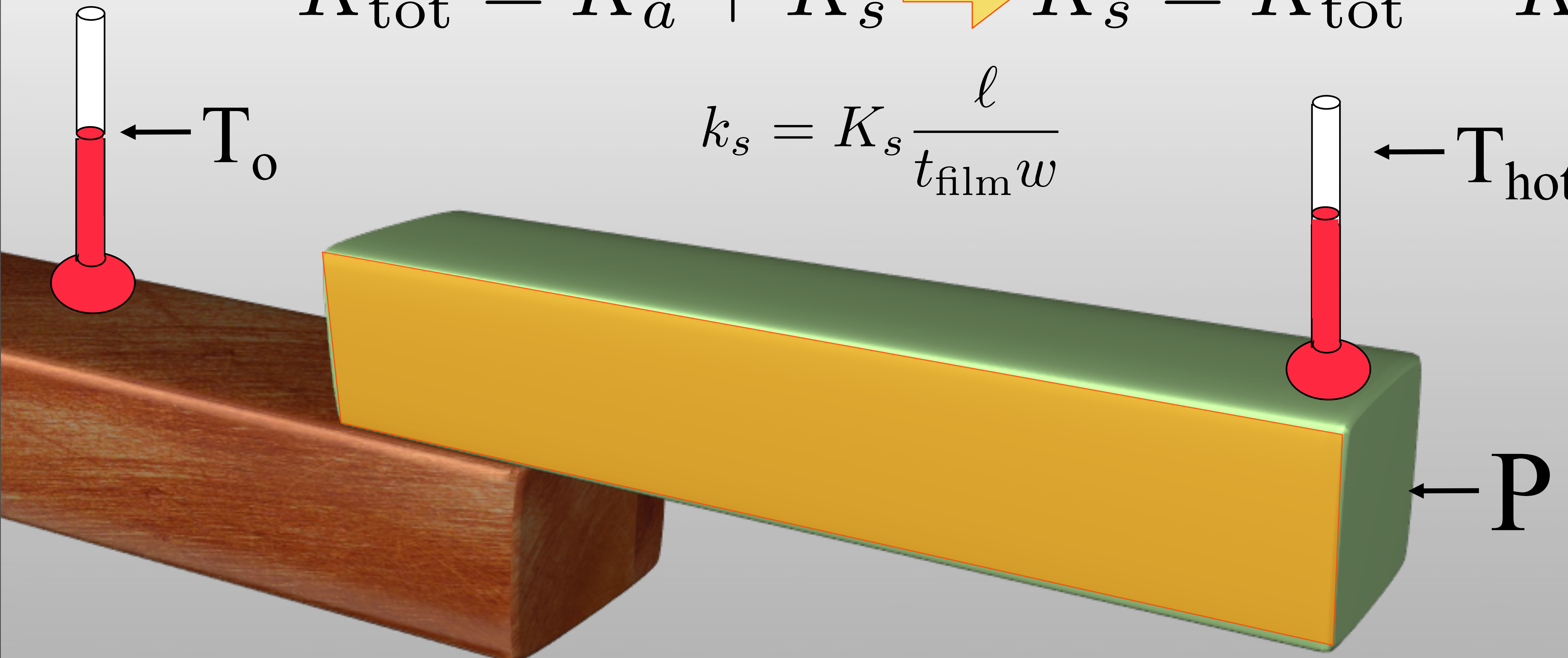
Thermal measurements at the nanoscale are challenging, and much remains to be explored!

Measuring Thermal Conductivity of thin films

$$K_{\text{tot}} = K_a + K_s \Rightarrow K_s = K_{\text{tot}} - K_a$$

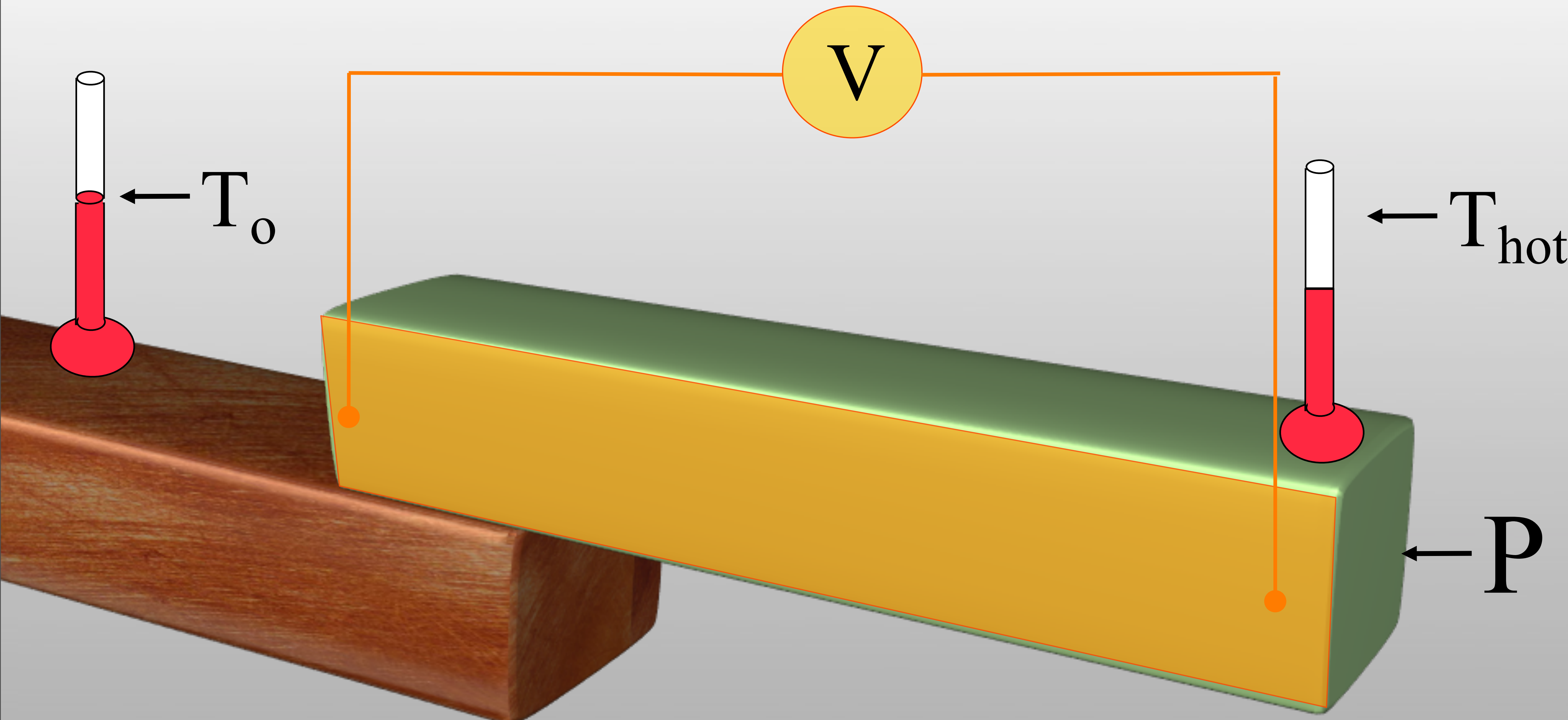
$$k_s = K_s \frac{\ell}{t_{\text{film}} w}$$



Subtraction of a large background nearly always leads to LARGE experimental error!

Assumes conduction of heat! Radiation is often important at 100+K

Measuring thermopower of thin-films

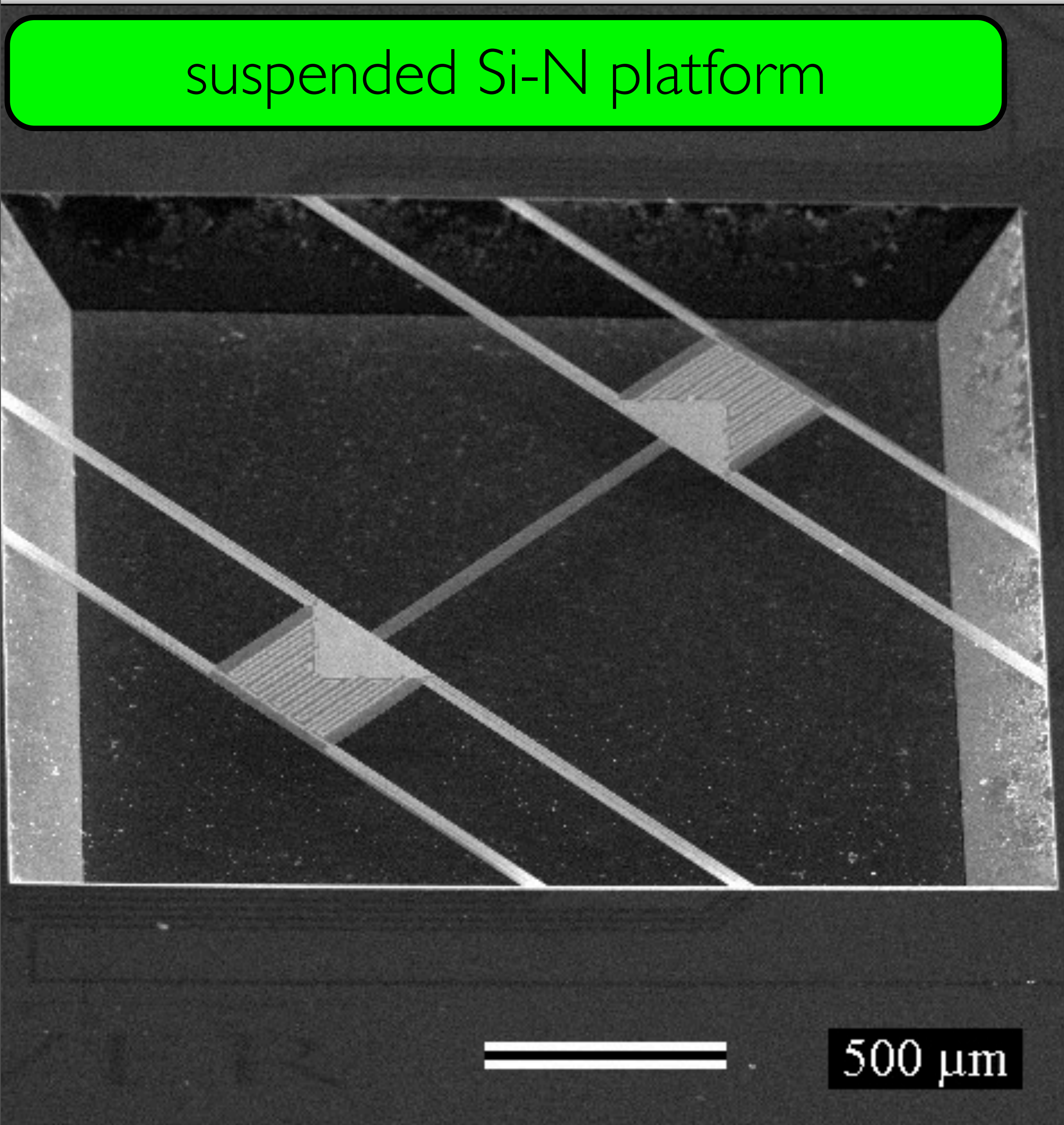


Several reports on thermoelectric power (TEP) and magnetothermoelectric (MTEP) power for spin-valves, other thin films.

many open questions remain…

1) L. Piraux, et al., *JMMM* **110**, L247 (1992)
2) J. Shi, et al., *JMMM* **125**, L251 (1993)
3) E. Yu. Tsymbal et al., *PRB* **59**, 8371 (1999)
…

Thermal Isolation Platforms



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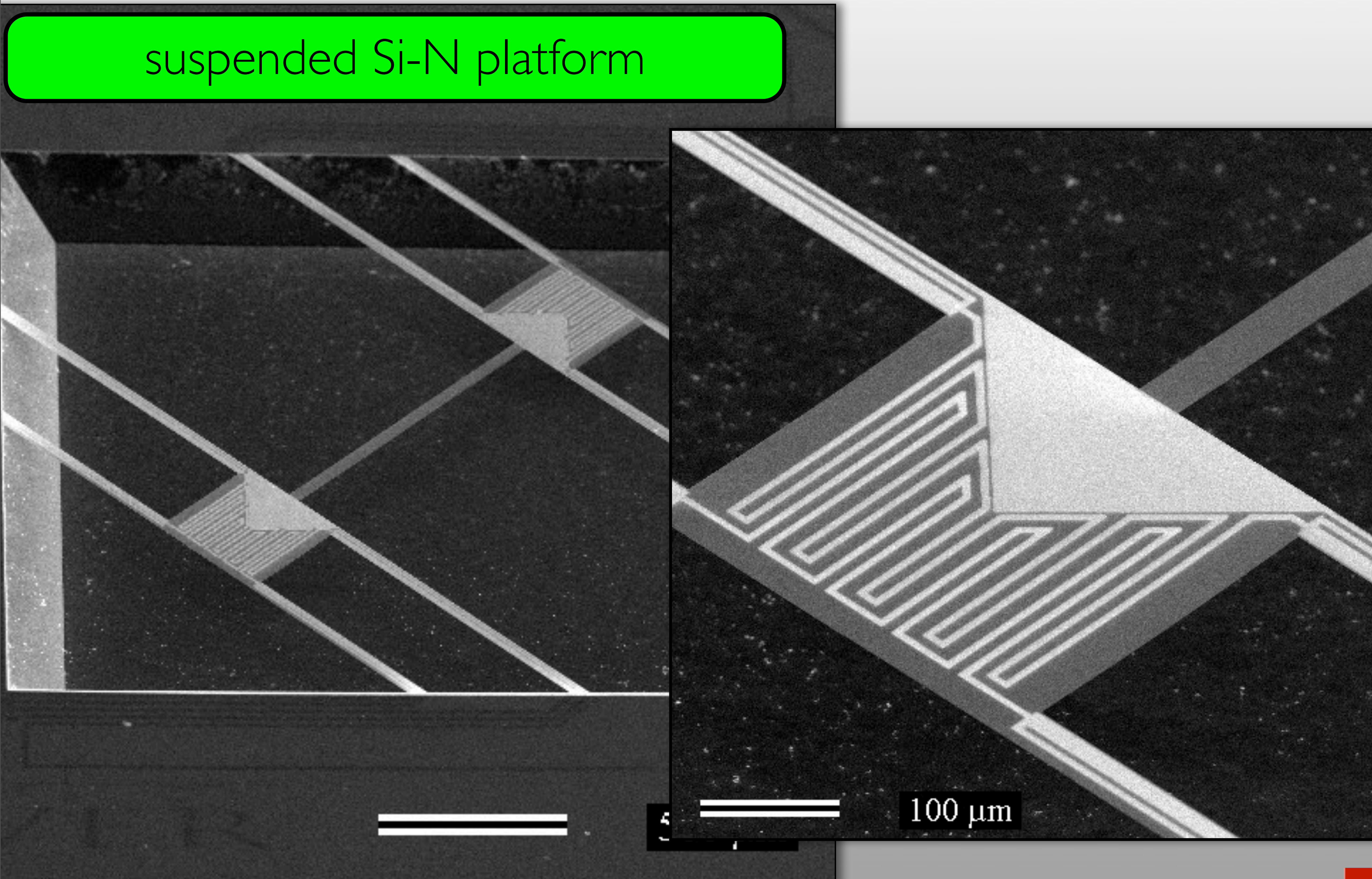

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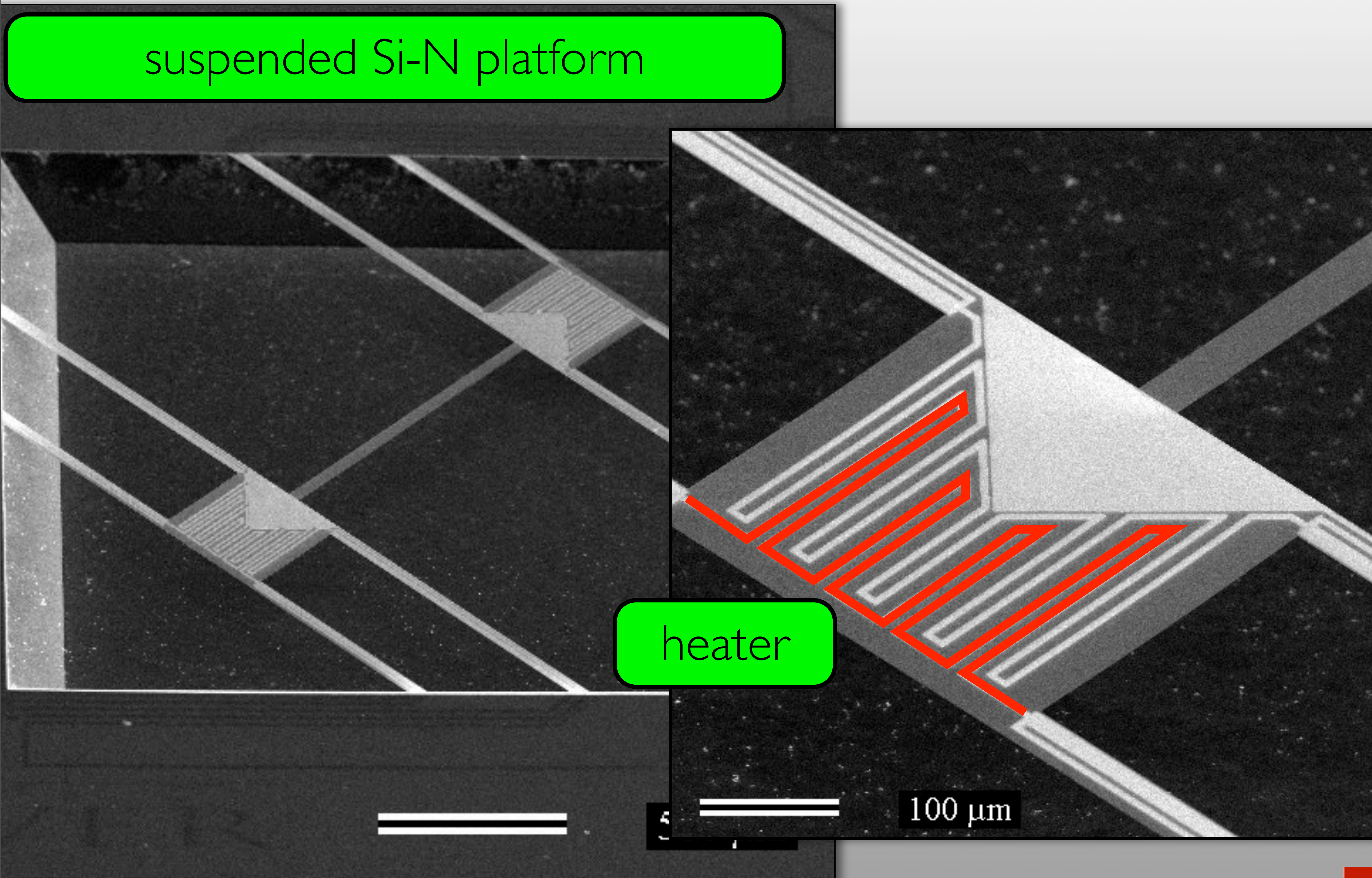

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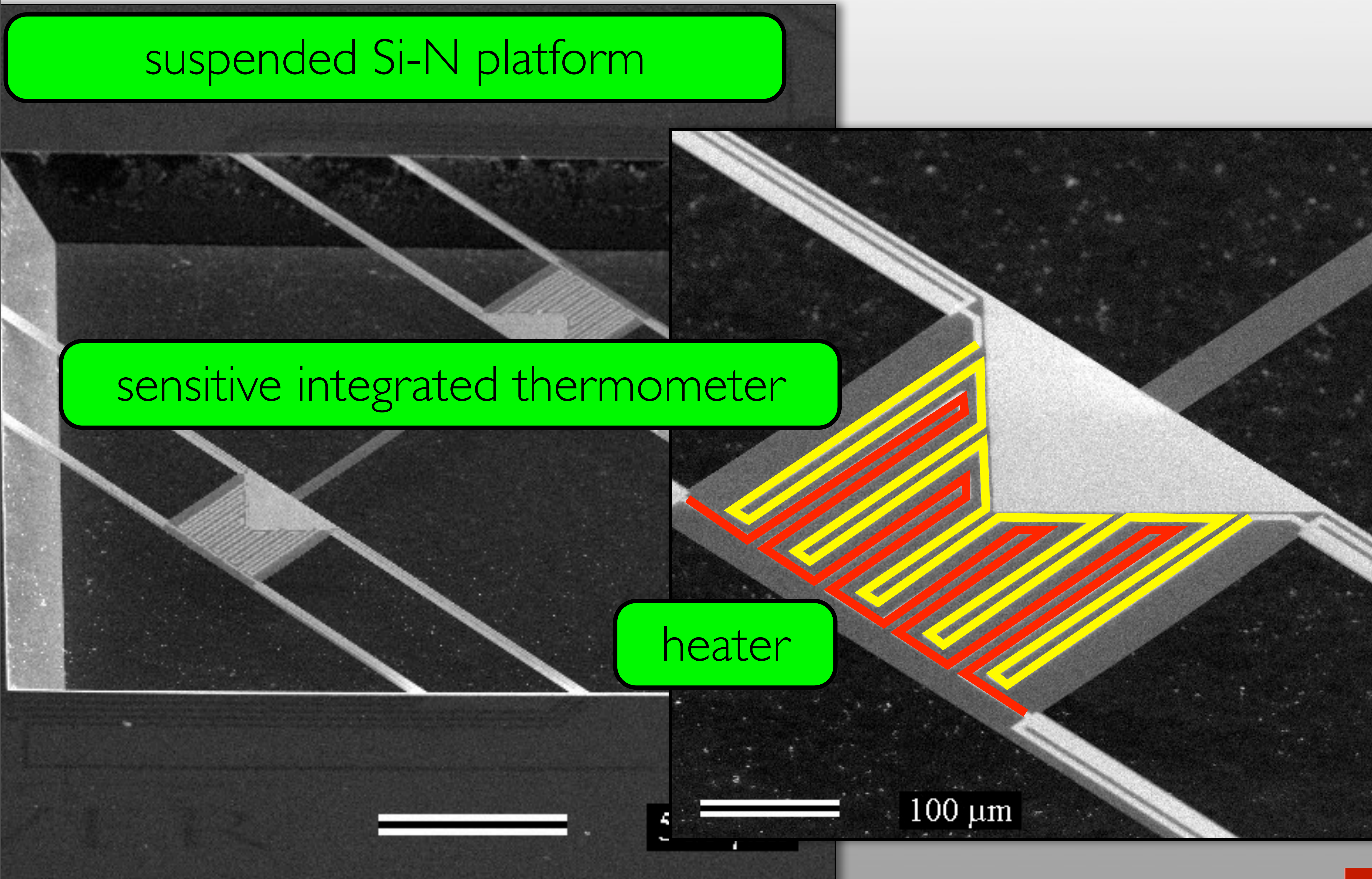

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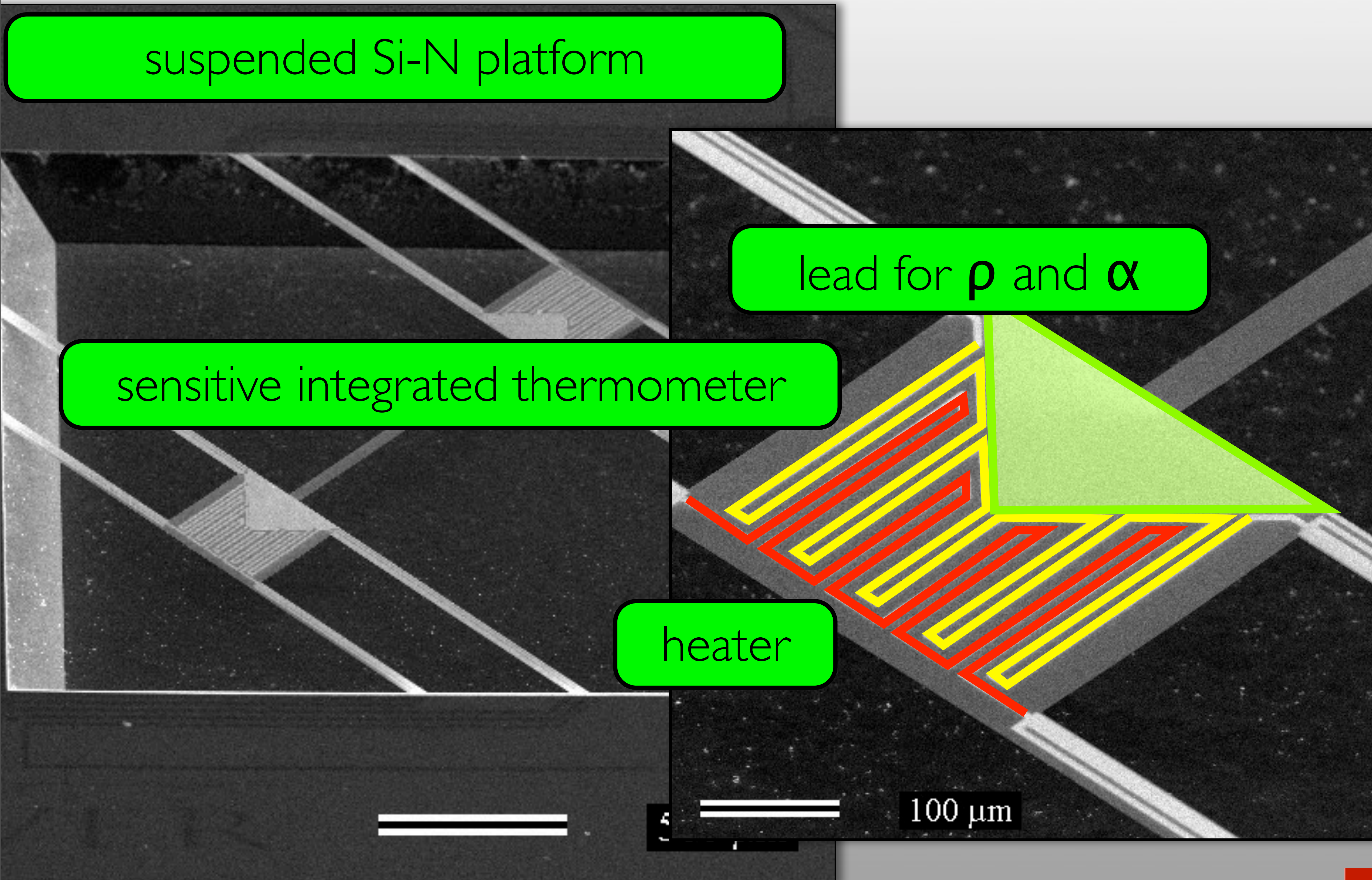

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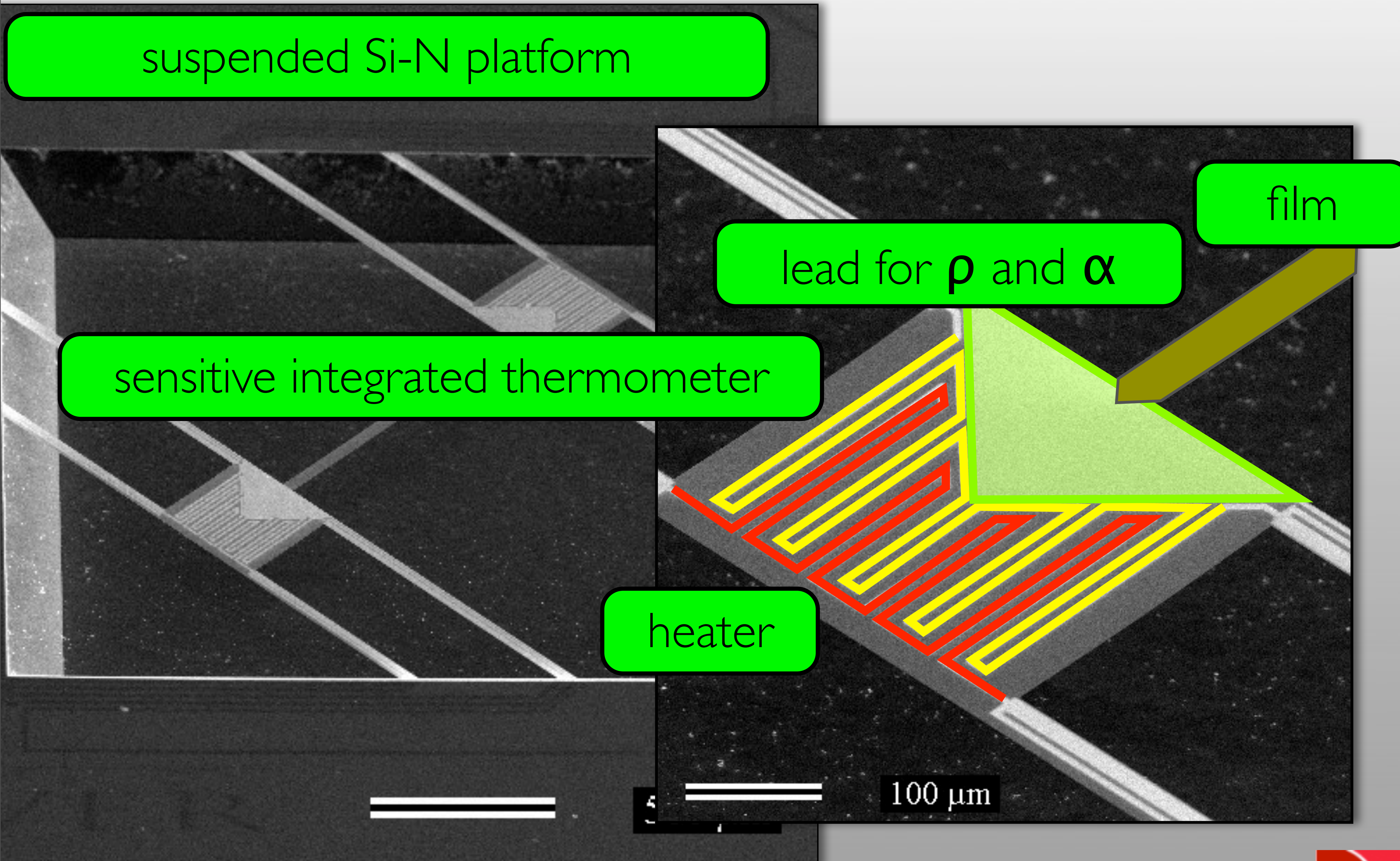


Zink's Personal Spin-Caloric Timeline

Late nineties (!):
Heat capacity and thermal conductivity of amorphous magnetic semiconductor thin films in spin glass state

2006

Fall 2006:
Start DU

Fall 2007-Spring 2008,
Working with Matt Pufall,
Wrote First Proposal on
"Thermal spin transfer..."

