Electro-Dynamics of strongly disordered superconducting TiN films

Pieter-Jan Coumou, Eduard Driessen, Rutger Tromp, Mark Zuiddam, Pieter de Visser, Akira Endo, and Teun Klapwijk

Workshop on the Physics and Applications of Superconducting Microresonators: 28 -29 July 2011

Why TiN for KIDs?

- High normal state resistivity (~ 100 μΩ·cm)
  - Efficient far-IR absorption with 20-50 nm thick films
  - Reasonable area filling fraction
  - High kinetic inductance fraction

- T_c varies with stoichiometry (0 - 4.5 K)

- Reasonable quasiparticle lifetime
  - Maximum lifetime varies as ~ T_c^2

- Extremely high quality factors (> 10^7)

- Improved sensitivity / figure of merit: $\mathcal{F} = \alpha_{\rm sc}\tau_{\rm max}Q_{i,\rm max}/N_0V_{\rm sc}$

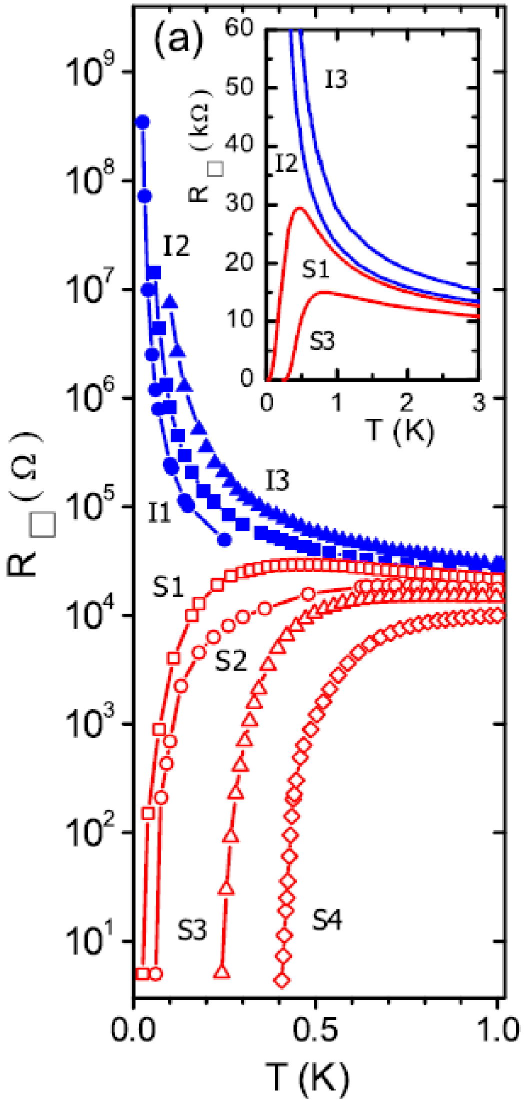
Leduc *et al*, APL **97**, 102509 (2010)

Superconductor-Insulator Transition

Competition between localization and Cooper-pairing

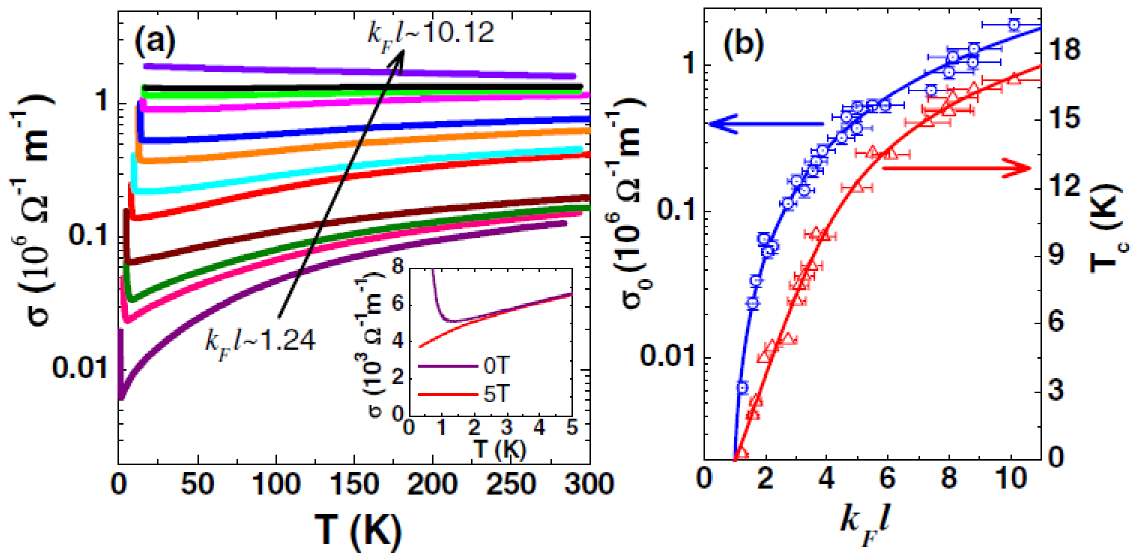
- Increasing disorder induces a transition from **superconductor** directly to **insulator**

TiN



Baturina, PRL **99**, 257003 (2007)

NbN



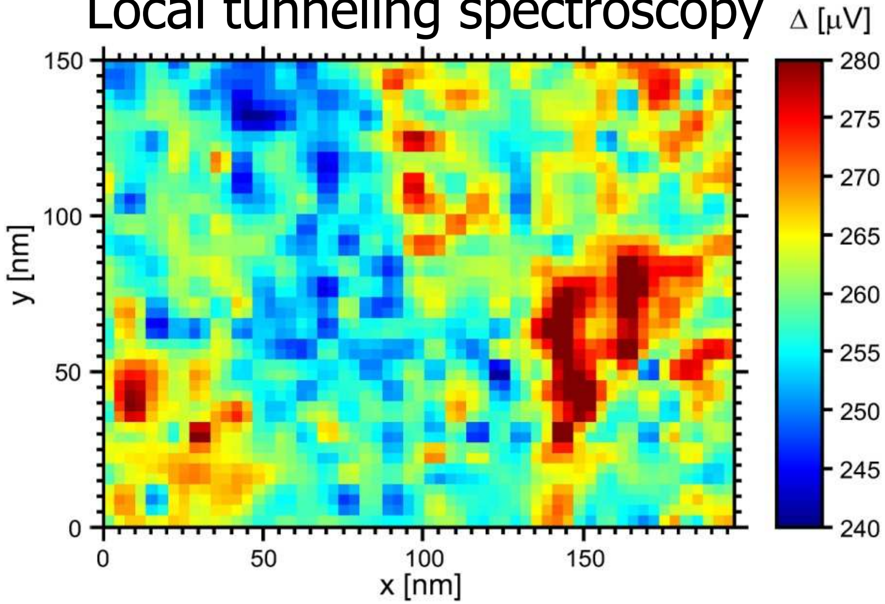
Mondal *et al*, PRL **106**, 047001 (2011)

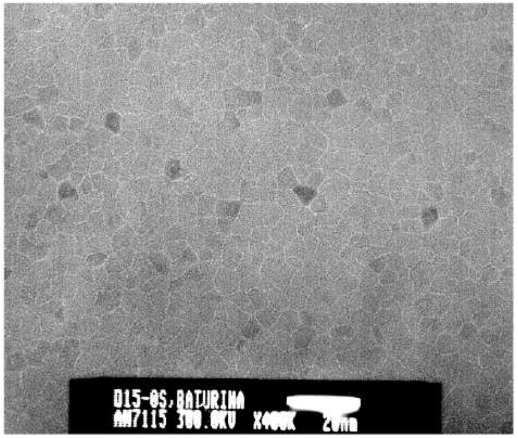
Electronic inhomogeneities

- Superconducting properties become inhomogeneous on a mesoscopic scale

  - Spatial fluctuation of spectral gap Δ
  - Formation of SC islands
  - Not directly linked to microscopic disorder (e.g. grain boundaries)

Local tunneling spectroscopy





TiN, >1000 μΩ·cm, 5 nm thick

B. Sacépé *et al*, PRL **101**, 157006 (2008)

How do we describe the electrodynamics of strongly disordered SC TiN films?

