Magnon scattering in the transport coefficients of CoFe thin films

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Spin, charge and energy transport in novel materials
Hvar 2017

SpinCat

Spin - caloritronics

many new types of spin-dependent transport effects:

- spin-Hall and inverse spin-Hall effects

  Kato *et al*., Science 2004; Wunderlich *et al*., PRL 2005; Saitoh *et al*., APL 2006

- ~~transverse~~ and longitudinal spin-Seebeck effects

  Uchida *et al*., Nature 2008; Jaworski *et al*., Nat. Mat. 2010; Uchida et al., Nat. Mat. 2010

- spin-Peltier and spin-Nernst effects

  Flipse, *et* al., Nat. Nanotech. 2012; PRL 2014; Meyer *et al*., Nat. Mat. 2017

sometimes an effect can disappear again...

M. Schmid, S. Srichandan, C. S., C. Back et al., PRL 2013

how well do we understand the more conventional transport phenomena ?

- spin-dependent resistivity ?
- spin-dependent thermopower ?
- spin-effects in thermal conductance ?

Magnon scattering in itinerant ferromagnets

different types of quasi-particles contribute to and affect transport of charge, spin and heat in ferromagnets:

- electrons with majority and minority spins
- phonons
- magnons

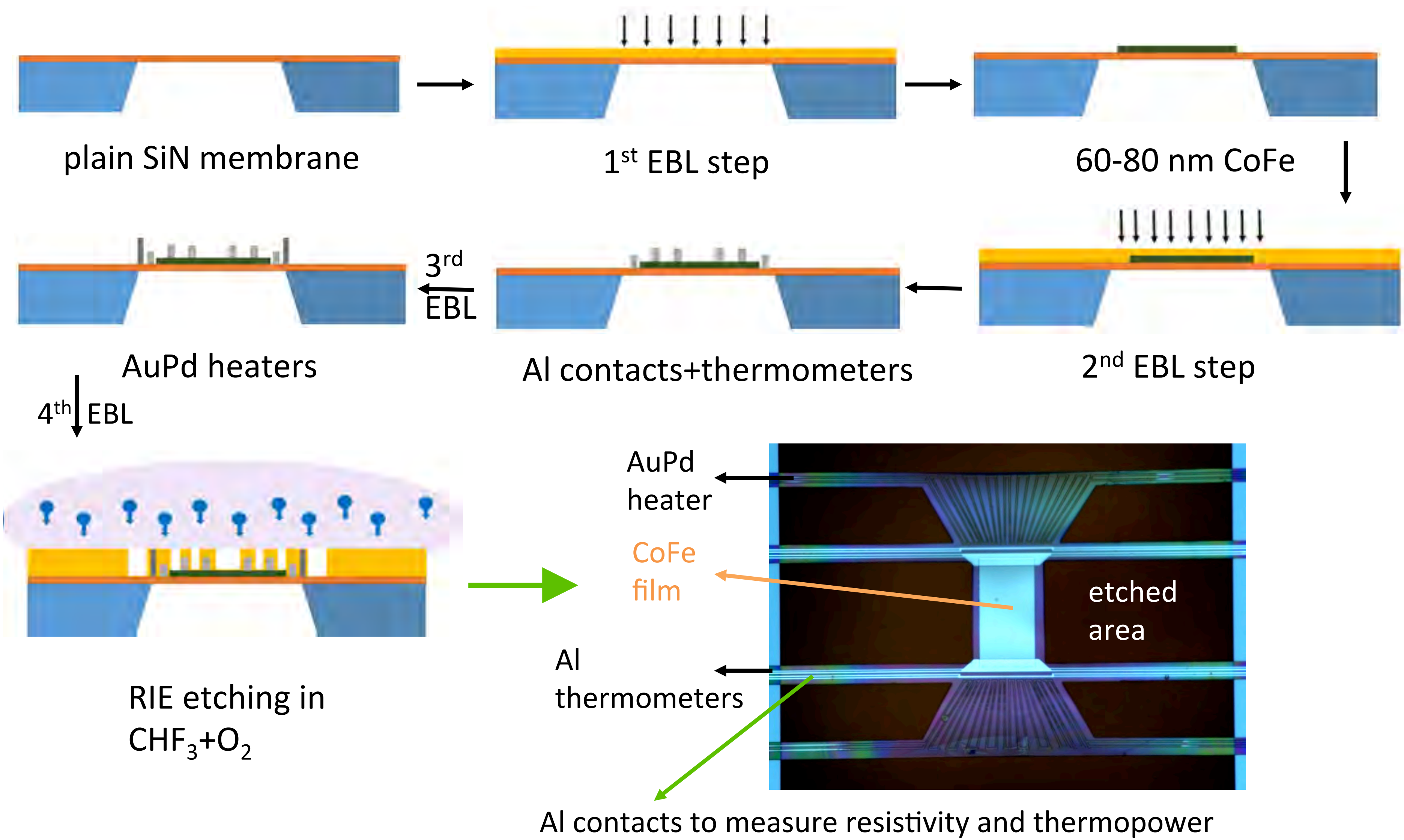
studied in the 1950's – 1970's, but no detailed understanding at that time

– time to take a fresh view:

- precise role of spin-degrees of freedom?
- systematic change of electron density as control parameter
- comparison to state-of-the-art model calculations

Can we separate the effects from different sub-systems?