MAR 2008,
First Thermal
Transport
Results

Fall 2008,
Uchida, et al. first
observe SSE

MMM 2008,
Presented First
Results on TEP
and k of Ni films

Early 2009,
"Hey, these SSE
measurements
should be easy
for us..."

Myers/Heremans
collab. report
strong substrate
dependence

First SSE
platforms
constructed,
first data.

2011

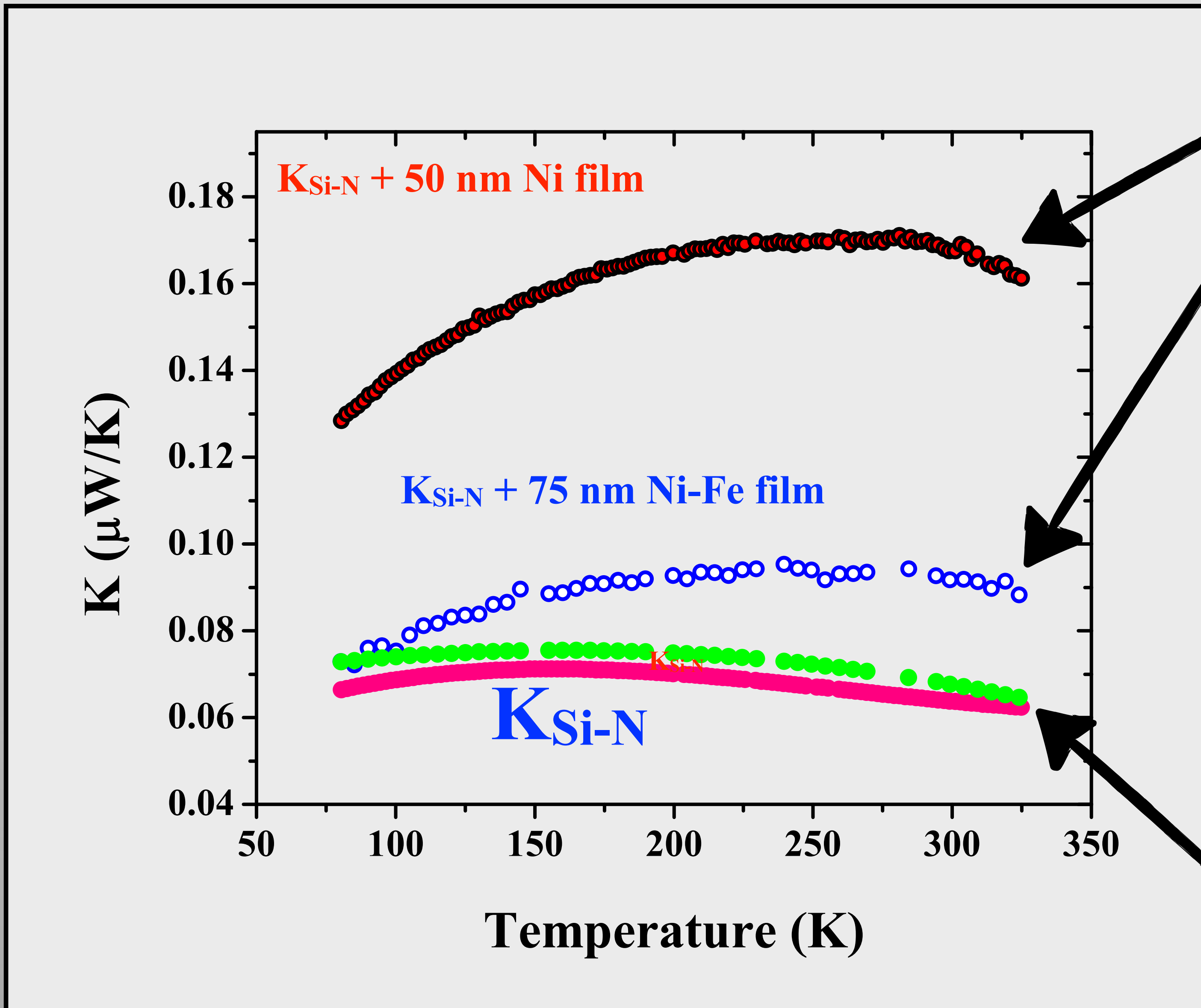
Physical Review B

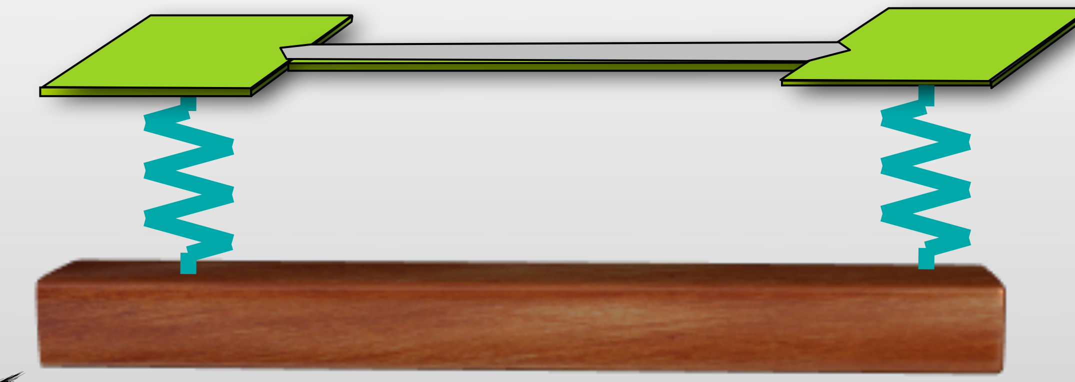
Uchida, et al.
report ~zero
SSE signal on
amorphous
substrate

Maybe Barry
Understands
our SSE
data?

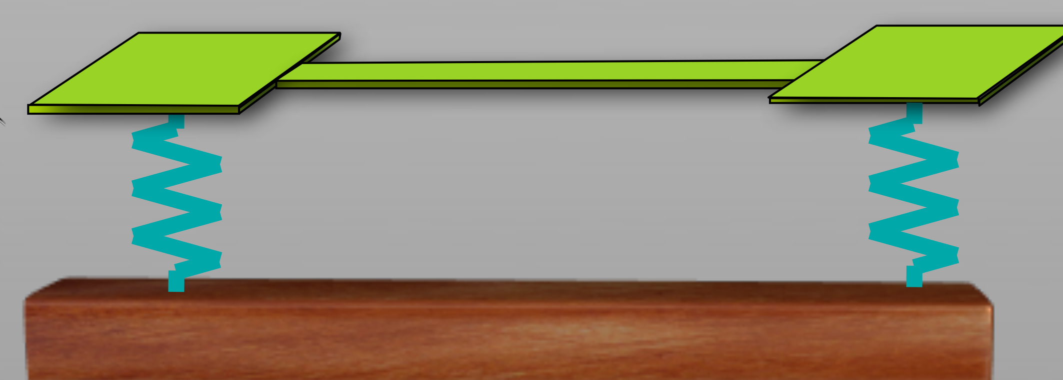
May 13, 2011

Comparing Backgrounds...



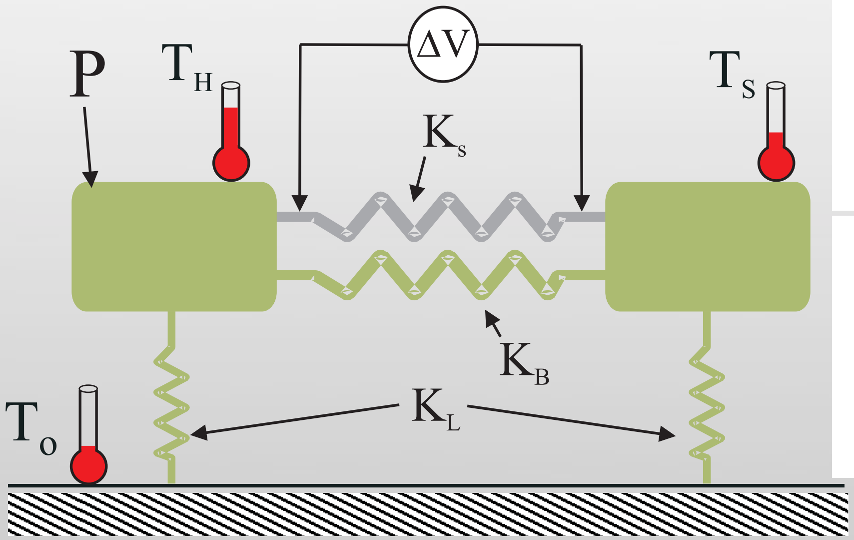


$K_B + K_S$



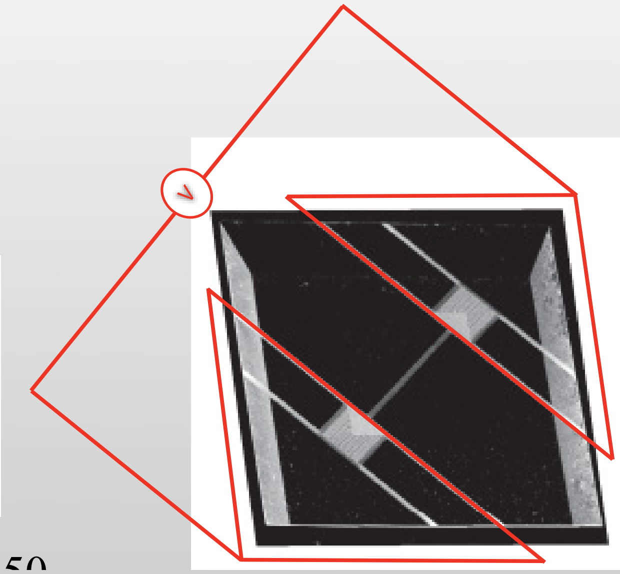
K_B

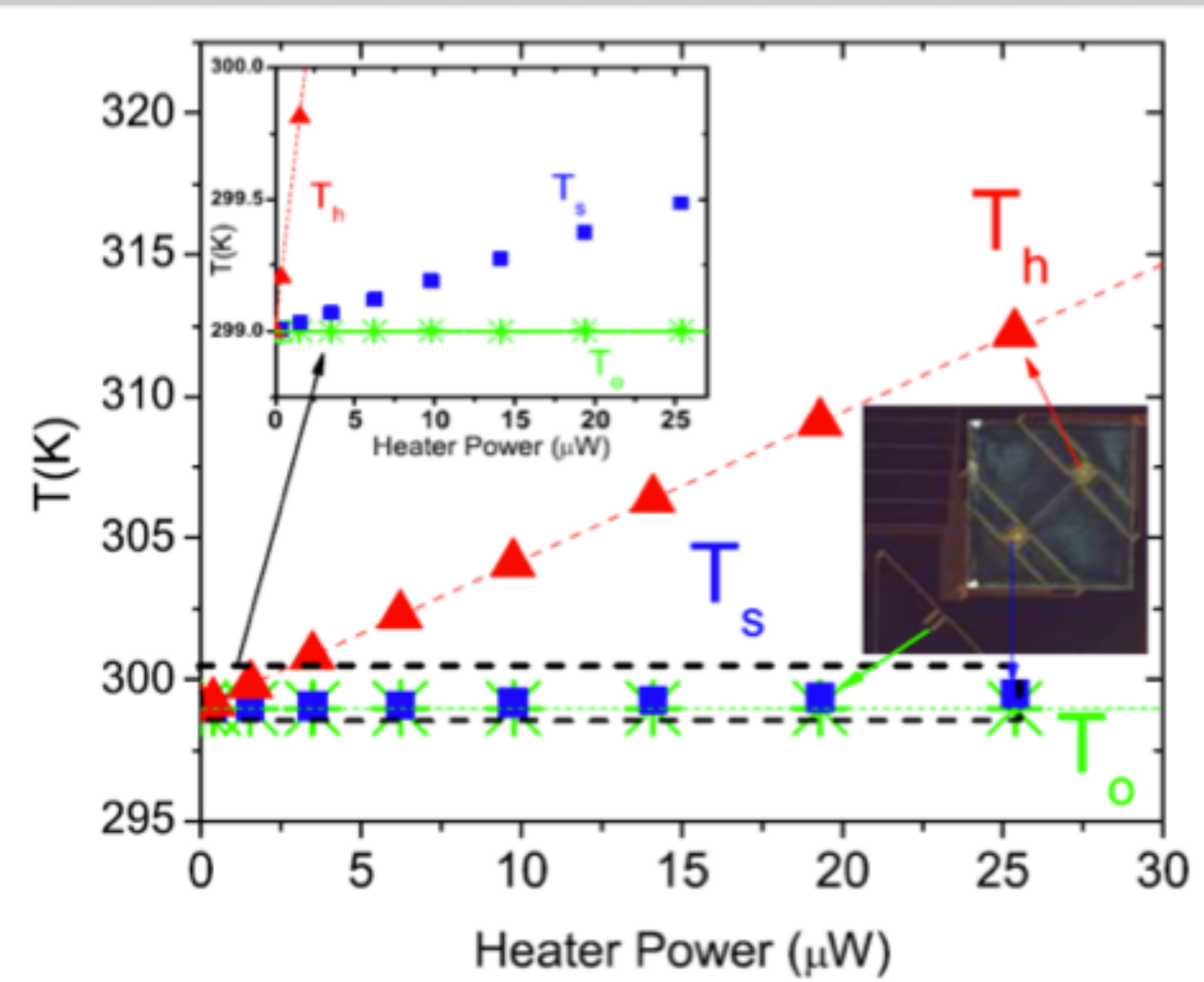
A few details…

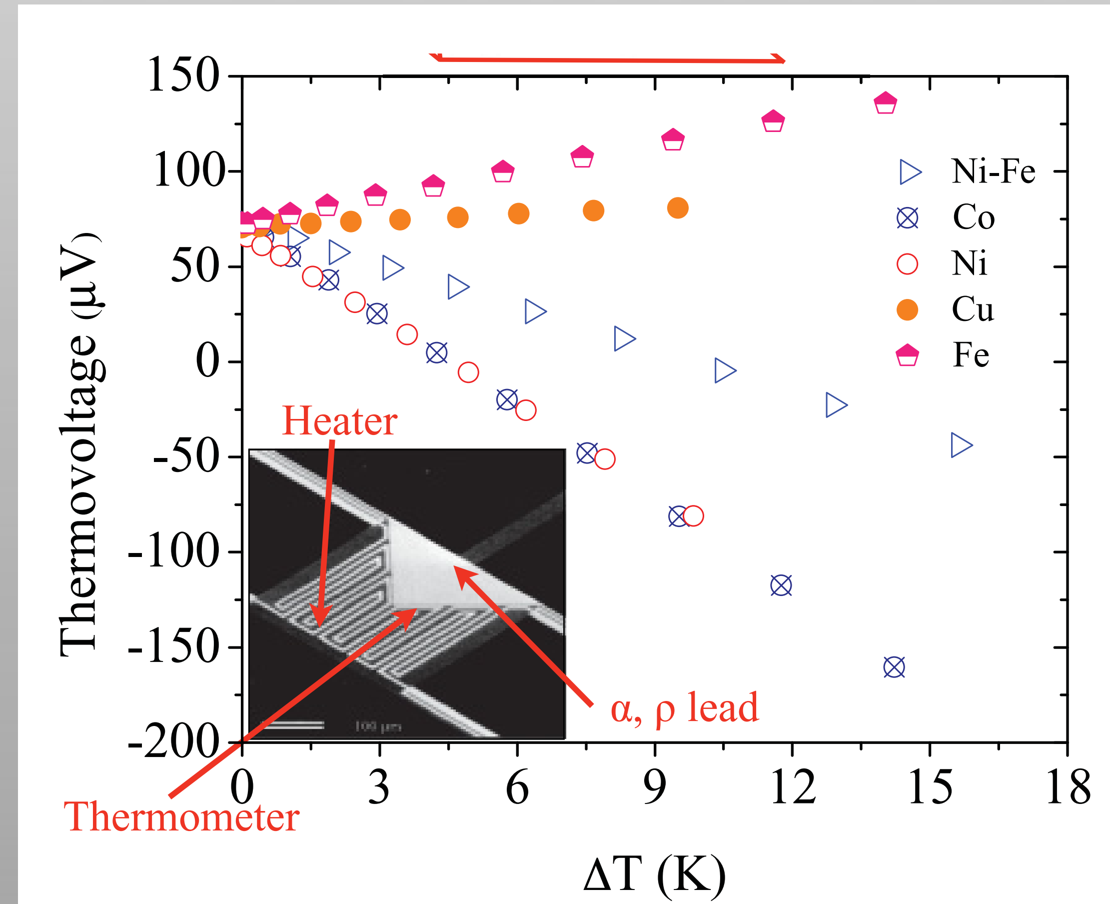


$$T_H = T_o + \frac{K_L + K_B}{K_L(K_L + 2K_B)} P$$

$$T_S = T_o + \frac{K_B}{K_L(K_L + 2K_B)} P$$

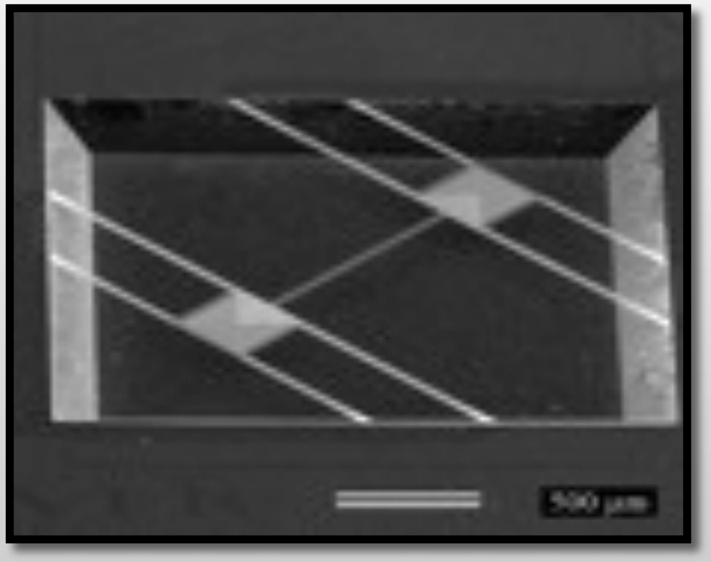






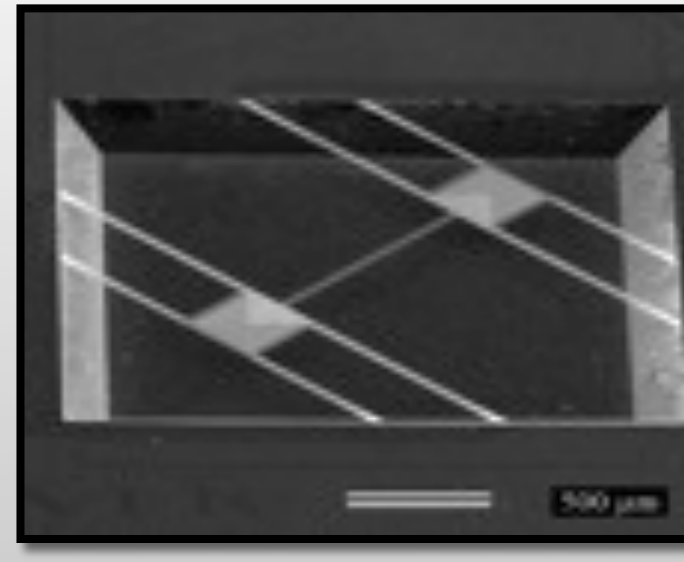
May 13, 2011

Advantages of Micromachined Thermal Platforms



Advantages of Micromachined Thermal Platforms

- Stupid simple geometry



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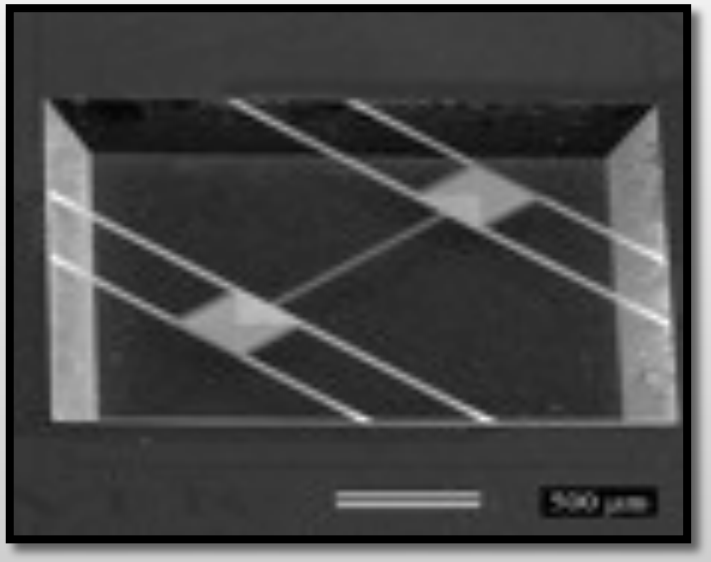

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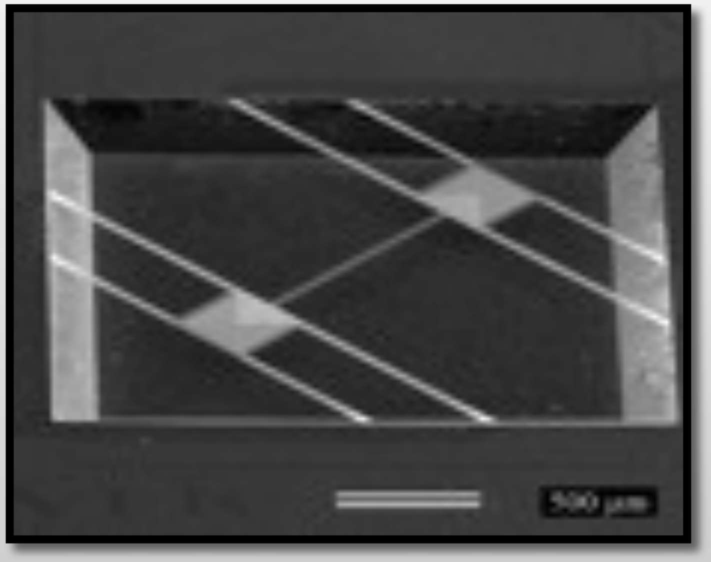
  - 77 to > 300 K for these experiments



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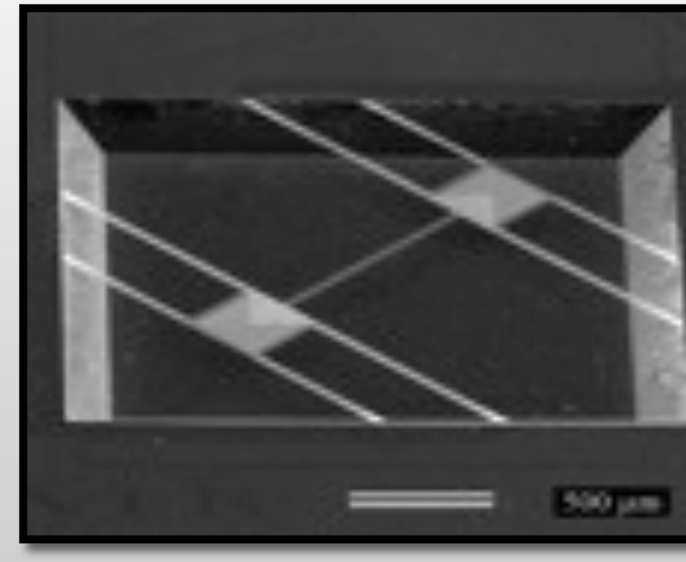

