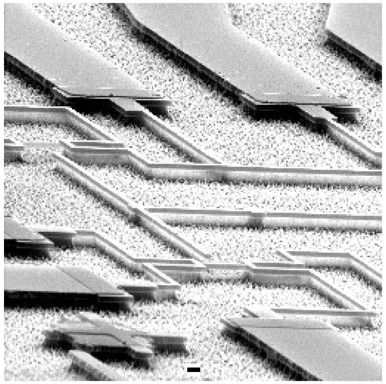
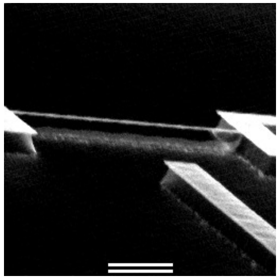


Electron Dephasing Times in Disordered Metals

J. J. Lin

National Chiao Tung University (Taiwan)



Quantum Phenomena at Low Temperatures

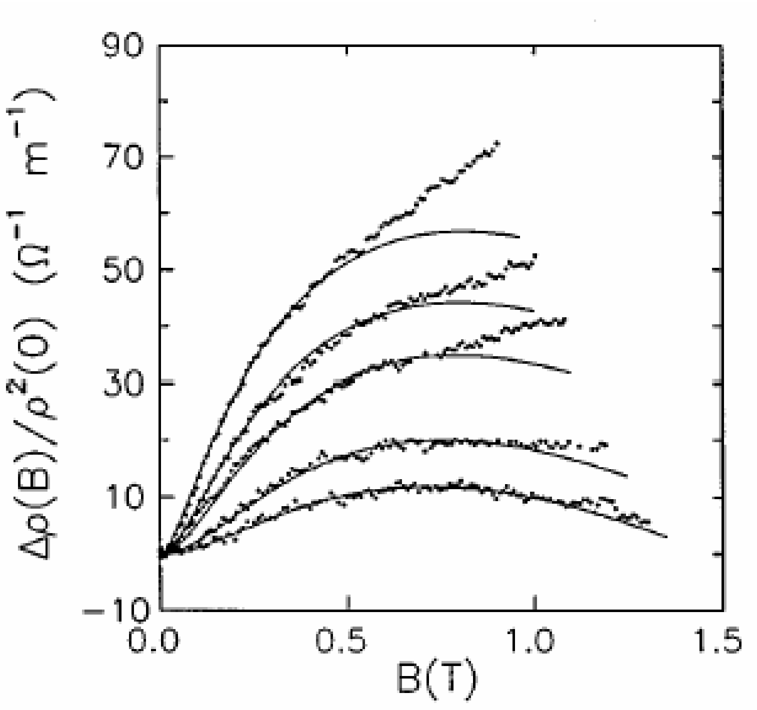
ULTI III Users Meeting

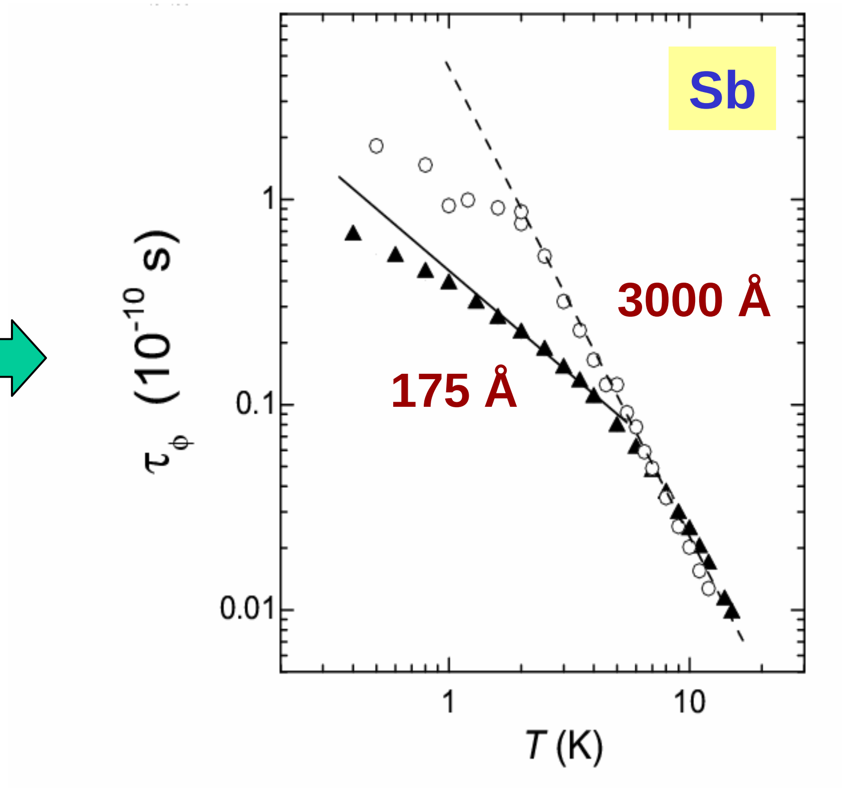
Lammi Biological Station, January 2004

Experimental Method

Weak-localization magnetoresistances

Electron dephasing times as function of temperature





Outline

- **Experimental electron dephasing times from weak-localization studies: low-field magnetoresistance**

- **Electron-phonon scattering in disordered metals**
  ***weakened* or *enhanced* electron-phonon interaction**
  ***static* or *vibrating* defects (impurities)**

- **Very short dephasing lengths in some cases**

- **Saturation in electron dephasing time as $T \to 0$**
  magnetic-impurity scattering ?
  two-level systems ?
  electron-electron interactions ?
  ……

The Problem

- To study the electron-phonon interaction in disordered metals

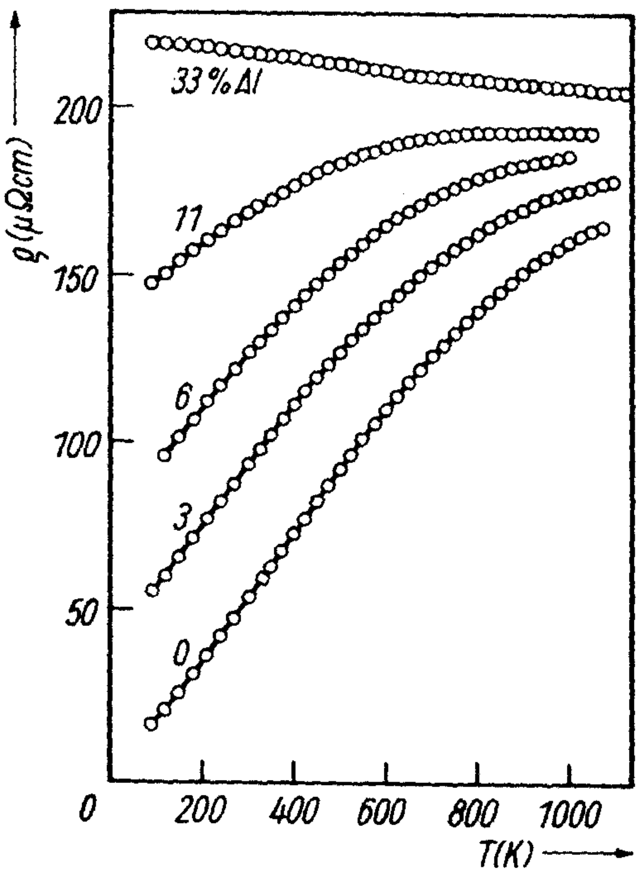
The dirty limit for electron-phonon interaction:

$$q\,l \approx \frac{k_B T}{\hbar v_s}\, l \ll 1$$

q **= wavenumber of thermal phonons**
l **= electron mean free path**
v_s = sound velocity of acoustic phonons

Short Mean Free Path and the Dirty Limit

$Ti_{100-x}Al_x$



- $Ti_{73}Al_{27}$ has a very high resistivity

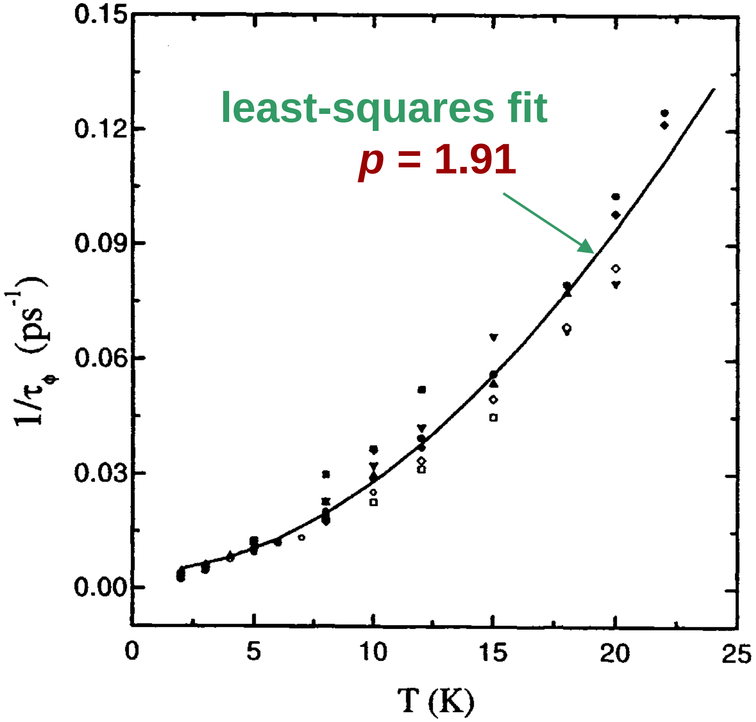
$\Rightarrow$ Suitable for 3D weak localization studies

- Sn-doped $Ti_{73}Al_{27}$ alloy possesses strong spin-orbit scattering

$\Rightarrow$ τ_φ is the only fitting parameter

Mooij,
Phys. Stat. Sol. (a) 17 (1973) 521

Electron-Phonon Time in $Ti_{73-x}Al_{27}Sn_x$ alloys



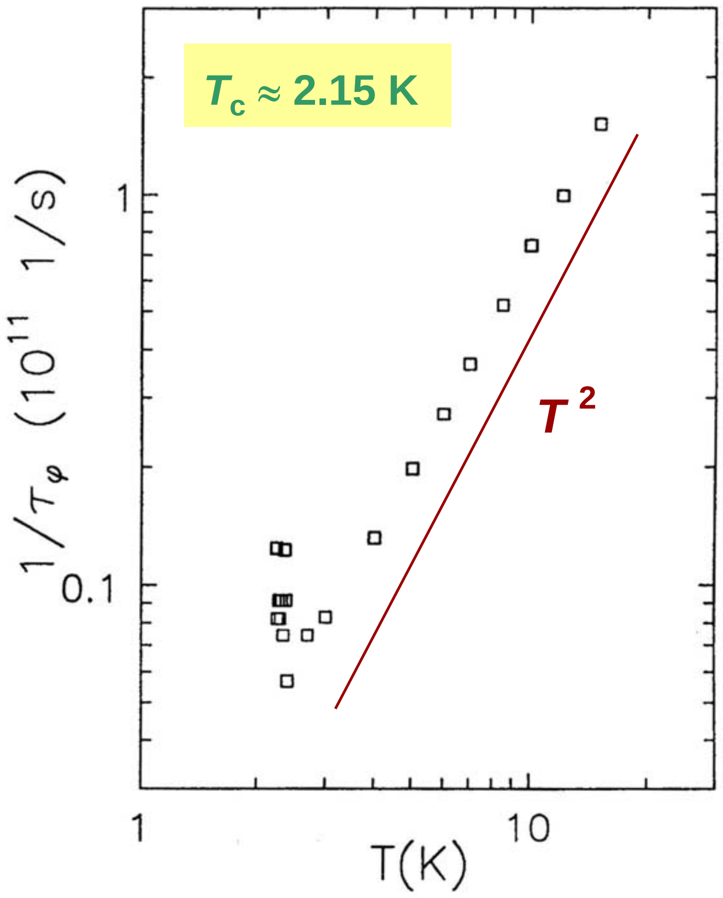
$\rho(10\ K) \approx 225\ \mu\Omega\ cm$