Device fabrication



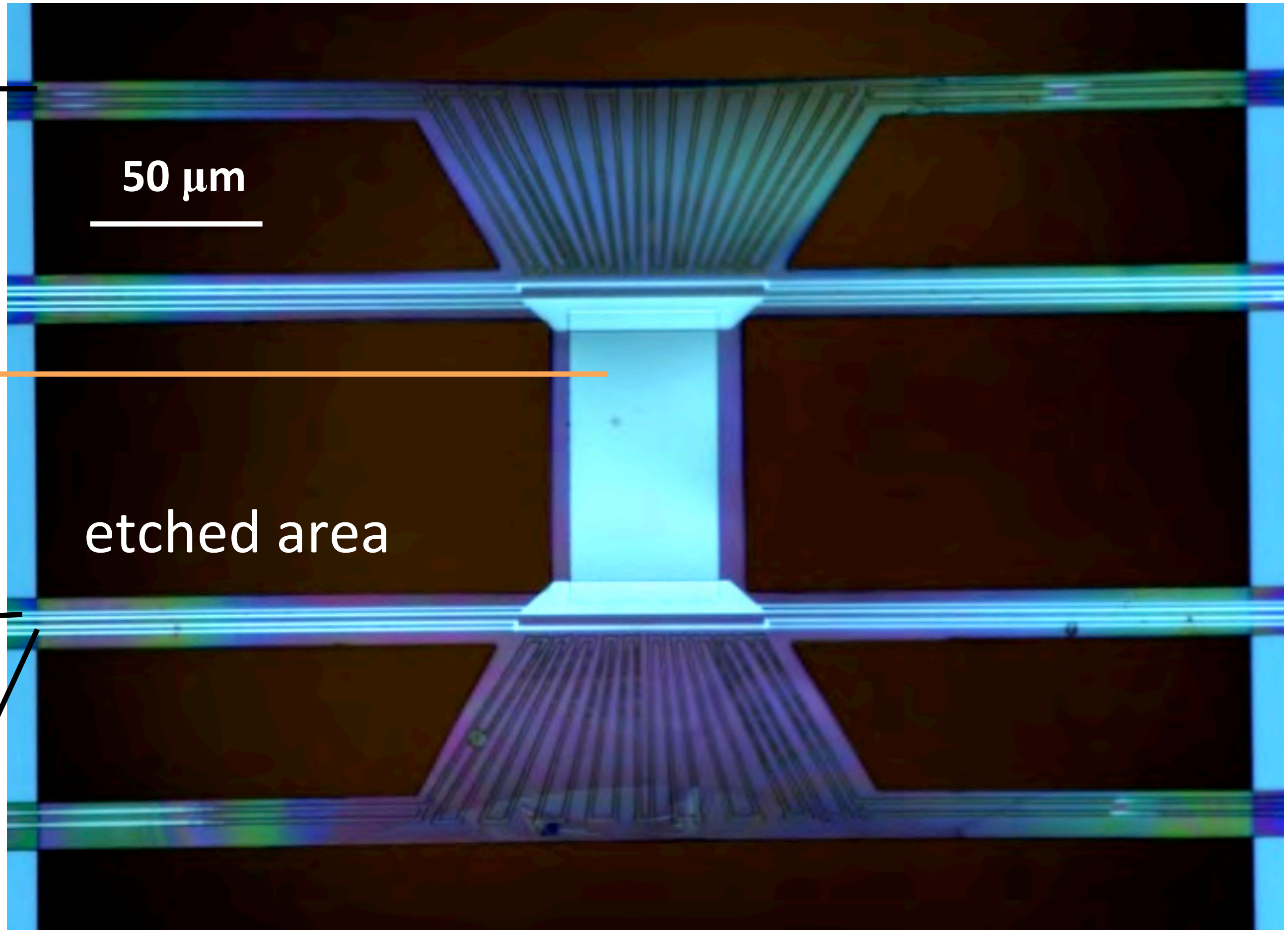
SiN based suspended microcalorimeter

AuPd heater

CoFe film

Al contacts

Al thermometer



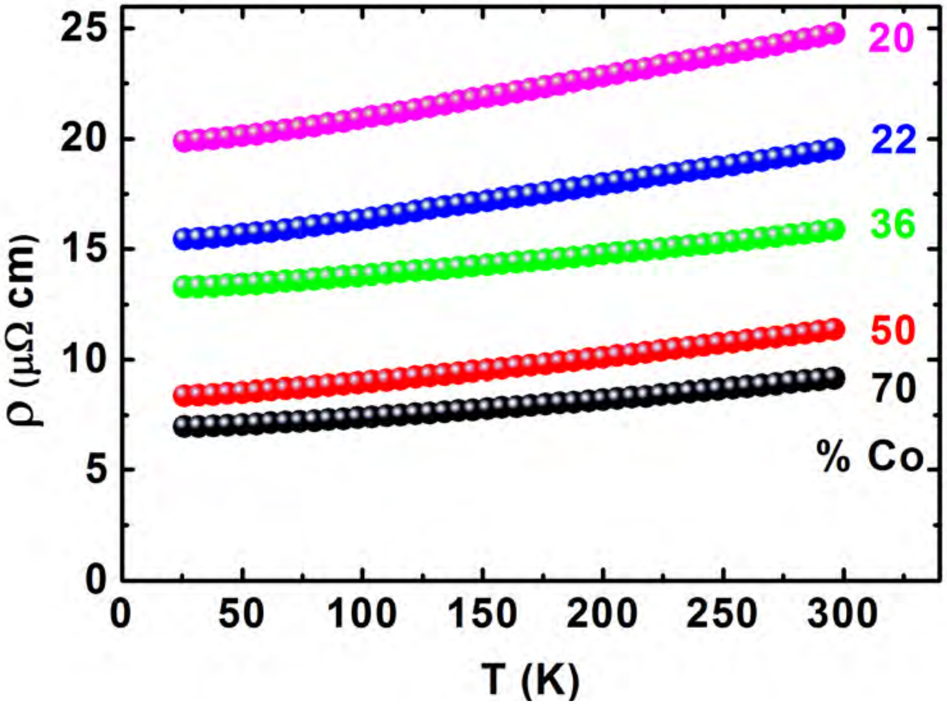
top view of device

XRD characterization of CoFe films:

- x_{Co}= 0. 22, 0.22: single **bcc** phase,
- x_{Co}=0.36, 0.7: mixed **bcc + fcc** phase

see also A. D. Avery, et al., PRL 2012

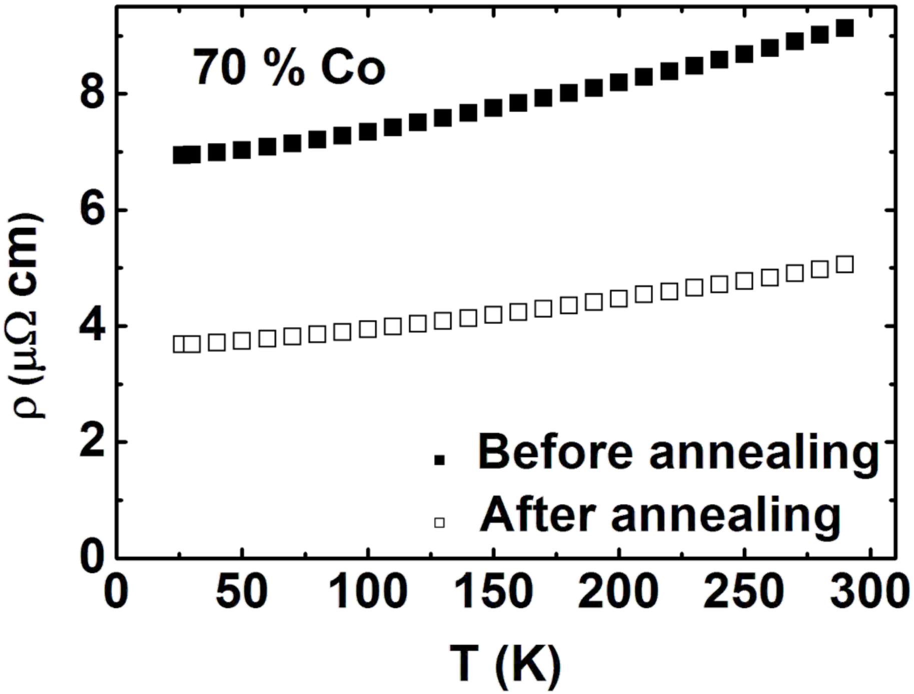
Electrical resistivity



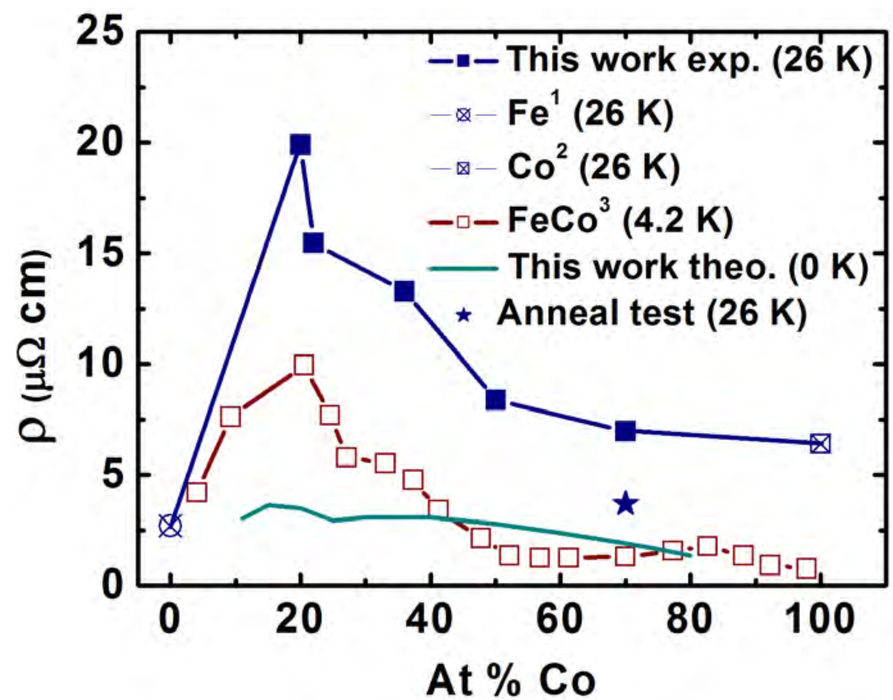
- monotonic decrease with decreasing electron density
- temperature dependent part: $\Delta\rho=\rho(296\ K)-\rho(25\ K) \sim 2\text{-}5\ \mu\Omega$ cm, comparable to other experimental group[1].
- $\Delta\rho$ smaller than the $\Delta\rho$ of bulk Fe[2] (10.41 μΩ cm) and of Co[3] (6.23 μΩ cm), respectively.

[1]C. Ahn *et al.*, *Jour. Appl. Phys.* **108**, 023908 (2010)
[2]M. Rubinstein *et al., Phys. Rev. B* **37**, 15 (1988)
[3]J. W. C. De Vries *et al., Thin Solid Films* **167**, 25-32 (1988)

Resistivity as a function of Co concentration



- besides chemical disorder strong contribution from grain boundary scattering
- violation of Matthiessen's rule



[1]M. Rubinstein *et al., Phys. Rev. B* **37**, 15 (1988)
[2]J. W. C. De Vries *et al., Thin Solid Films* **167**, 25-32 (1988)
[3]P. P. Freitas *et al., Phys. Rev. B* **37**, 6079 (1988)

Understanding the effects of different scattering processes

- measure T-dependence of different transport coefficients while systematically tuning the Fermi level through the (pseudo)band structure
- comparison to microscopic theory (Ebert group, LMU Munich)

1. For band structure calculation, Munich **SPR-KKR-program package** has been used. This includes the fully relativistic Korringa-Kohn-Rostoker multiple scattering Green's function formalism to evaluate Kubo'sformula.

   H. Ebert *et al., Rep. Prog. Phys.* **74**, 096501 (2011)

2. Temperature dependent calculation for resistivity using **alloy-analogy model** (AAM) based on coherent potential approximation (CPA) **including vertex corrections**.