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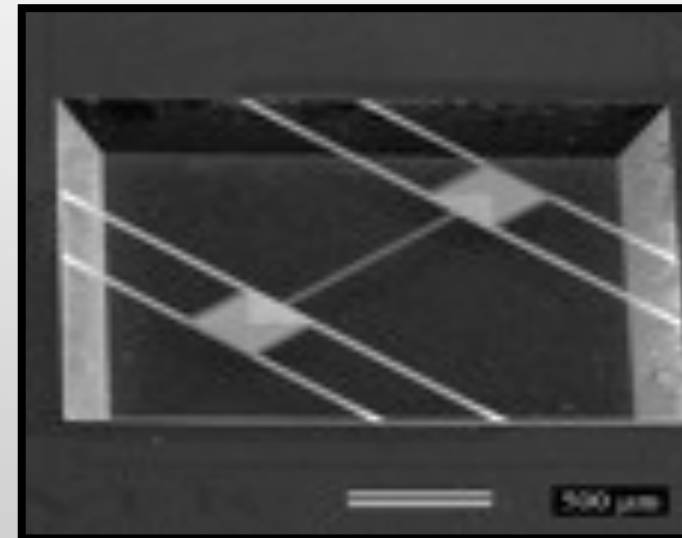

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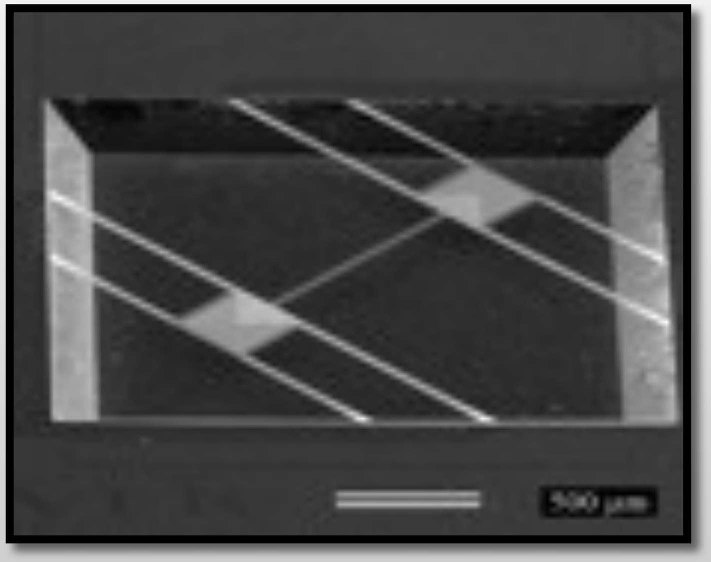

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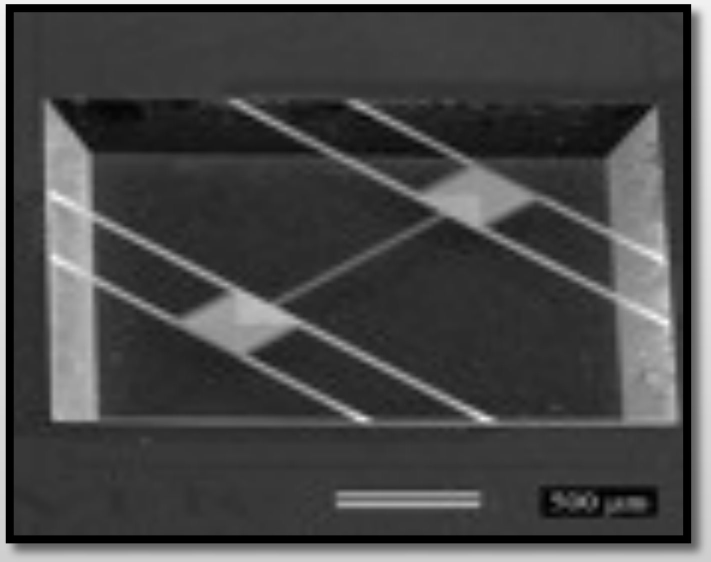

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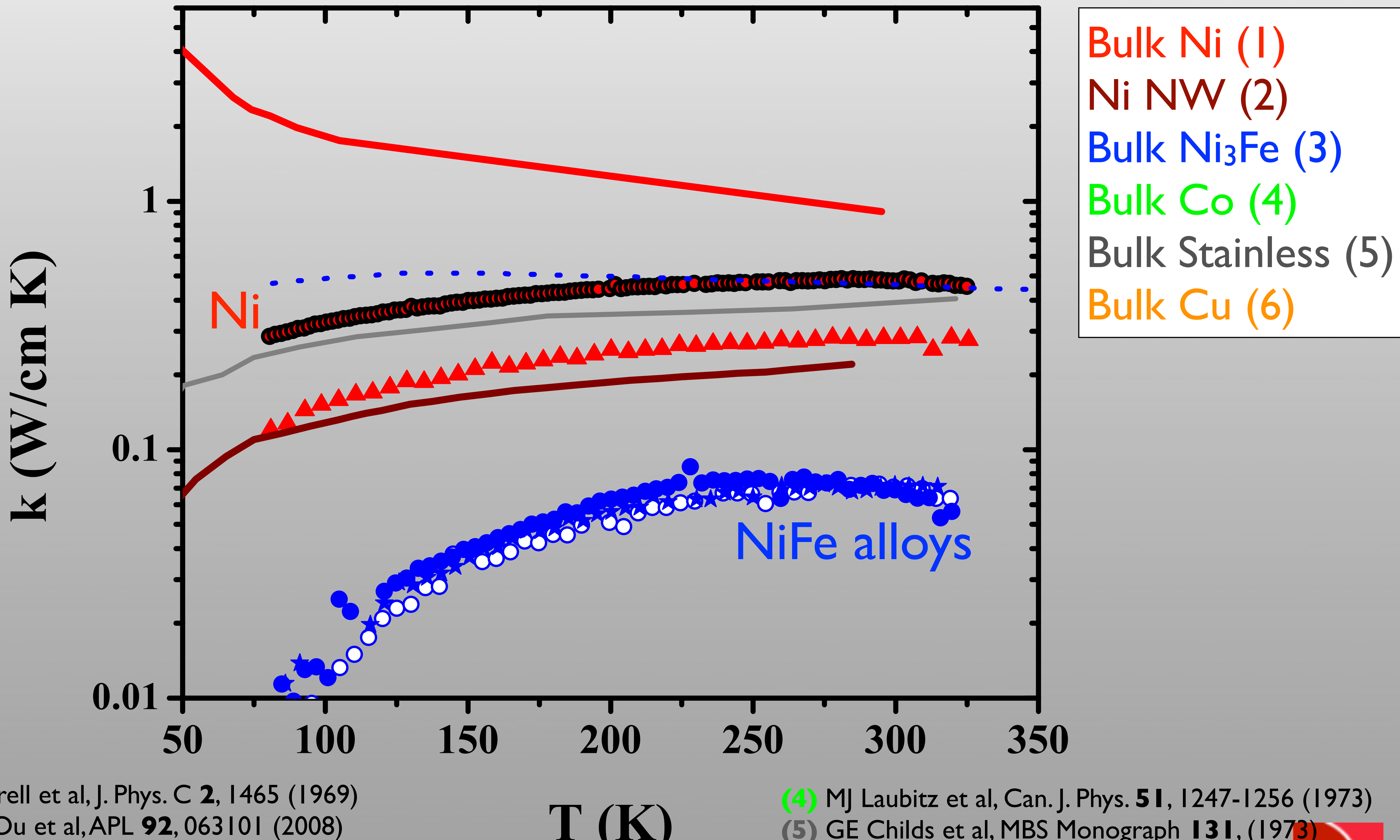
- measurement of k, α and σ on the SAME sample

Closer look at k for films near RT

First step toward thermoelectric, thermal spin current measurements in nanostructures? → k and TEP on films



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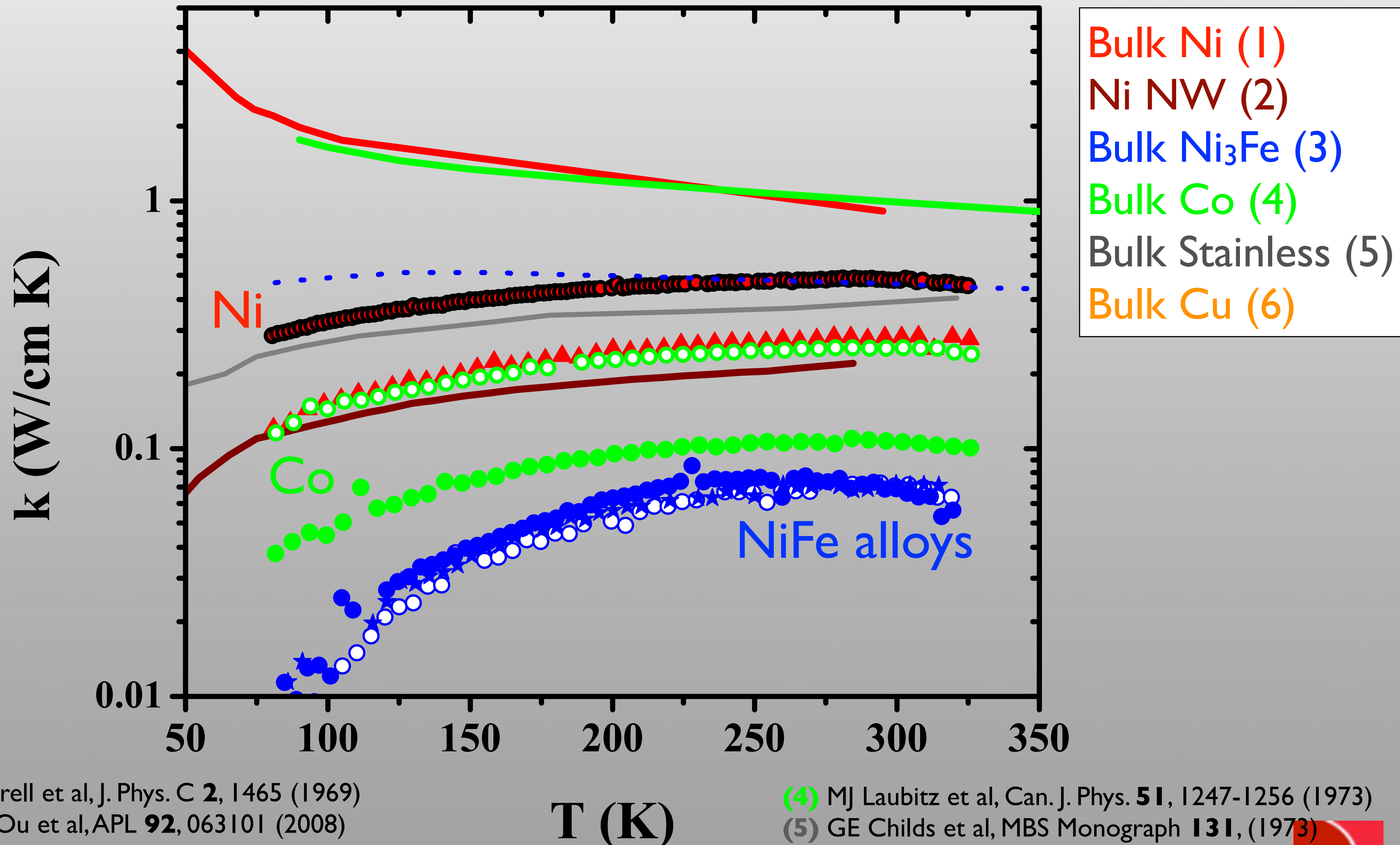

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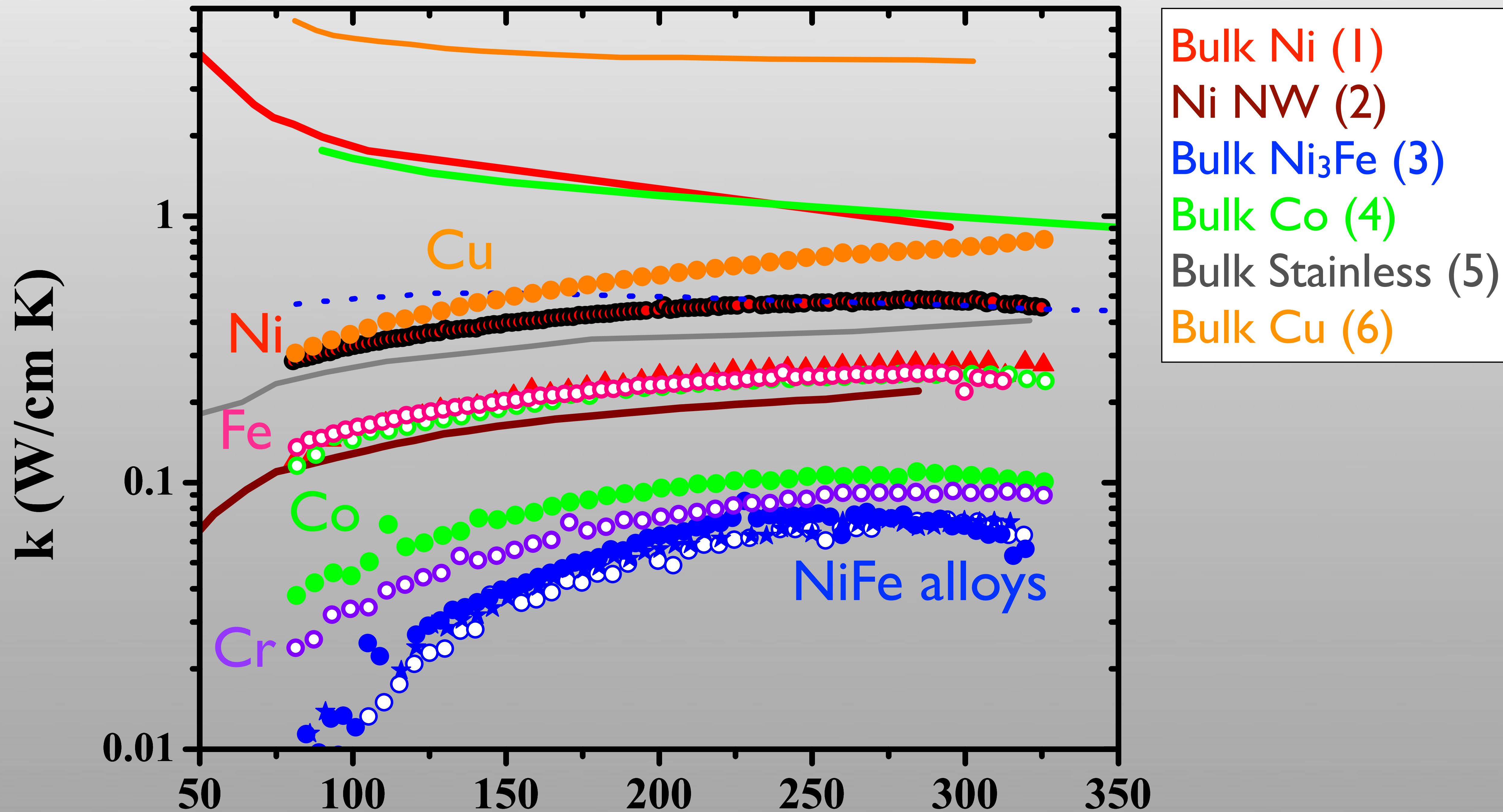

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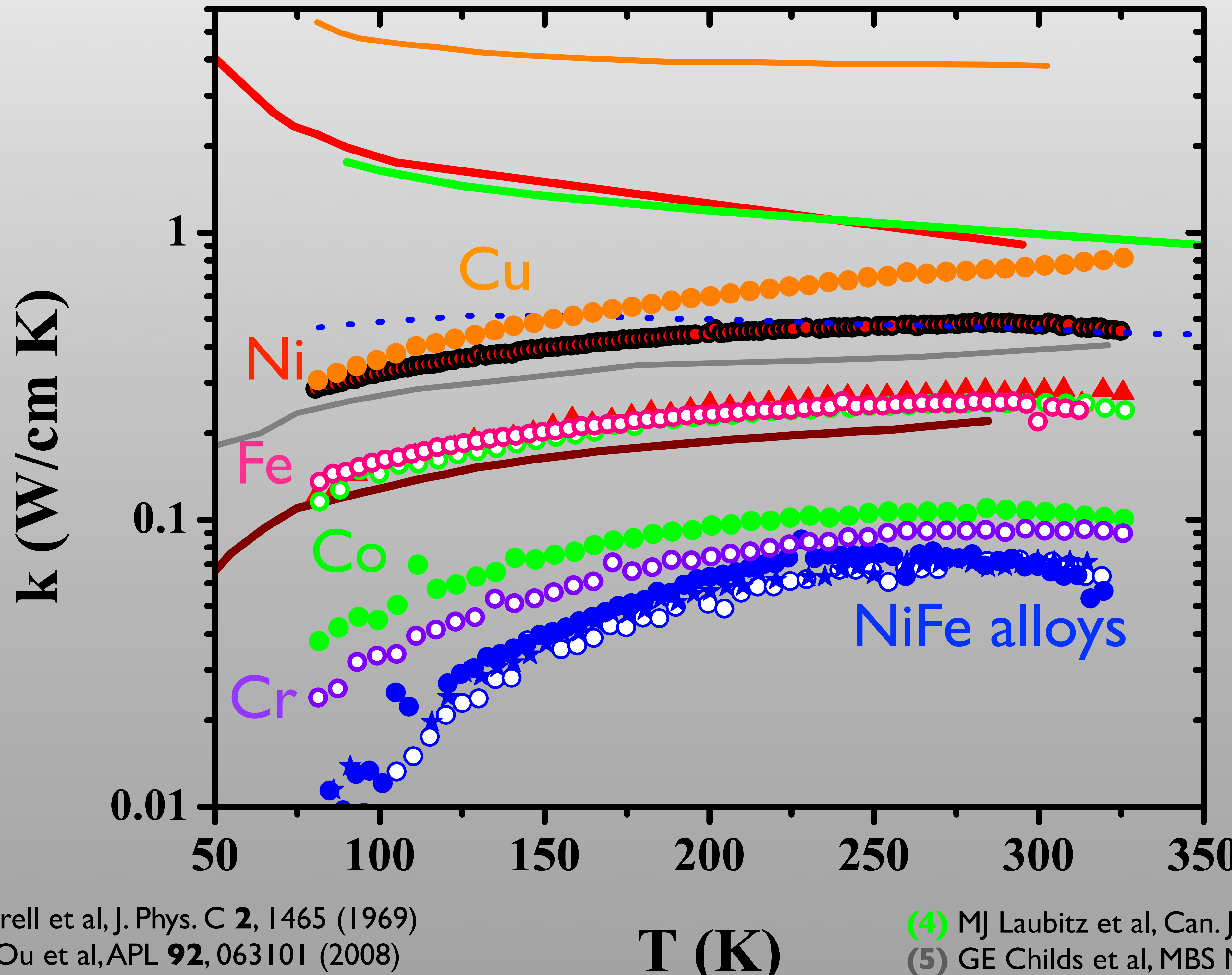

Bulk Ni (1)
Ni NW (2)
Bulk Ni_3Fe (3)
Bulk Co (4)
Bulk Stainless (5)
Bulk Cu (6)

ρ (μΩ cm)

Cu 1.7
Co 6.0
Ni 7.2
Fe 10
Cr 12.8

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- In clean bulk materials, breaks down for intermediate T
  - small q, "vertical" scattering relaxes thermal conduction but has little effect on electrical...
- Additional contributions to k can also cause apparent "violations"

Lorenz Number

Since we measure ρ and *k* on EXACTLY the same sample, examination of the Wiedemann-Franz law is simple

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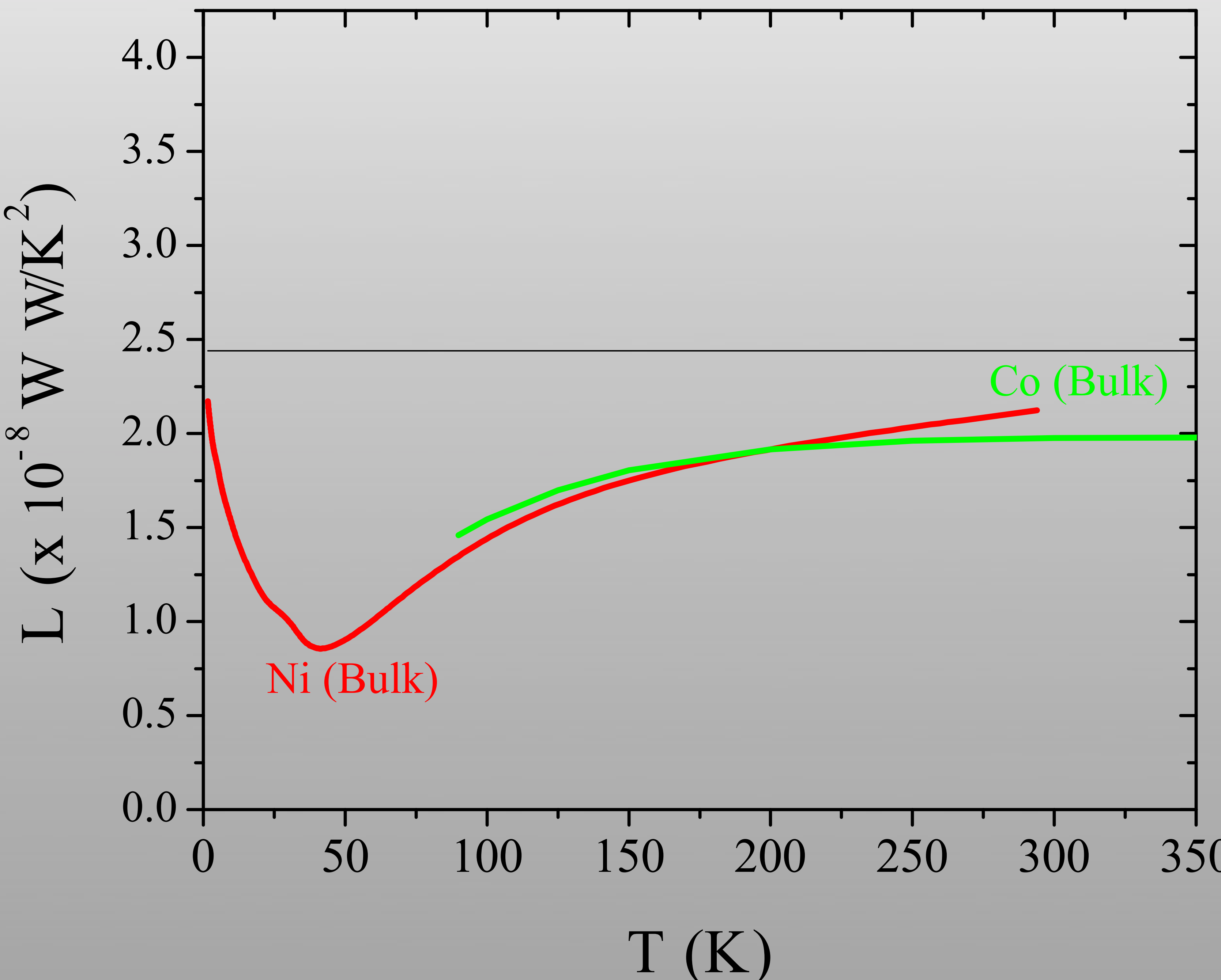
$$\boxed{L = \frac{K_{film} R_{film}}{T}}$$



Ni NW: M. N. Ou, et al., *APL* **92**, 063101 (2008)
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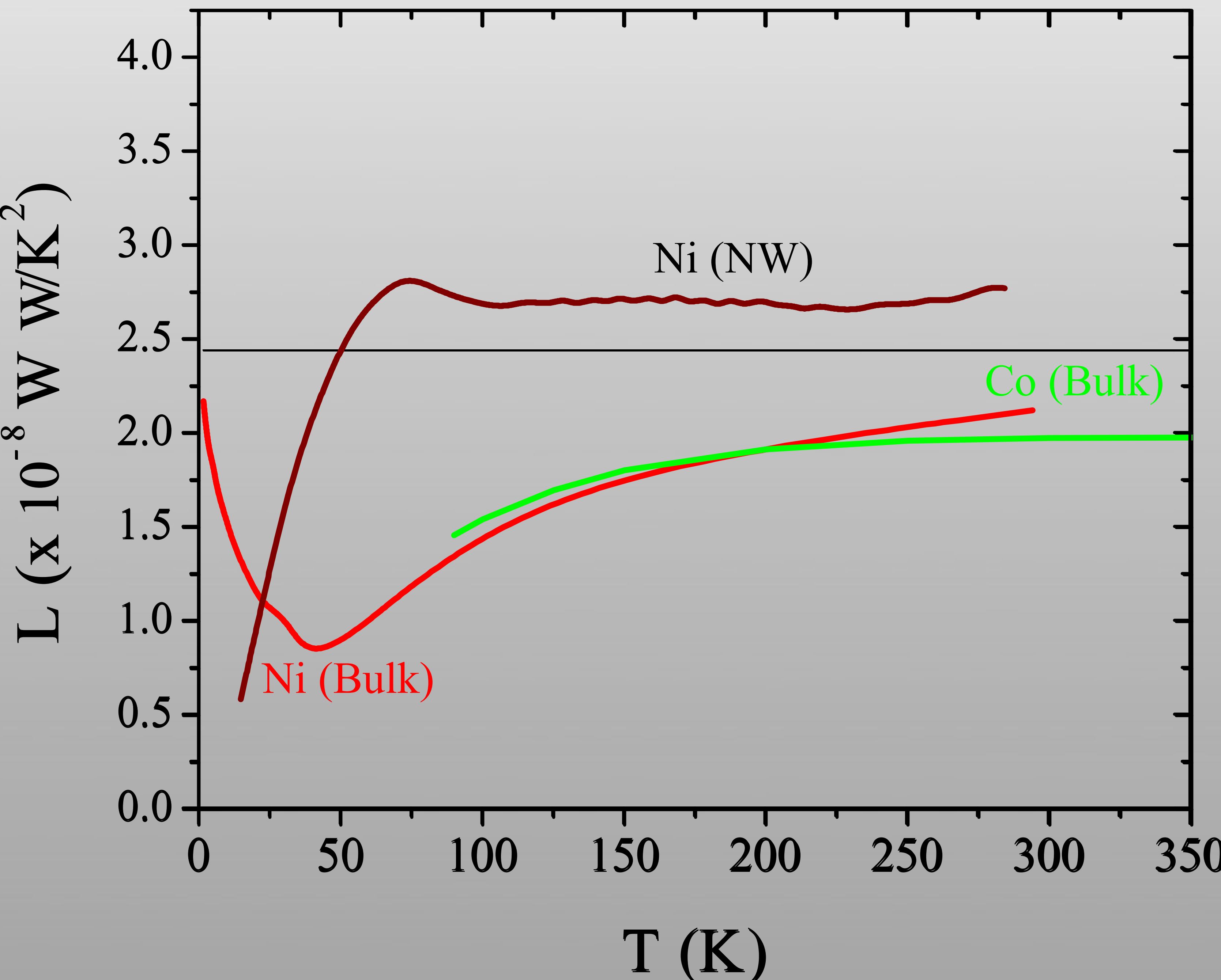