$l \approx 2$ Å (mean free path)

$ql \approx 0.006\ T << 1$

- In these alloys, the electron-phonon interaction is well within the dirty limit
- The exponent of temperature for τ_{ep}^{-1} is $p \approx 2$

Electron-Phonon Time in Superconducting $Ti_{88}Sn_{22}$ Alloys



$\tau_\varphi^{-1} \propto T^2$ **in the normal state**

Jian, Lin (1996)

Electron-Phonon Interaction in Disordered Metals

- **For many years, the electron-phonon interaction in impure conductors has been thought to be well understood**

Pippard (1955); Schmid (1973, 1985, 1986); Sergeev, Reizer (1986); Belitz (1987)

Conventional wisdom:

- **Impurity atoms (defects) move in phase with vibrating lattice atoms, resulting in long-wavelength phonons being unable to scatter electrons** **(the `Pippard ineffectiveness condition')**

$$\tau_{ep}^{-1} \propto T^4 l \qquad (ql < 1)$$

Cf. ***weakened*** ***e*-ph interaction, compared with the pure case:**

$$\tau_{ep}^{-1} \propto T^3 \qquad (ql > 1)$$

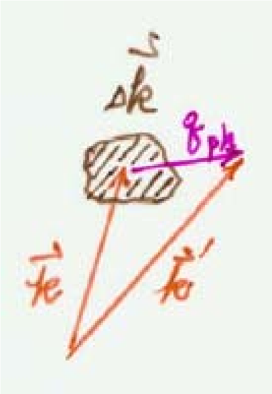
Pippard Ineffectiveness Condition

- **Electrons having very short mean free path are not effective in scattering long wavelength phonons**

$$l < \lambda_{ph} = \frac{2\pi}{q} \quad \text{or} \quad ql < 1$$

- **In disordered metals, the electron wavenumber is subject to an uncertainty of**

$$\Delta k \sim \frac{1}{l}$$



$\Rightarrow$ **Effective scattering requires:**

$$q > \Delta k \sim \frac{1}{l} \quad \text{or} \quad ql > 1$$

Cf*. Kittel:** ***Quantum Theory of Solids*, Ziman:** ***Electrons and Phonons

Experimental situation:

- A $\tau_{ep}^{-1} \propto T^{2}$ has been observed in metal films and narrow wires from time to time

$\Rightarrow$ But, basically, no systematic studies on both the temperature and mean free path dependences of τ_{ep}

Theoretical situation (up to 1999):

- "We have thus no evidence now indicating the existence of a new mechanism of phase relaxation which has heretofore not been analyzed theoretically and which could account for a function of the type $\tau_\varphi \sim T^{-2}$."

[Altshuler, Aronov, Gershenson, Sharvin, Sov. Sci. Rev., Sect. A 9 (1987) 223]

Theories seem to suggest that a T^2 dependence is not possible

Why 3D Superconducting $Ti_{1-x}Al_x$ Alloys

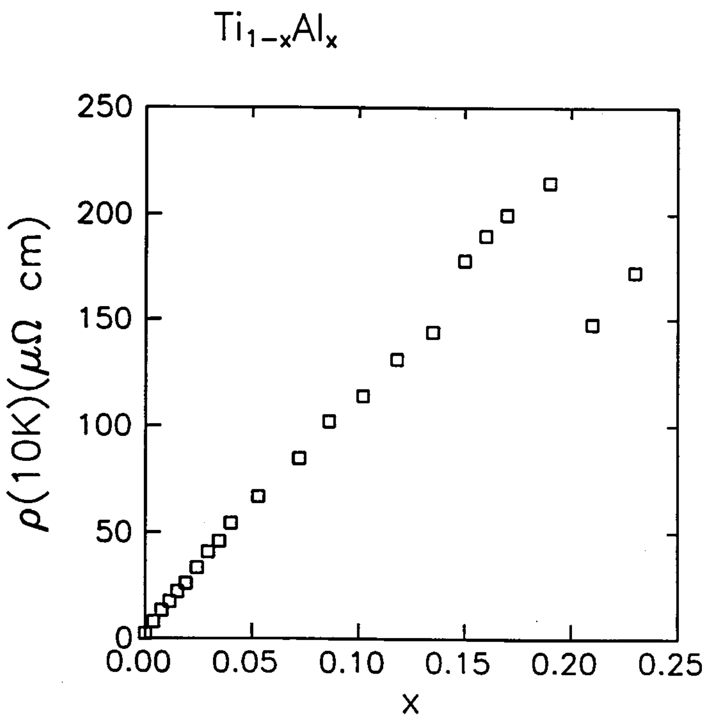
- Arc-melted, single-phased alloys for $x \leq 0.13$
- Resistivity (disorder) increases linearly with increasing x

$\Rightarrow$ to study disorder dependence of τ_{ep}

- Diffusion constant can be determined from H_{c2} measurement
- Fe, Co, Cr, and Ni do **not** form localized moments in a Ti host
- 3D mesoscopic samples: $(L_\varphi < L_x, L_y, L_z)$

$$\tau_\varphi^{-1} = \tau_{ep}^{-1} + \tau_{ee}^{-1} + \tau_s^{-1} \approx \tau_{ep}^{-1}$$

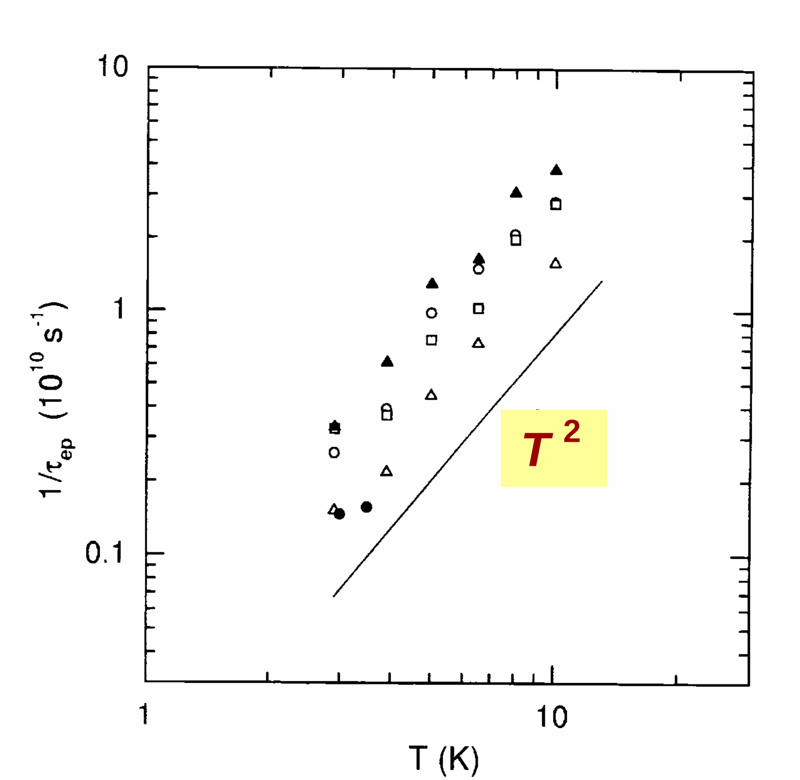
(at not too low temperatures)

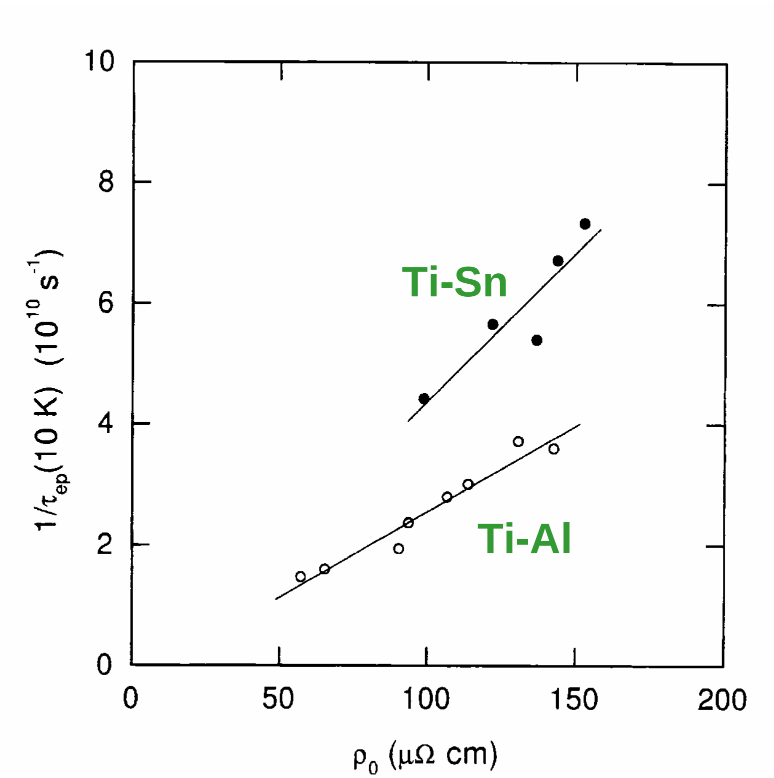


The resistivity increases linearly with increasing *x*

$Ti_{1-x}Al_x$ alloys with a wide range of disorder: Compositional Disorder

- The temperature dependence of τ_{ep} is difficult to measure
- The disorder dependence of τ_{ep} is even much more difficult to measure





$$\tau_{ep}^{-1} \propto T^2 \rho_0 \propto T^2 l^{-1}$$

Lin & Wu,
Europhys. Lett. 29, 141 (1995)

Why non-superconducting $Au_{50}Pd_{50}$ thick films

- A prototypical disordered metal, by DC or RF sputtering
- Resistivity was "tuned" by adjusting the deposition rate