   H. Ebert *et al., Phys. Rev. B* **91**, 165132 (2015)

Thermopower from generalized Mott model using temperature dependence from electrical conductivity and Fermi-Dirac distribution.

S. Wimmer *et al.*, *Phys. Rev. B* **88**, 201108 (R) (2013); *Phys. Rev. B* **89**, 161101 (R) (2014)

Band structure (Bloch spectral function)

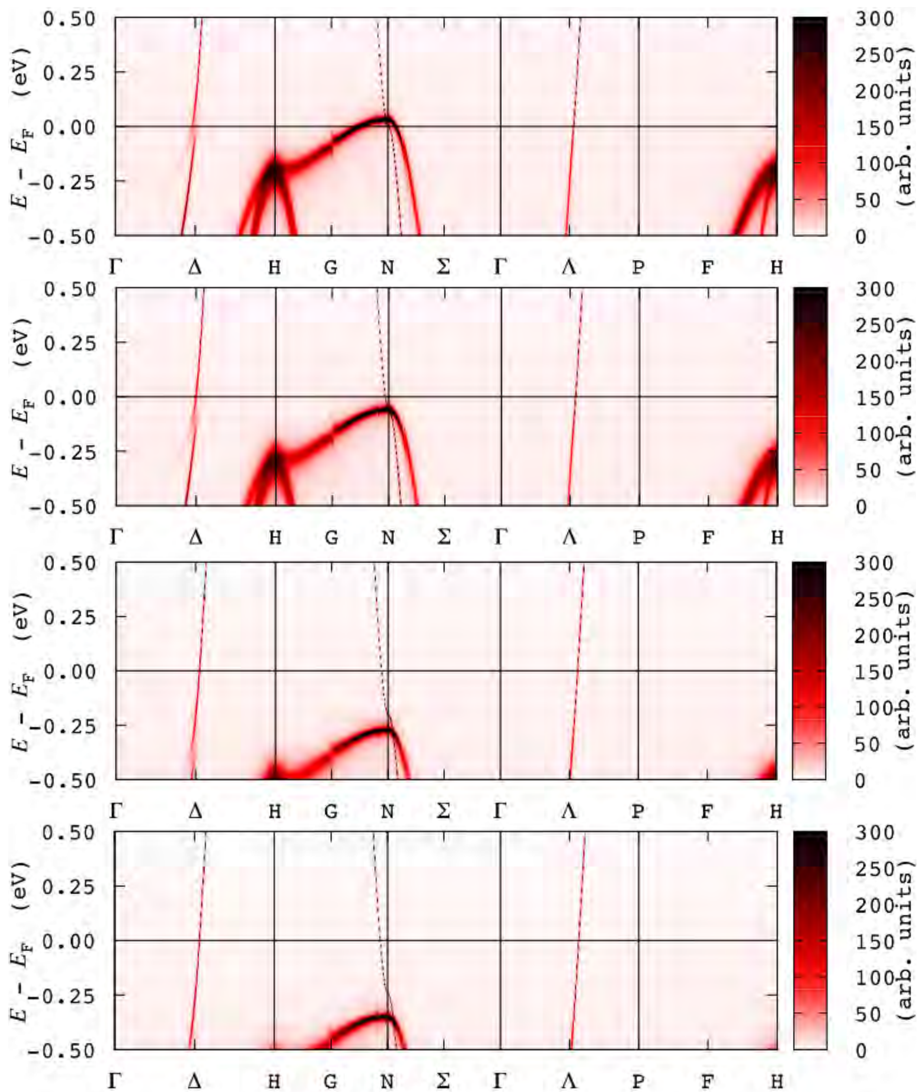
x_{Co}

0.2

0.25

0.4

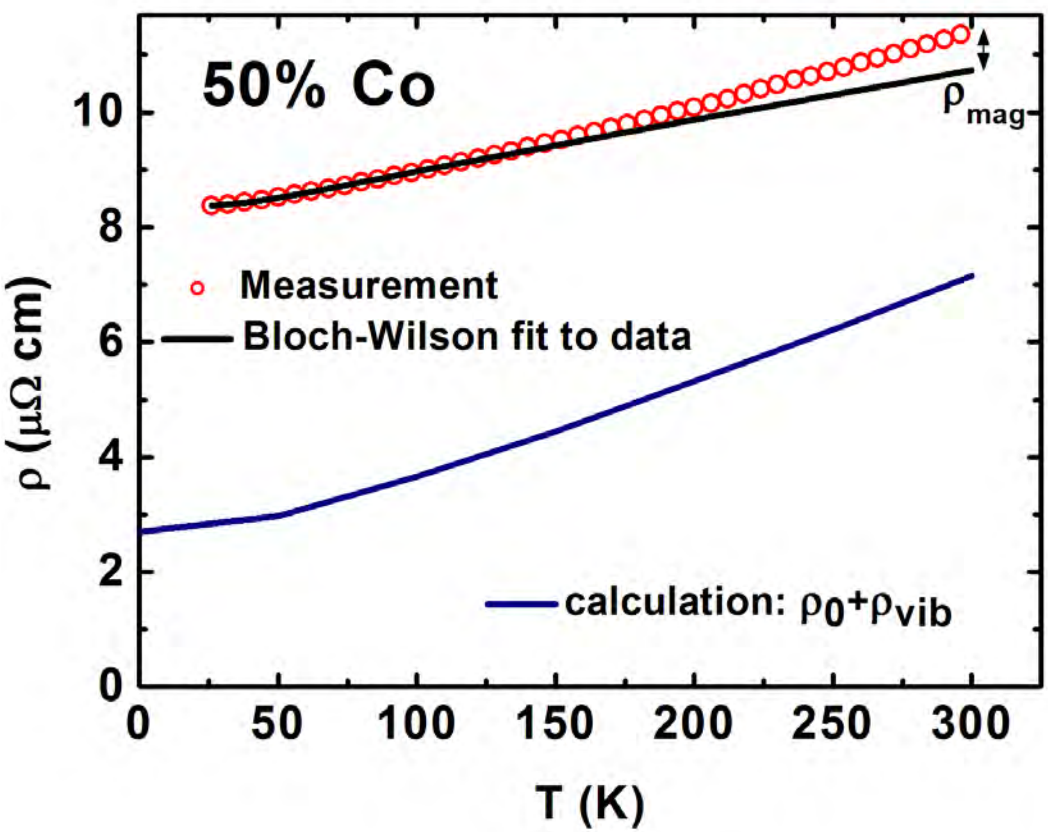
0.5



- red lines: shape of d-like band of the spin-up channel
- 0 represents the Fermi energy E_F
- E_F inreases with respect to bands when electron density increases