- To whish degree is TiN (NbTiN, NbN) a well-behaving textbook BCS superconductor like Al?
- To what extent is Mattis-Bardeen applicable for TiN?
- How can we justify the use of a large broadening parameter?
- What kind of problems can the high resistivity in the normal state of TiN films (that we whish to use) pose on the development of KIDs?

AC resistance

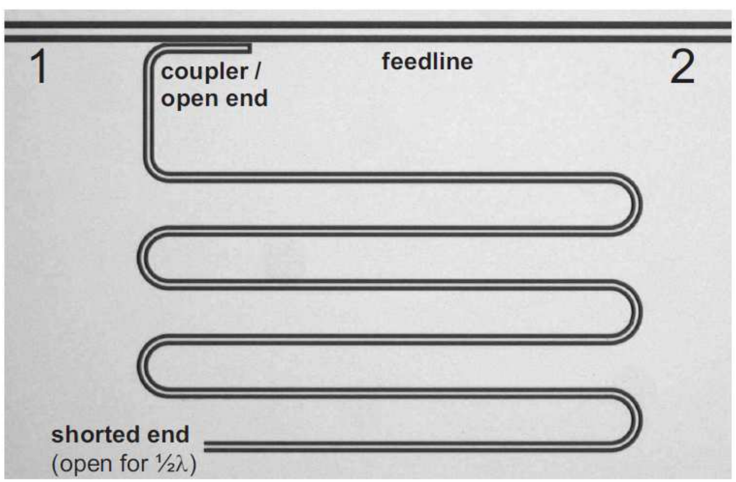
Inductive phase change

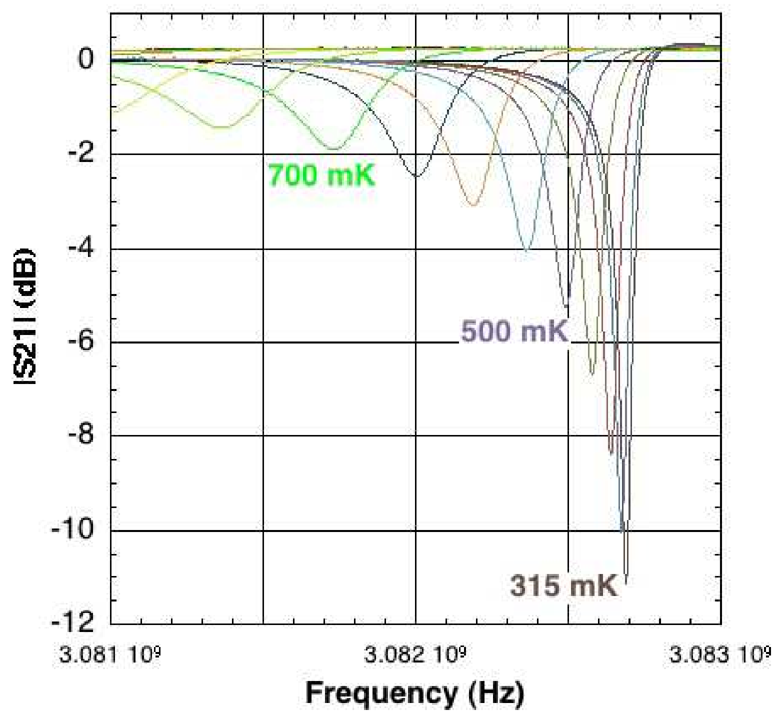
Complex conductivity: $\sigma_1 - i\sigma_2$

$$Q = \frac{\omega E}{P}$$

$$\omega_0 = \frac{2\pi}{4l\sqrt{(L_g + L_k)C}}$$

Microwave SC Resonators





Jiansong Gao's formulas (JLTP 2008)

$$Q = \frac{2}{\alpha\beta}\frac{\sigma_2}{\sigma_1}$$

$$\frac{\delta Q}{Q} = -\left(\frac{\delta\sigma_1}{\sigma_1} - \frac{\delta\sigma_2}{\sigma_2}\right)$$

$$\delta\left(\frac{1}{Q}\right) = \frac{\alpha\beta}{2}\frac{\delta\sigma_1}{\sigma_2}$$

$$\frac{\delta f_0}{f_0} = \frac{\alpha\beta}{4}\frac{\delta\sigma_2}{\sigma_2}$$

Complex conductivity response: $\sigma_1 - i\sigma_2$

Mattis-Bardeen, Phys. Rev. **111** (1958)

$$\frac{\sigma_1(\omega)}{\sigma_N} = \frac{2}{\hbar\omega}\int_{\Delta}^{\infty} dE[f(E) - f(E+\hbar\omega]\left(1 + \frac{\Delta^2}{E(E+\hbar\omega)}\right) N_S(E) N_S(E+\hbar\omega)$$

$$\frac{\sigma_2(\omega)}{\sigma_N} = \frac{1}{\hbar\omega}\int_{\max(\Delta-\hbar\omega,-\Delta)}^{\Delta} dE[1-2f(E+\hbar\omega]\frac{1}{i}\left(1 + \frac{\Delta^2}{E(E+\hbar\omega)}\right) N_S(E) N_S(E+\hbar\omega)$$

$$N_S(E) = \frac{E}{\sqrt{E^2 - \Delta^2}}$$

$$\frac{\Delta_0 - \Delta}{\Delta_0} \approx 2\int_{\Delta}^{\infty} dE \frac{1}{\sqrt{E^2 - \Delta^2}} f(E)$$