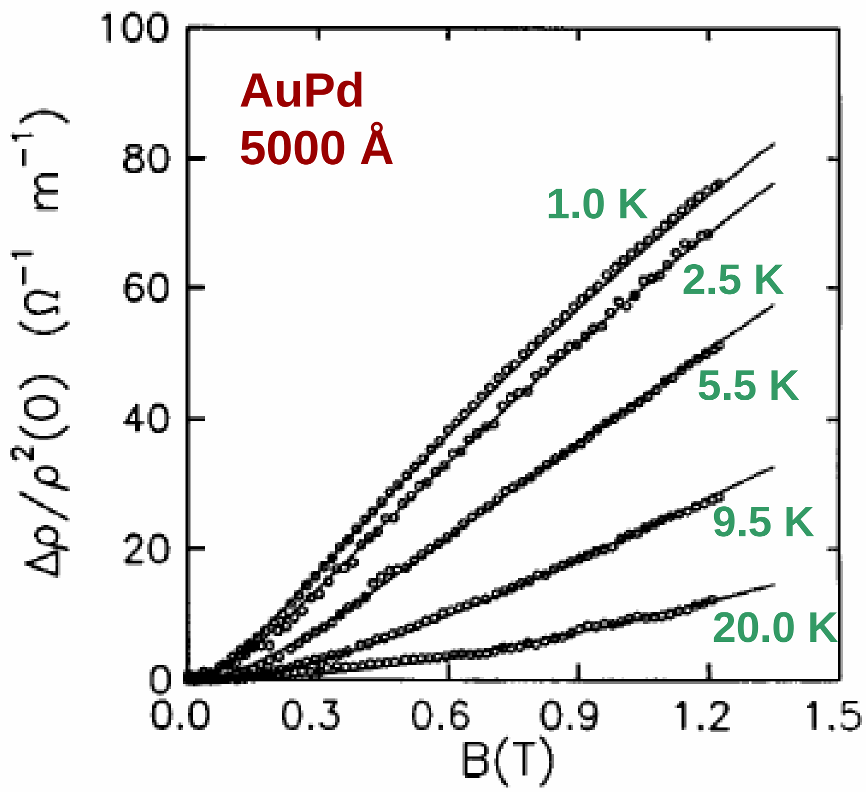
  $\Rightarrow$ a wide range of electron mean free path
- Strong spin-orbit scattering $\Rightarrow \tau_\varphi$ is the sole fitting parameter
- Absence of superconductivity

  $\Rightarrow \tau_\varphi(T \to 0)$ can be directly measured

$$\tau_\varphi^{-1} = \tau_{ep}^{-1} + \tau_{ee}^{-1} + (\tau_\varphi^0)^{-1} \approx \tau_{ep}^{-1} + C$$

experimentally measured

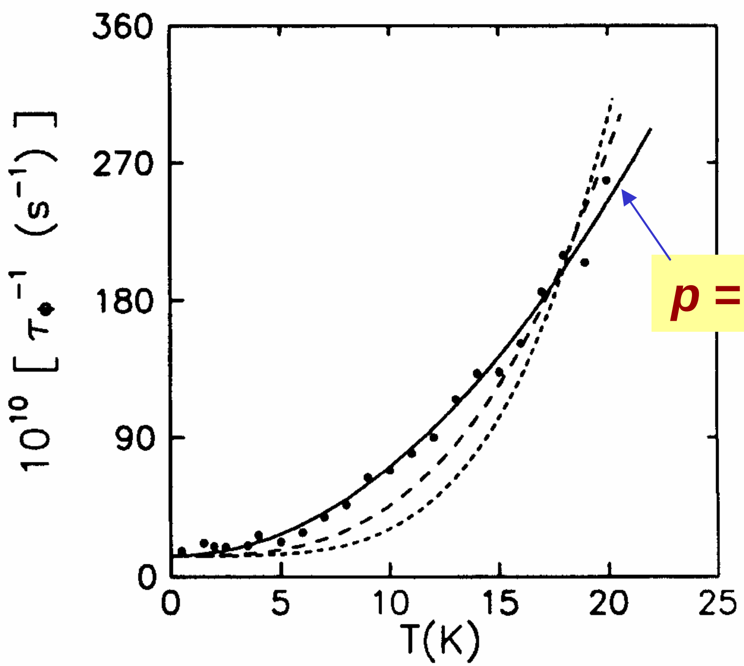
Measured & theoretical magnetoresistances

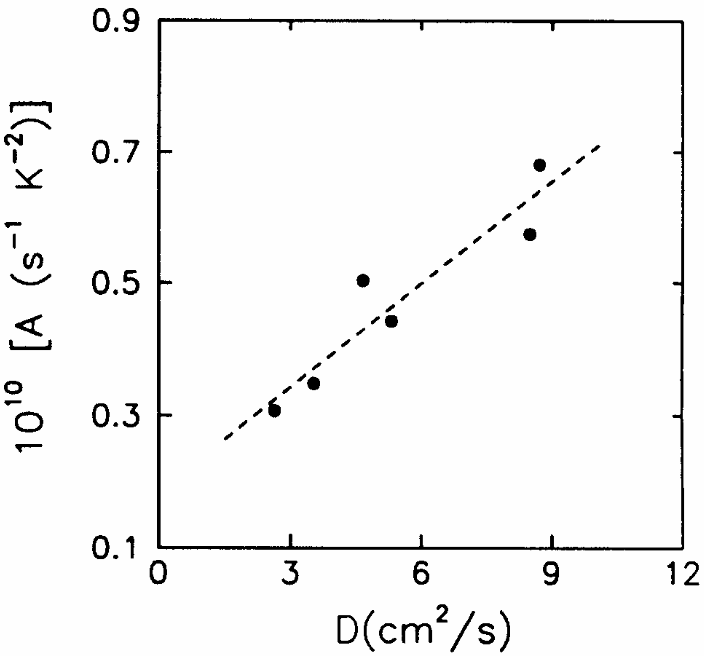


- The 3D weak-localization theoretical predictions (solid curves) can well describe the experimental data

$Au_{50}Pd_{50}$ Thick Films: Structural Disorder

- The temperature dependence of τ_{ep} is difficult to measure
- The disorder dependence of τ_{ep} is even much more difficult to measure

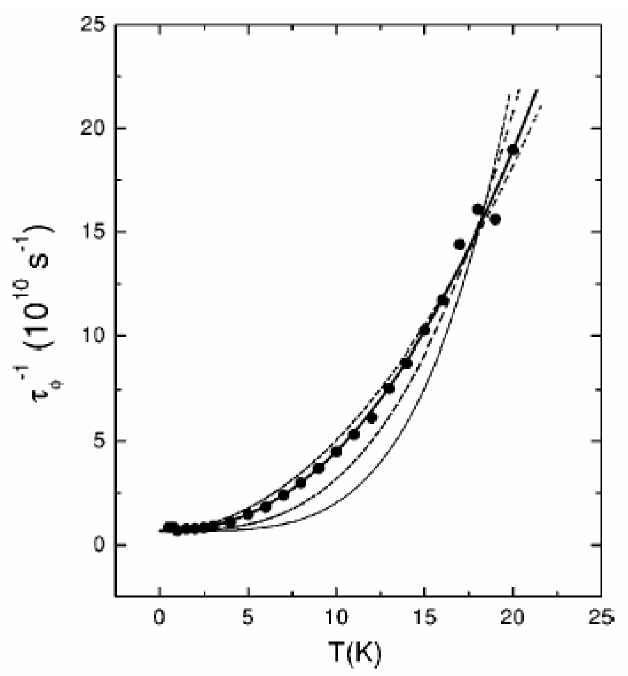


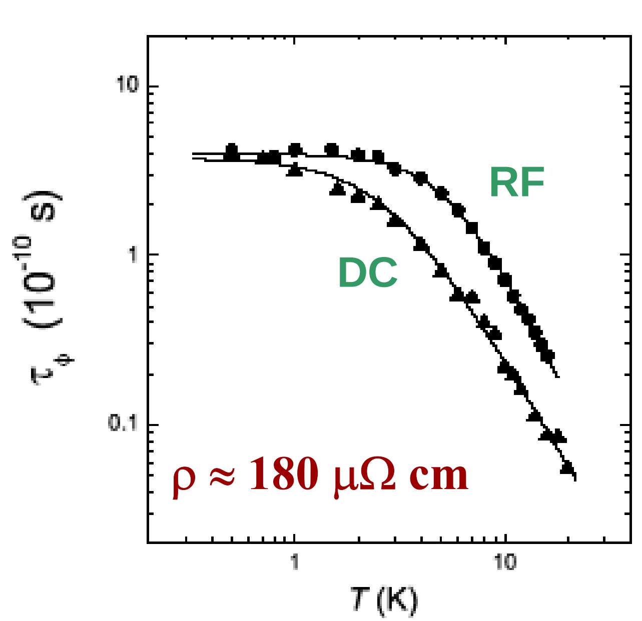


$$\tau_\varphi^{-1} = C + \tau_{ep}^{-1} = C + AT^p \Rightarrow \tau_{ep}^{-1} \propto T^2 l$$

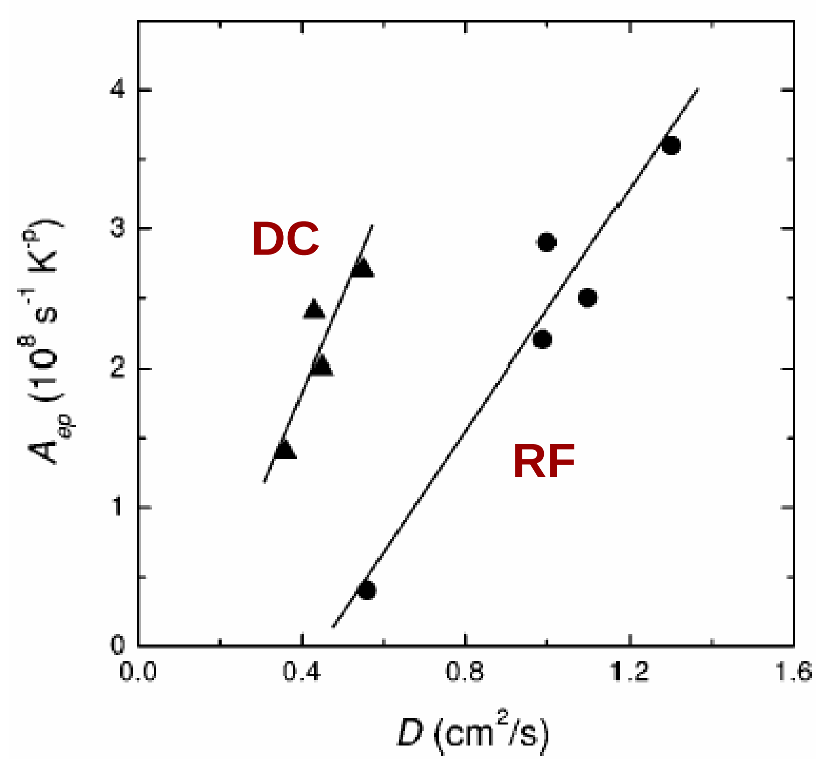
Zhong & Lin,
Phys. Rev. Lett. 80, 588 (1998)

$Ag_{40}Pd_{60}$ think films





$$\tau_{ep}^{-1} \approx A_{ep}\, T^{2}$$



Zhong *et al.*,
Phys. Rev. B 66, 132202 (2002)