S. Wimmer *et.al.* (2016)

Separation into electron-phonon and electron-magnon scattering contributions



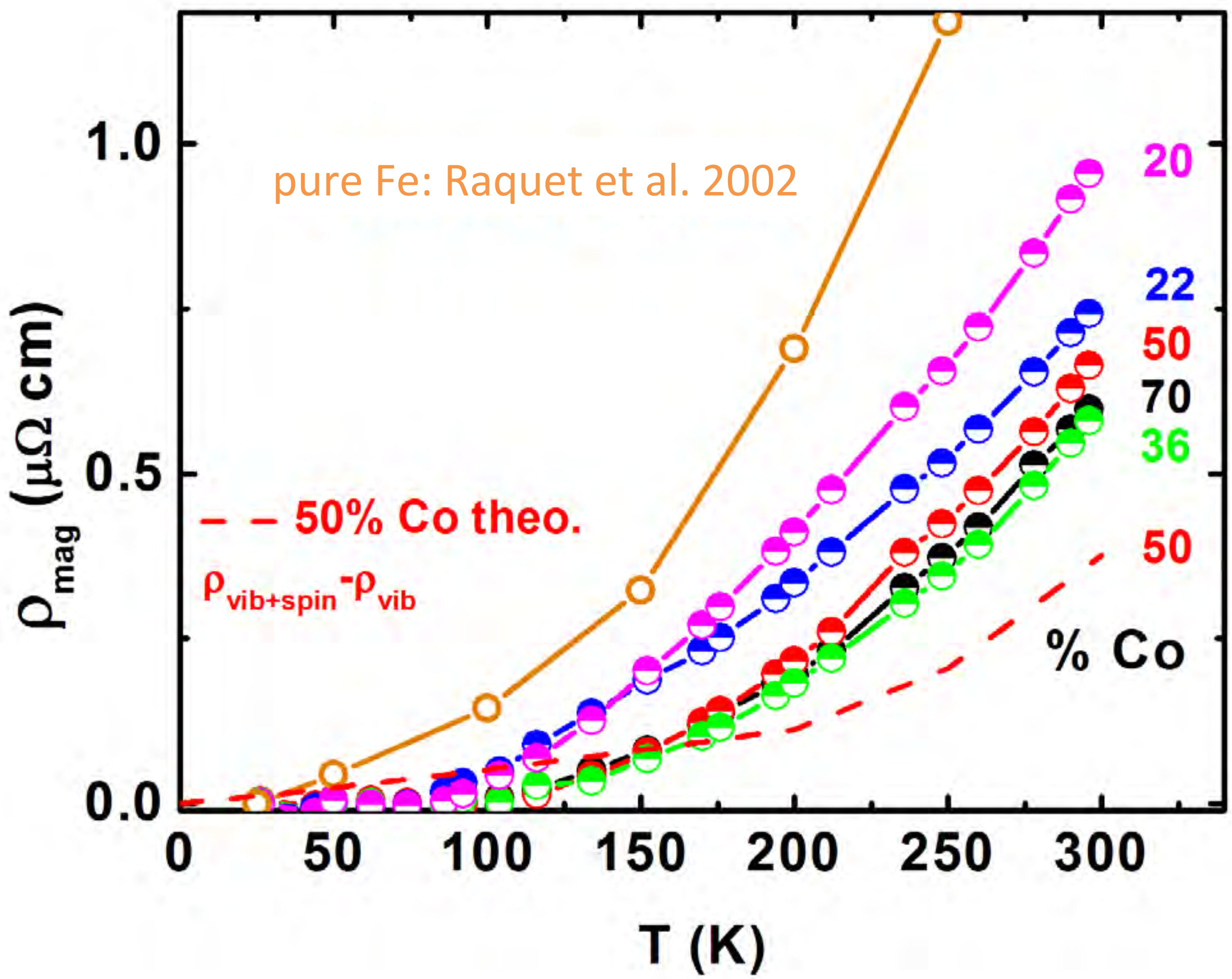
- phonon and magnon energy scales differ by a factor 10
- electron-magnon scattering contribution is small

M. V. Kamalakar *et al.*,
Appl. Phys. Lett. **95**, 013112 (2009)

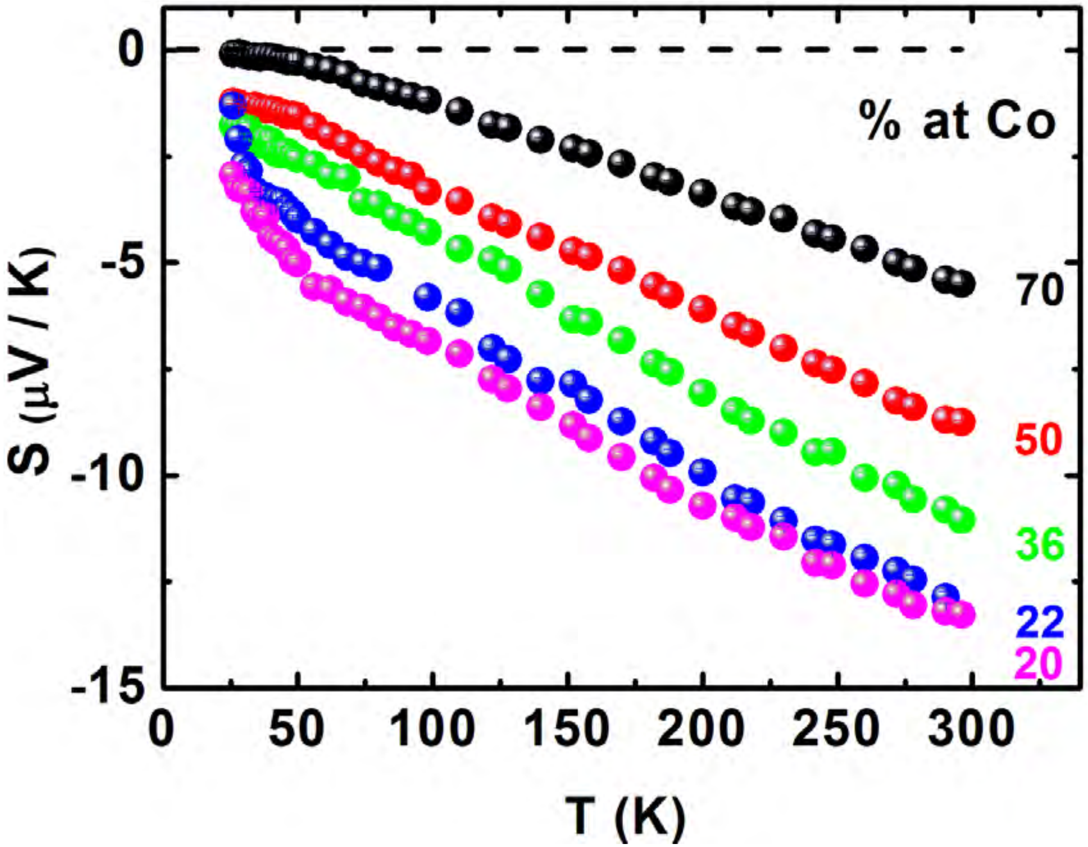
- chemical and vibronic disorder scattering contribution in calculations underestimates the residual resistivity and overestimates the temperature dependence

S. Wimmer *et.al.* (2016)

Magnetic contribution to resistivity remaining after subtraction of Bloch-Wilson fit (?)



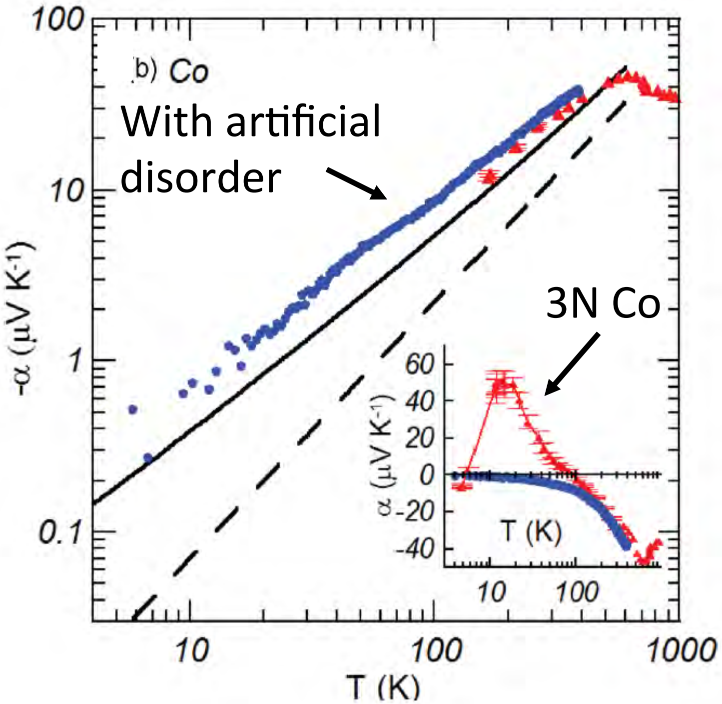
Thermopower S(T)

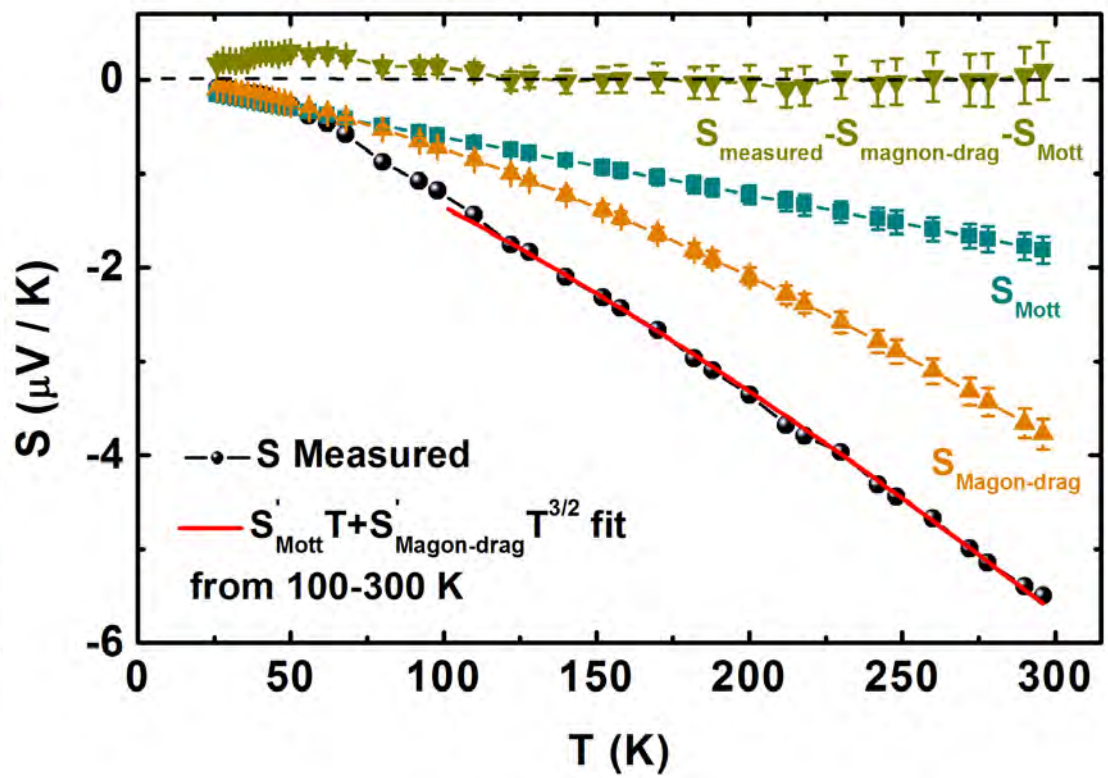


- **S**(T) is mostly negative in sign.
- monotonic increase with decreasing electron density.
- visible change of sign of curvature at lower temperatures.