$E \rightarrow E - i\Gamma$ or $\Delta \rightarrow \Delta - i\Gamma$

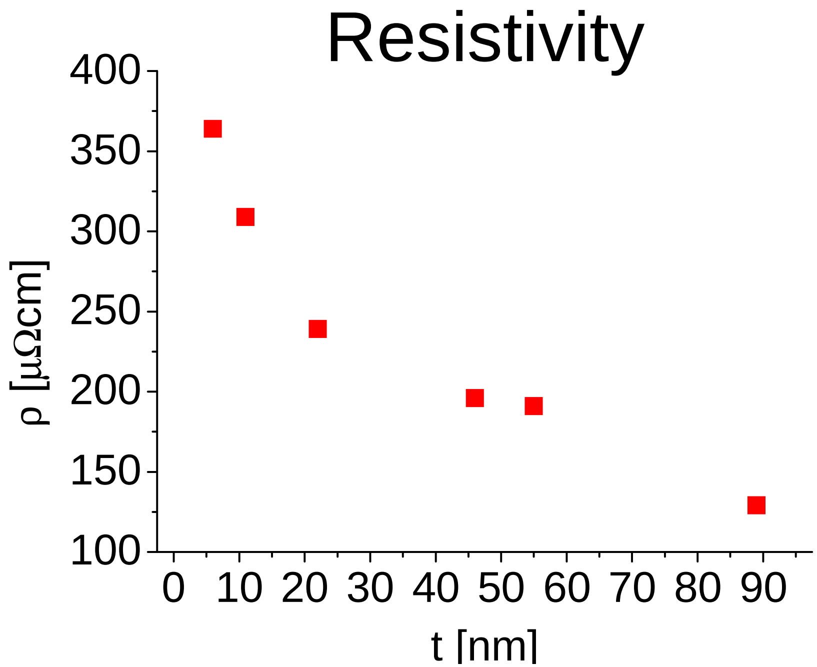
Broadening of the BCS density of states

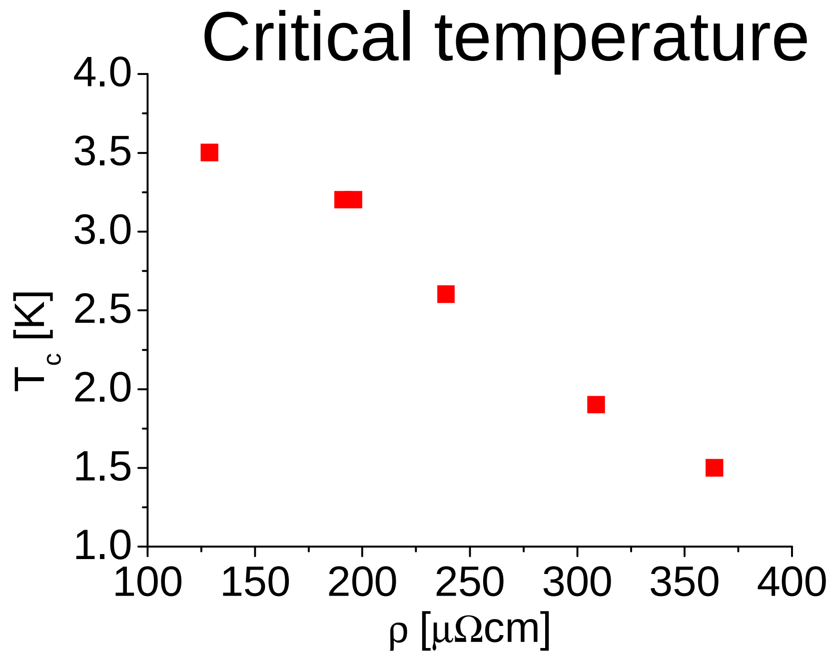
Results

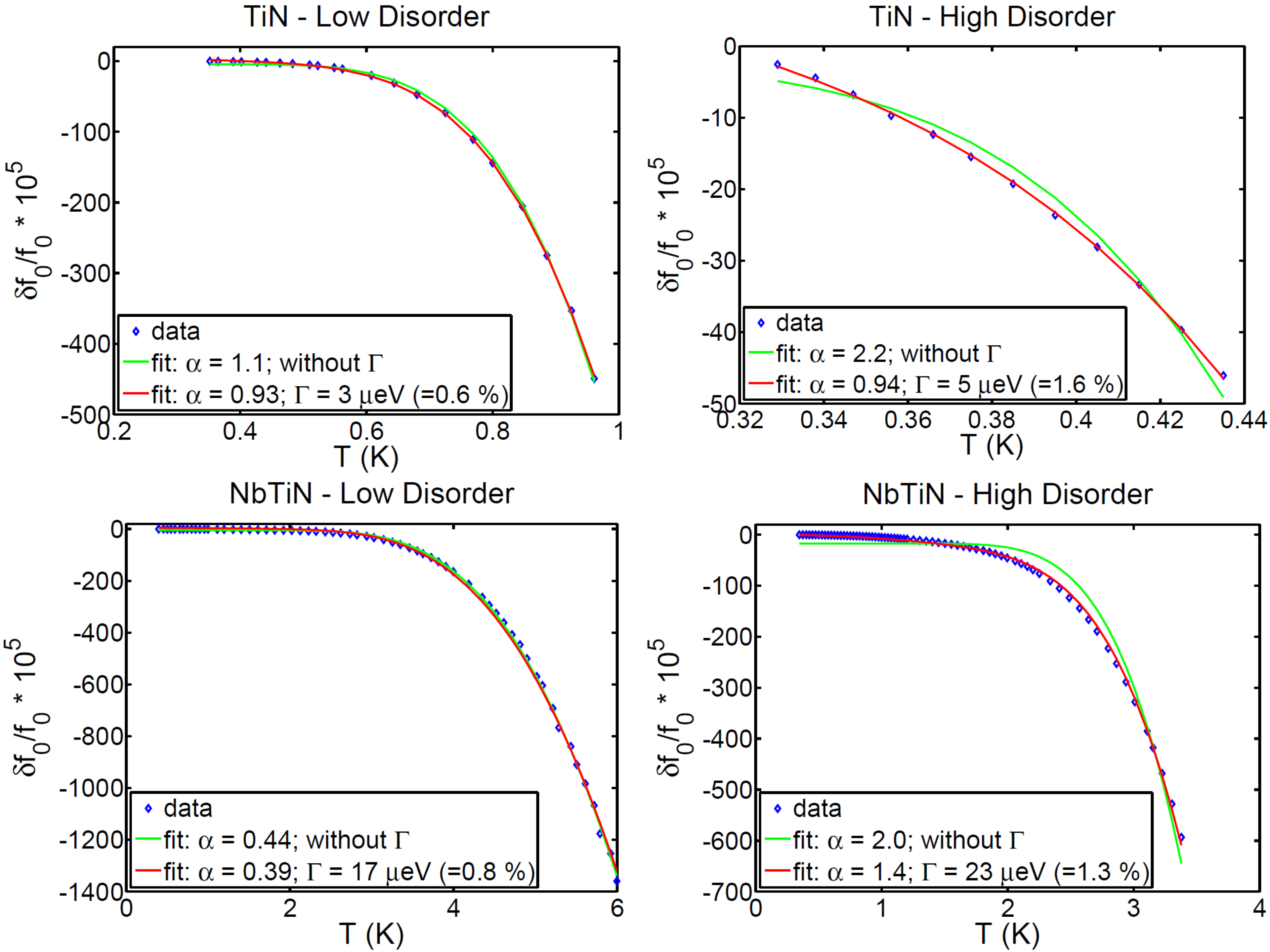
- TiN (Atomic Layer Deposition)
  - Low Disorder: ρ = 191 μΩ·cm, T_c = 3.2 K, t = 55 nm, $k_F l$ = 6.7
  - High Disorder: ρ = 309 μΩ·cm, T_c = 2.1 K, t = 11 nm, $k_F l$ = 3.4

- NbTiN (Sputtering)
  - Low Disorder: ρ = 141 μΩ·cm, T_c = 13.6 K, t = 50 nm
  - High Disorder: ρ = 506 μΩ·cm, T_c = 11.8 K, t = 50 nm