New theory

pp. 6041-6047

PHYSICAL REVIEW B VOLUME 61, NUMBER 9 1 MARCH 2000-I

Electron-phonon interaction in disordered conductors: Static and vibrating scattering potentials

A. Sergeev and V. Mitin
Department of ECE, Wayne State University, Detroit, Michigan 48202
(Received 2 July 1999; revised manuscript received 23 September 1999)

See, also, Europhys. Lett. 51 (2000) 641

• **Defects such as heavy (light) impurities and tough boundaries may not move in phase with deformed lattice atoms**

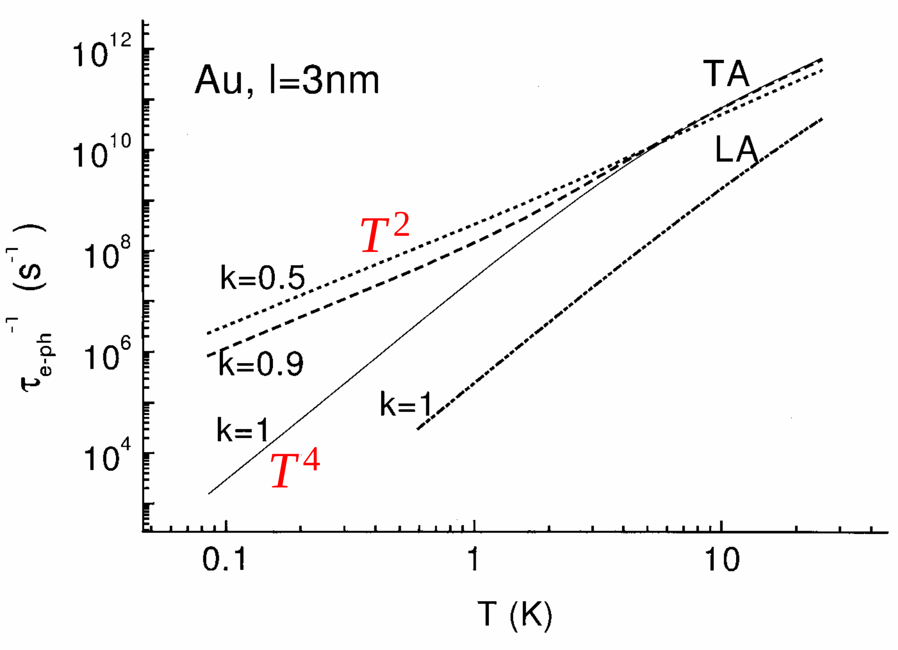
$\Rightarrow$ **static impurities result in *enhanced* e-ph interaction:**

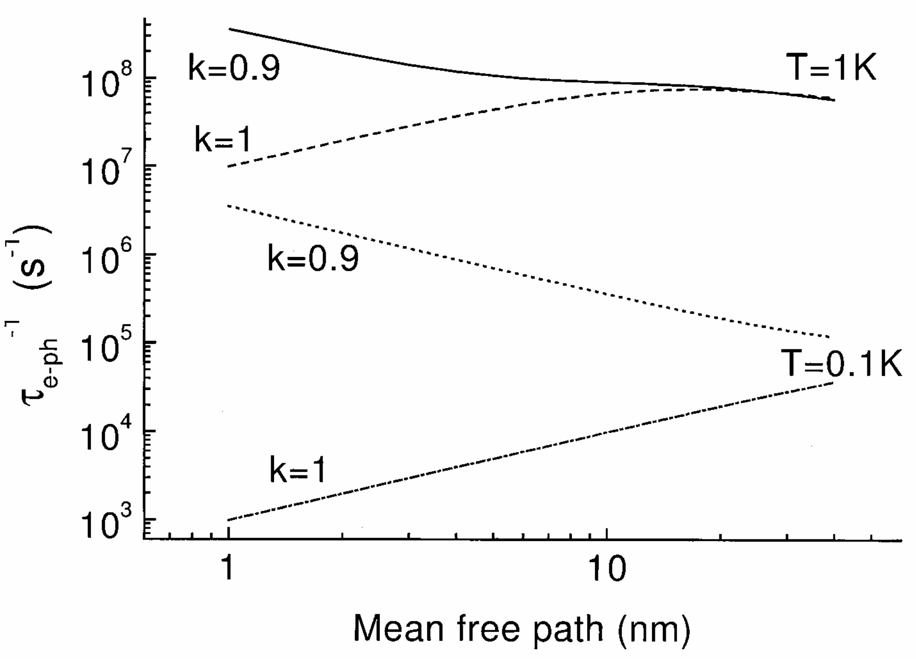
$$\tau_{ep}^{-1} \propto T^{2} l^{-1}$$

Cf. **vibrating impurities** $\Rightarrow$ **standard result:** $\tau_{ep}^{-1} \propto T^{4} l$

Predictions of the Sergeev-Mitin theory

k **=1, if impurities move in phase with deformed lattice atoms**
k **= 0, if impurities remain *completely static***



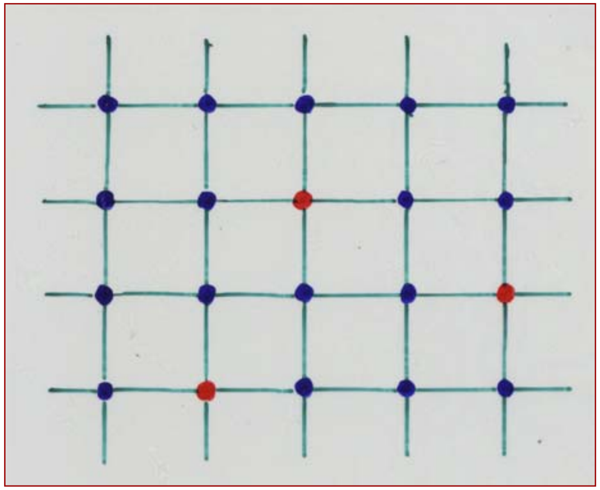


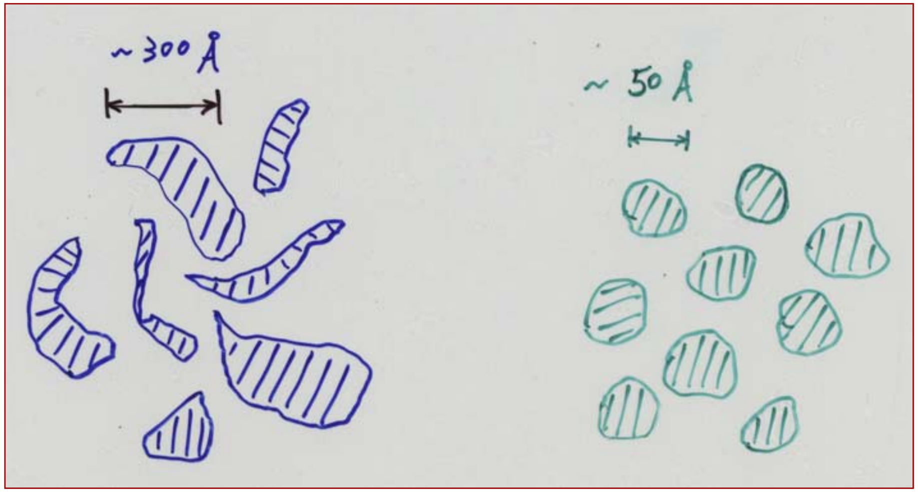
- **The *T* dependence of τ_{ep}^{-1} can change from T^4 to T^2**
- **The disorder dependence of τ_{ep}^{-1} can change from *l* to l^{-1}**

Comparison with Previous Works

- 3D Granular films are not microscopically homogeneous
  $\Rightarrow$ no disorder dependence was observed

- 3D amorphous metals are already in the limit of strong randomness $\Rightarrow$ level of disorder cannot be "tuned"





<u>microscopically homogeneous:</u>
Al atoms randomly substitute for Ti lattice sites

<u>microscopically inhomogeneous:</u>
metal or insulator grains of tens or hundreds Å

Comparison with Previous Works (continued)

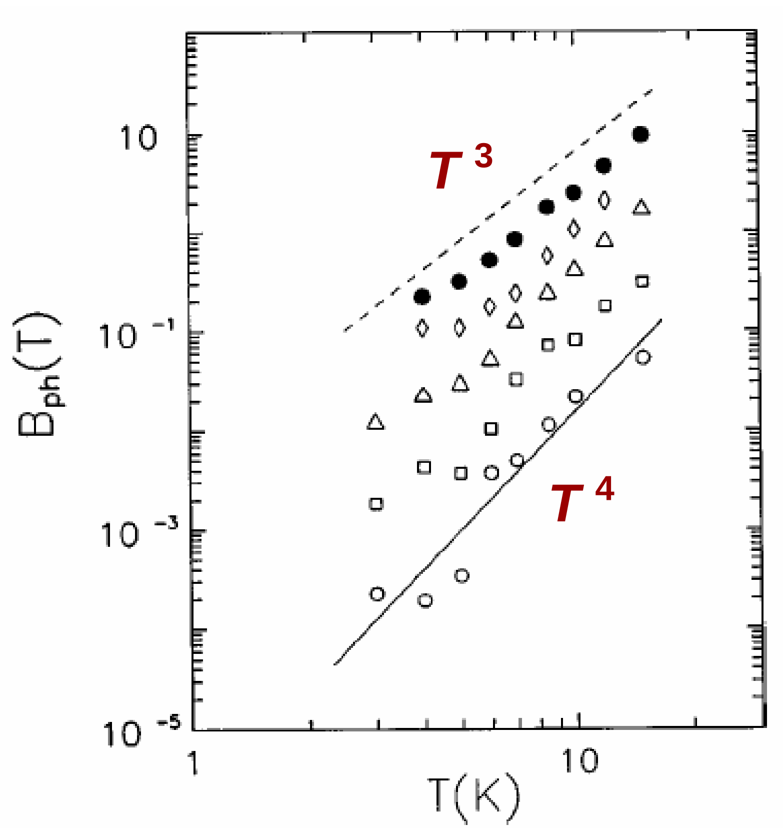
<u>In reduced dimensions:</u>

many fitting parameters: $\tau_{in}^{-1} = \tau_{ep}^{-1} + \tau_{ee}^{-1} = AT^{p} + BT^{q}$

even worse: $\tau_{ep}^{-1} < \tau_{ee}^{-1}$

- **Phonon dimensionality is not well defined, depending on the film thickness, phonon wavelength, acoustic transparency of the film-substrate interface, etc.**