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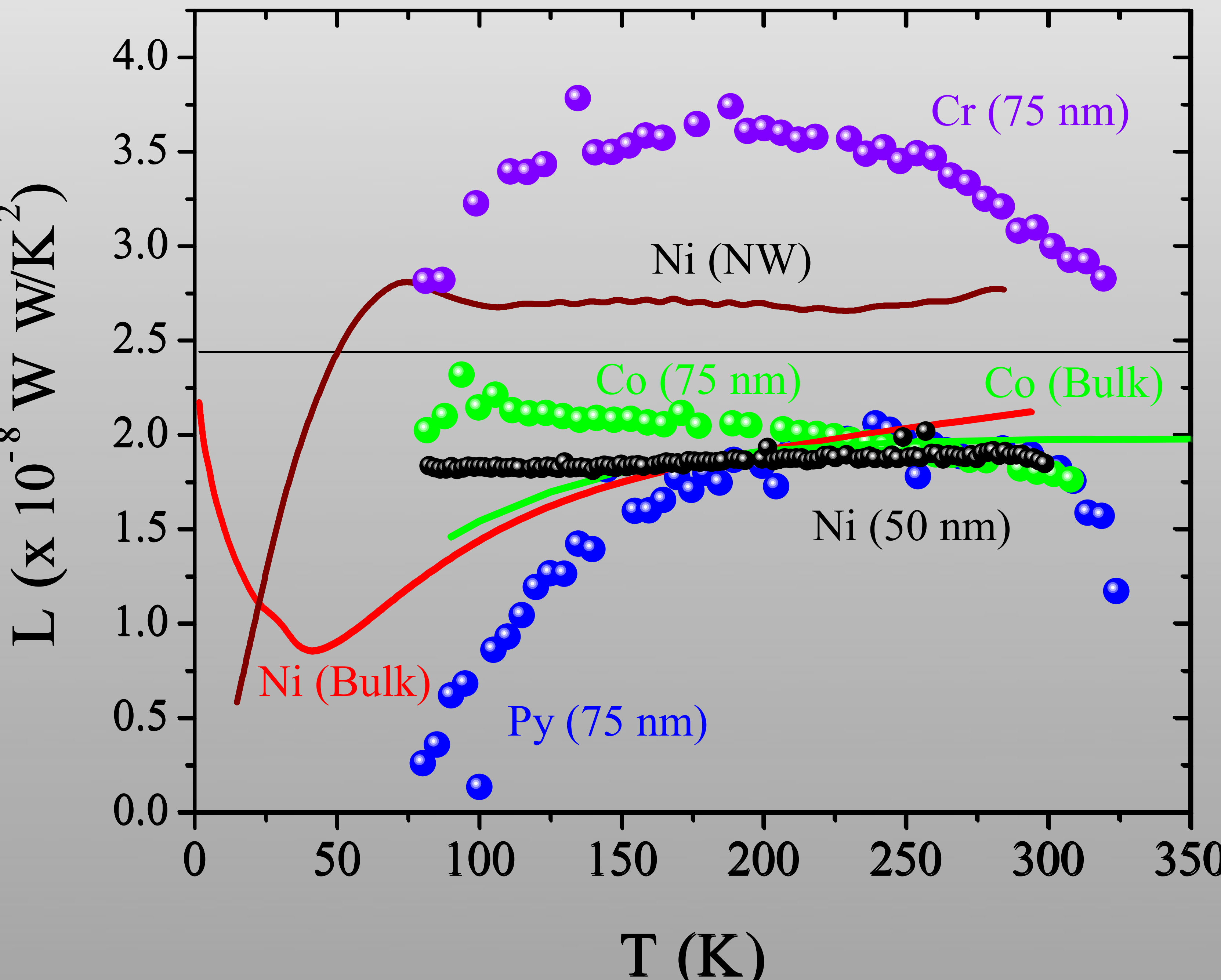

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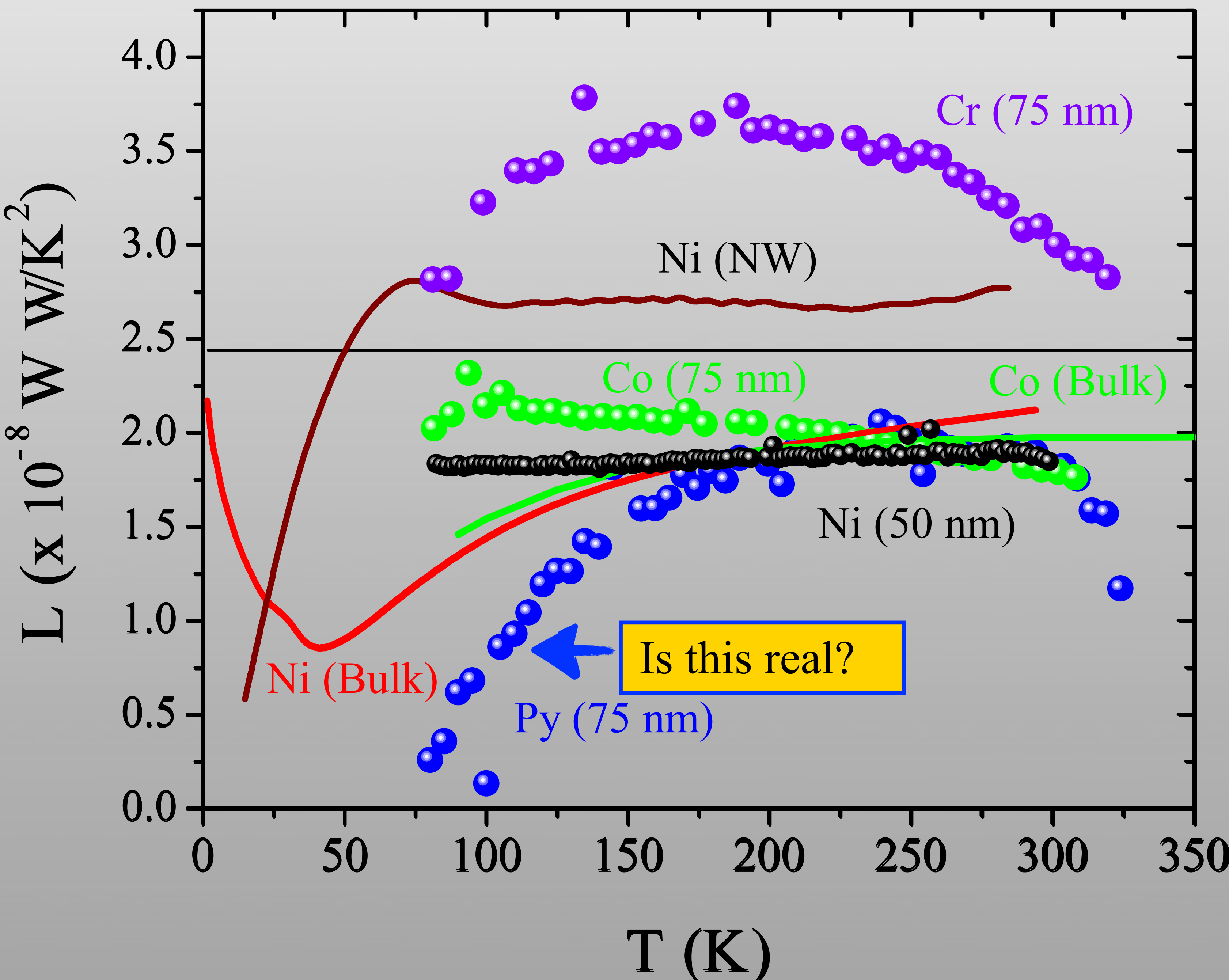

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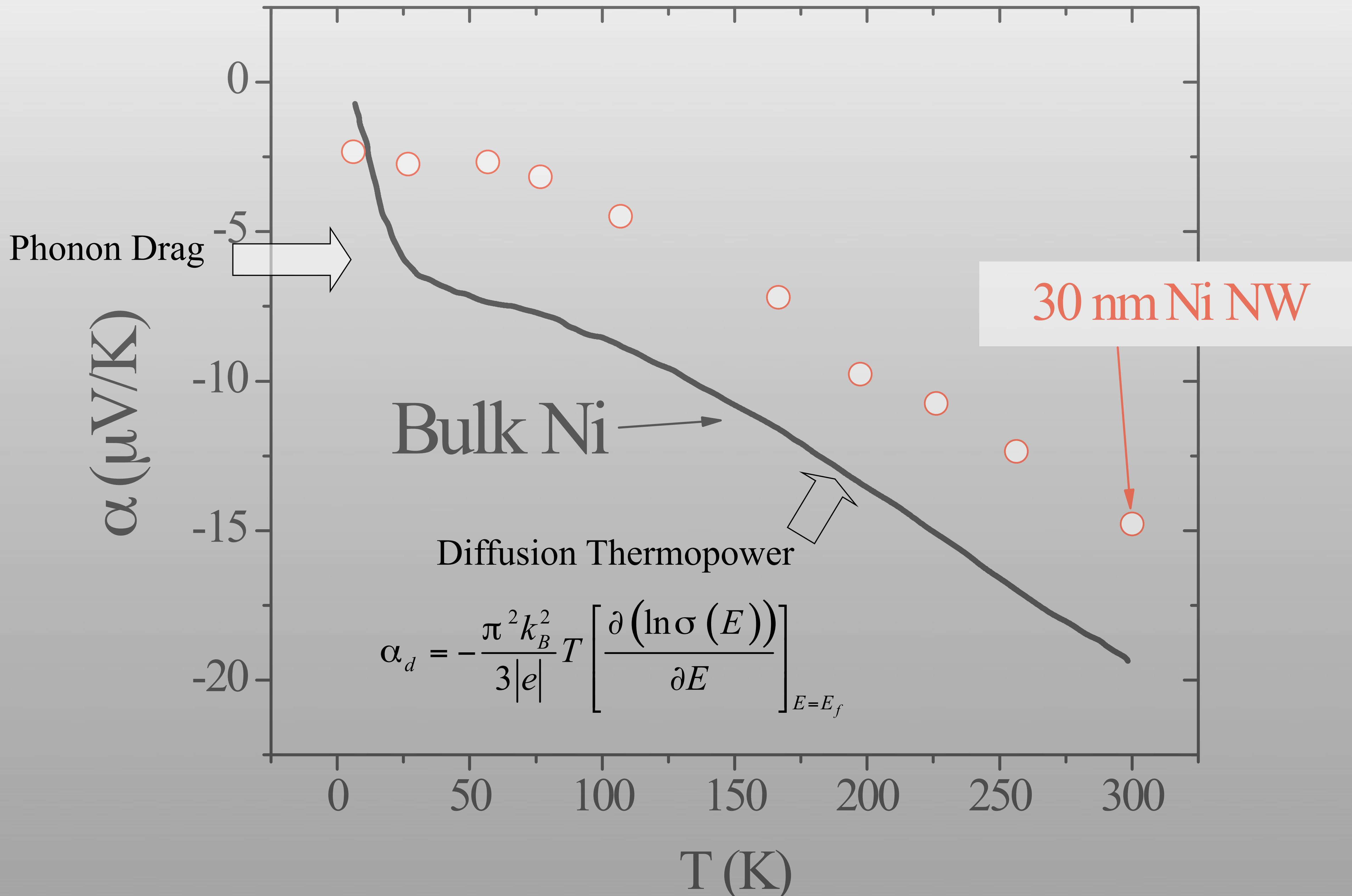
Thermopower



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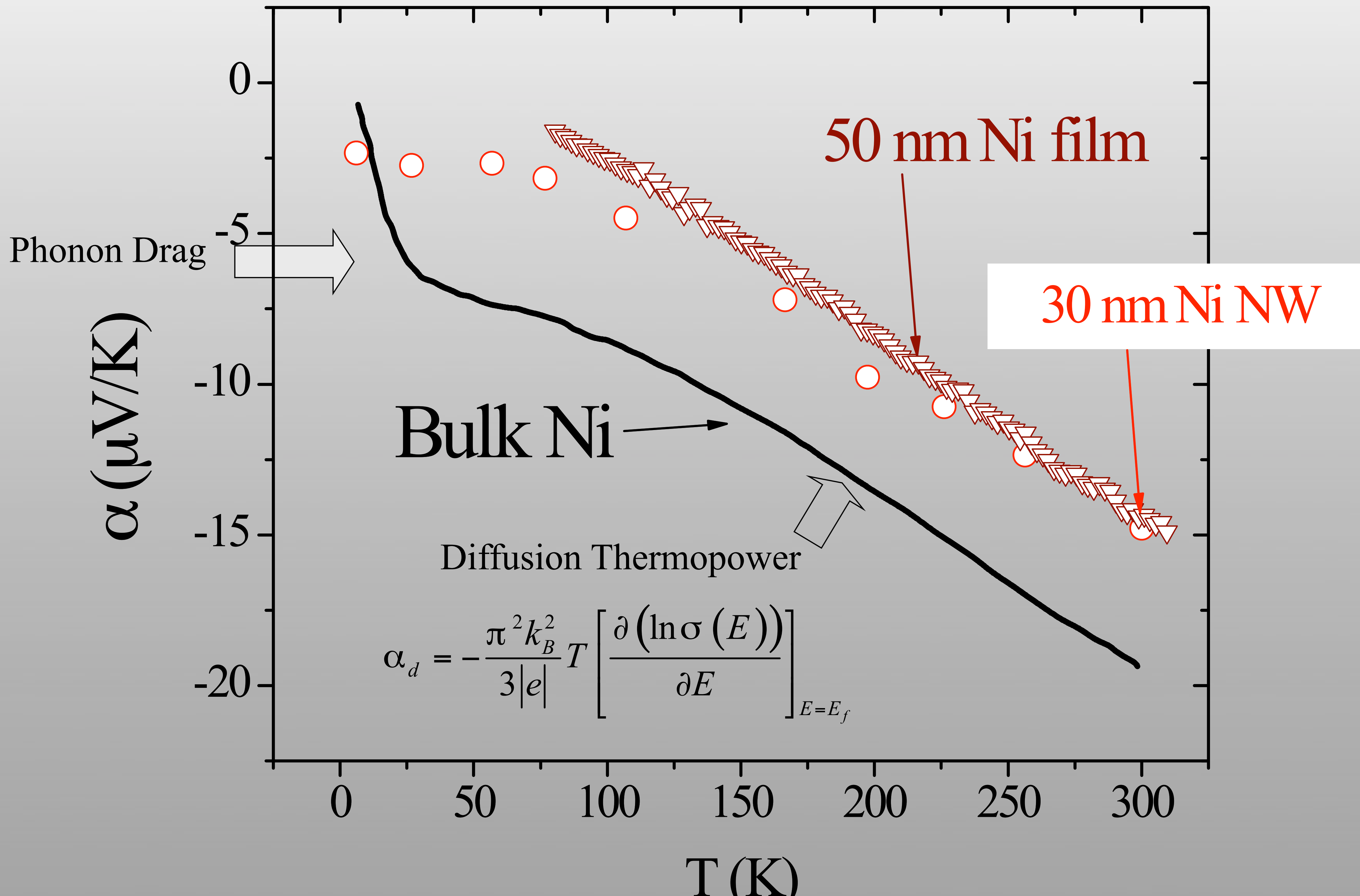

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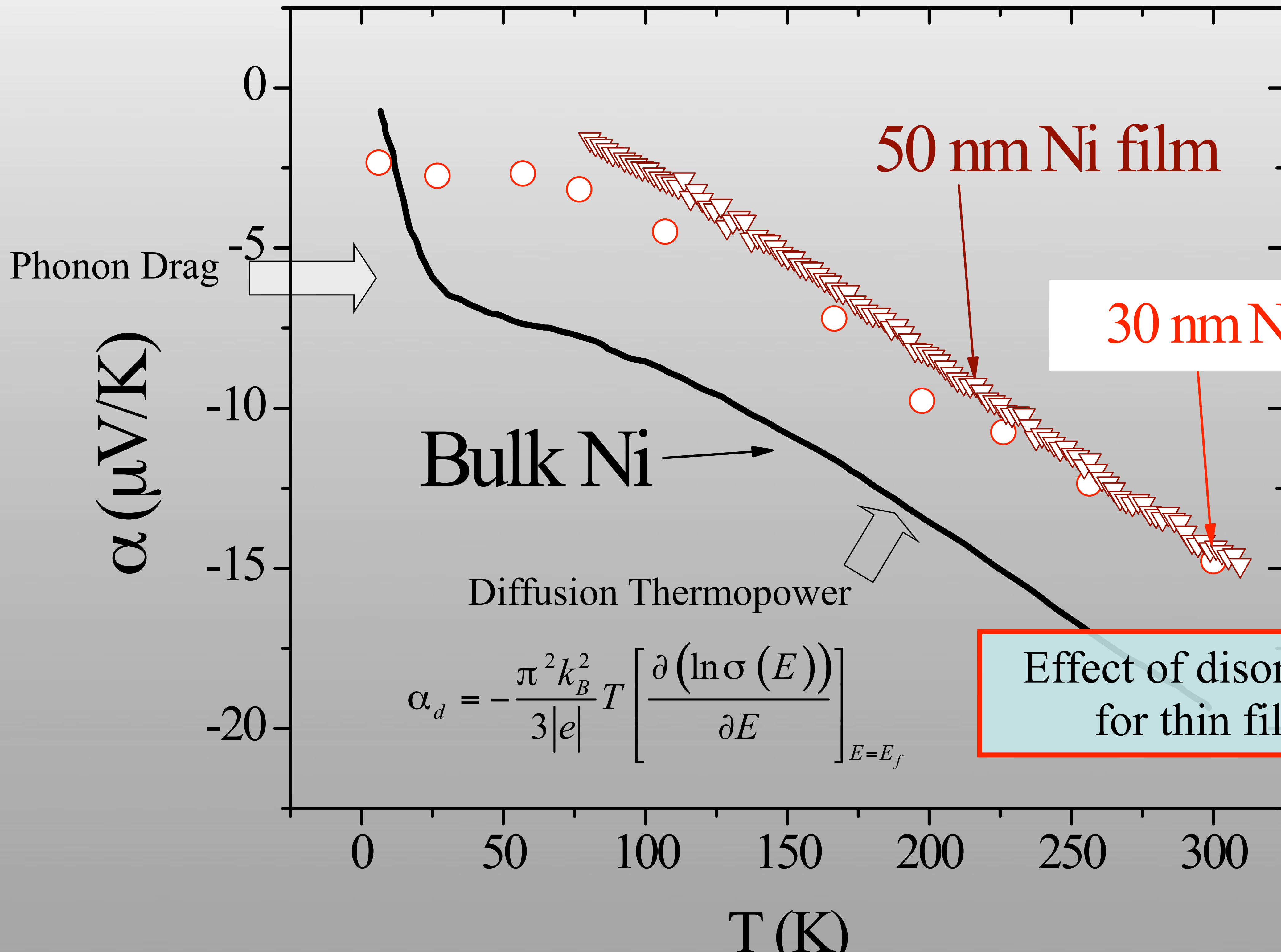

Effect of disorder ~ the same for thin film and NW

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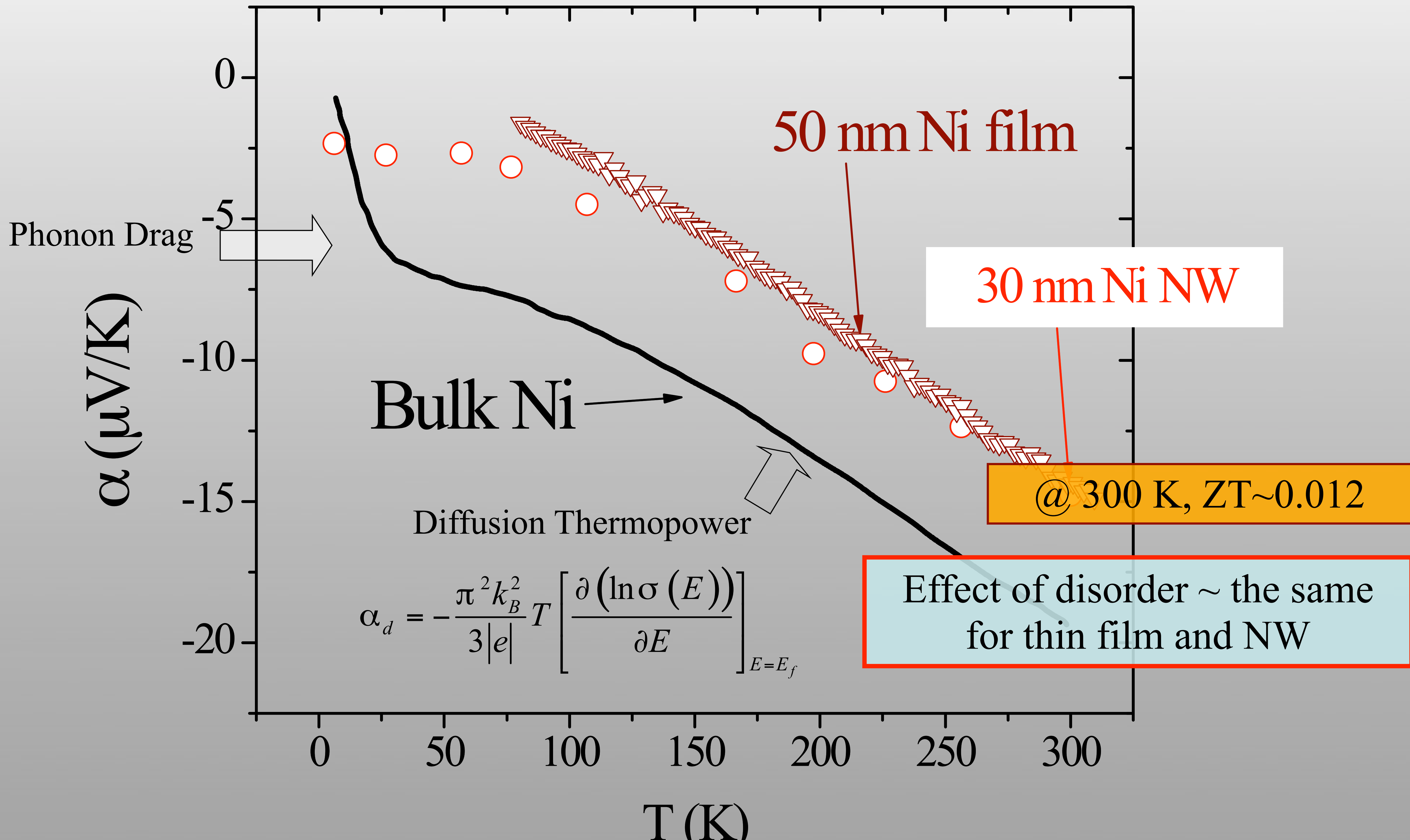