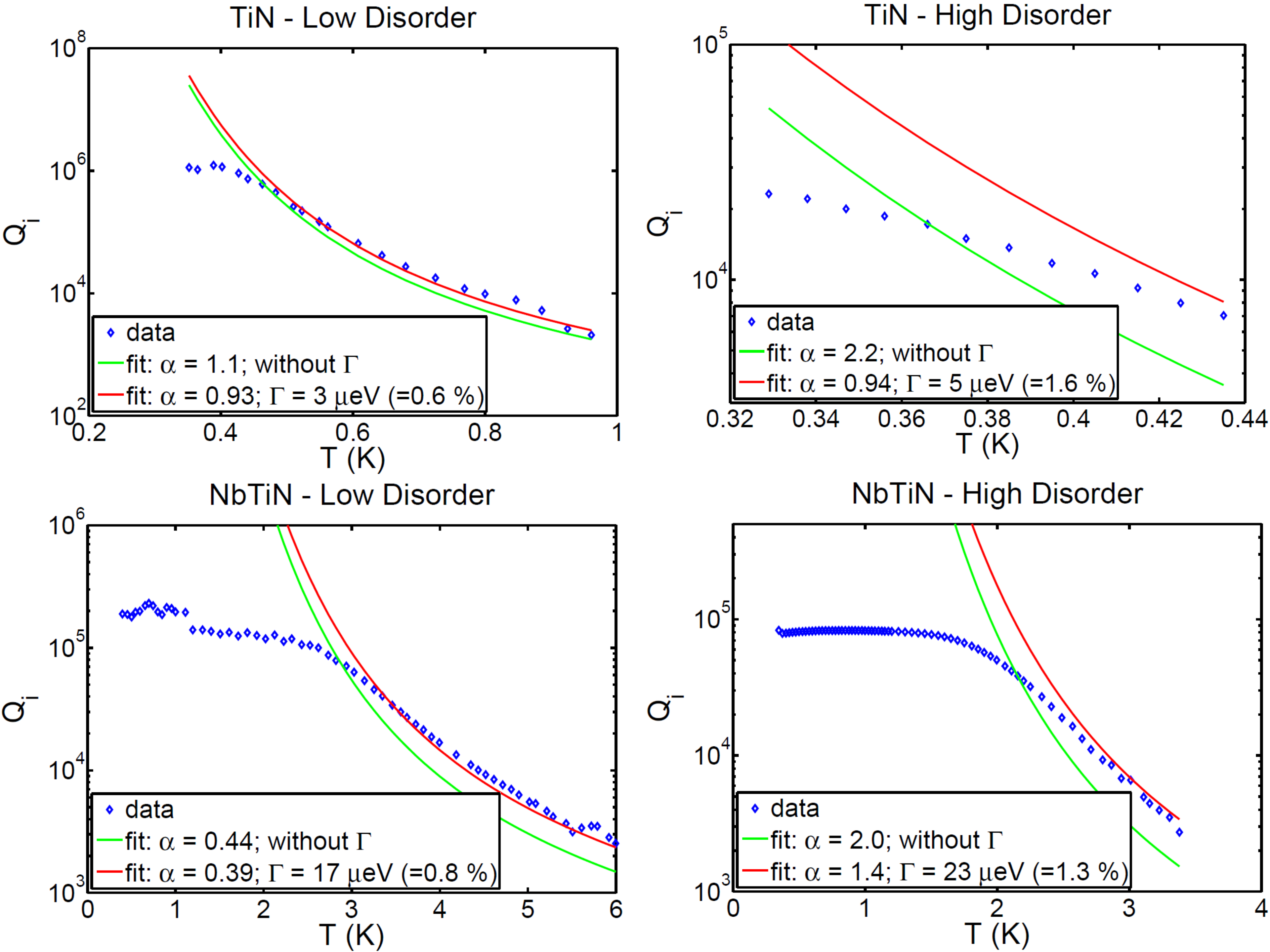
TiN ALD – series of: films with decreasing thickness