$Ti_{1-x}Ge_x$



$$B_{ph} = \frac{\hbar}{4eD\tau_{ph}}$$

- We have shown that a T^2 dependence is often observed in real metals

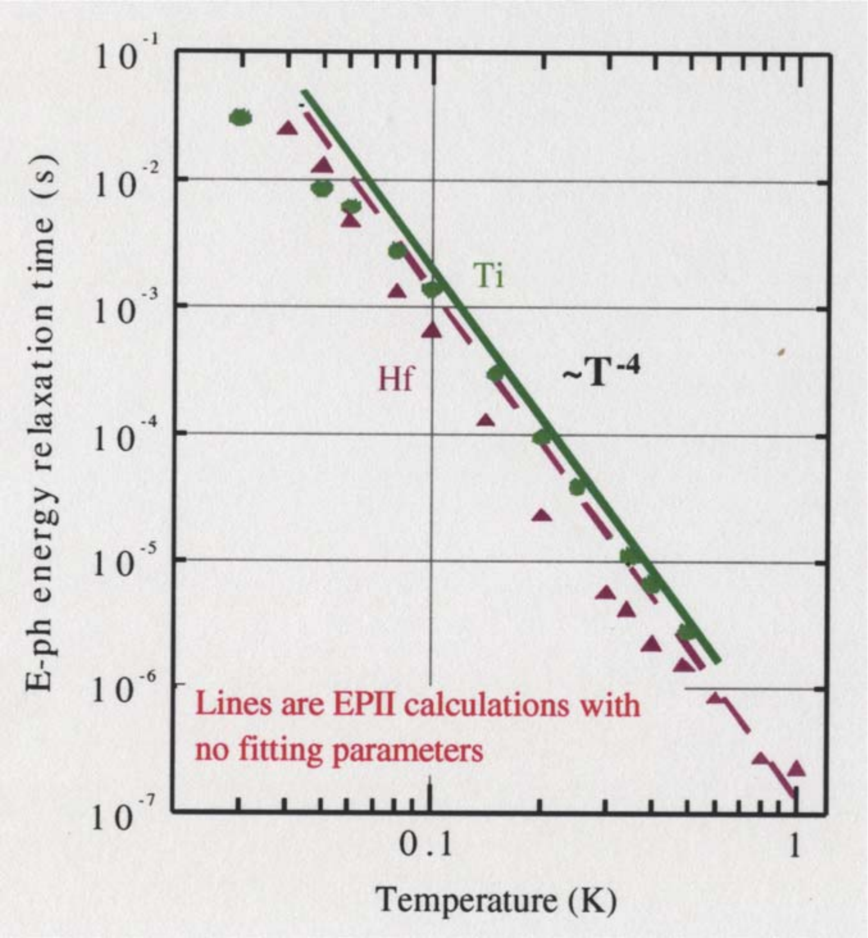
- But, other power law is not impossible

$\Rightarrow$ Apart from the total level of disorder, the temperature and disorder dependences of τ_{ep} is very sensitive to the microscopic quality of the defects

Question:
Can one observe the T^4 dependence

Wu *et al.*,
Phys. Rev. B 57, 11232 (1998)

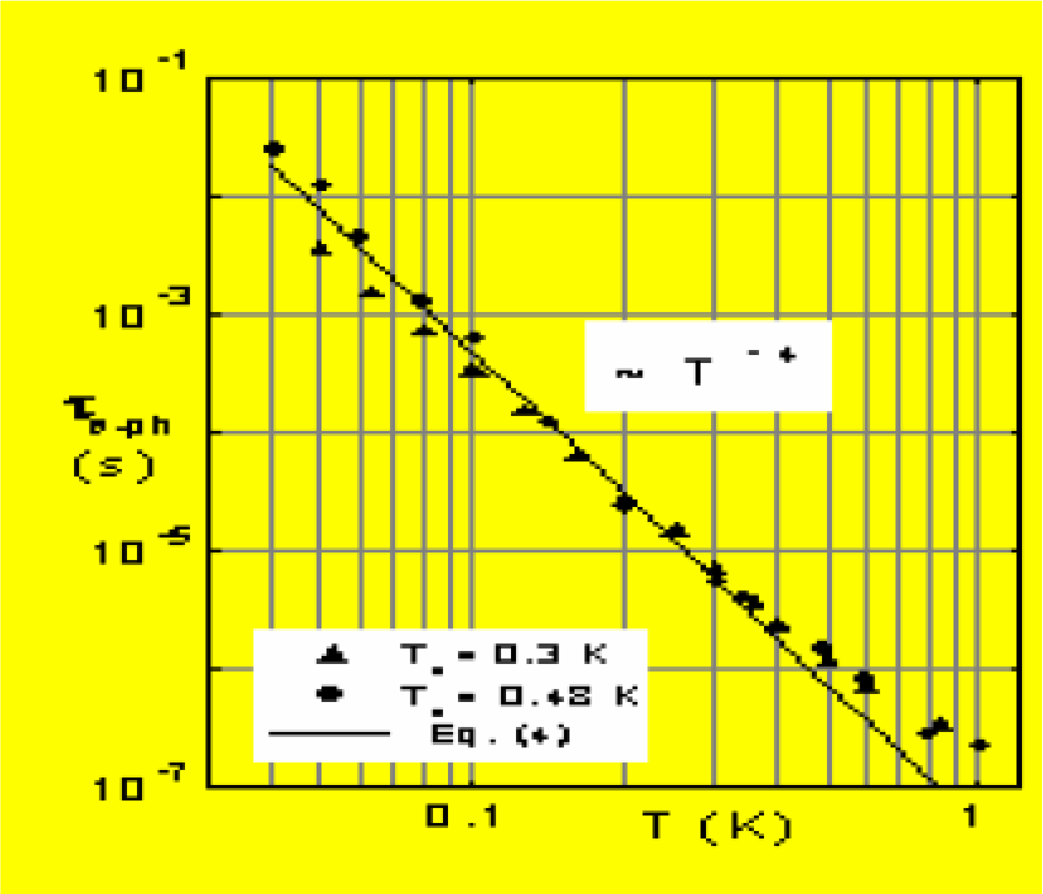
Hafnium and Titanium thin films on sapphire substrates



- From thermal conductance measurement, a T^{-4} dependence was observed between 40-700 mK

- But, a weaker temperature dependence above 0.7 K, where $ql \approx 0.04 << 1$

Gershenson *et al*.,
Appl. Phys. Lett. 79, 2049 (2001)



Gershenson *et al*.,
Appl. Phys. Lett. 79, 2049 (2001)

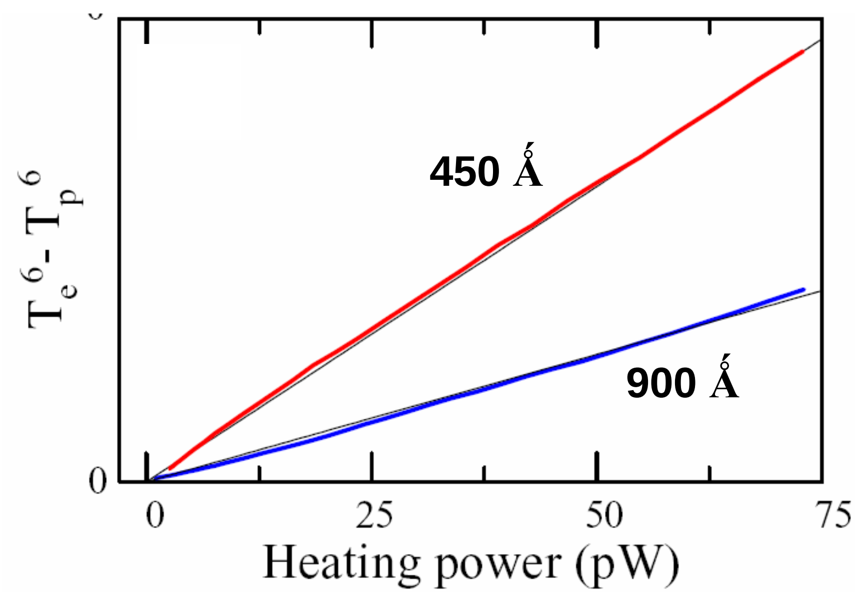
Recent experiment

arXiv:cond-mat/0311031

Electrons and phonons at sub-Kelvin temperatures: validation of the disorder-mediated scattering theory

I. J. Maasilta, J. T. Karvonen, J. M. Kivioja*, and L. J. Taskinen
NanoScience Center, Department of Physics, P.O. Box 35, FIN-40014 University of Jyväskylä, Finland
(Dated: October 4, 2003)

From Joule heating the electron gas and measuring both the electron and the lattice temperatures simultaneously, τ_{ep} is determined



- **First observation of disorder-mediated e-ph scattering in Cu thin films: $\tau_{ep}^{-1} \sim T^4$**
- **Measuring temperatures:**
  60–135 mK (900 Å)
  60–195 mK (450 Å)

Recent experiment

pp. 3201-3205

JOURNAL OF APPLIED PHYSICS VOLUME 94, NUMBER 5 1 SEPTEMBER 2003

Electron–phonon heat transport and electronic thermal conductivity in heavily doped silicon-on-insulator film

P. Kivinen,[a] A. Savin, M. Zgirski, and P. Törmä
Department of Physics, University of Jyväskylä, P.O. Box 35, FIN-40014 Jyväskylä, Finland

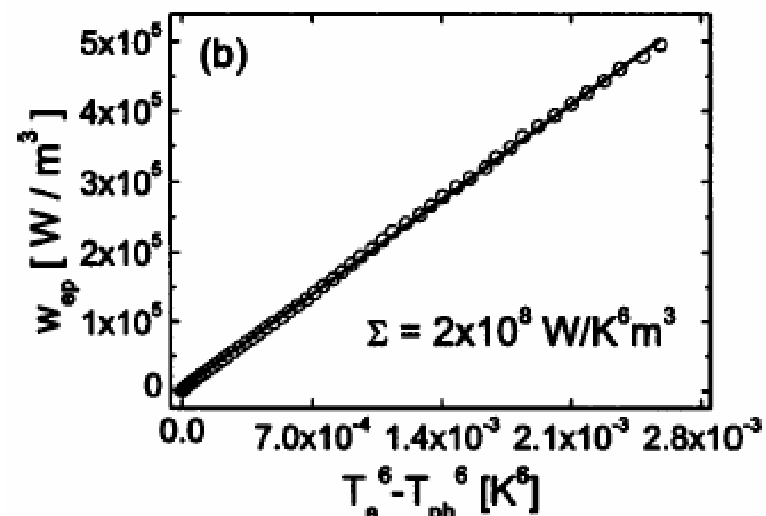
J. Pekola
Low Temperature Laboratory, Helsinki University of Technology, P.O. Box 2200, 02015 HUT Helsinki, Finland

M. Prunnila and J. Ahopelto
VTT Center for Microelectronics, P.O. Box 1101, FIN-2044 VTT, Finland

* **Heavily doped Si** is in the dirty limit at mK and the phonon system has **a complete phonon drag**

• The heat flow between electron and phonon systems has a T^6 dependence $\Rightarrow$ $\tau_{ep}^{-1} \propto T^4$ for the e-ph interaction relaxation time

• Measuring temperature: **100-500 mK**



Applied power versus ($T_e^6 - T_{ph}^6$)

The sample needs to have:

- $ql < 1$
- Contain little non-vibrating disorder
- Have 3D phonons coupled to electrons by the deformation potential

The Heat flow from electrons to phonons:

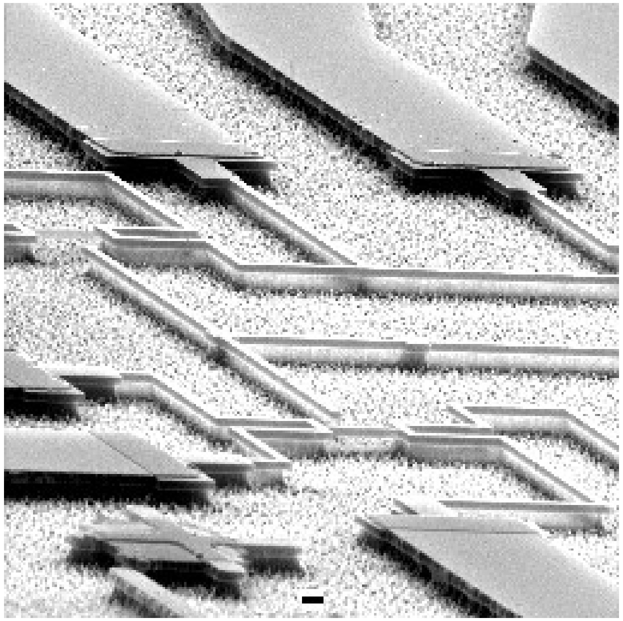
The change of electron temperature is determined by:

$$dP = C_e \, dT_e / \tau_{ep} \qquad (C_e\text{: electronic heat capacity})$$

By substituting $\tau_{ep}^{-1} = \alpha T^{p} \;\Rightarrow\; P = \Sigma\, \Omega\, (T_e^{p+2} - T_{ph}^{p+2})$

Σ: material-dependent electron-phonon coupling constant
Ω: the volume of the sample

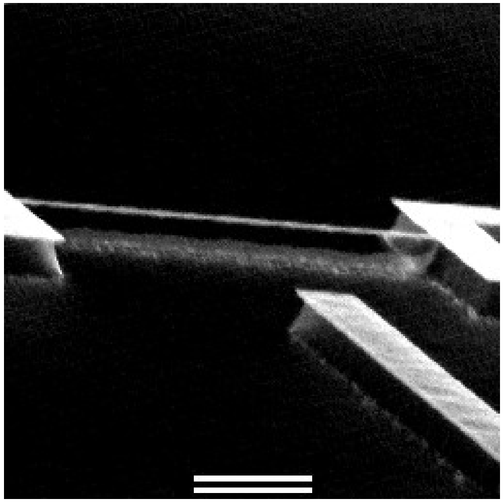
Yuan-Liang Zhong
Chiidong Chen
Juhn-Jong Lin

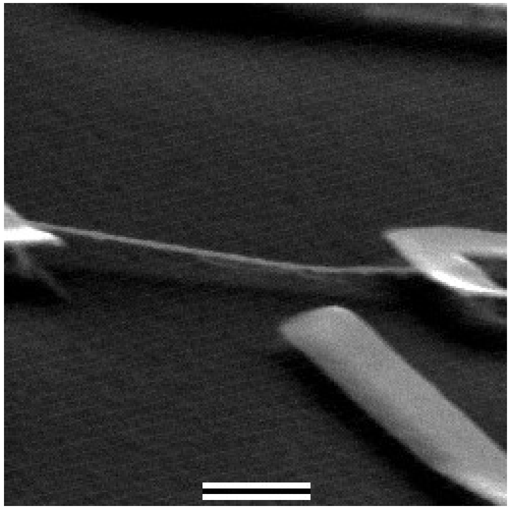


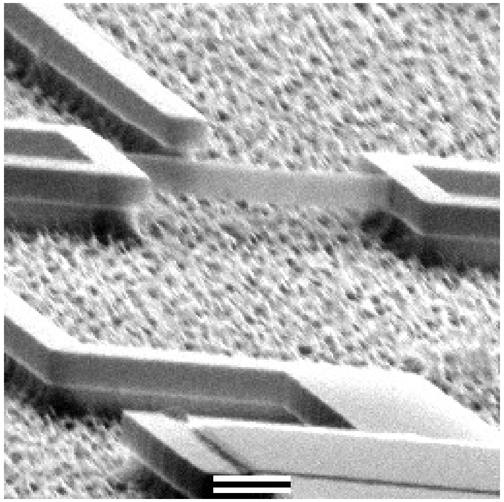
Supported and free-standing films and wires for studies of τ_{ep}

Samples were prepared by *e*-beam lithography technique

$\Rightarrow$ e.g., phonon confinement effect



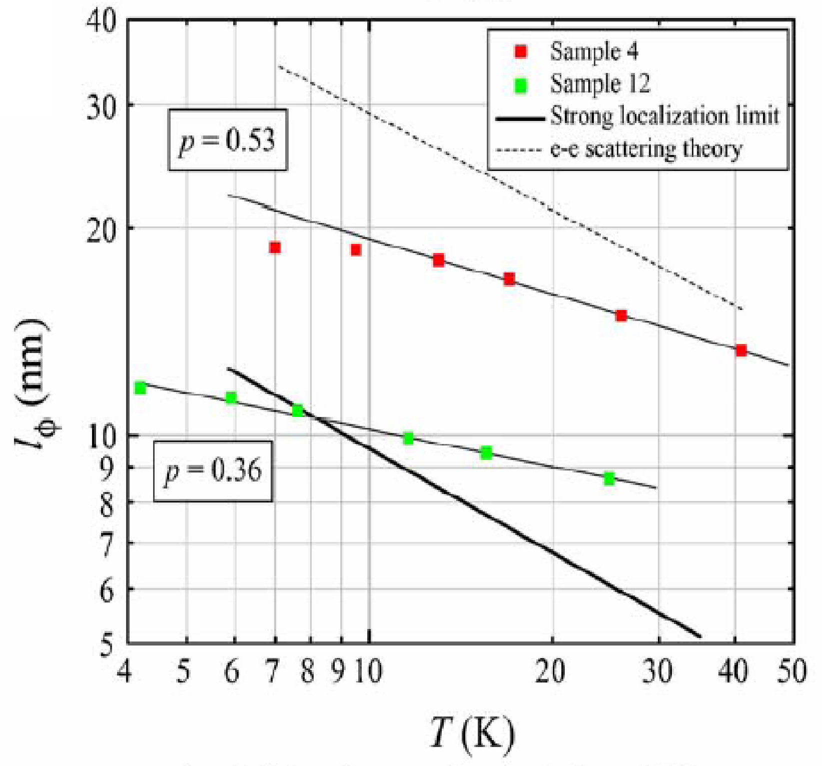




Very Short Electron Dephasing Lengths

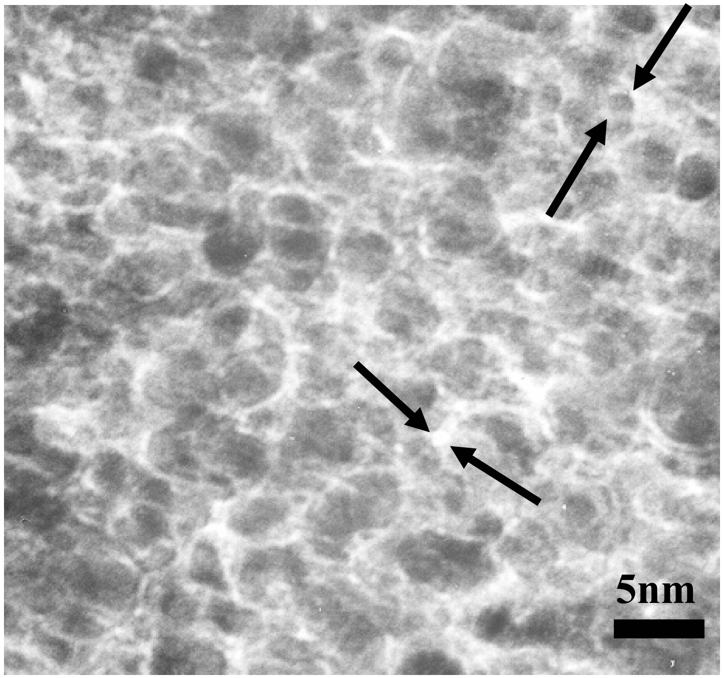
- **The dephasing length in dirty multi-wall carbon nanotubes, determined from weak-localization studies, is only ~ 10 nm**

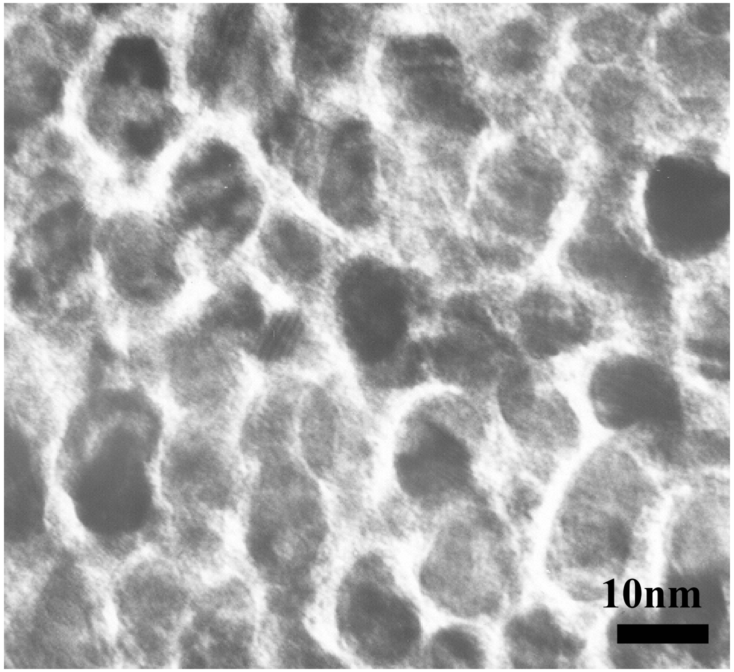
Recent experiment



Very Short Dephasing Length: Cu-SiO_2 Nano-Granular Films

- **Cu_x-$(SiO_2)_{1-x}$ films were prepared by co-sputtering on glass substrates, 1 μm thick**