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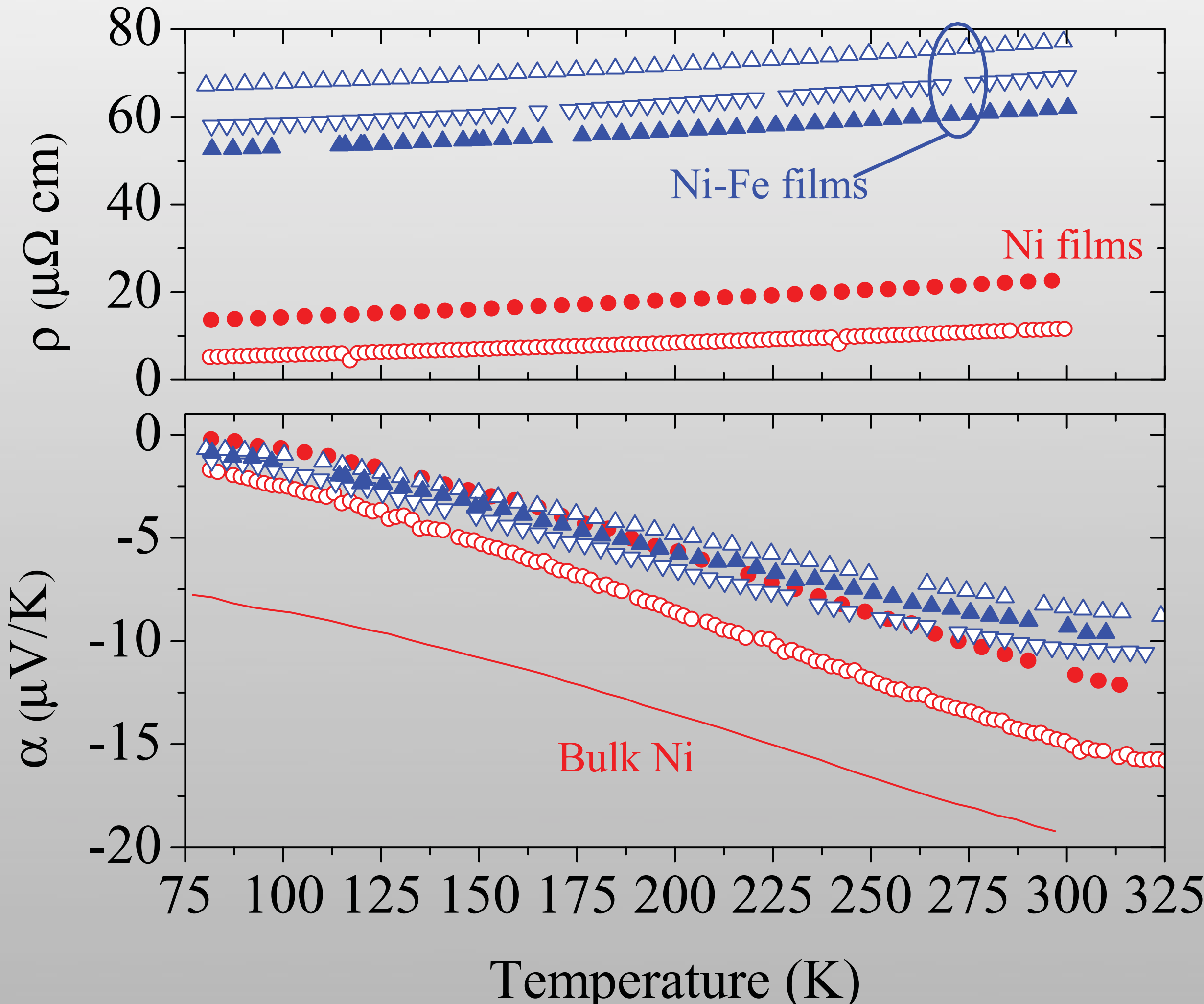
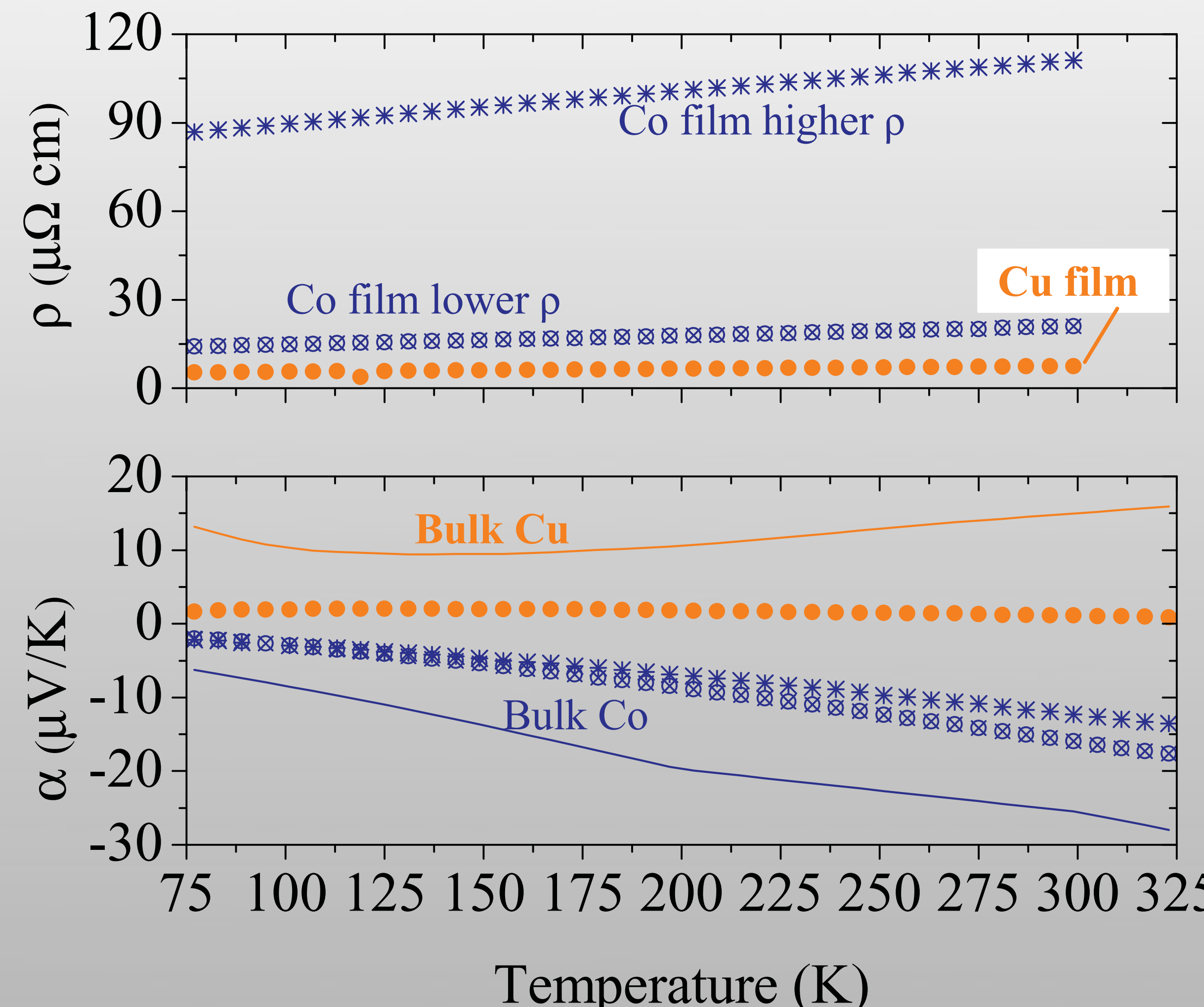
More Thermopower





- Sign of TEP matches bulk
- Disorder reduces TEP
  - correlates with film resistivity
- No Phonon Drag effects?

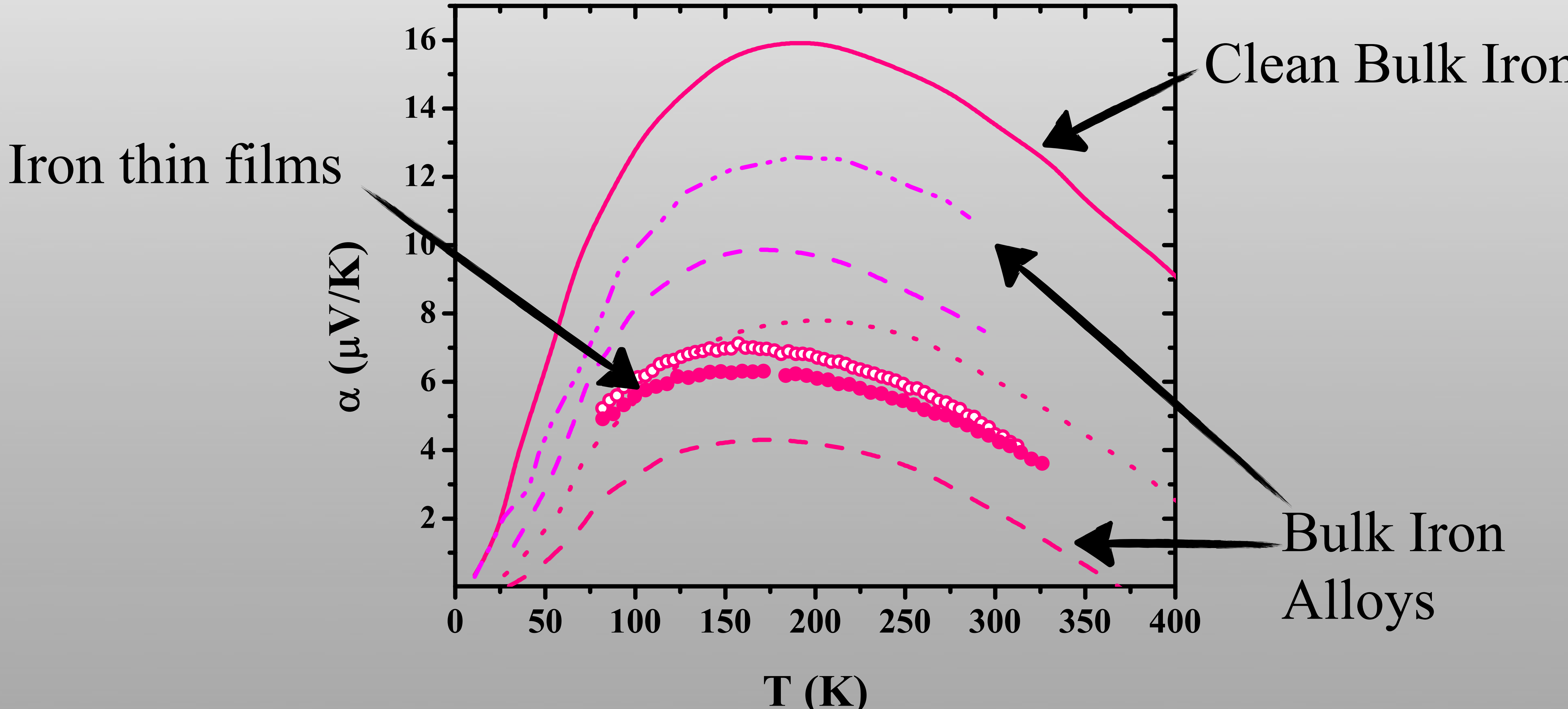
PHYSICAL REVIEW B **83**, 100401(R) (2011)

A. D. Avery, Rubina Sultan, D. Bassett, D. Wei, and B. L. Zink*

Department of Physics and Astronomy, University of Denver, Denver, Colorado 80208, USA

May 13, 2011

Electron-Magnon coupling leads to additional contribution to thermopower in Iron



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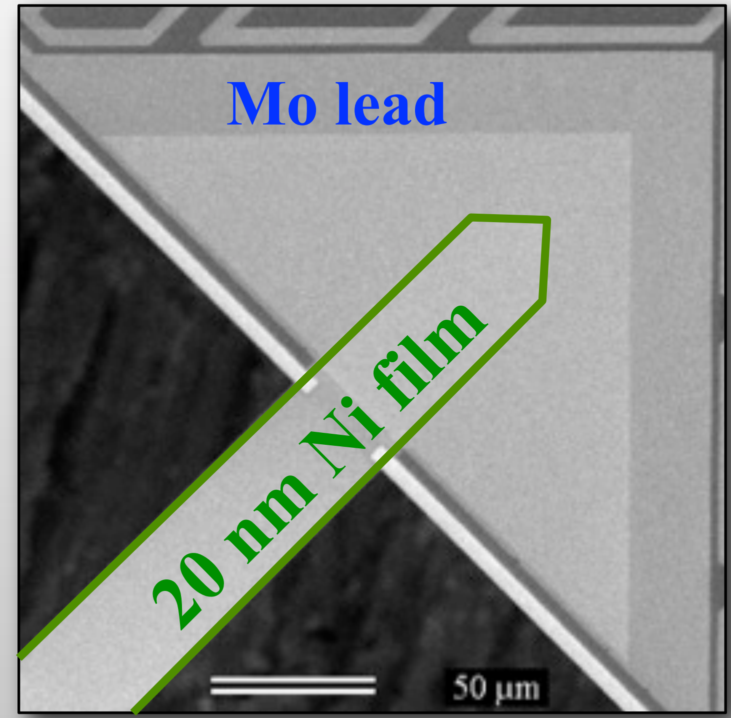
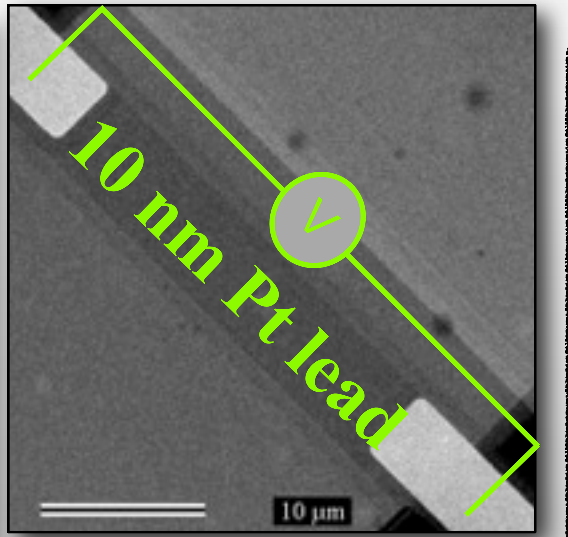
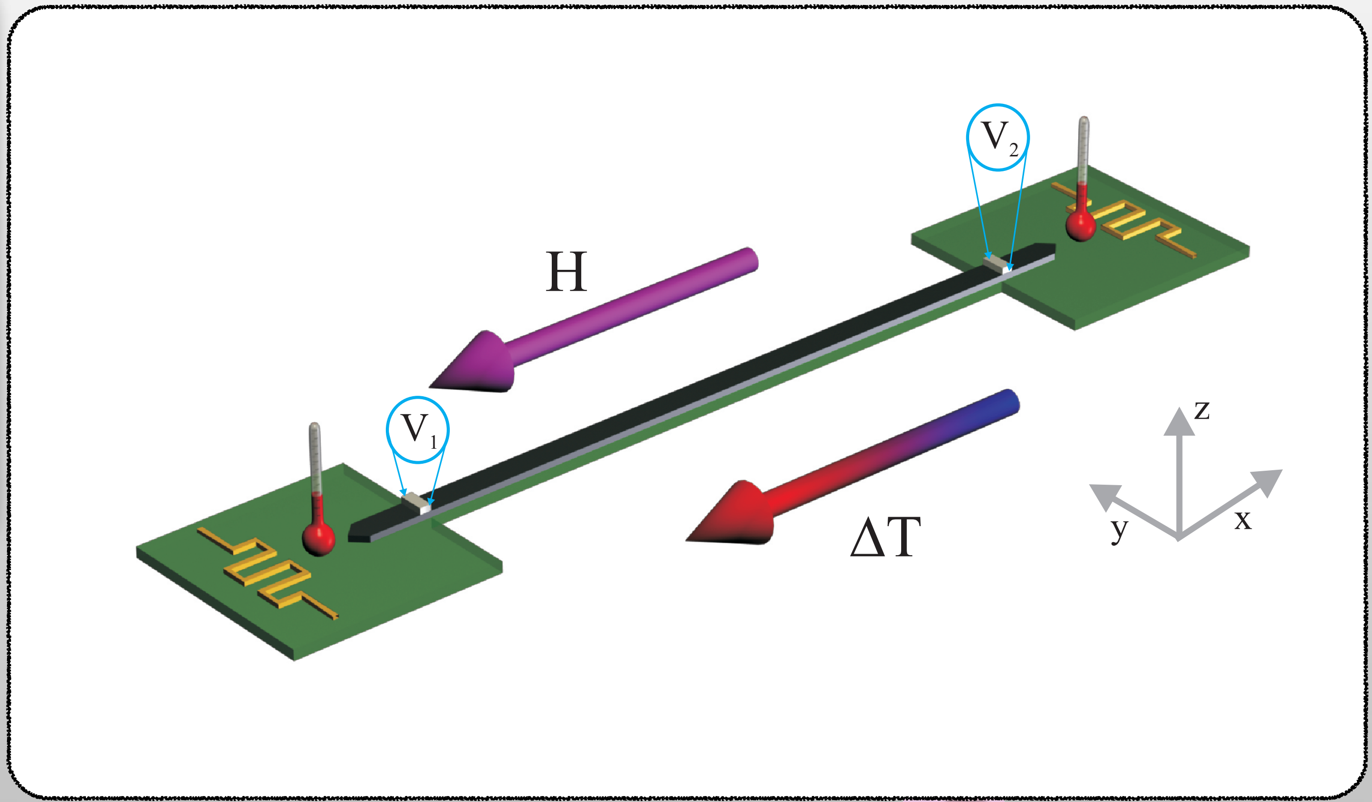
Thermal Platforms for Spin Seebeck Studies



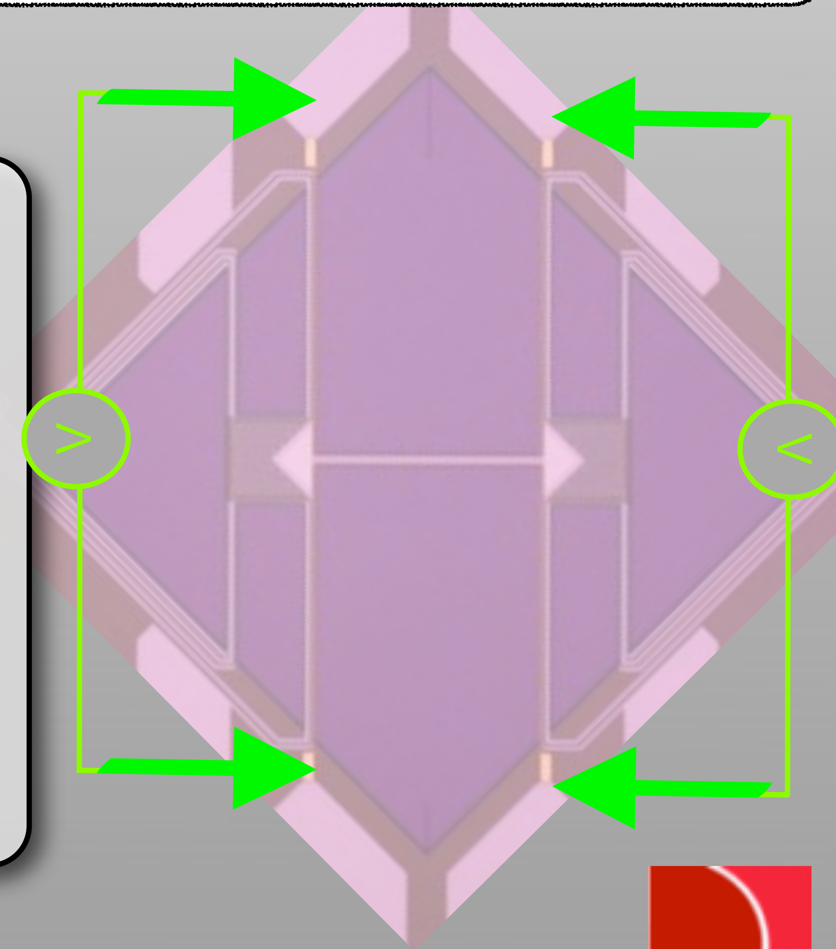




Thermal platforms were prepared with identical contacts using both Ni and Au films in order to test for background effects

Each island is fabricated with a Pt SSE detector, allowing concurrent voltage measurements and easy reversal of the thermal gradient.

The transverse voltage generated by the inverse spin Hall effect (*ISHE*) in response to I_s is measured across the Pt lead of the *SSE* detector.



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Thermal Platforms with ISHE Detectors

Advantages

- Excellent control and measurement of applied thermal gradients.
- Two Pt ISHE detectors allow concurrent measurement of the hot and cold ends of the sample, thermal gradient can be easily reversed

20 nm Ni Film

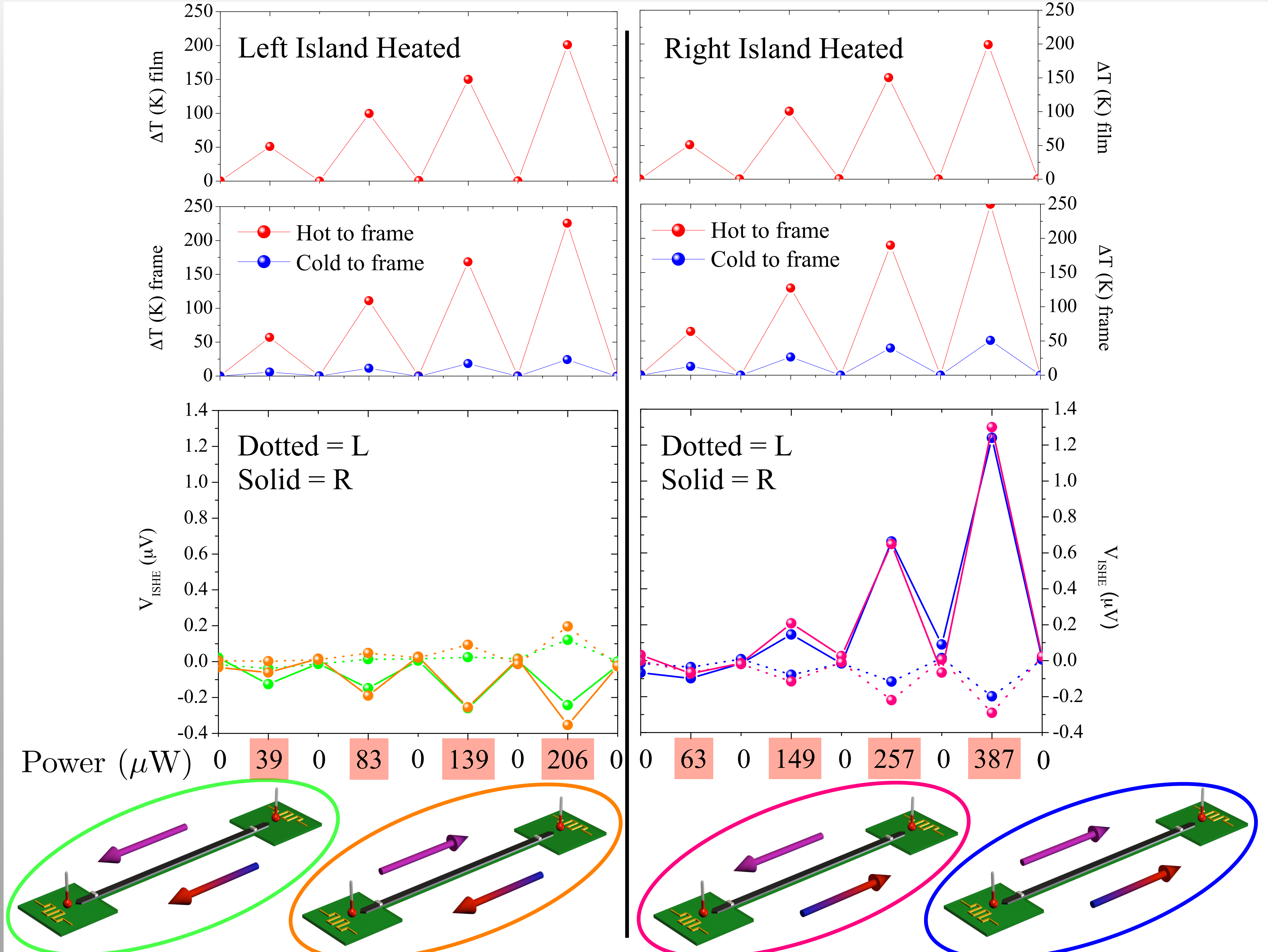
10 nm Pt Film

Challenges

- Due to process compatibility with various materials and interfaces, fabrication is more complicated (requires through-wafer etching in ICP-RIE Deep-trench Si etcher)
- Because the width of the Pt contact is smaller, signals expected to be smaller than the Saitoh experiments for the same thermal gradient (by 100x)
- Substrate is both low thermal *conductivity* (though higher than typical glass) and VERY low thermal *conductance*

20 nm Ti/Au Film

First Thermal Platform Data: Nickel



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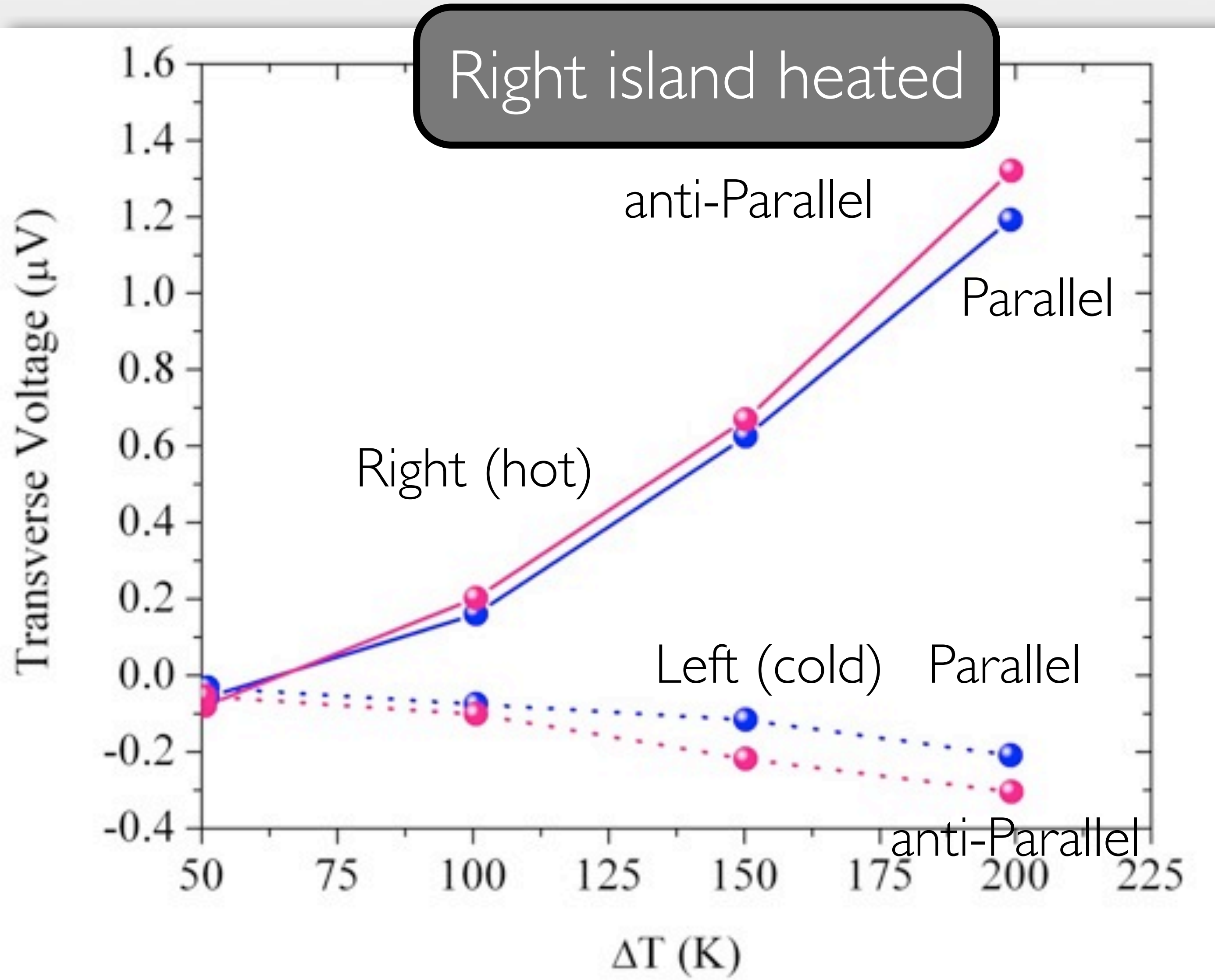