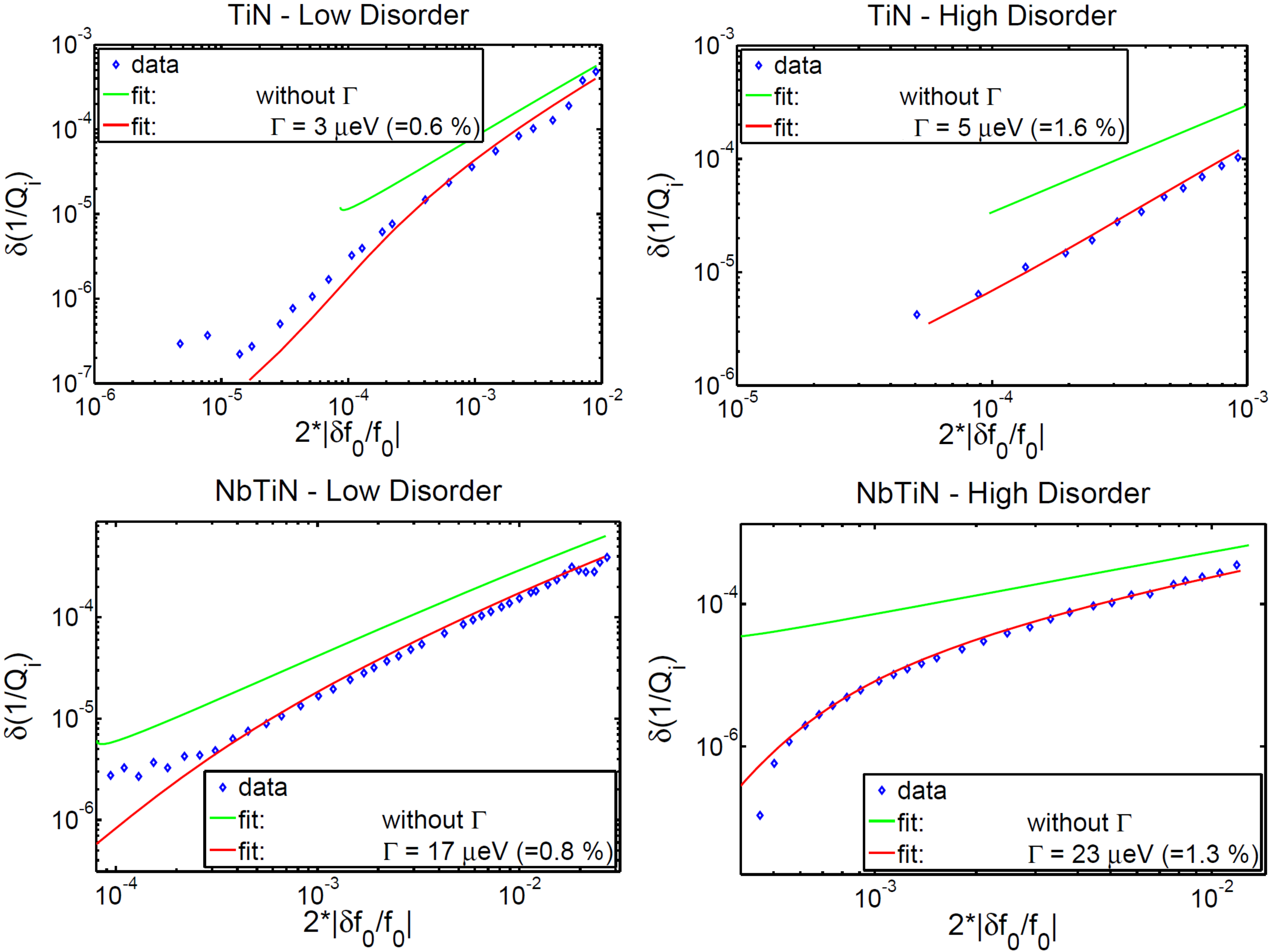




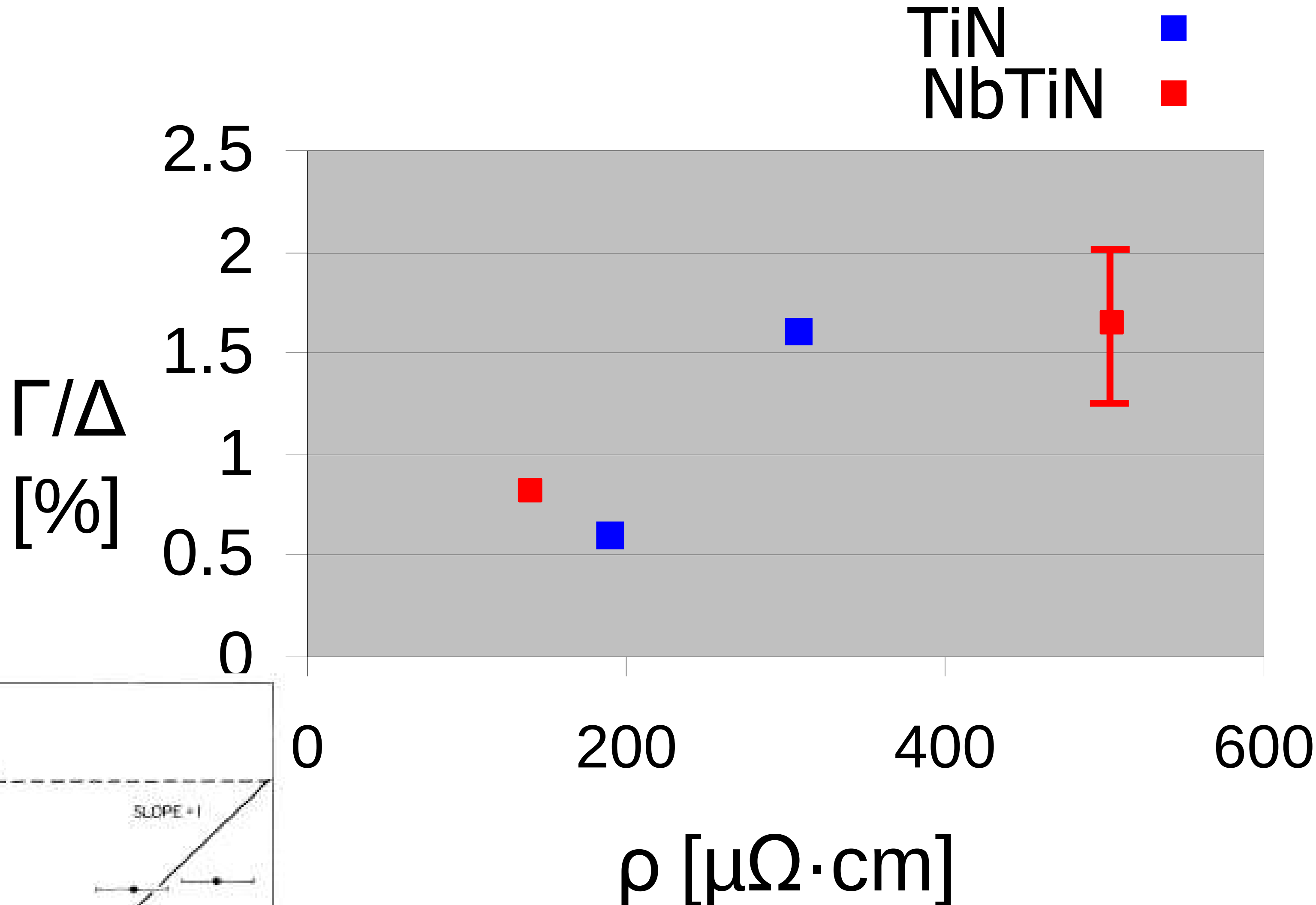
TiN - Low Disorder
δf0/f0 * 10^5
T (K)
data
fit: α = 1.1; without Γ
fit: α = 0.93; Γ = 3 μeV (=0.6 %)
TiN - High Disorder
δf0/f0 * 10^5
T (K)
data
fit: α = 2.2; without Γ
fit: α = 0.94; Γ = 5 μeV (=1.6 %)
NbTiN - Low Disorder
δf0/f0 * 10^5
T (K)
data
fit: α = 0.44; without Γ
fit: α = 0.39; Γ = 17 μeV (=0.8 %)
NbTiN - High Disorder
δf0/f0 * 10^5
T (K)
data
fit: α = 2.0; without Γ
fit: α = 1.4; Γ = 23 μeV (=1.3 %)

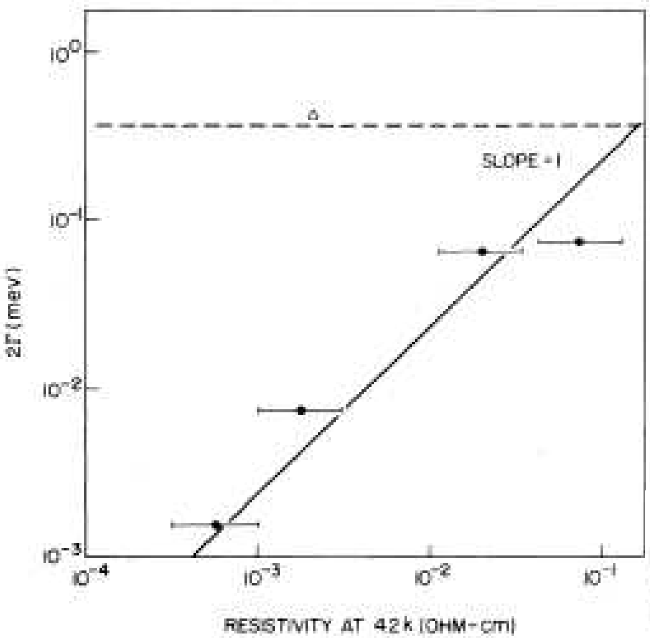


TiN - Low Disorder
TiN - High Disorder
NbTiN - Low Disorder
NbTiN - High Disorder
Q_i
T (K)
data
fit: α = 1.1; without Γ
fit: α = 0.93; Γ = 3 μeV (=0.6 %)
fit: α = 2.2; without Γ
fit: α = 0.94; Γ = 5 μeV (=1.6 %)
fit: α = 0.44; without Γ
fit: α = 0.39; Γ = 17 μeV (=0.8 %)
fit: α = 2.0; without Γ
fit: α = 1.4; Γ = 23 μeV (=1.3 %)



TiN - Low Disorder
TiN - High Disorder
NbTiN - Low Disorder
NbTiN - High Disorder
data
fit: without Γ
fit: Γ = 3 μeV (=0.6 %)
fit: Γ = 5 μeV (=1.6 %)
fit: Γ = 17 μeV (=0.8 %)
fit: Γ = 23 μeV (=1.3 %)
δ(1/Q_i)
2*|δf_0/f_0|