Separation of Mott-like and magnon drag contributions

from Watzman *et al*.





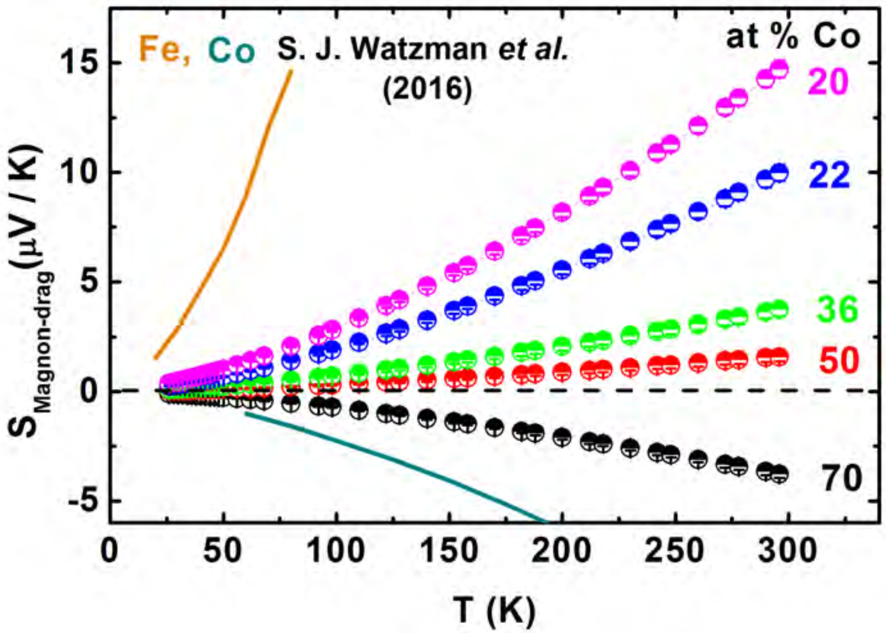
$$S(T) = S'_{Mott}T + S'_{Magnon-drag}T^{3/2}$$

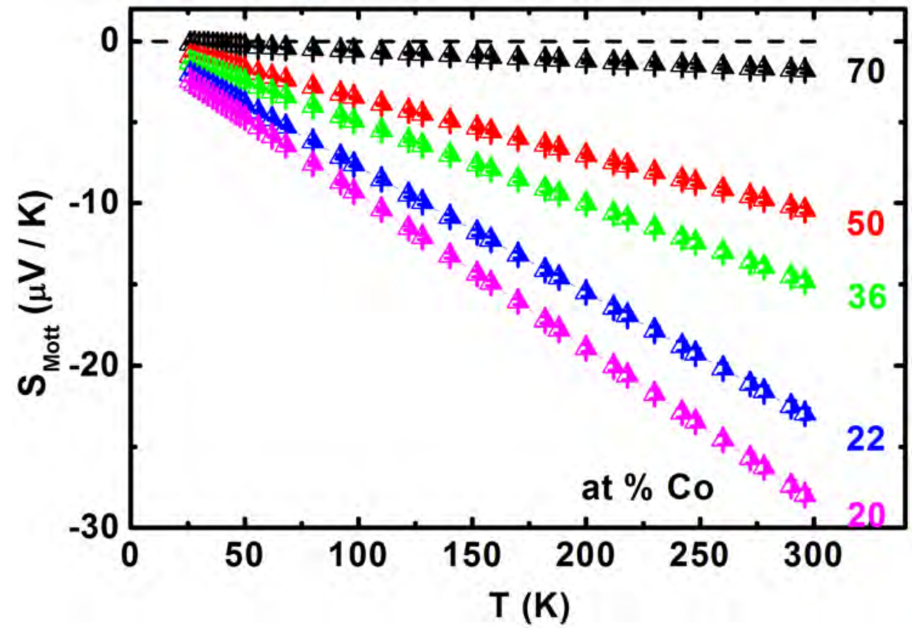
low energy magnon number ~ $T^{3/2}$

70 % Co

S. J. Watzman *et.al., Phys. Rev. B* **94**, 1444 (2016)

Separate magnon drag and Mott-like contributions





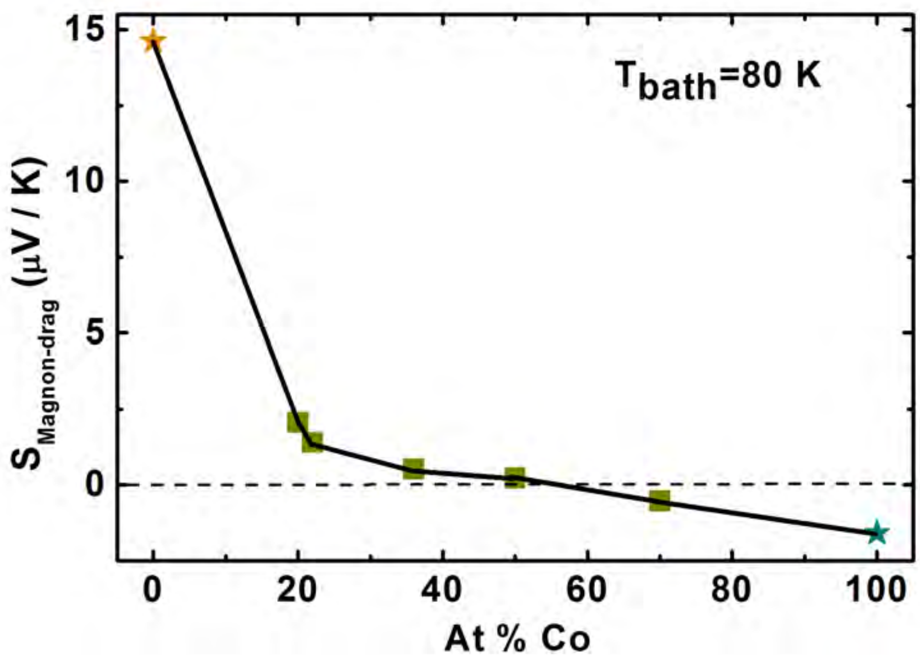
- maximum $\mathbf{S}_{\mathbf{magnon\text{-}drag}}$ is 15 μV/K at 296 K for film with x_{Co}=0.2.
- $\mathbf{S}_{\mathbf{magnon\text{-}drag}}$ changes sign from negative to positive following sign of bulk Co and Fe

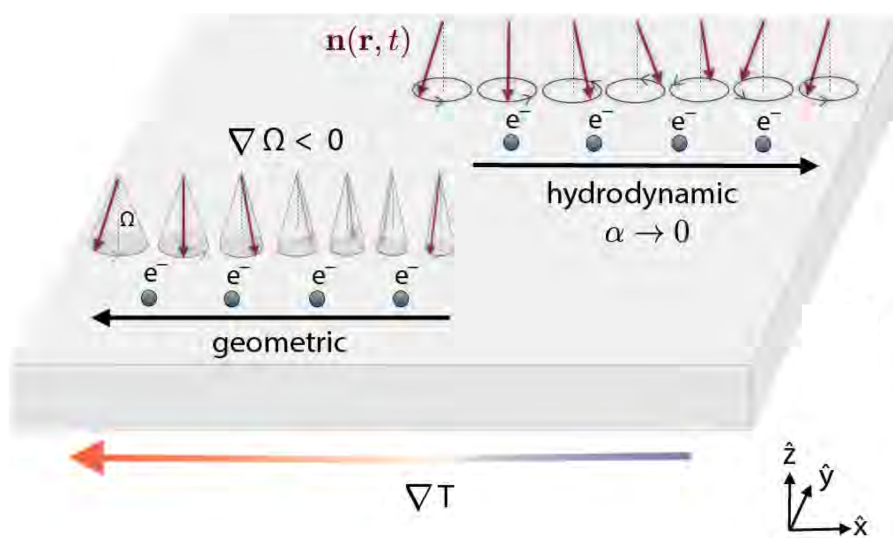
S. J. Watzman *et.al., Phys. Rev. B* **94**, 1444 (2016)

- conjectured $\mathbf{S}_{\mathbf{Mott}}$ extracted from experiment is linear in T by construction.
- thermoelectric parameter $\eta = -3e\mathbf{S}_{\mathbf{Mott}}T_F/\pi^2 k_B$ = 5.2 for film with x_{Co}=0.2 is comparable with η=7.6 for liquid Fe

K. Hirata *et al.* J. Phys. F: Metal Phys. **7**, 3 (1977)

origin of the sign change of magnon drag thermopower?