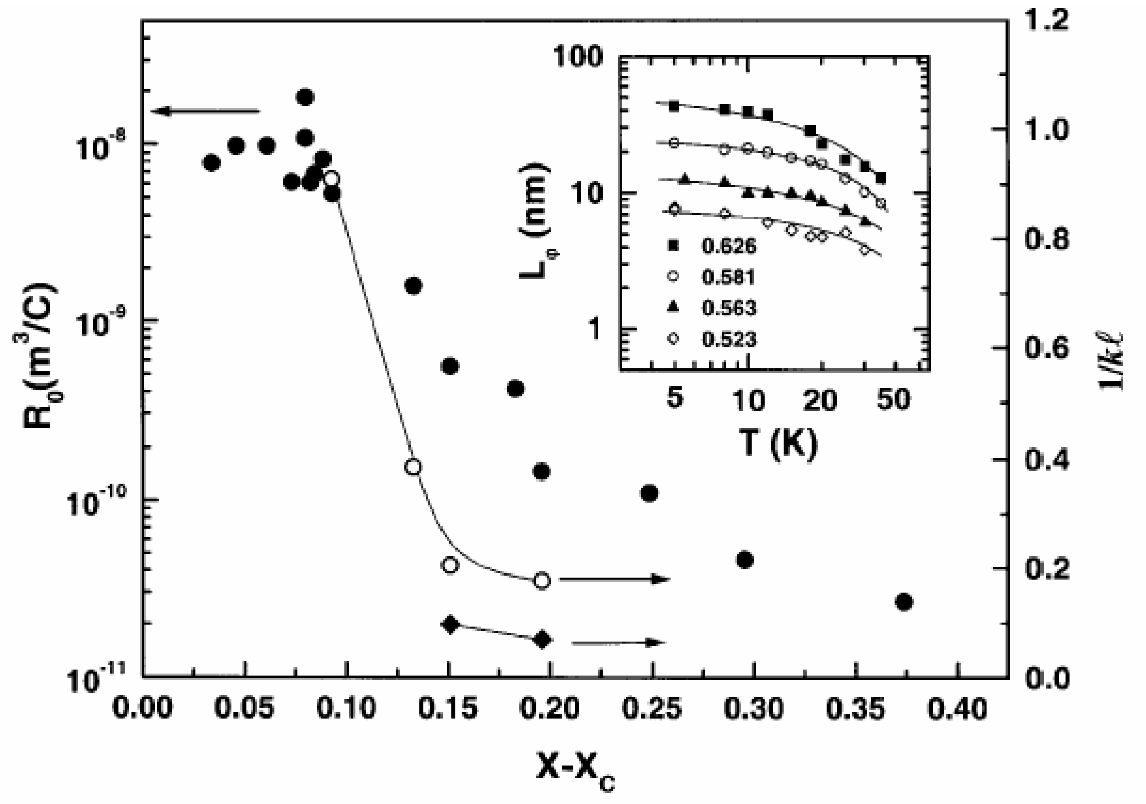


as-sputtered: ~ 1-3 nm

annealed: ~ 10 nm

Cu_x-$(SiO2)_{1-x}$ nano-granular films

- The dephasing length is only ~ tens nm near the quantum percolation threshold



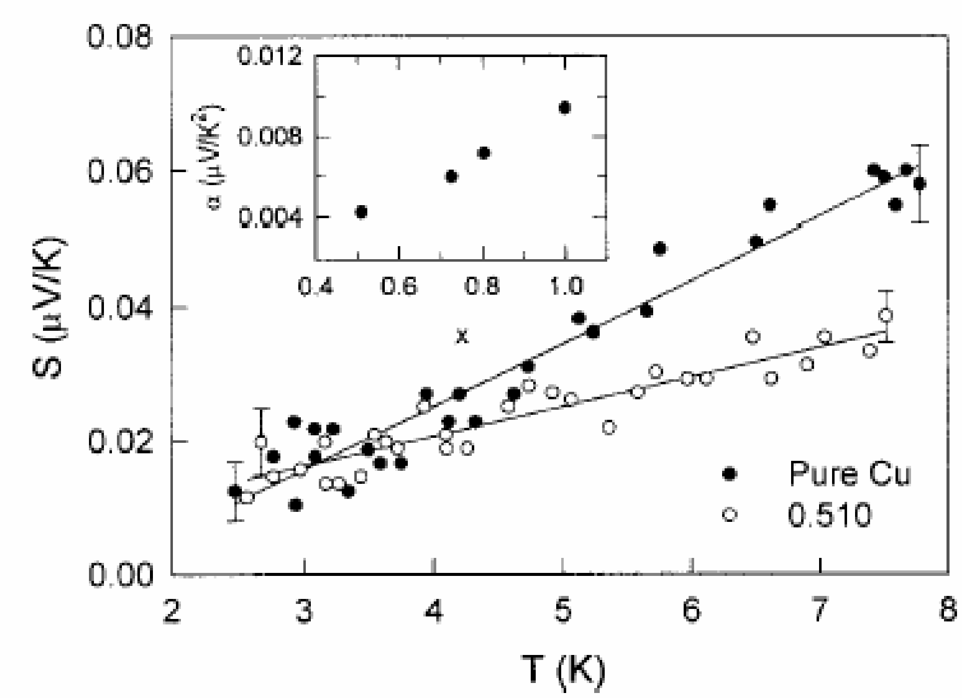
Zhang *et al*.,
Phys. Rev. Lett. 86, 5562 (2001)

Cu_x-$(SiO2)_{1-x}$ nano-granular films

- At a few degrees Kelvin, the thermoelectric power is very small; it is linear in *T* $\Rightarrow$ typical metal behavior

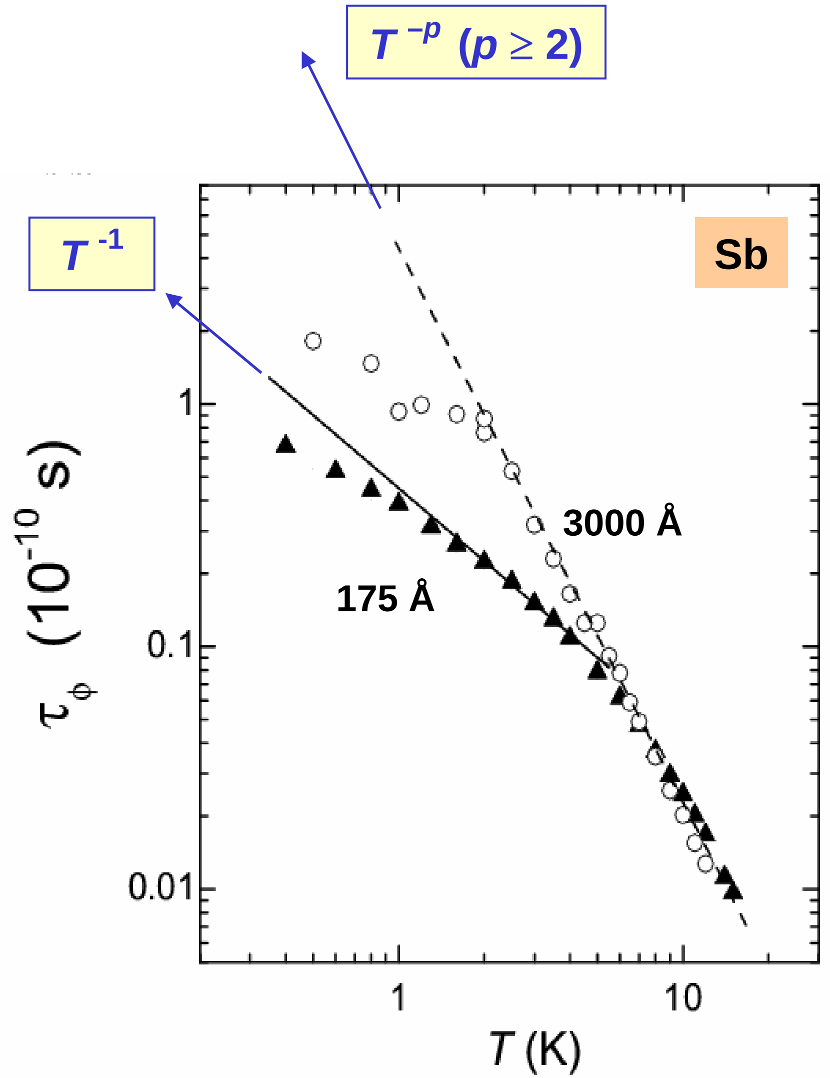
- There is no indication of a huge, broad Kondo bump (or dip)

$\Rightarrow$ Seemingly no sign of (appreciable) magnetic impurities



Chen *et al*.,
Appl. Phys. Lett. 81, 523 (2002)

Importance of Three-Dimensional Structures



*** There is an increased contrast between the saturation and the strong dependence of $\tau_{in}(T)$ with increasing sample dimensionality**

Minimized magnetic contamination:

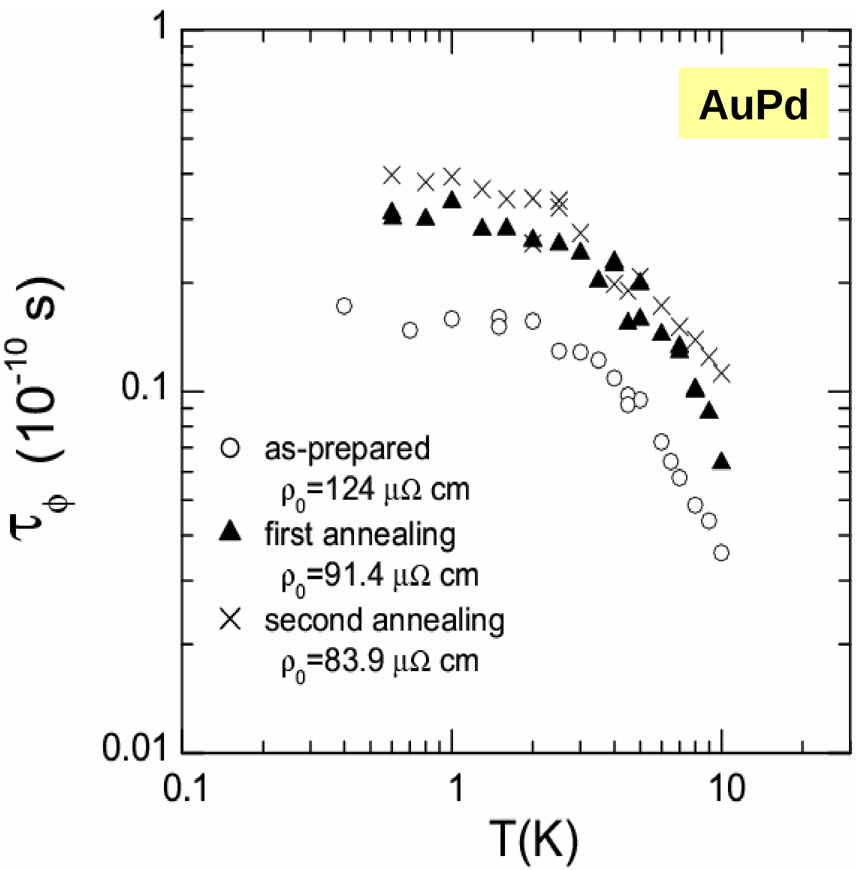
- **3D samples are insensitive to surface effects (substrates, interfaces, paramagnetic oxidation)**

- **3D samples do not require sophisticated lithographic processing**

Lin *et al.*,
J. Phys. Soc. Jpn. 72, 7 (2003), Suppl. A

Effect of Thermal Annealing on the Dephasing Time

⇒ **testing the role of magnetic scattering and dynamical defects**



Moderately-disordered films:

ρ_0 (as-prepared) ~ 100 μΩ cm

- **Thermal annealing results in a decrease in disorder**
- **τ_φ ($T \to 0$) increases with decreasing disorder**
- **One might think that a decrease in disorder could be accompanied by a decrease in TLS**

Lin *et al*.,
Europhys. Lett. 57, 872 (2002)

Difficulties in comparison to TLS theories:

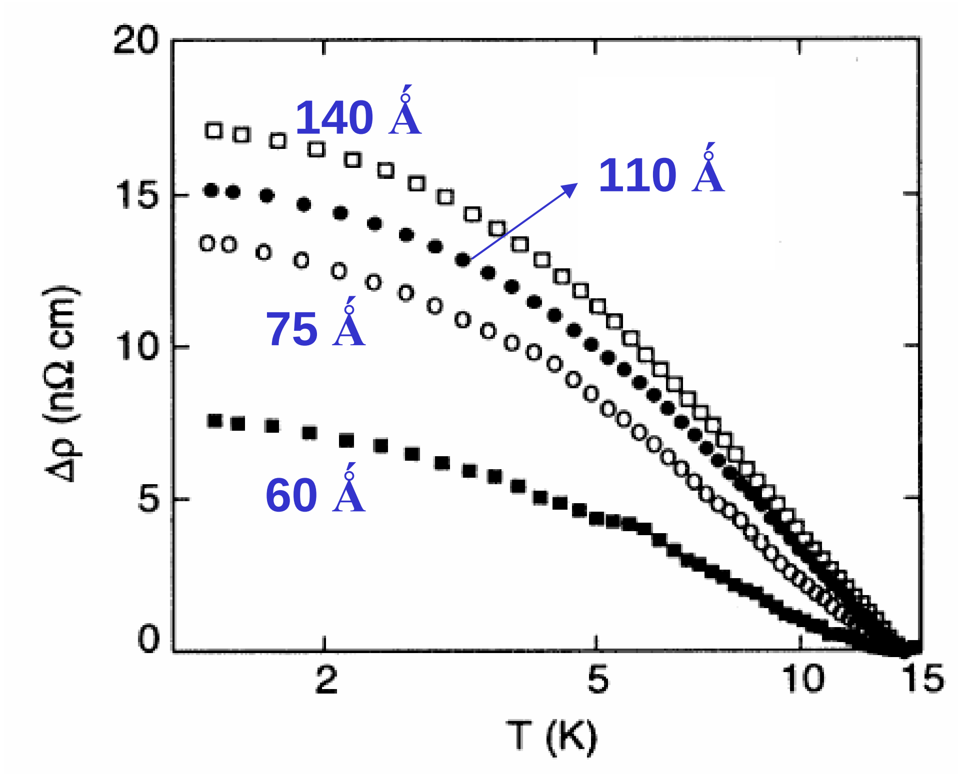
- Number concentration of two-level tunneling modes is unknown

- Coupling between conduction electrons and a TLS is poorly understood

- Dynamical properties of real defects are unclear

Cf. Zawadowski et al. (1999, 2003)
Imry et al. (1999)
Galperin (2003)
……

Magnetic scattering and Kondo effect



Cu(Fe) films, 750 Å

Blachly, Giordano,
Europhys. Lett. 27, 687 (1994);
PRB 51, 12537 (1995)

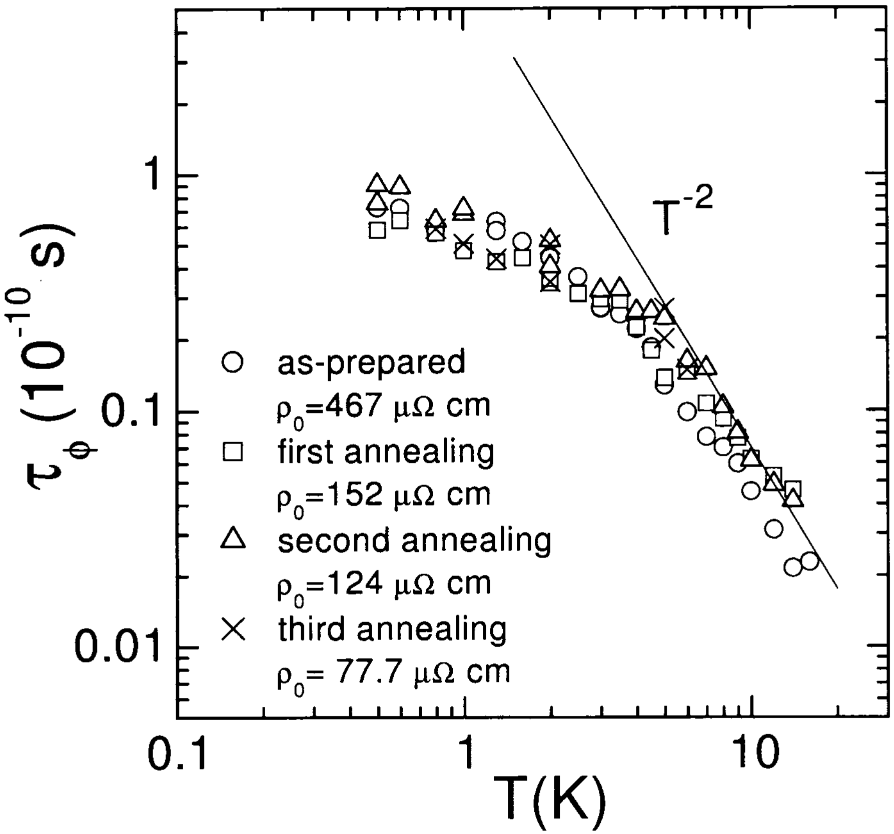
P. Phillips (1997)

"The Kondo effect is very sensitive to disorder; decreasing disorder enhances the Kondo effect."

$\Rightarrow$ **Stronger magnetic scattering with increasing annealing**

Effect of Thermal Annealing on the Dephasing Time

AuPd thick film



Strongly-disordered films:

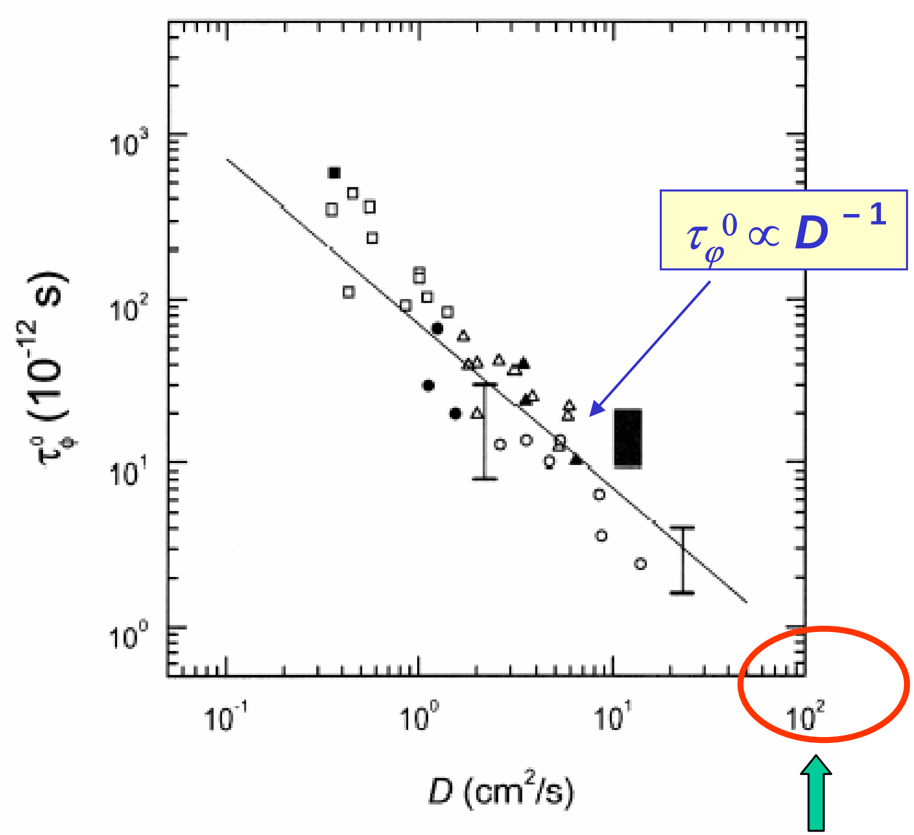
ρ_0 (as-prepared) ~ 500 $\mu\Omega$ cm

- **Thermal annealing results in a decrease in resistivity by a factor ~ 6**
- **τ_φ ($T \to 0$) remains basically unchanged**
- **A picture based on TLS cannot apply**

Lin *et al*., Europhys. Lett. 57, 872 (2002)

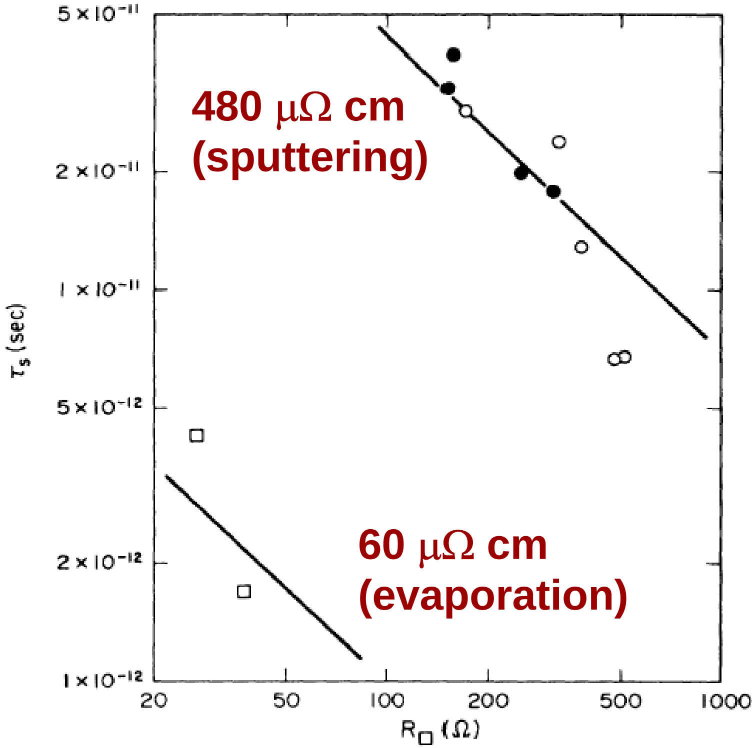
τ_φ ($T \to 0$) in Strongly Disordered Metals

- The measured $\tau_\varphi{}^0$ cannot be due to random magnetic contamination, e.g. $\tau_\varphi{}^0 \propto n_m{}^{-1}$



Mohanty
Saclay-MSU

AuPd thin films



Lin, Kao
JPCM 13 (2001) L119

Lin, Giordano
Phys. Rev. B 35 (1987) 1071

Conclusion

- **Apart from the total level of disorder, e-ph interaction is very sensitive to the microscopic quality of the defects**

- **"Electron-phonon engineering" may be promising**

  weakened (T^4) or enhanced (T^2) e-ph interaction is possible

  $\Rightarrow$ **How to observe the T^4 dependence over a wider T range?**
  How to observe the disorder dependence: $T^4 l$?

- **The appearance of very short dephasing lengths of ~ 10 nm (e.g., in carbon nanotubes and Cu-SiO_2 nano-granular films) is not understood**

  $\Rightarrow$ **Do we really have a large amount of magnetic impurities?**

Conclusion (continued)

- **Saturation in $\tau_\varphi(T \to 0)$ cannot be readily explained in terms of TLS models**

- **Magnetic-scattering induced dephasing cannot explain the saturation of τ_φ found in strongly disordered metals**