Parallel
Anti-parallel

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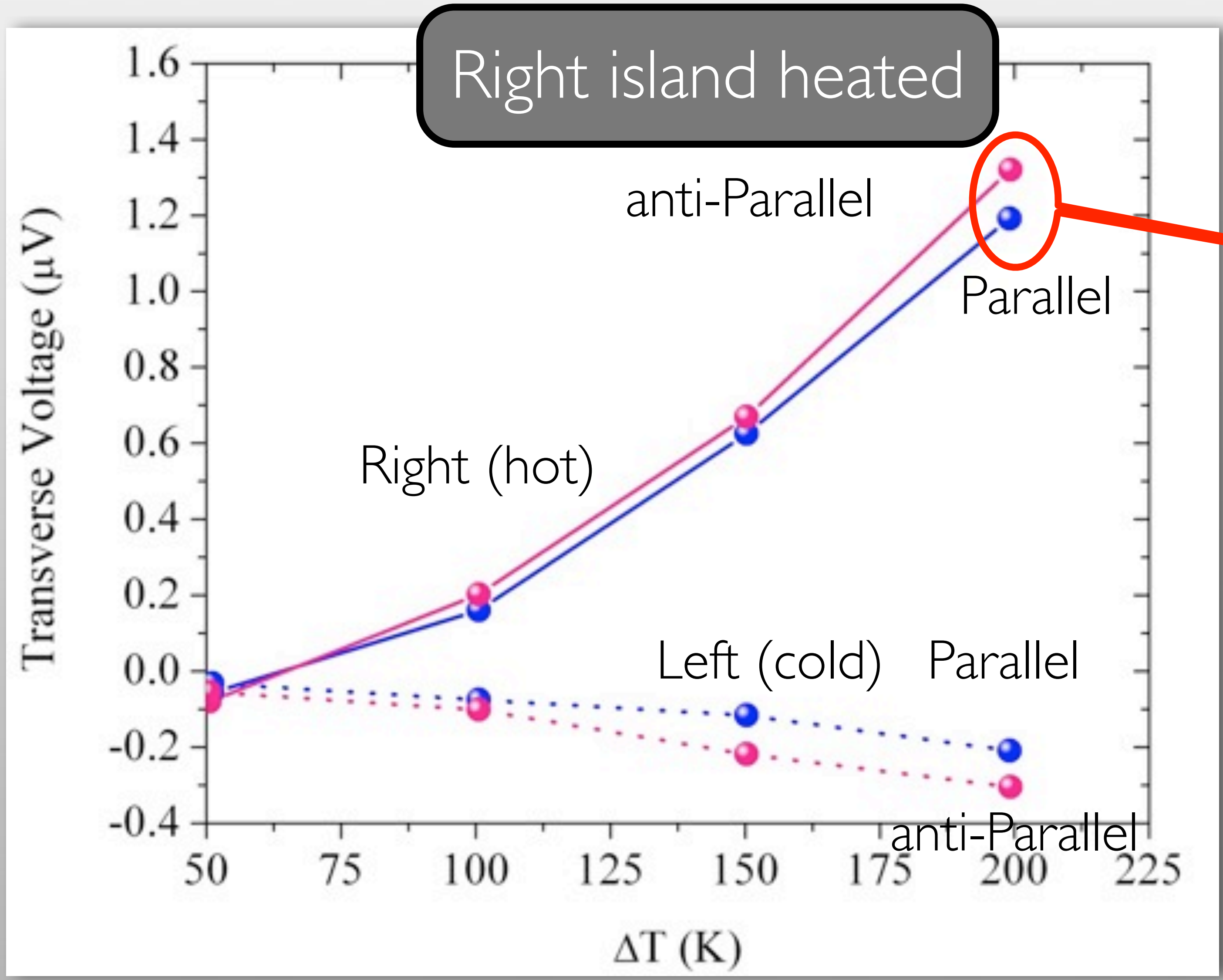

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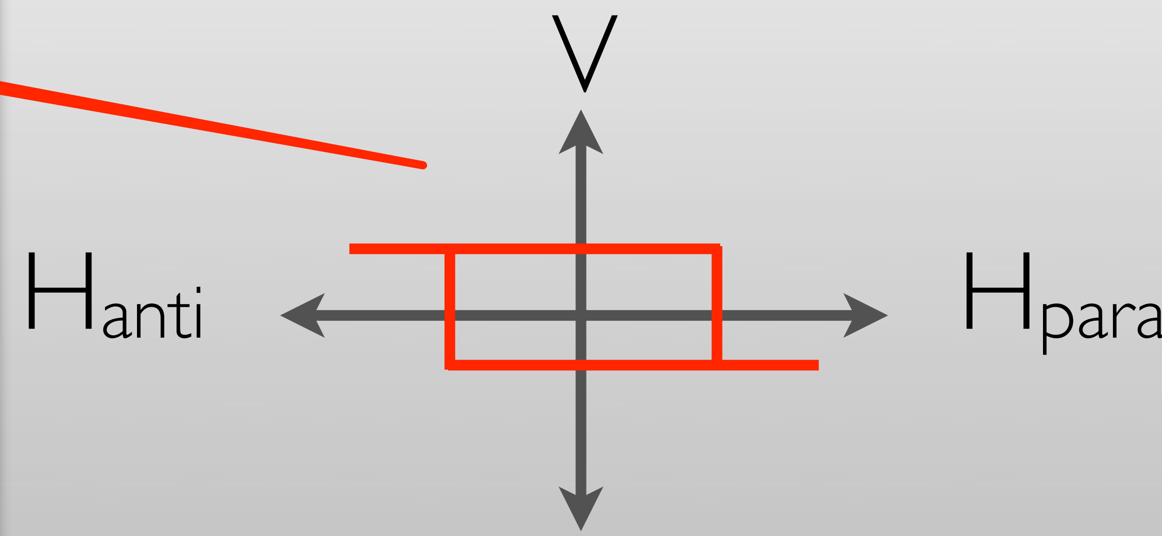

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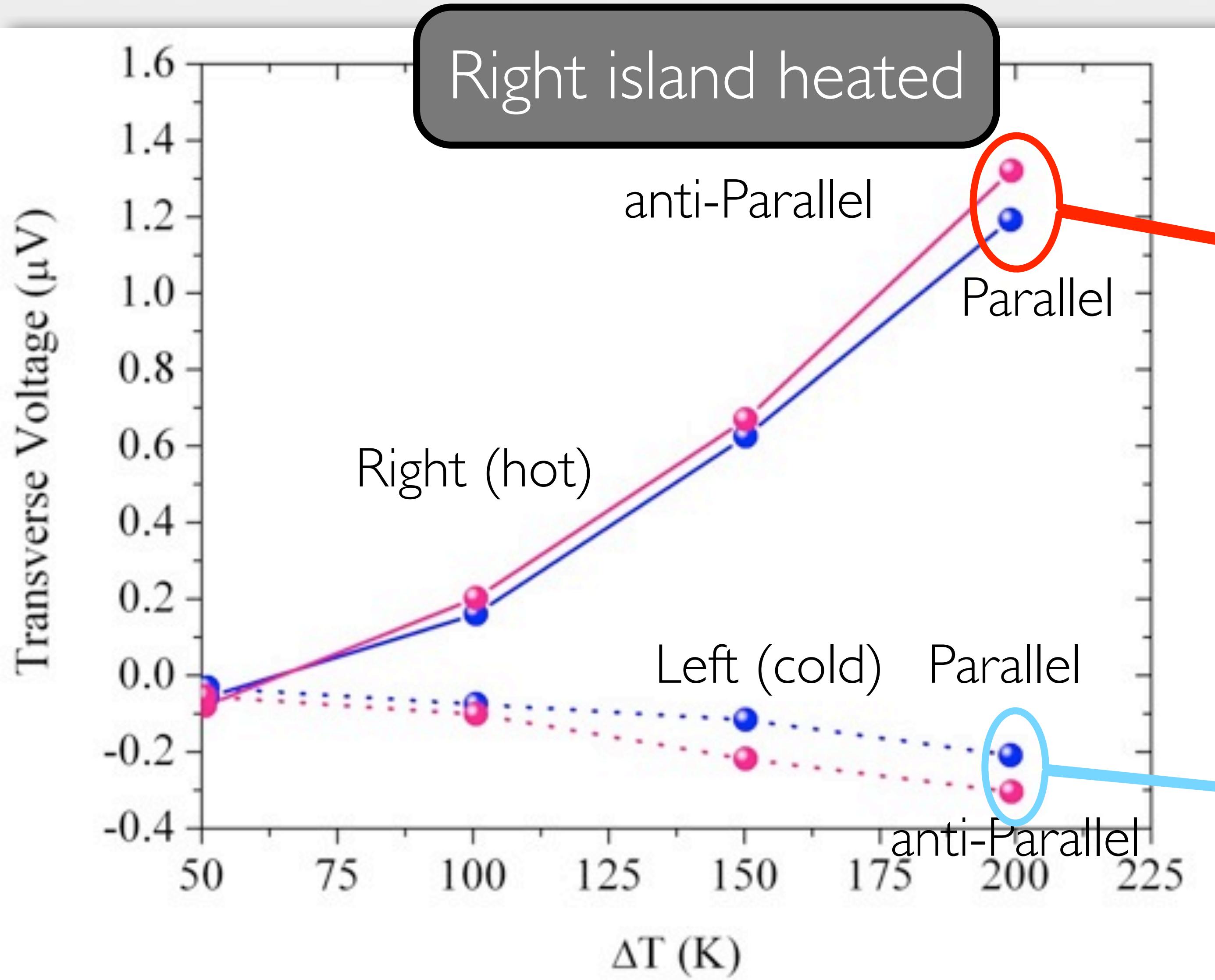

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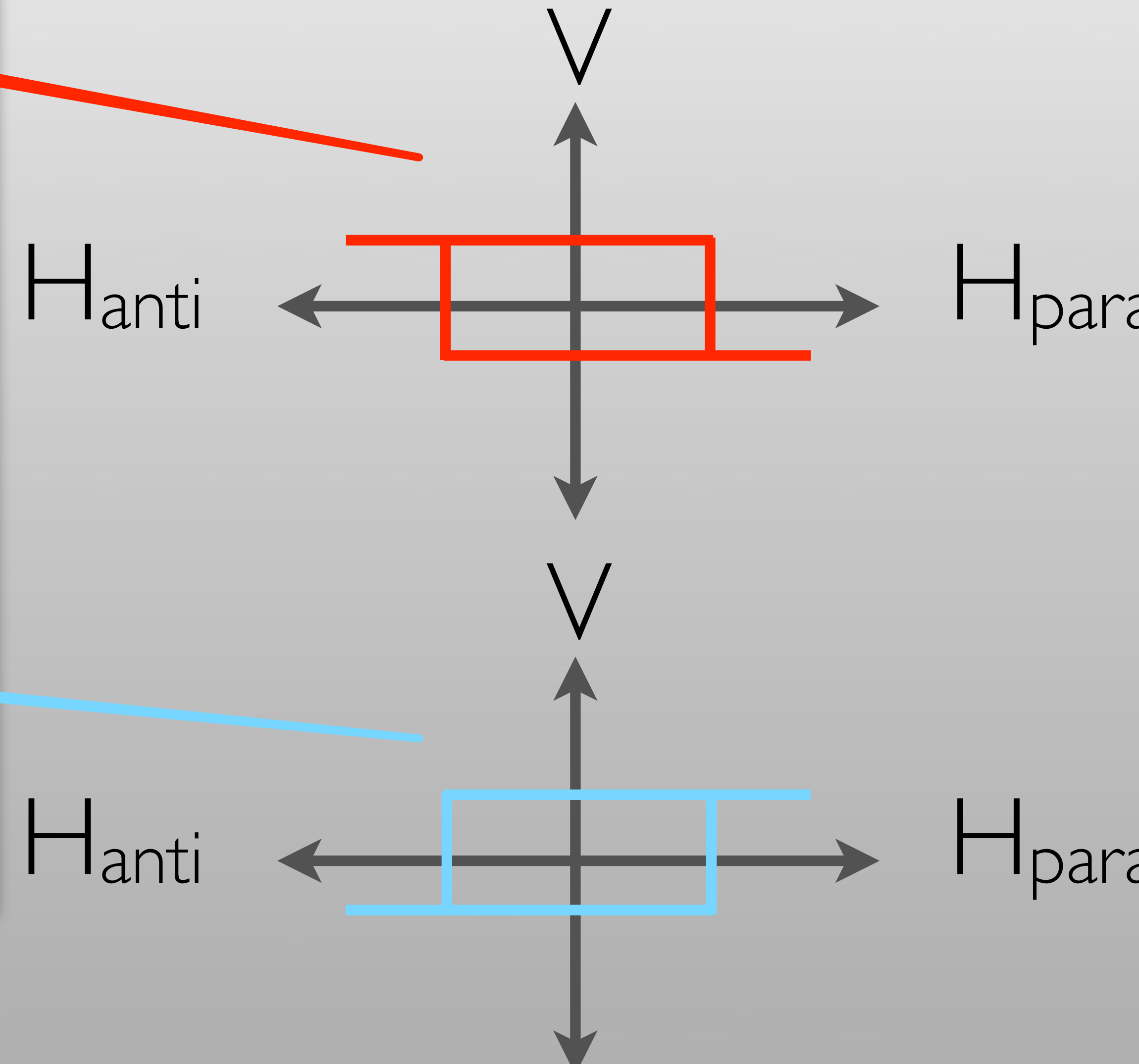

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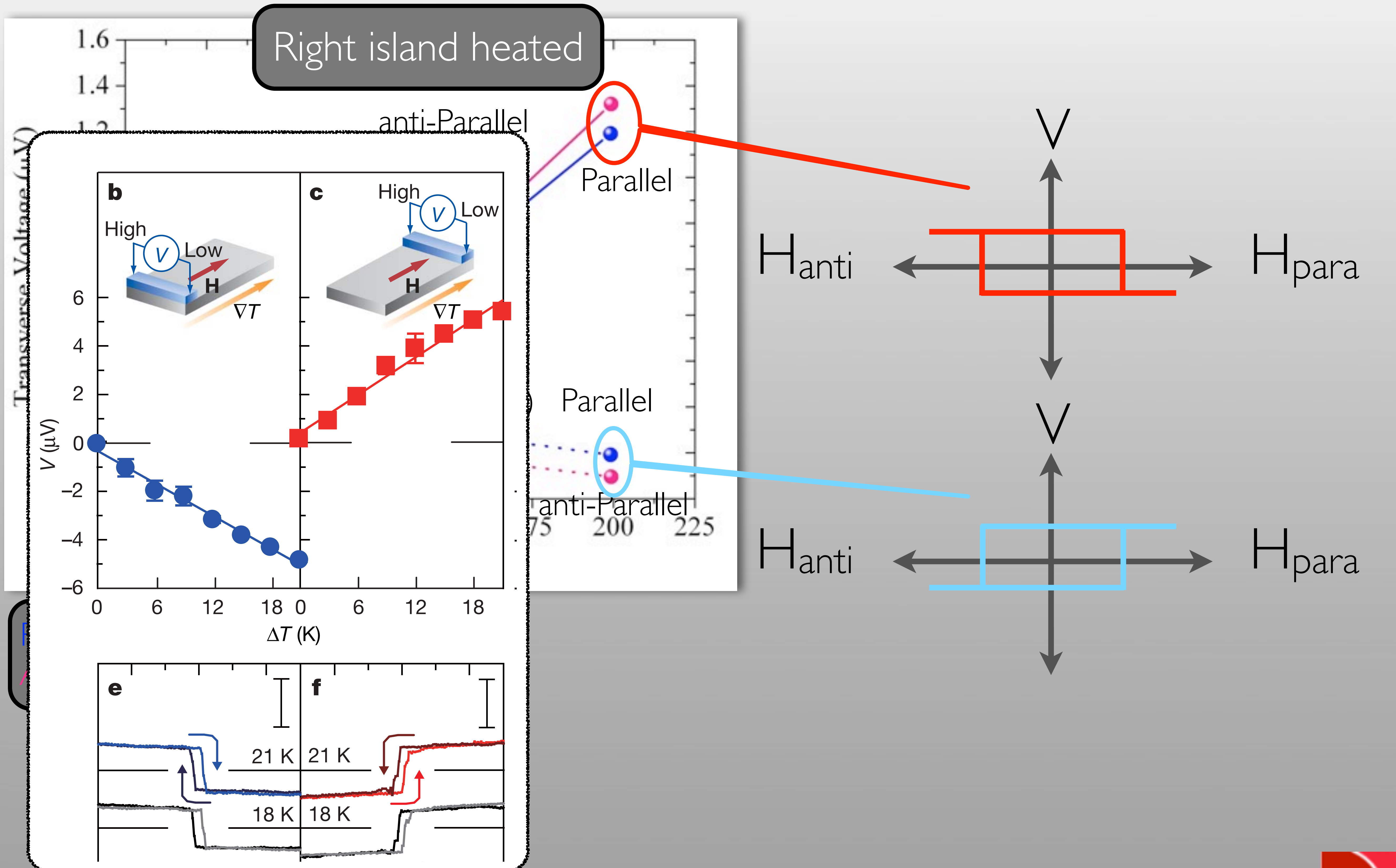

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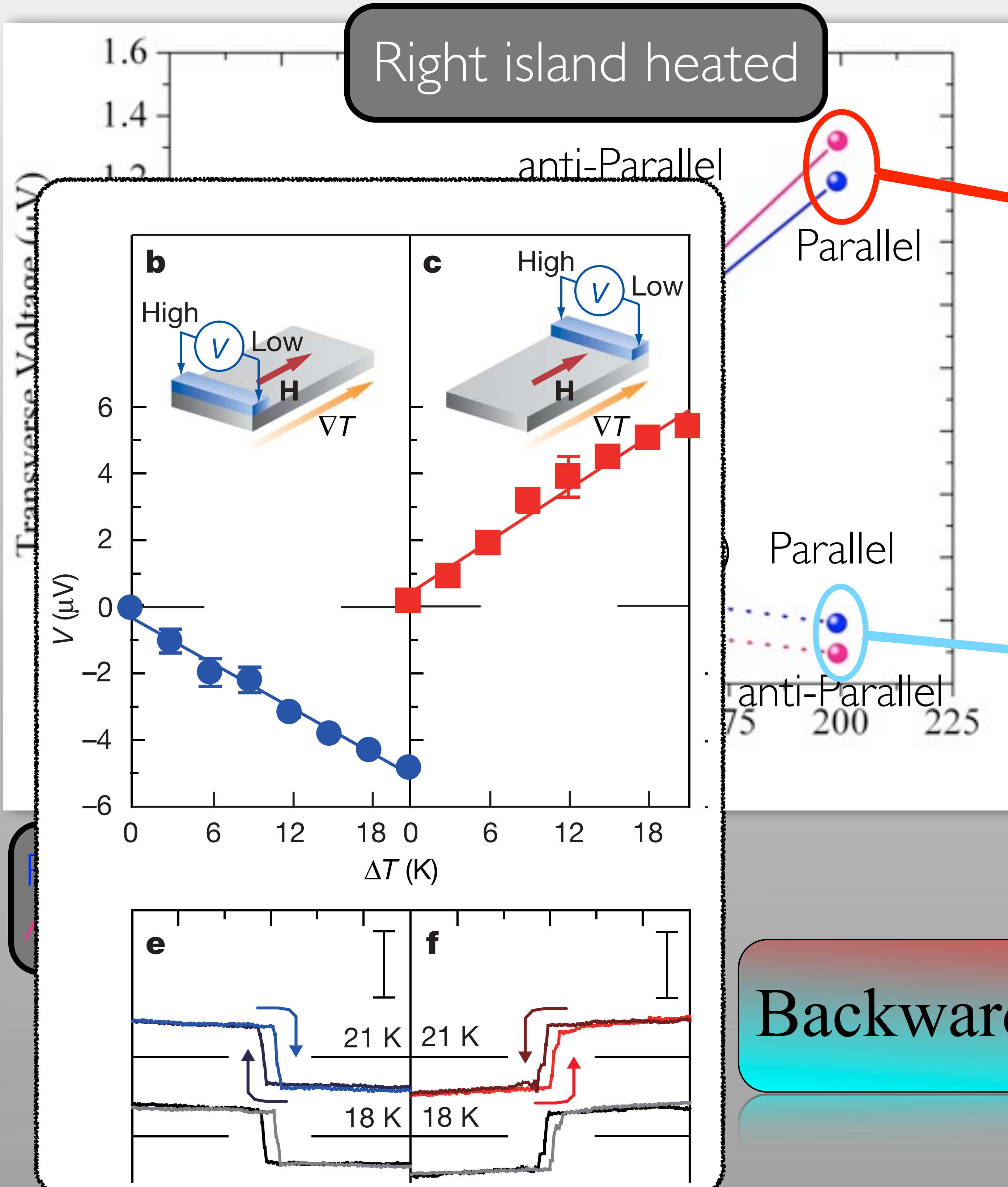

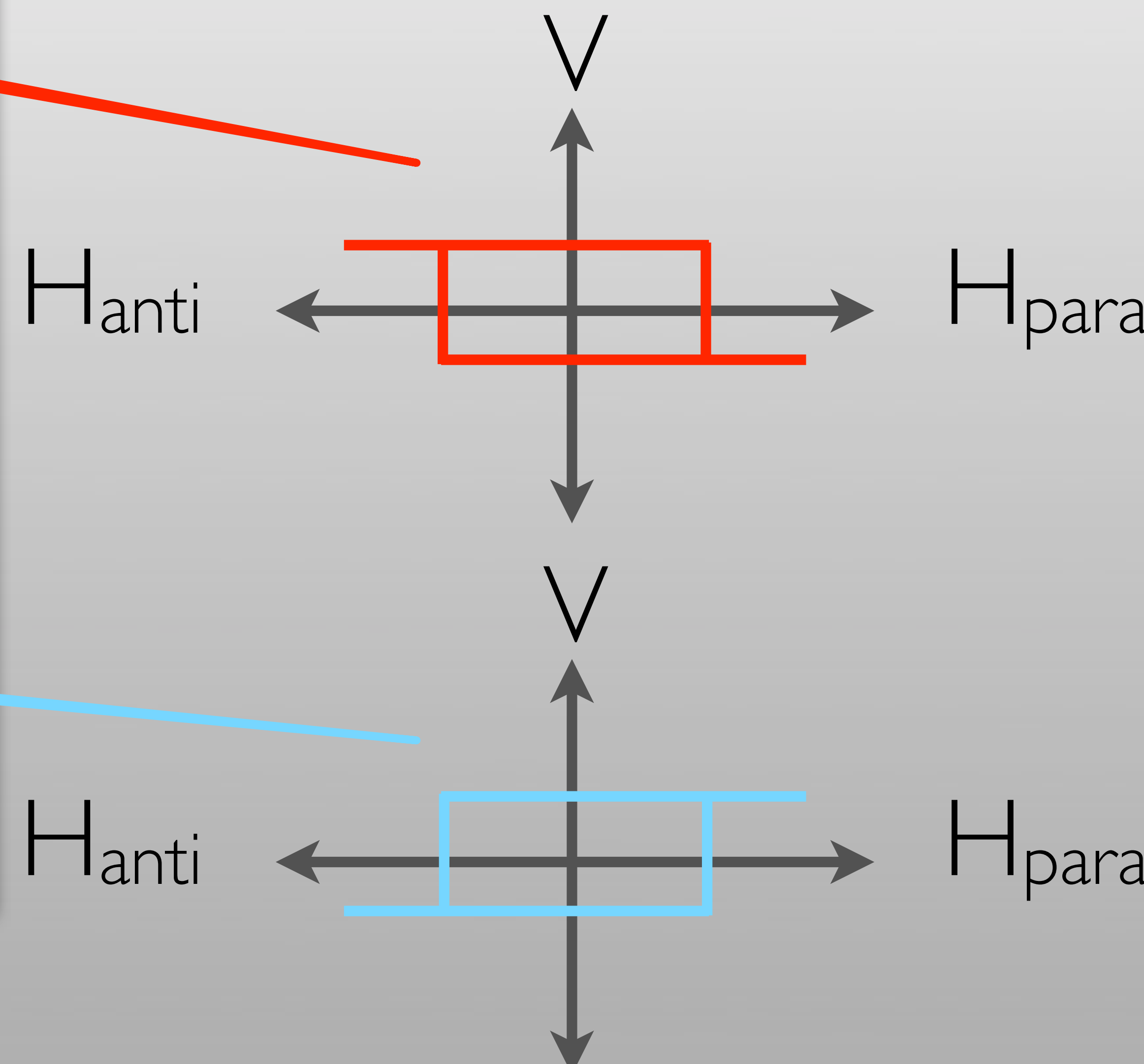

Backward from Uchida's original data.