B. Flebus et al. arXiv 1605.06578

- **$S_{magnon\text{-}drag}$** may contain information on the spin transfer torque parameters

$$S_{magnon-drag} \propto (\beta - 3\alpha)\kappa_{magnon}$$

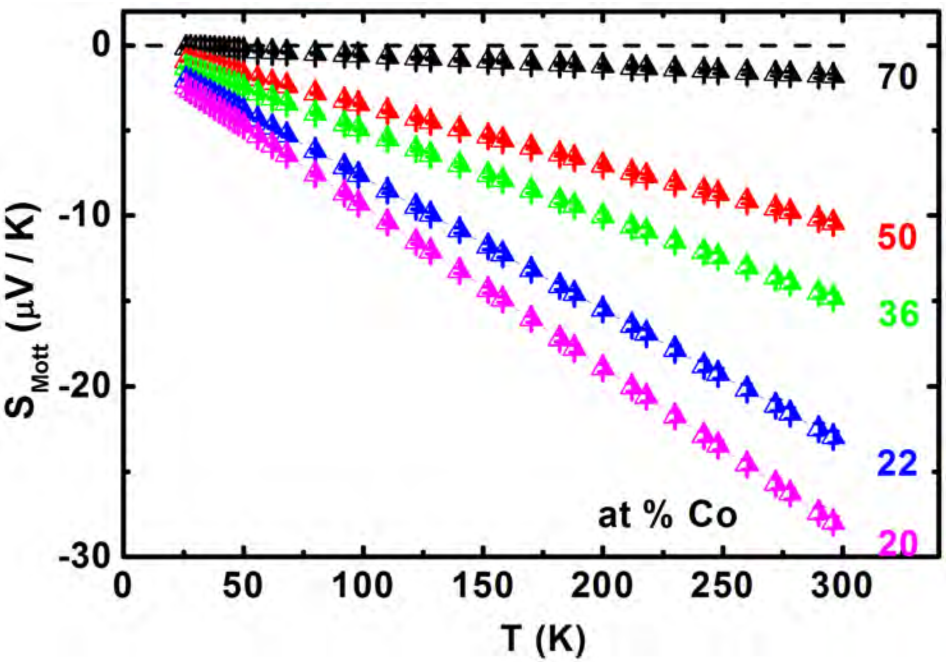
hydrodynamic drag like

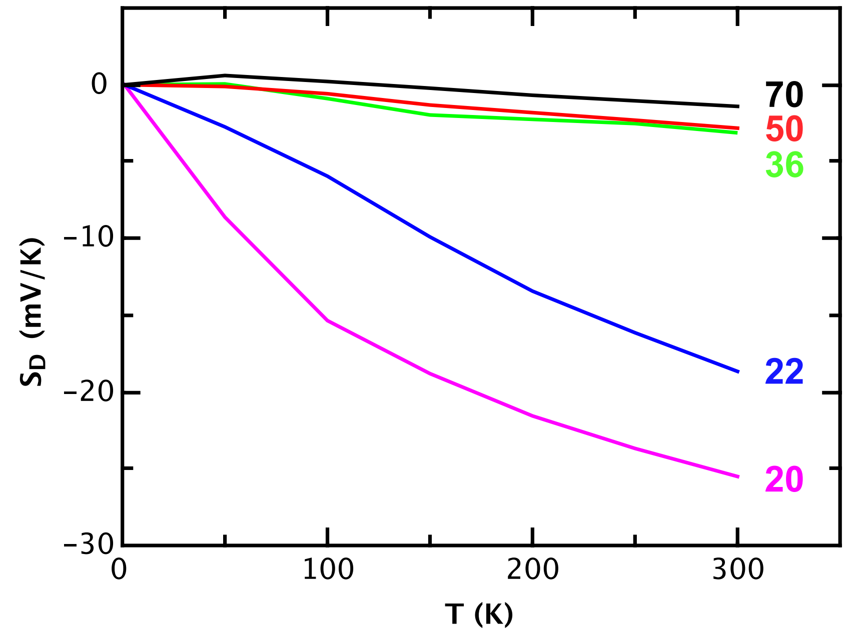
Gilbert damping parameter, Berry phase like

- relation to **$S_{magnon\text{-}drag}$** sign change?

Y. Tserkovnyak *et al., J. Magn. Mag. Mat.* **320**, 1282 (2008)

Mott-like contribution compared to microscopic calculation



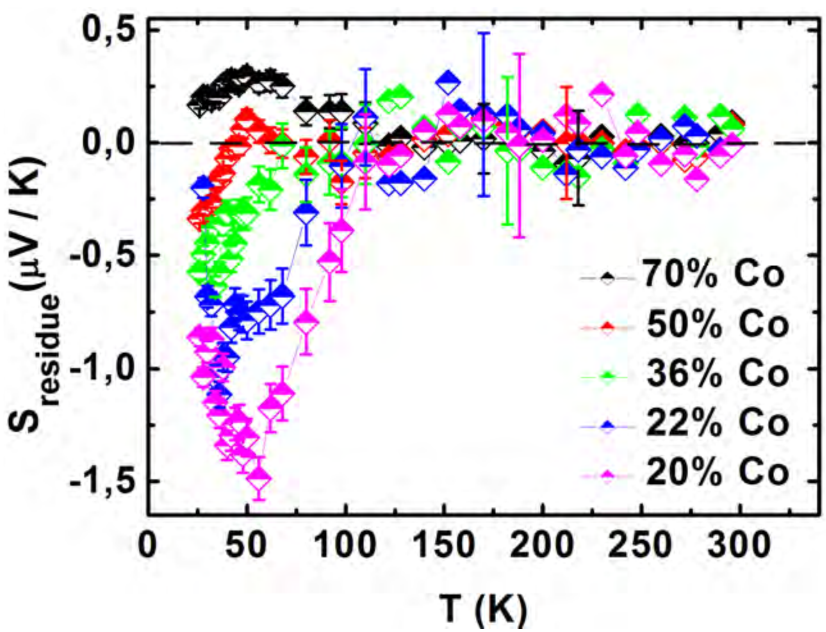


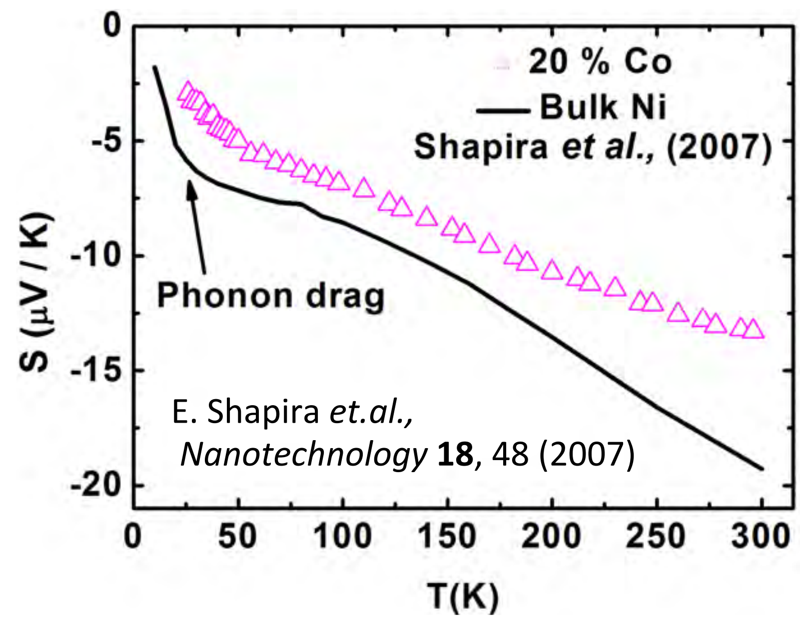
- Mott-like contribution to thermopower extracted from phenomenological decomposition