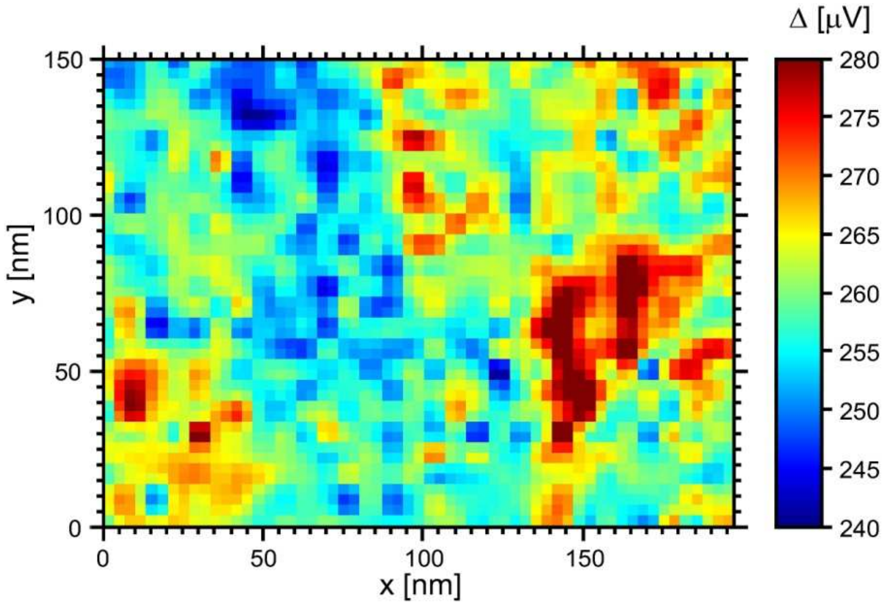


Dynes *et al.*, PRL **53** (1984)

FIG. 4. The broadening factor 2Γ as a function of the resistivity of the granular Al. The dashed line is the value for the superconducting energy gap $\Delta_{gr\,Al}$.

Explanations for Γ

- Lifetime broadening (but what determines the lifetime?)
- Electronic inhomogeneities
- Phase fluctuations
  (breakdown of long range superconducting coherence)



Conclusion

- Low disorder →
  MB theory + broadening of the BCS density of states
- For increasing disorder →
  broadening parameter increases
- Broadening is directly related to the increase in disorder
- In agreement with numerical simulations of disordered superconductors
  - Ghosal et al, PRL 81, 3940 (1998)
  - Bouadim et al, arXiv 1011.3275v1 (2010)

Outlook

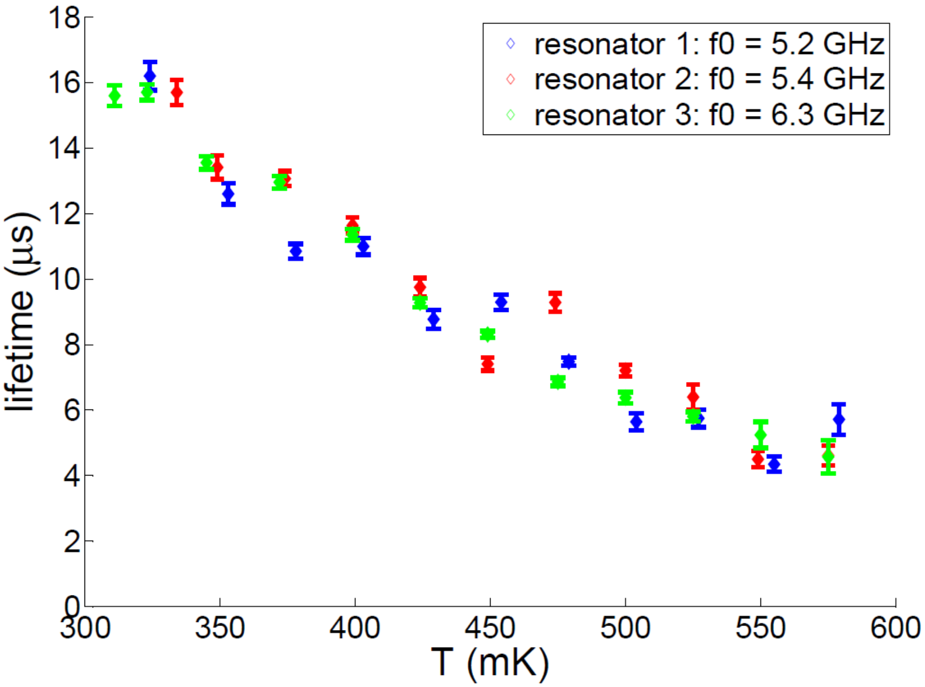
- Microwave properties of a complete series of TiN film with increasing disorder
  - ALD TiN
  - Sputtered TiN (stoichiometry)
  - NbTiN

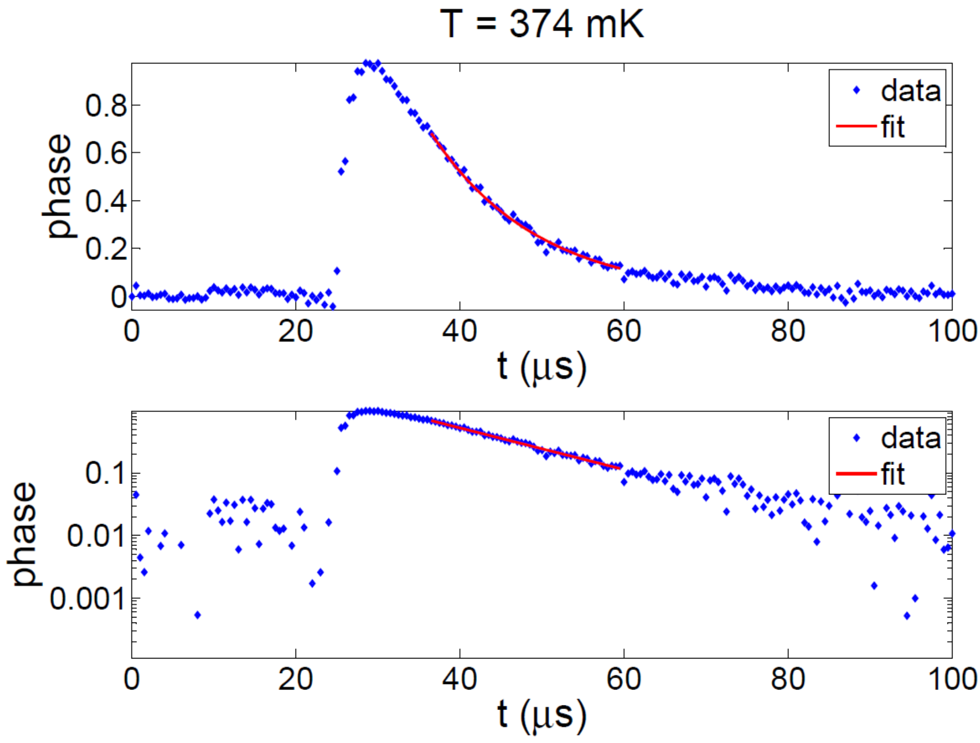
- Lifetime measurements

- Complete characterization (DC and normal state properties of TiN)