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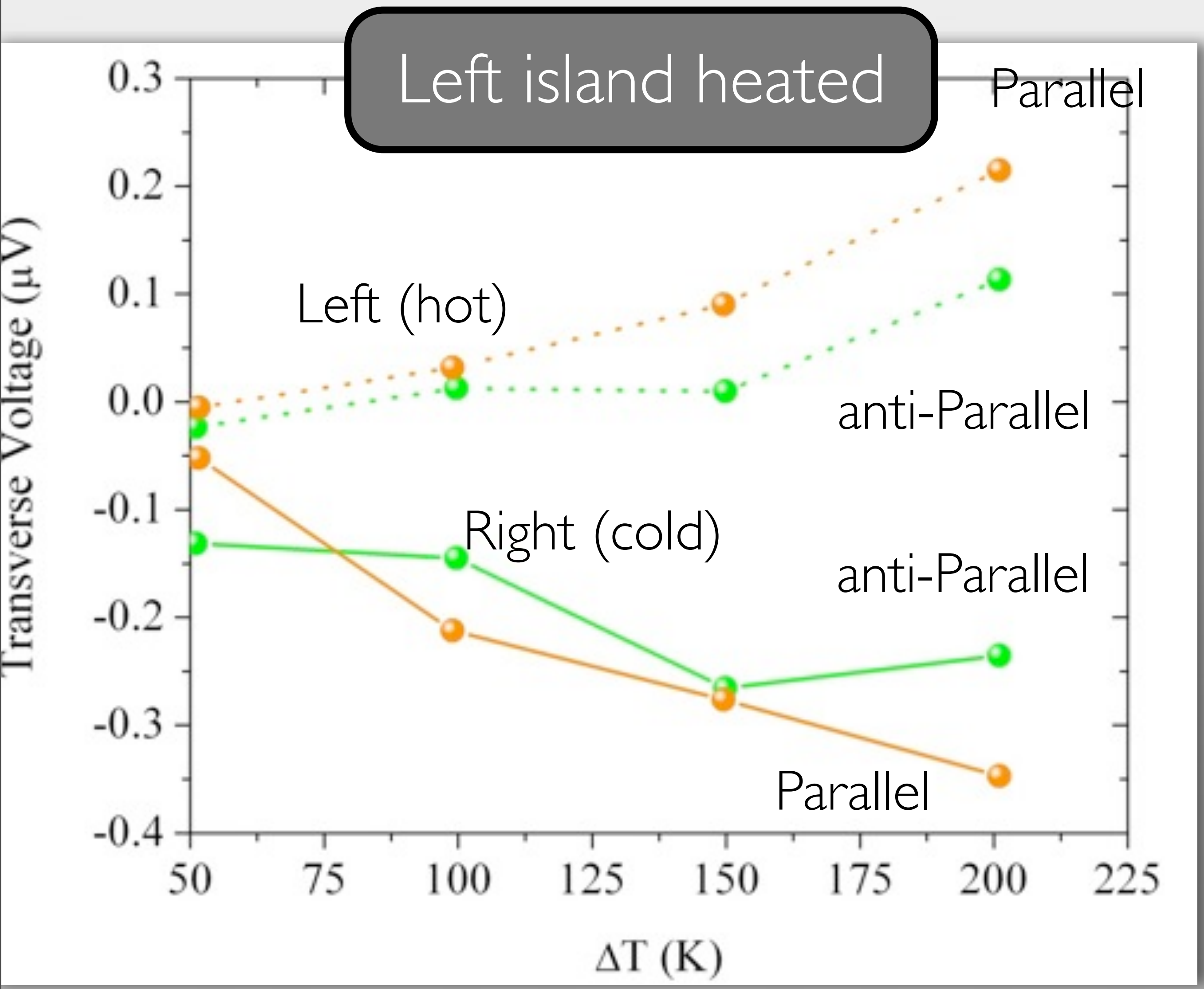

Parallel
Anti-parallel

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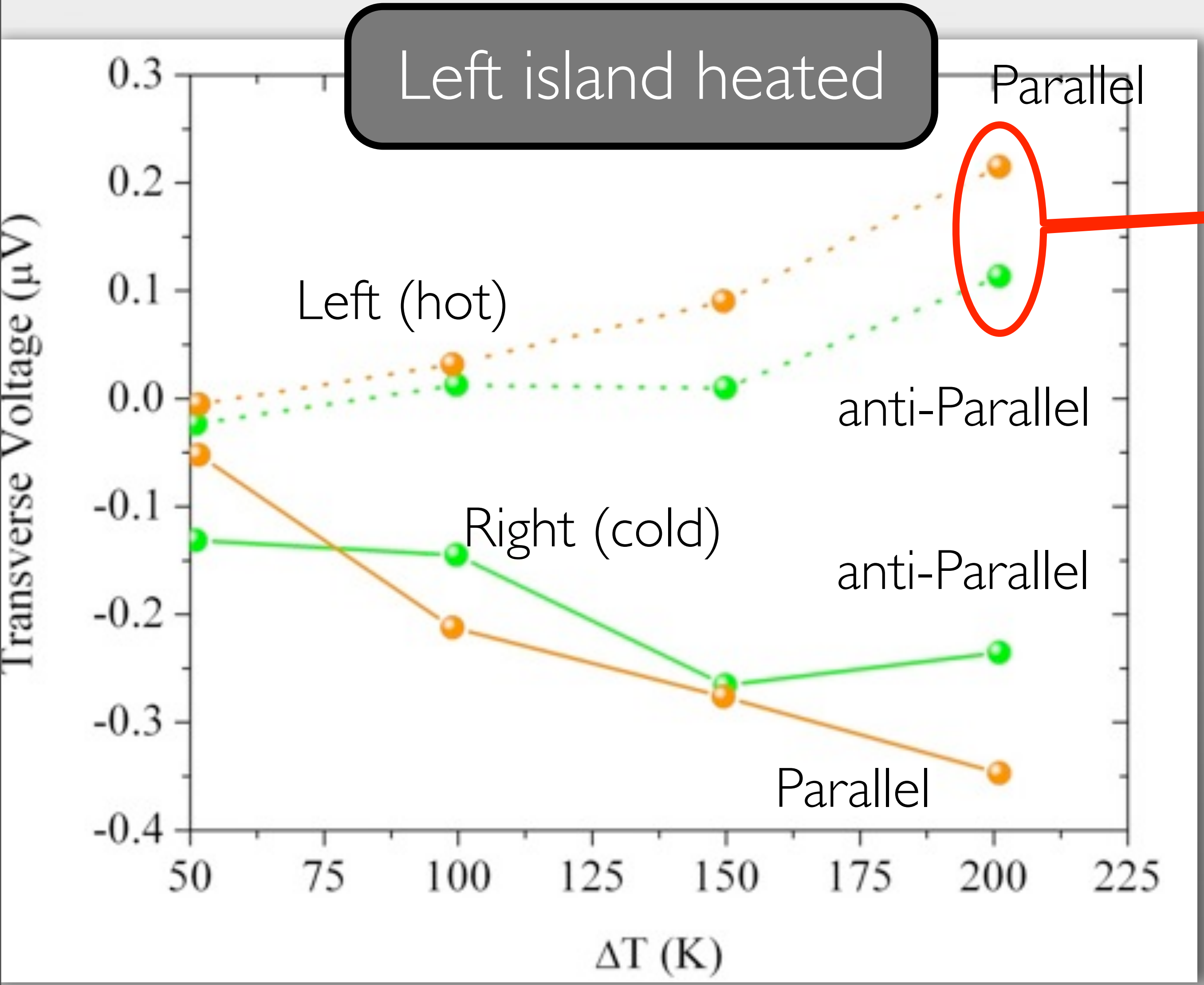

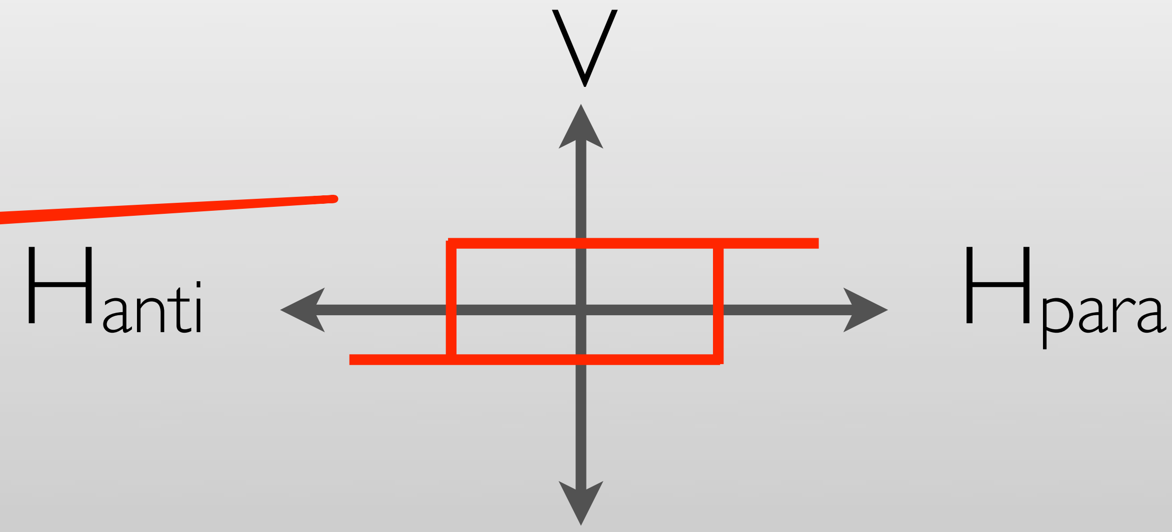

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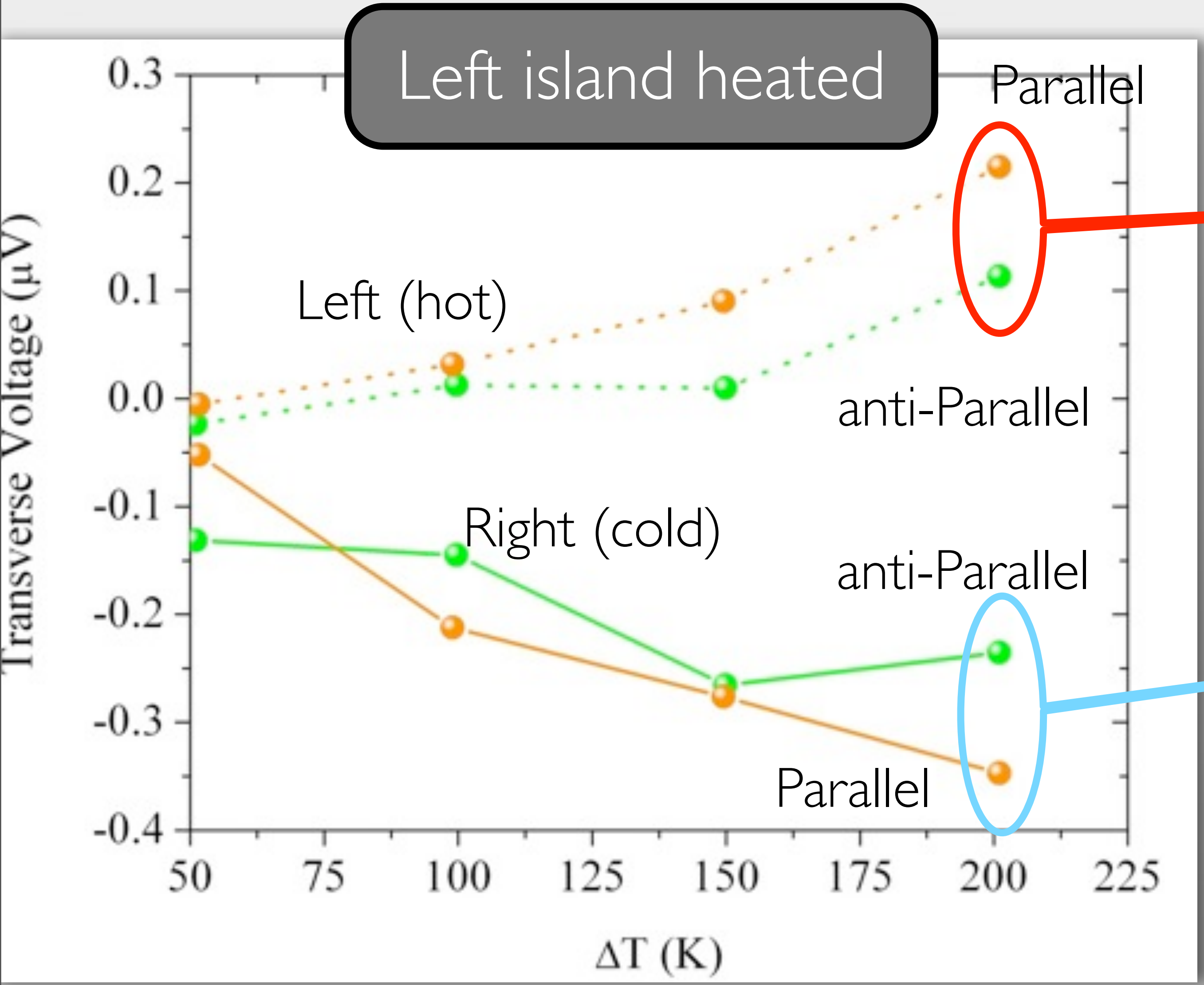
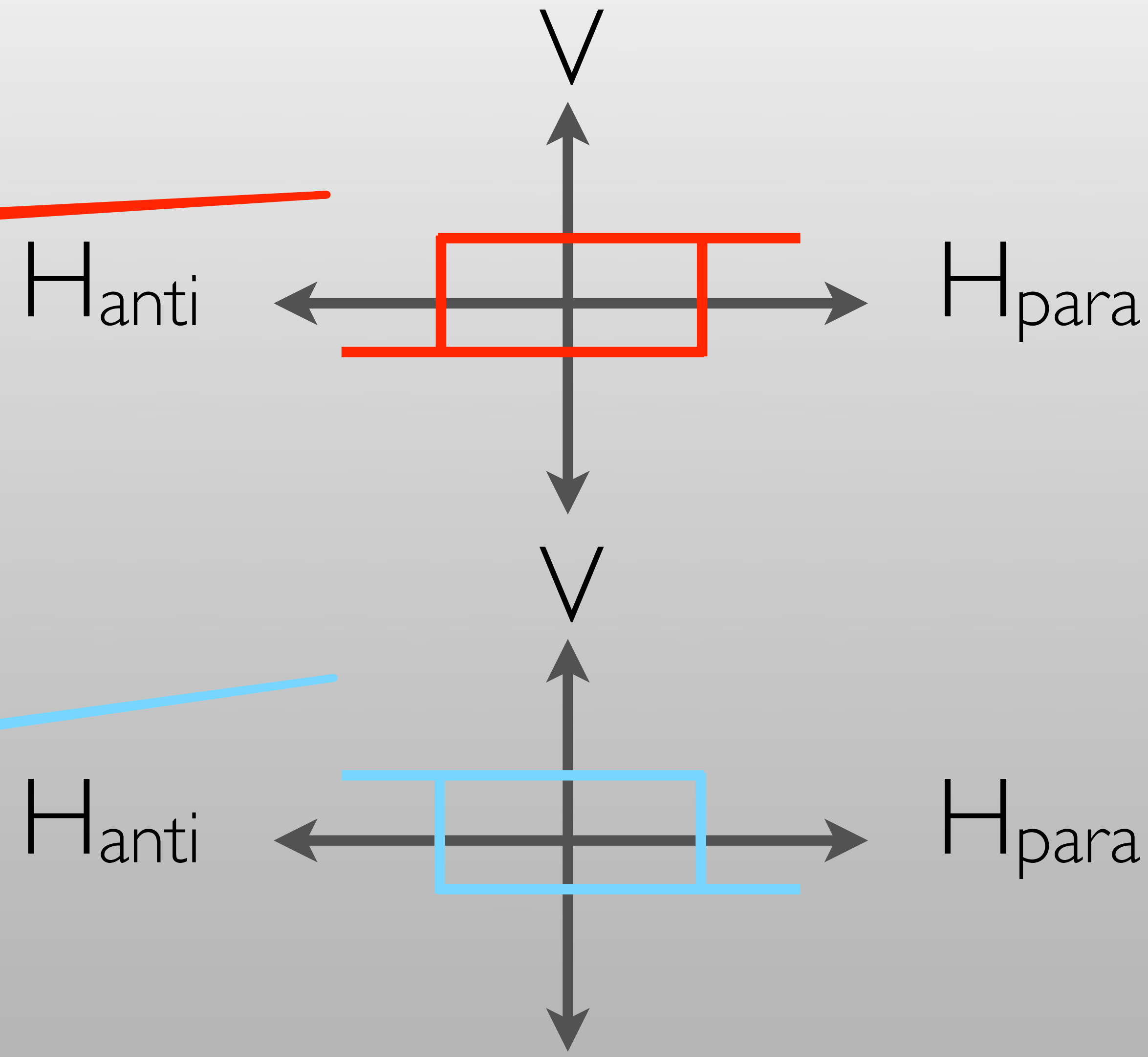
May 13, 2011

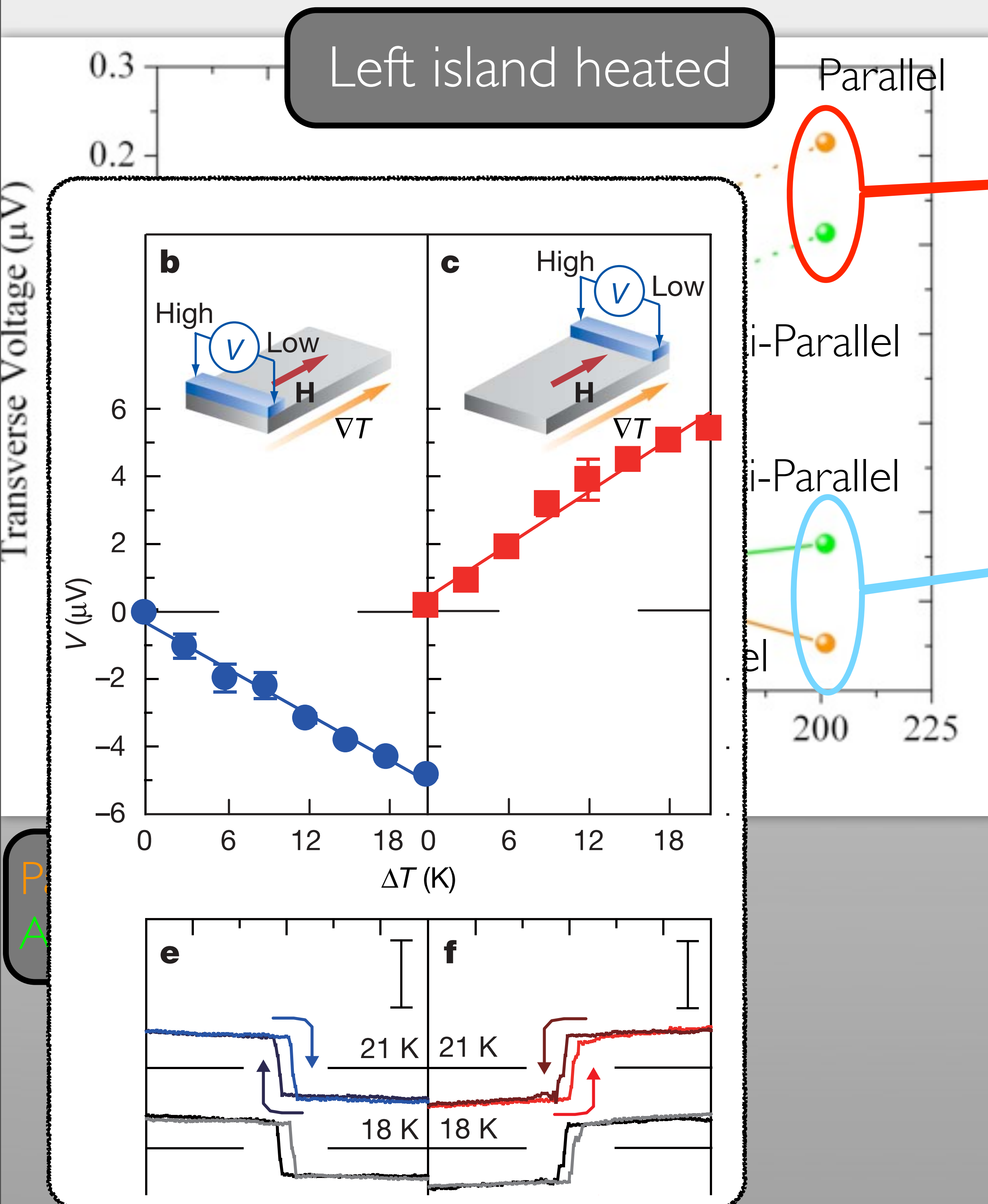
First Thermal Platform Data: Nickel

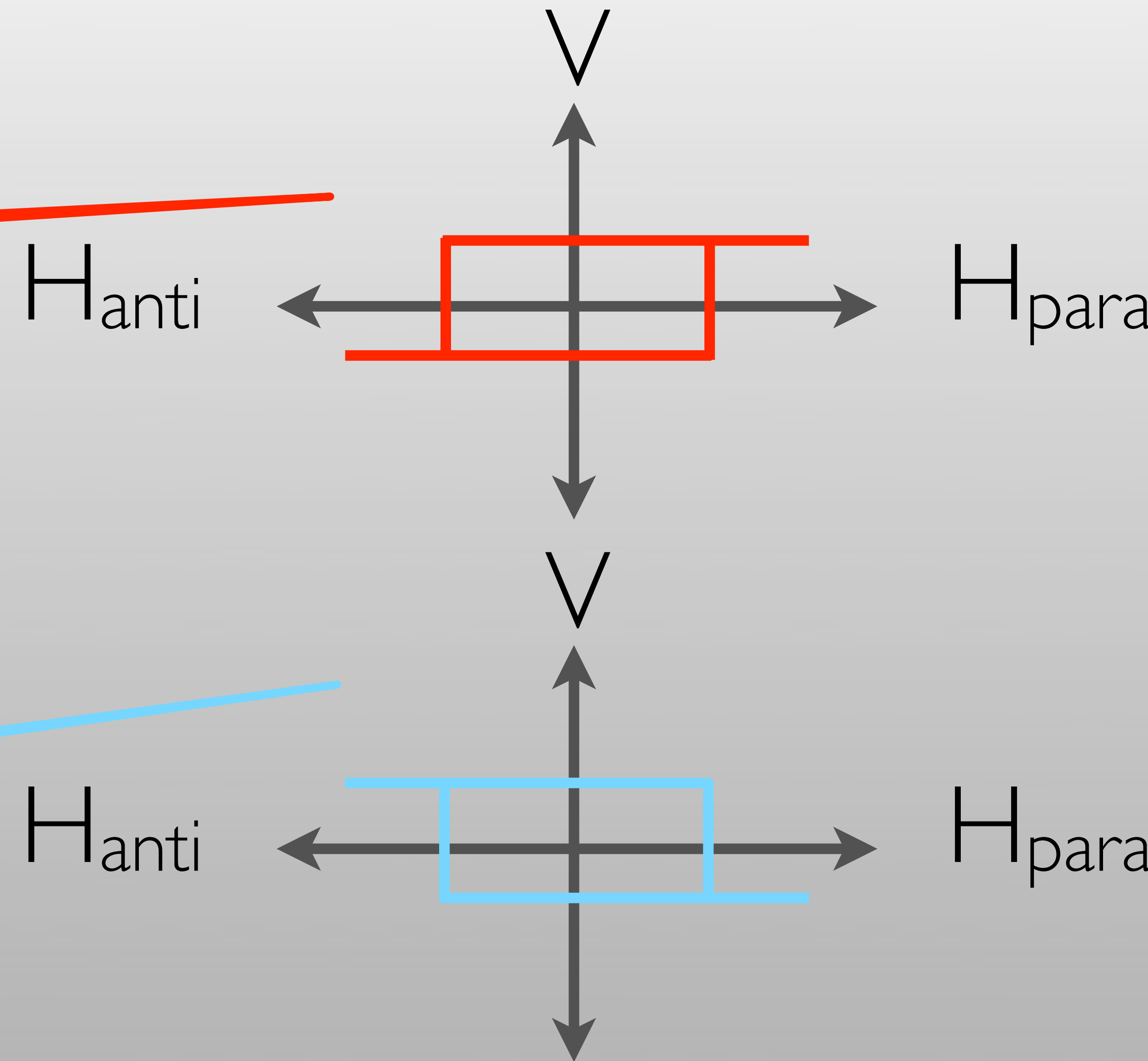




Parallel
Anti-parallel

First Thermal Platform Data: Nickel





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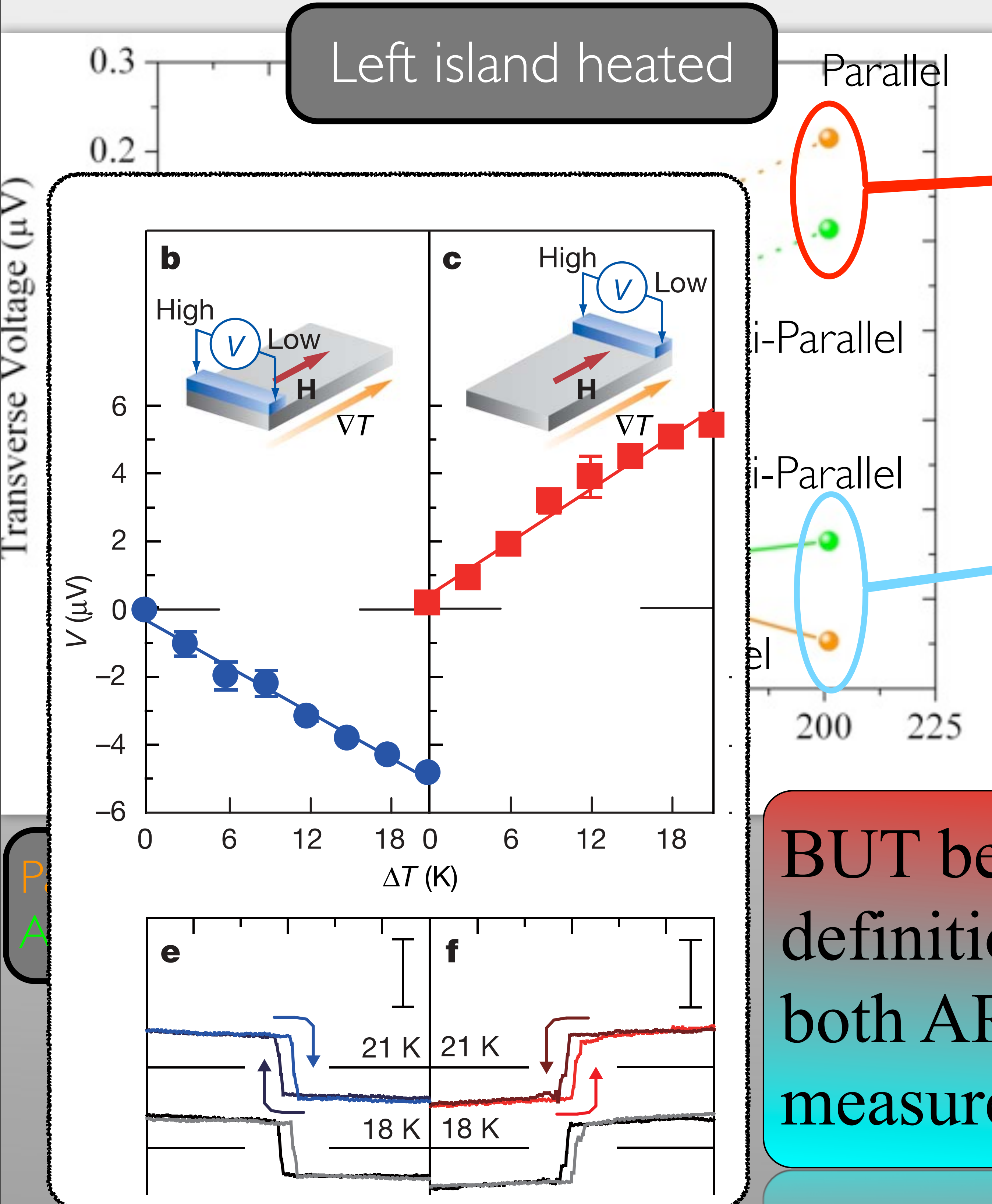
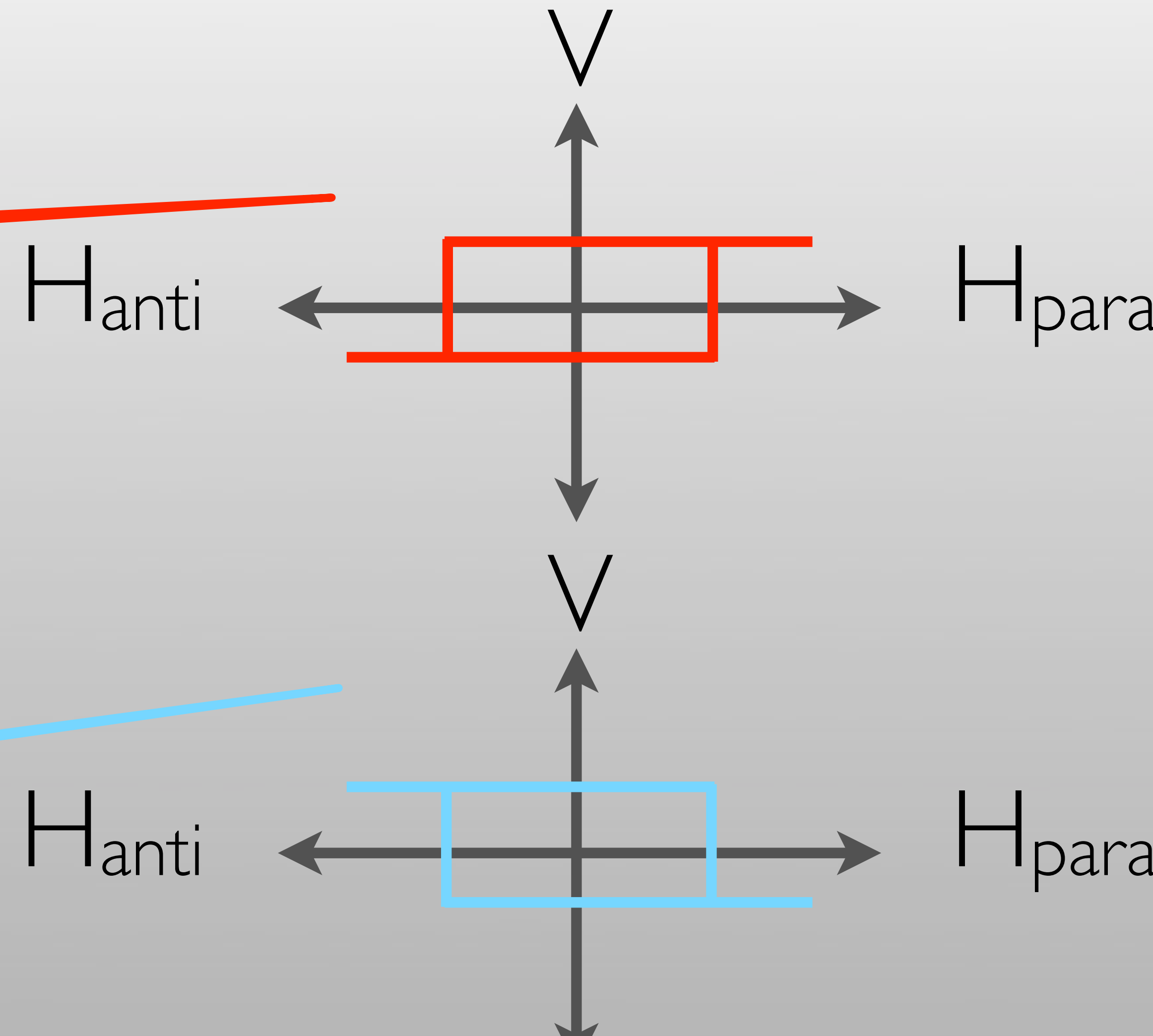
First Thermal Platform Data: Nickel





BUT be careful! We didn’t switch the definition of “High” and “Low”!!! So both ARE consistent with Saitoh group’s measurement of nickel!