- Calculation using generalized Mott relation shows band structure effects.

$$S = -\frac{1}{eT}\frac{\int \sigma(\varepsilon)(\varepsilon-\mu)\frac{-\partial f(\varepsilon,\mu,T)}{\partial \varepsilon}d\varepsilon}{\int \sigma(\varepsilon)\frac{-\partial f(\varepsilon,\mu,T)}{\partial \varepsilon}d\varepsilon}$$

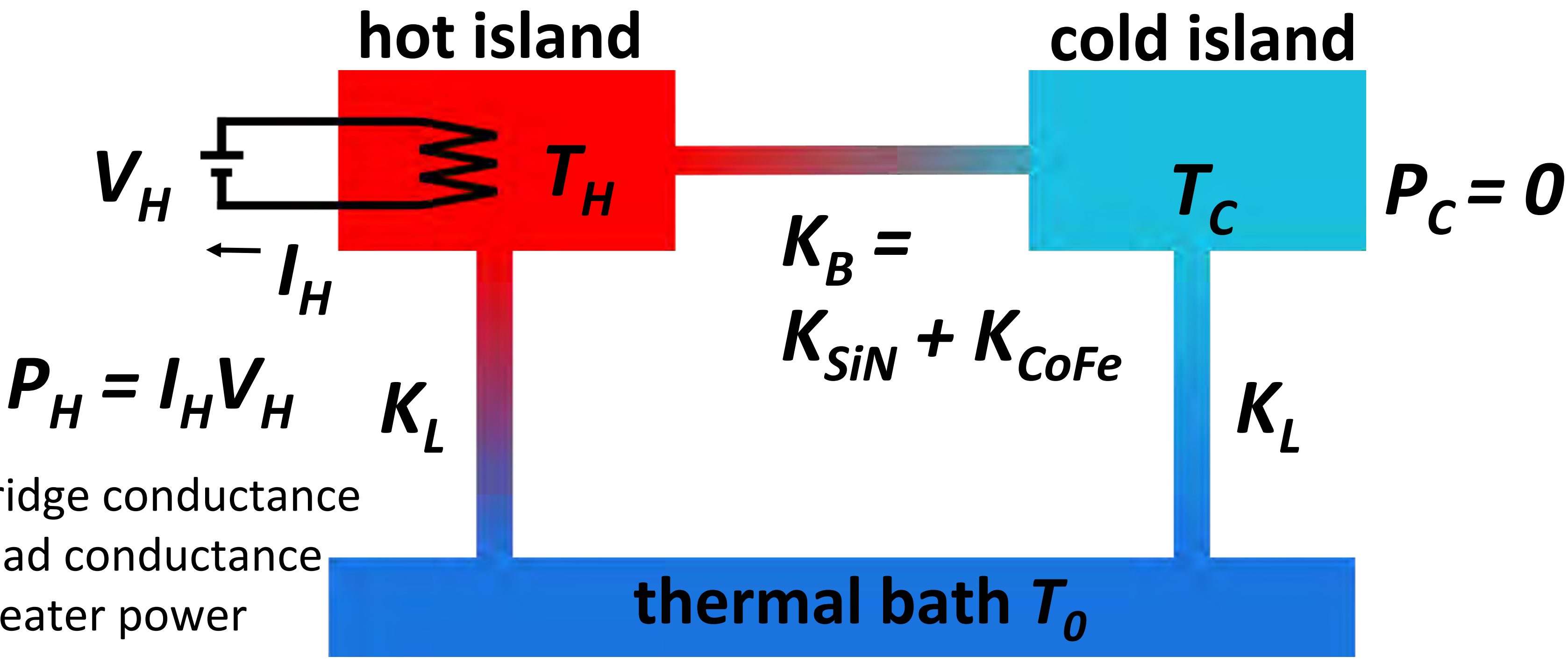
Residual thermopower





- $\boldsymbol{S_{residue}}$ *(T)* = $\boldsymbol{S - S_D - S_M}$ is (much) smaller than $\mathbf{S_M}$ and $\mathbf{S_D}$
- For films with x_{Co}= 0.2 and 0.22,
  $\boldsymbol{S_{residue}}$ is similar to phonon drag in bulk Ni (and Al reference leads)
- For films with x_{Co}= 0.36, 0.5 and 0.7, effective in-elastic scattering and phonon drag effect

Thermal platform model for thermal conductance



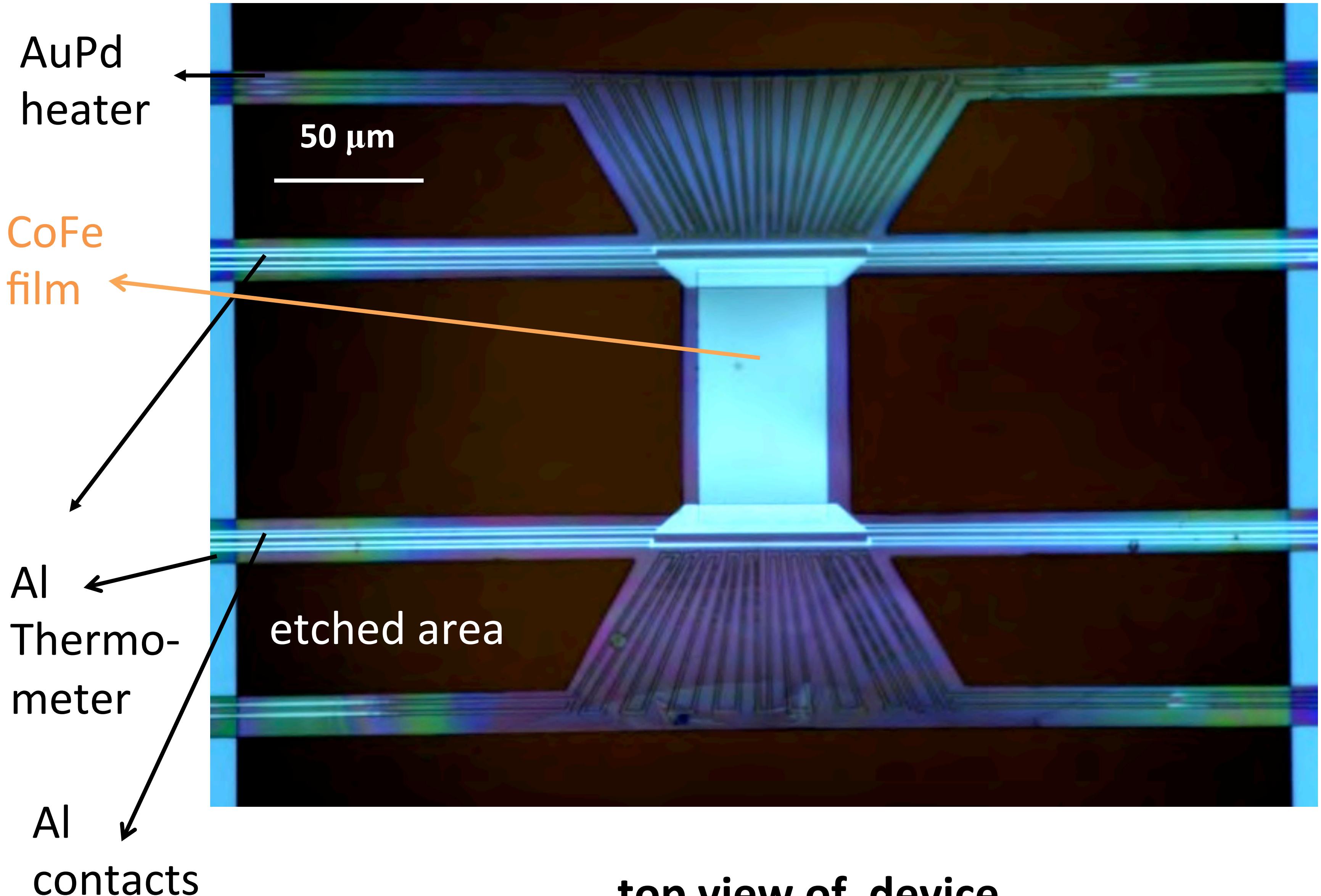
K_B = bridge conductance
K_L = lead conductance
P_H = heater power

Solution of 1D thermal diffusion equation →

$$\boxed{T_H = T_0 + \frac{K_L + K_B}{K_L(K_L + 2K_B)} P_H, \quad T_C = T_0 + \frac{K_B}{K_L(K_L + 2K_B)} P_H}$$