Lifetime measurements

TiN Low Disorder



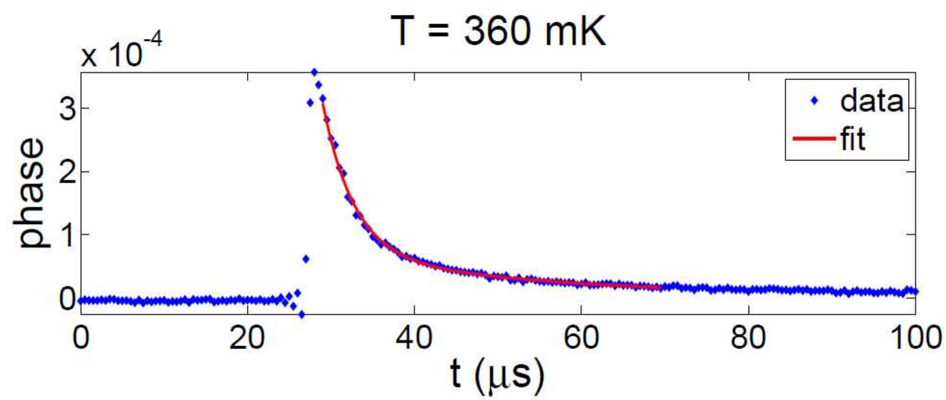


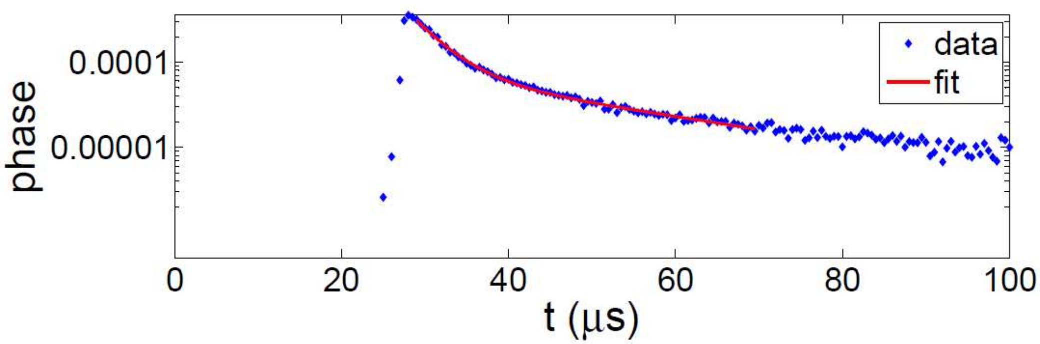
TU Delft

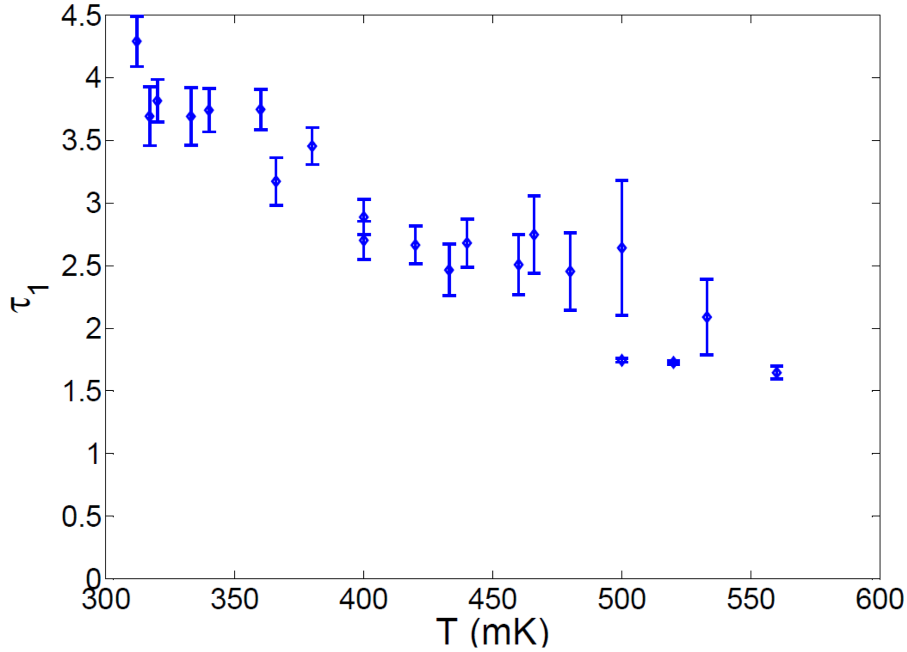
Lifetime measurements

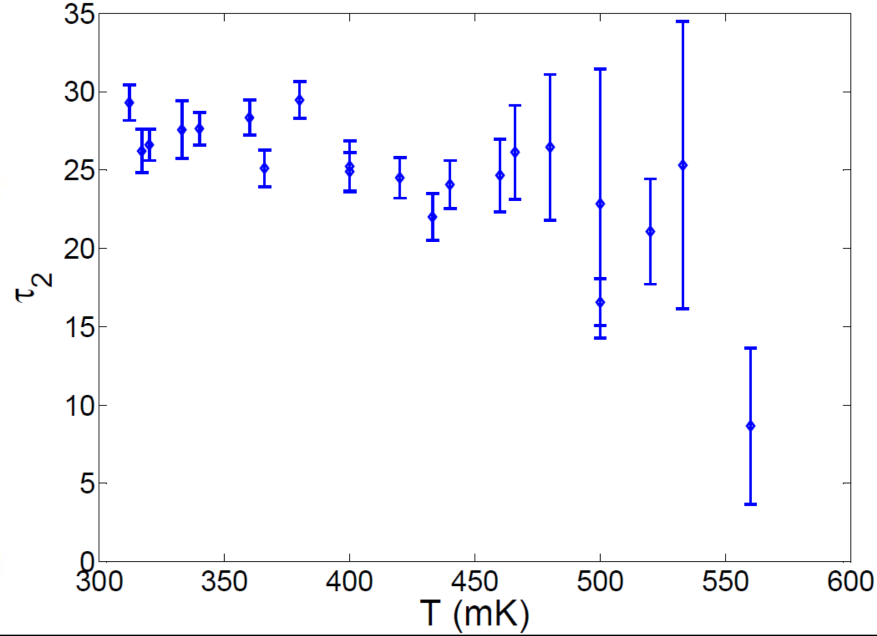
TiN High Disorder
two decay times!

$r_1 * \exp[-t/\tau_1] + r_2 * \exp[-t/\tau_2]$









Complete characterization

Film ID	Measured					Calculated				
	d [nm]	T_c [K]	*ρ* [μΩcm]	*D* [cm^2/s]	*n* @10 K [cm^{-3}]	*N(0)* [$eV^{-1}cm^{-3}$]	*ξ* [nm]	m^* [m_e]	*ℓ* [Å]	$k_F \cdot \ell$ [-]
ALD1	55	3.2	191	0.94	2.9E+22	3.5E+22	6.0	2.8	7.0	6.7
ALD2	11	1.9	360	0.36	3.2E+22	4.8E+22	4.8	3.7	3.5	3.4
S2	250	4.7	100	1.60	4.4E+22	3.9E+22	6.4	2.7	10.2	11.1
S3	320	4.7	365	0.44	2.5E+22	3.9E+22	3.4	3.2	4.1	3.7
S4	400	4.4	584	0.49	1.7E+22	2.2E+22	3.7	2.1	3.3	2.6