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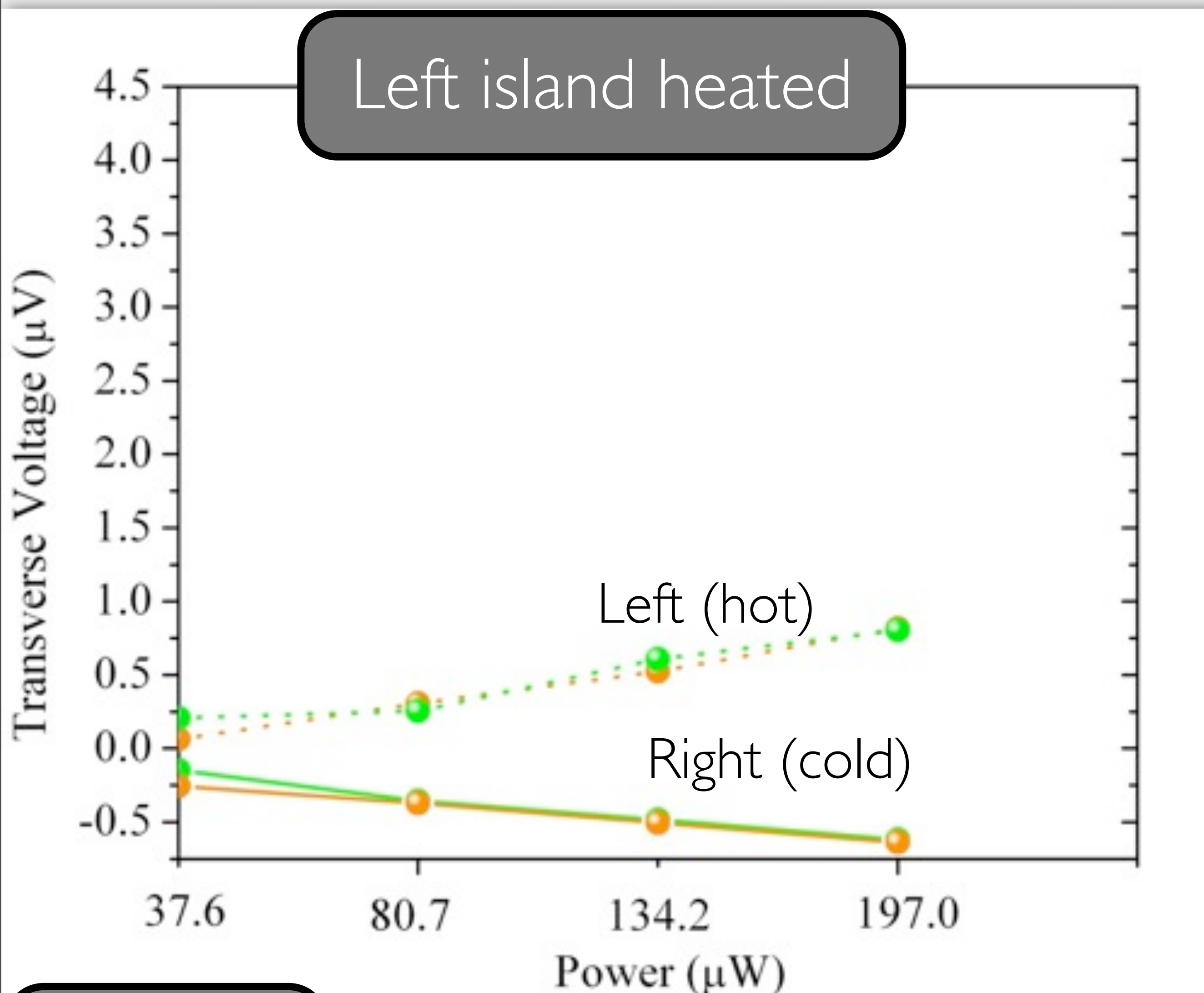
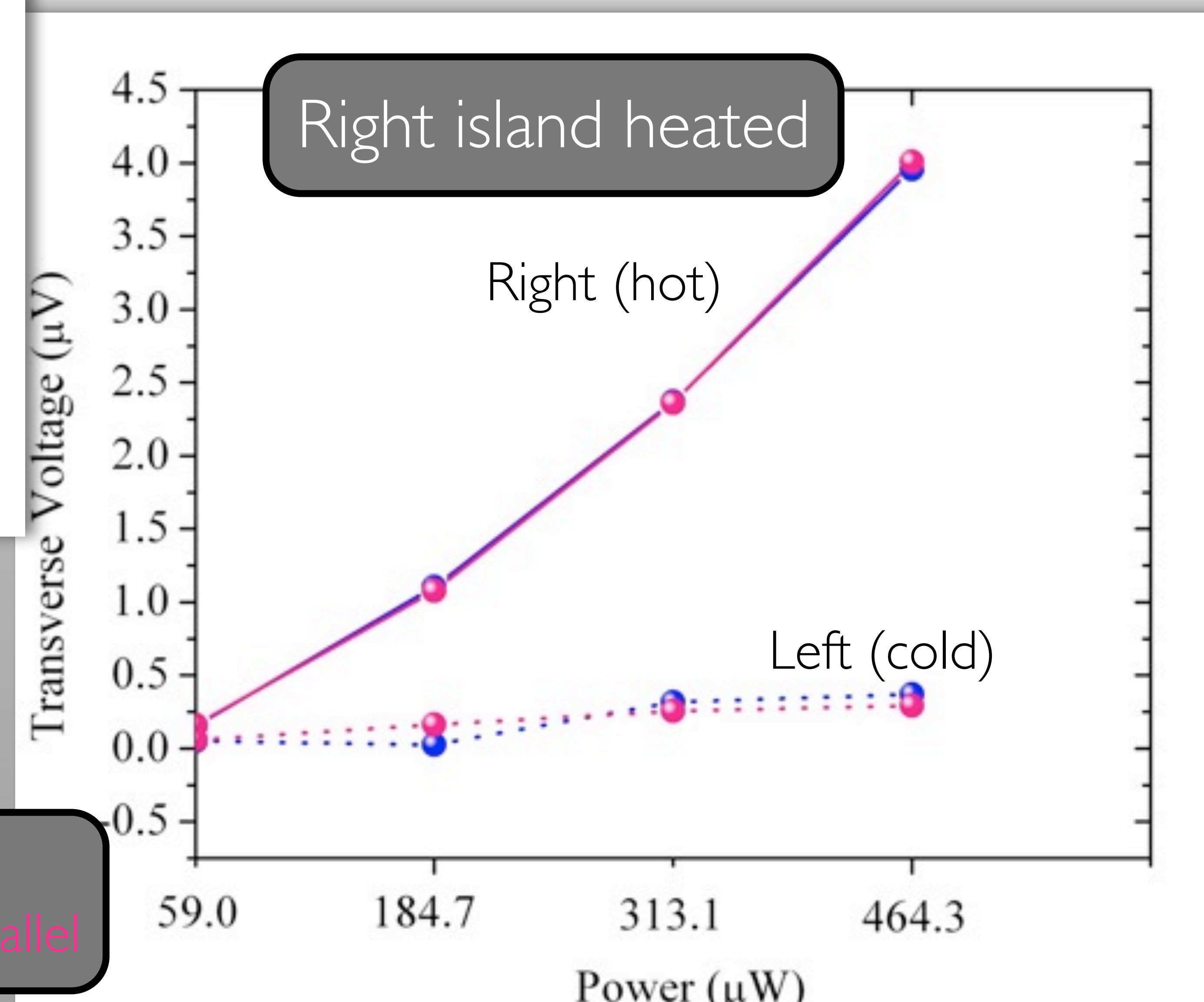
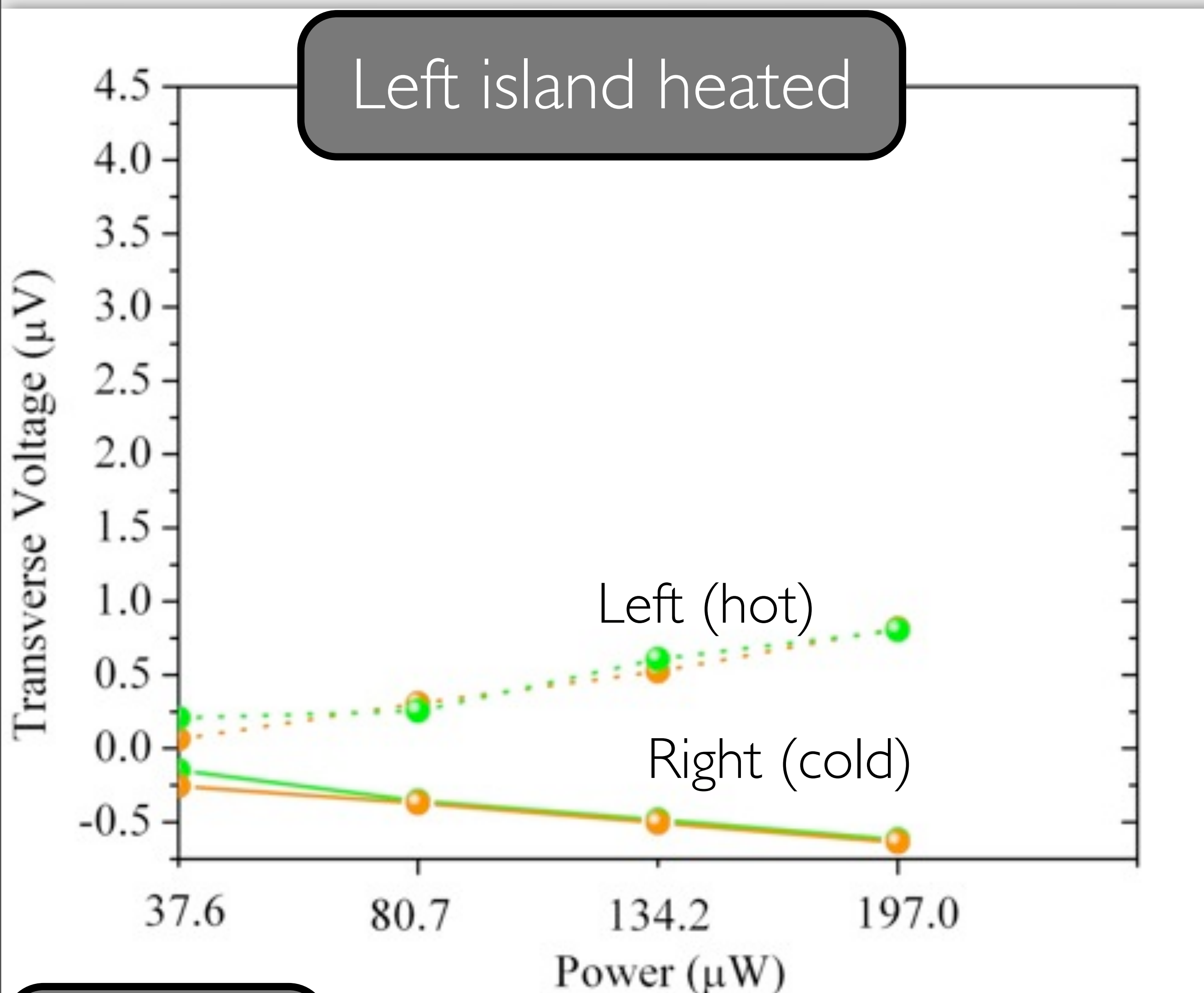
Au Film

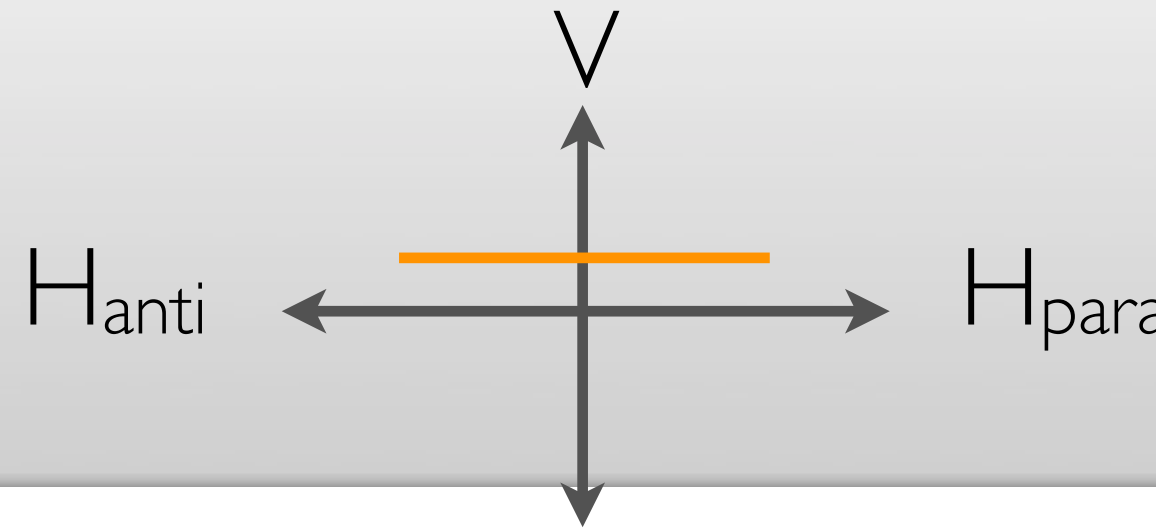


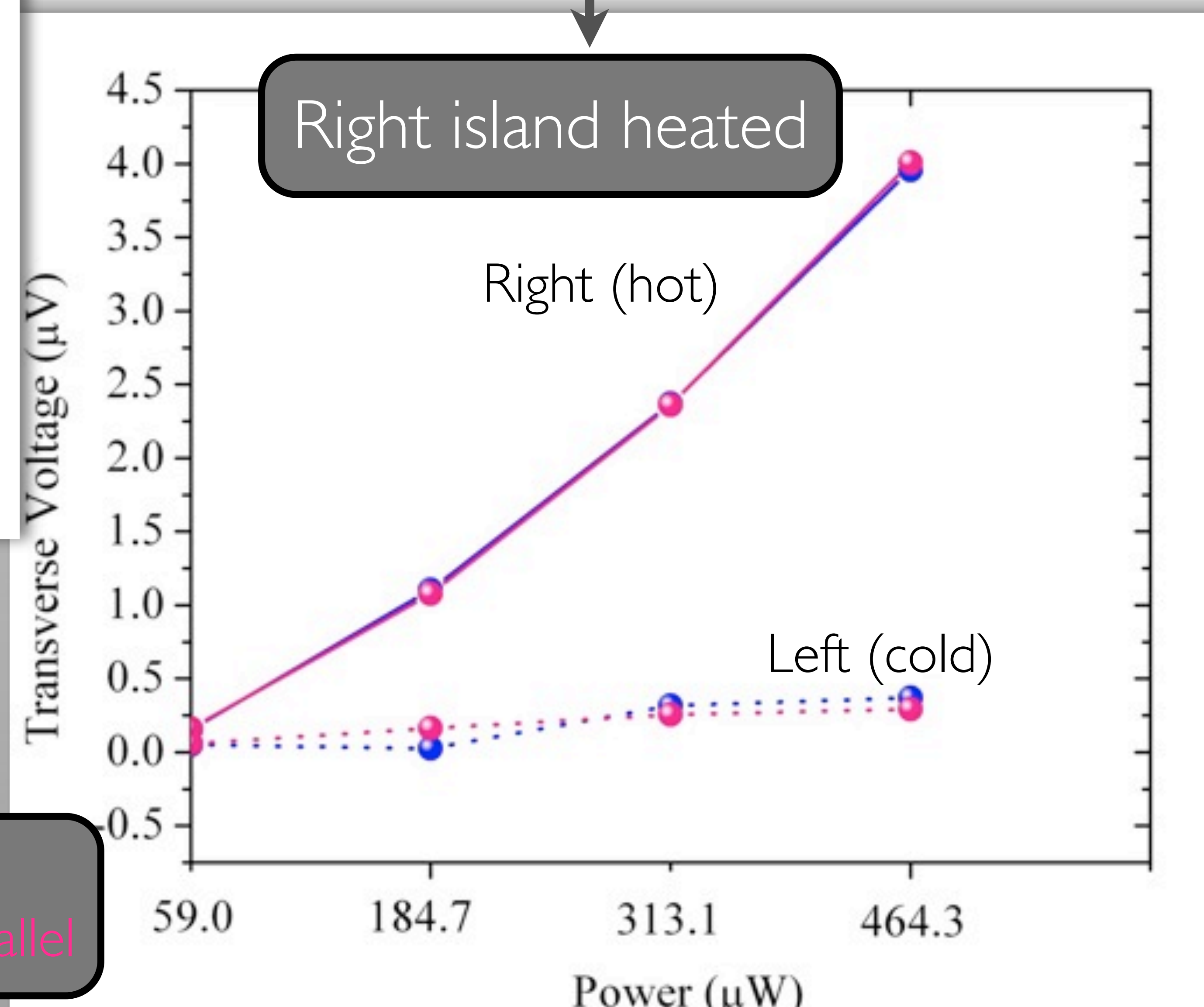
Parallel
Anti-parallel



Parallel
Anti-parallel







Parallel
Anti-parallel

Neither detector shows change in transverse V with switch from H_{para} to H_{anti}

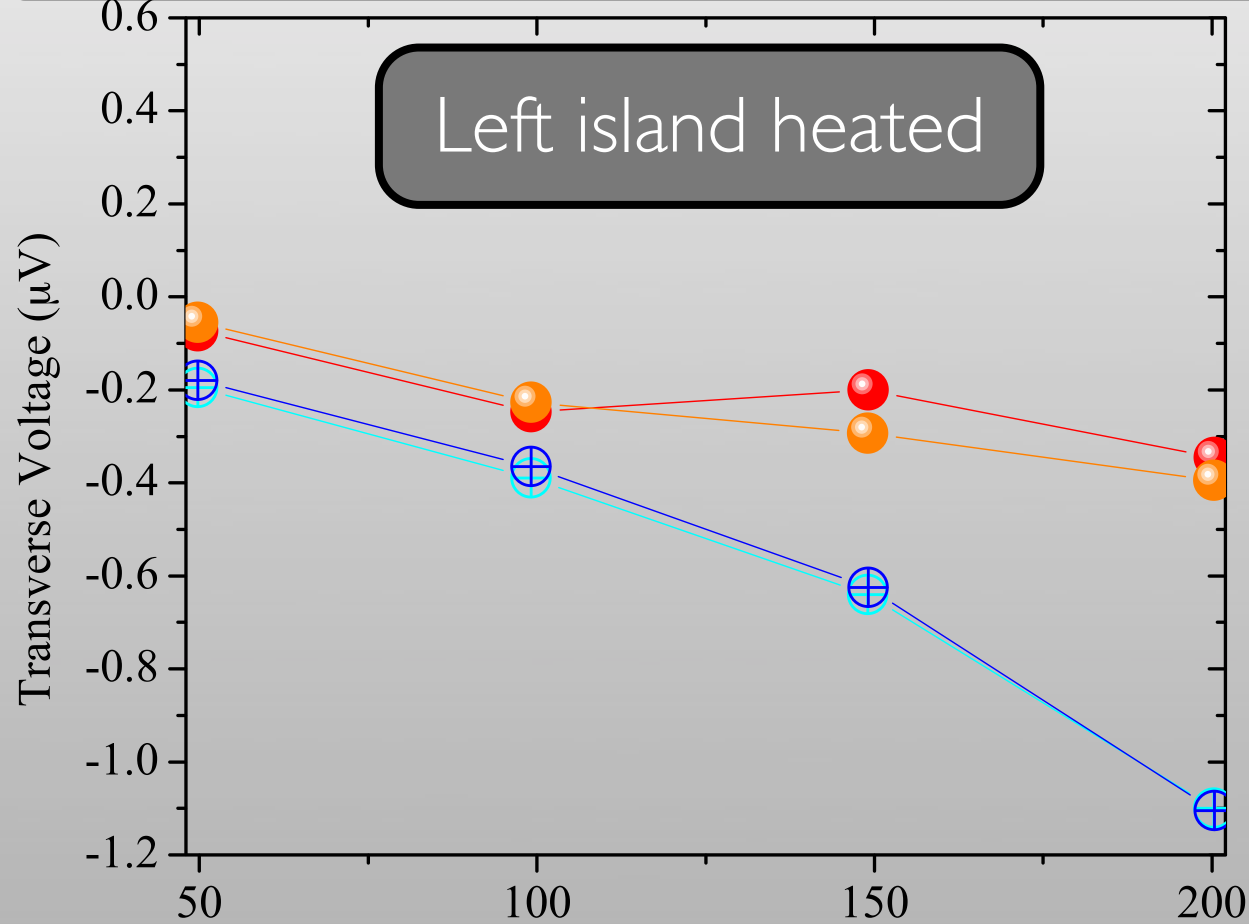
Parallel
Anti-parallel

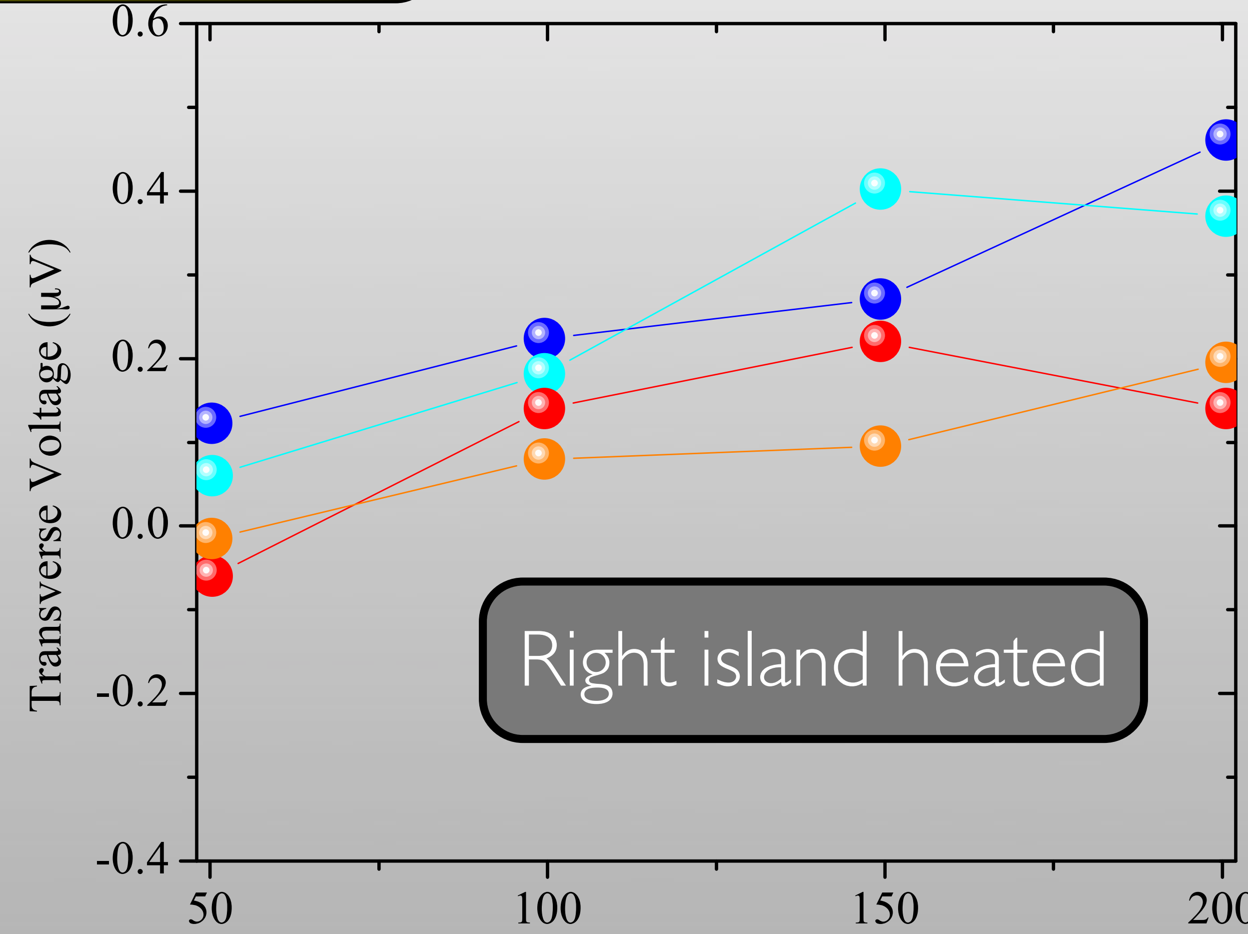
A pretty good start...

- Same sign of field-induced changes in V_{ishe} as Saitoh's group sees. Size of signal ~ comparable,with corrections for geometry and Delta T
- Clearly plagued somewhat by large background (presumably from charge Seebeck, etc.), makes this somewhat confusing.
- Platform broke at the end of first runs
- Recently completed fabrication of new samples
- Py films, attempt at improving isolation structure for more symmetric temperature response
- Working to implement ac lock-in detection...

Latest Data...(Py film)

WARNING!!! Extremely new....





Hard to believe there is a sensible field dependence here. Potential Reasons? Interface problems? SSE really zero in Py on amorphous substrate? Non-linear regime is just too kooky? Other random crap? Will have to stay tuned...

Questions, Questions...

- What is the mechanism(s) of the SSE?
- SSE on low conductivity substrates?
  - Maybe not so simple?
- Signal sizes in Ni, Py, Fe compare to magnon and phonon drag?
  - Still no help for overall sign there...
- As a community, still need more DATA

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