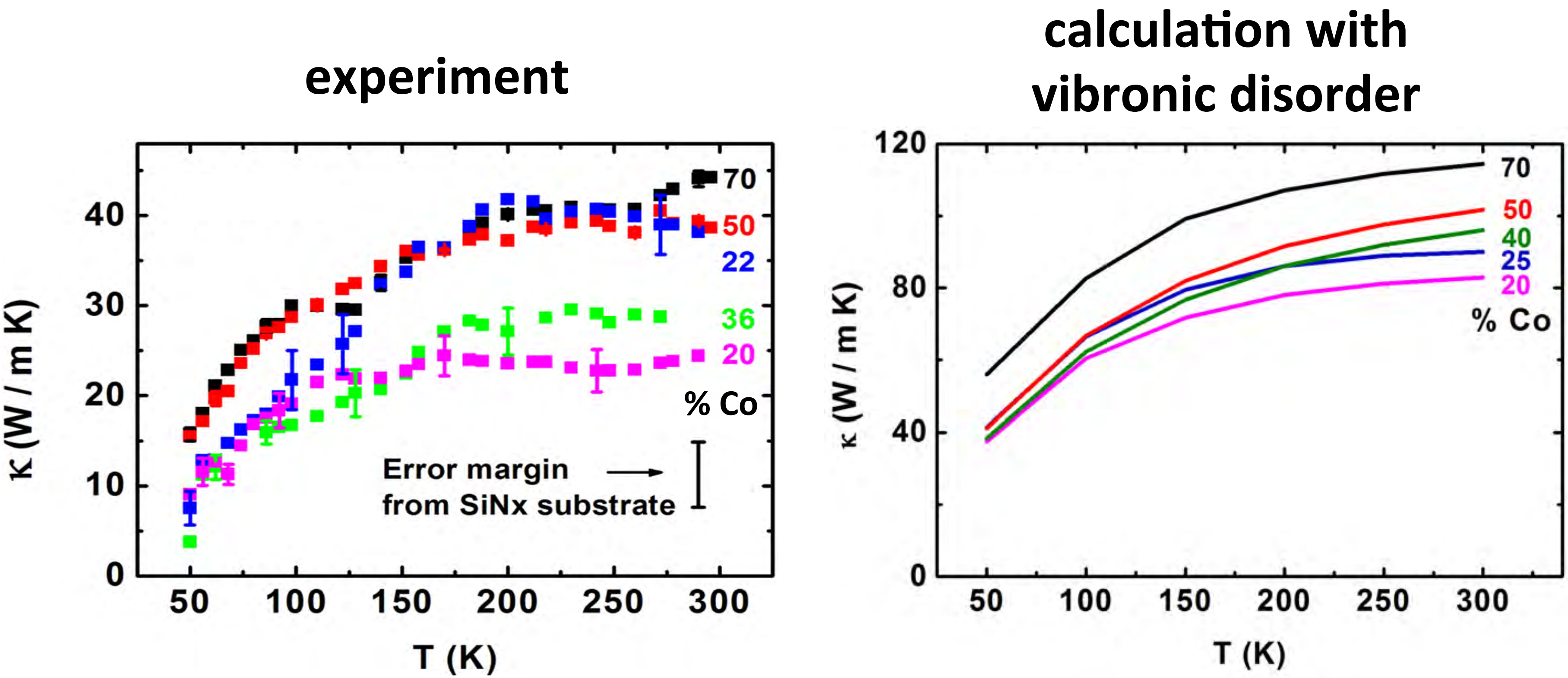
P. Kim *et al. Phys. Rev. Lett.* **87**, 215502 (2001)
R. Sultan *et al. J. Appl. Phys.* **105**, 043501 (2009)

SiN based suspended microcalorimeter



top view of device

Comparison with microscopic calculation results

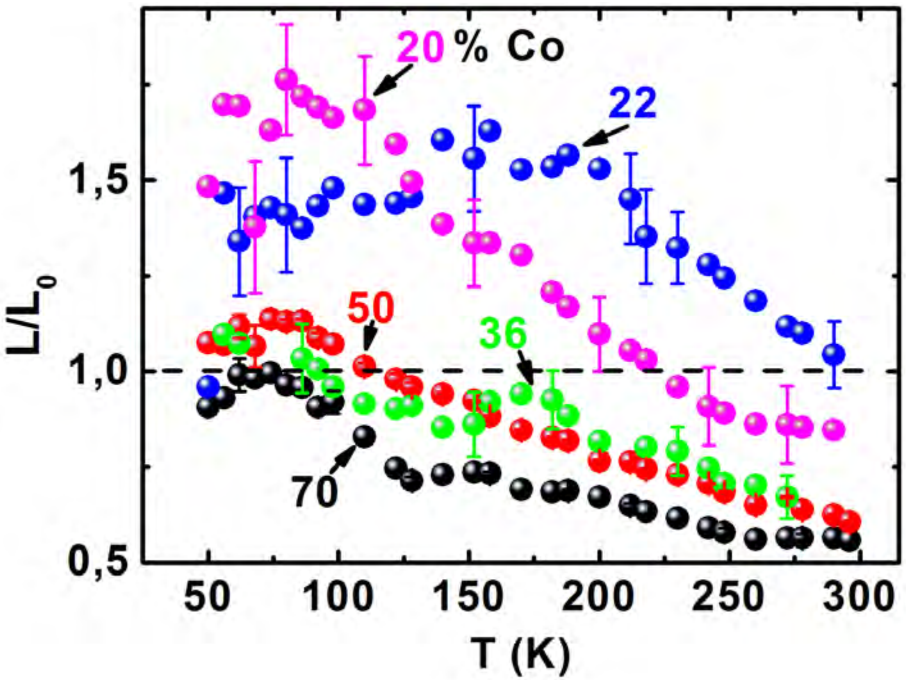


- theory reproduces nicely the concentration dependence
- numbers are a factor two larger values of κ

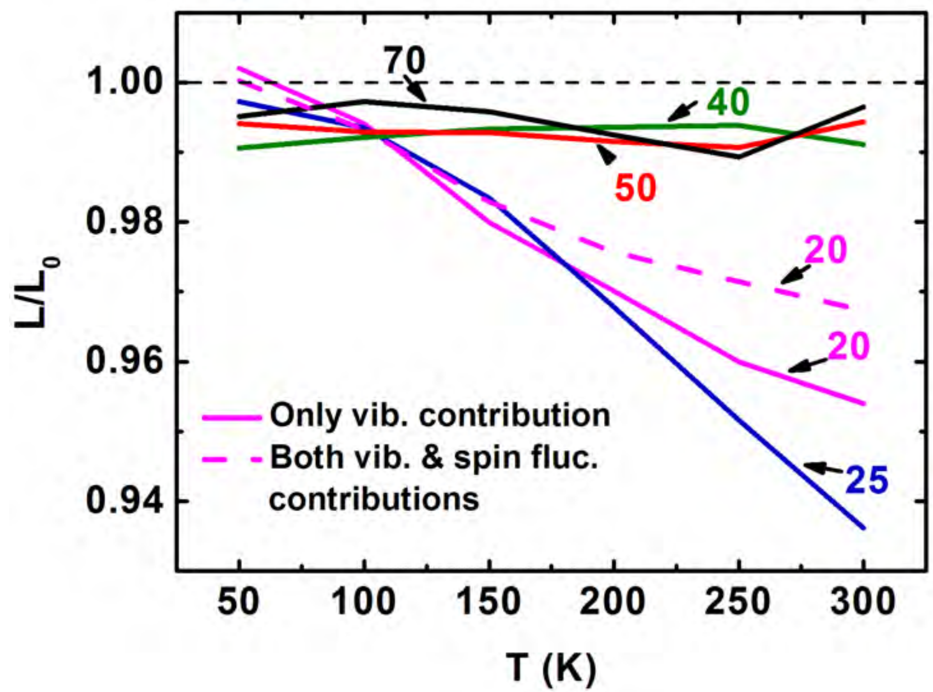
  - most probably connected to underestimation of ρ in theory
- theory works better than for ρ and **S**.

Lorenz ratio and violation of Wiedemann-Franz law

experiment



theory



- Lorenz number $L(T) / L_0 = \kappa(T)\, \rho(T) / T$
- $L > L_0$: For films with x_{Co}=0.2 and 0.22 due to the significant phonon (magnon?) contribution to thermal conductivity (no fcc phase precipitation)
- $L < L_0$: For films with x_{Co}=0.36, 0.5 and 0.7 due to enhanced inelastic scattering of electrons with phonons and magnons (with fcc phase precipitation)

Conclusions

- Experimental platform enables study of all transport coefficients of the very same film
- Theory significantly underestimates composition dependent resistivity
- Thermopower is phenomenologically decomposed into Mott-like and Magnon drag terms - the latter changes sign for large Co-concentrations
- Thermal conductivity is mainly electronic
- Significant deviations from Wiedemann-Franz law observed in experiment.