Questions

Homogeneously disordered versus granular disordered

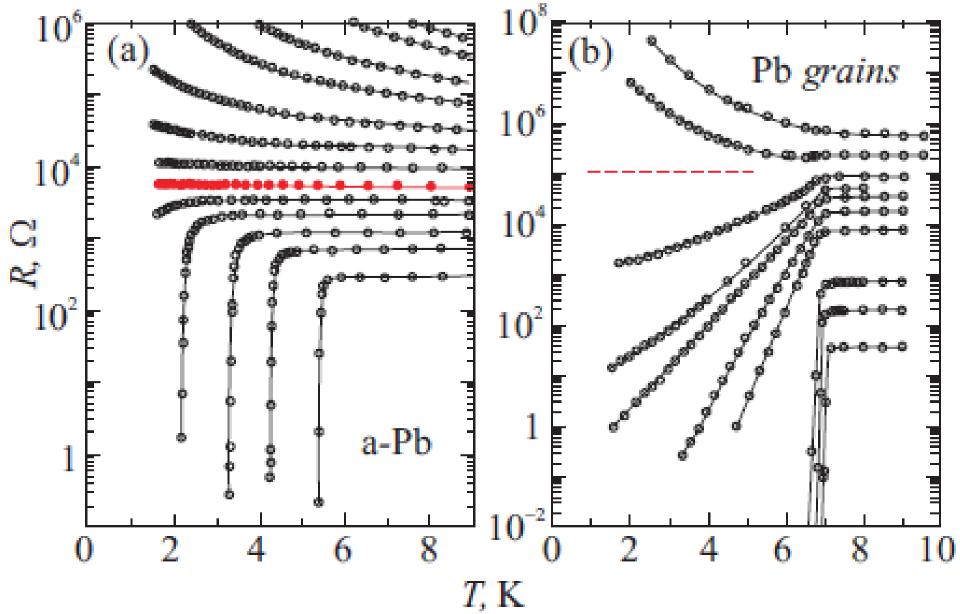


FIG. 3: Resistance variations with temperature in Pb films upon increasing their thickness (from top to bottom) [12]. (a) Superconductor–insulator transition in finely dispersed quasihomogeneous films deposited on an SiO surface over an intermediate thin layer of amorphous Ge. In the superconducting region, the $R(T)$ curves demonstrate a correlation between the normal resistance and the superconducting transition temperature. (b) Superconductor–insulator transition in granular films deposited directly onto the SiO surface. In such a method of deposition, the lead atoms coalesce into granules. The temperature of the superconducting transition in the film becomes constant at a film thickness exceeding the critical one.

Gantmakher *et al*, arXiv1004.3761v1 (2010)

Complex conductivity response: $\sigma_1 - i\sigma_2$

Mattis-Bardeen, Phys. Rev. **111** (1958)

$$\frac{\sigma_1(\omega)}{\sigma_N} = \frac{2}{\hbar\omega}\int_{\Delta}^{\infty} dE \frac{E^2 + \Delta^2 + \hbar\omega E}{\sqrt{E^2 - \Delta^2}\sqrt{(E+\hbar\omega)^2 - \Delta^2}}[f(E) - f(E+\hbar\omega]$$

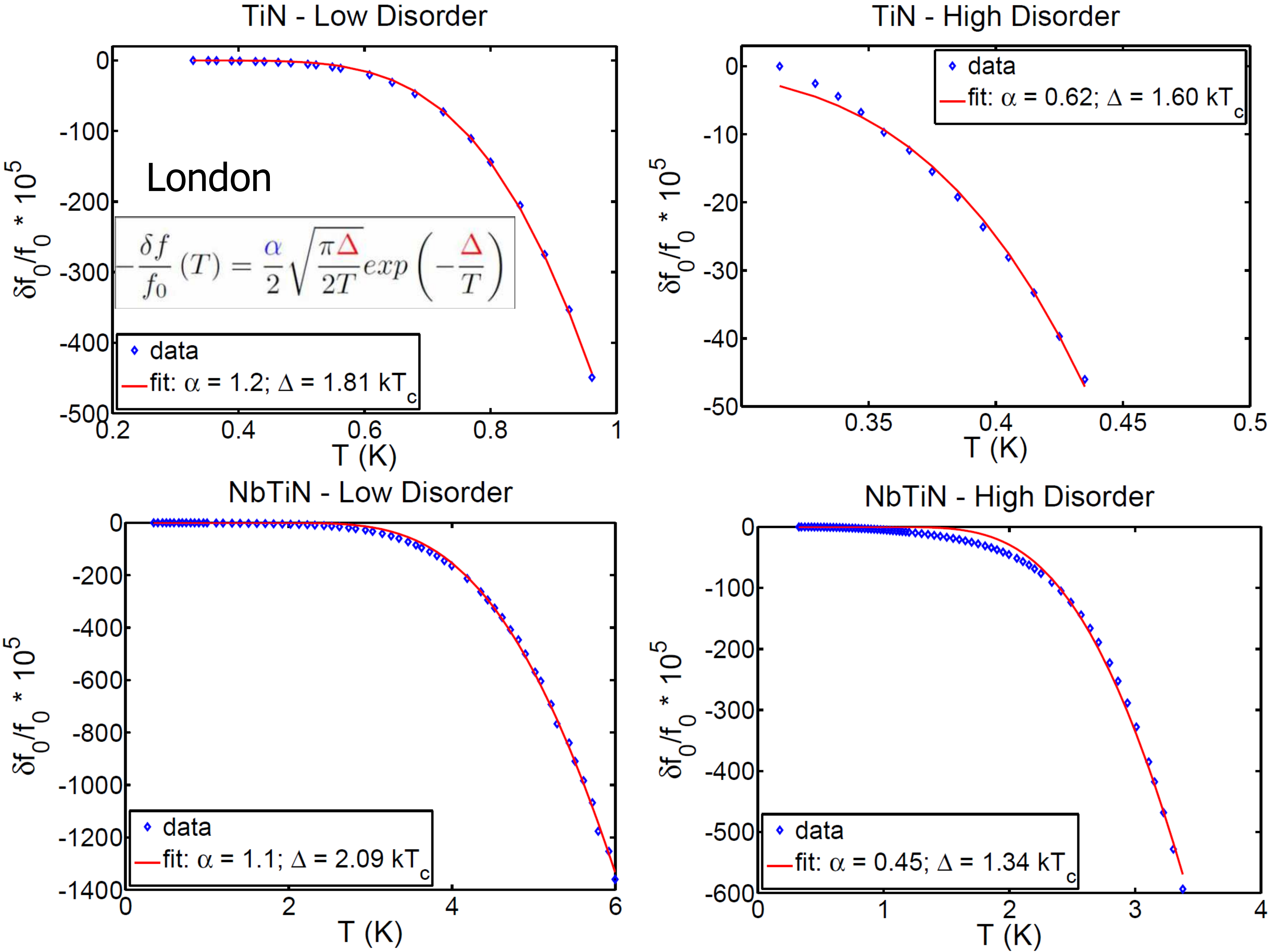
$$\frac{\sigma_2(\omega)}{\sigma_N} = \frac{1}{\hbar\omega}\int_{\max(\Delta-\hbar\omega,-\Delta)}^{\Delta} dE \frac{E^2 + \Delta^2 + \hbar\omega E}{\sqrt{\Delta^2 - E^2}\sqrt{(E+\hbar\omega)^2 - \Delta^2}}[1 - 2f(E+\hbar\omega]$$

$$N_S(E) = \frac{E}{\sqrt{E^2 - \Delta^2}}$$

$$\frac{\Delta_0 - \Delta}{\Delta_0} \approx 2\int_{\Delta}^{\infty} dE \frac{1}{\sqrt{E^2 - \Delta^2}} f(E)$$

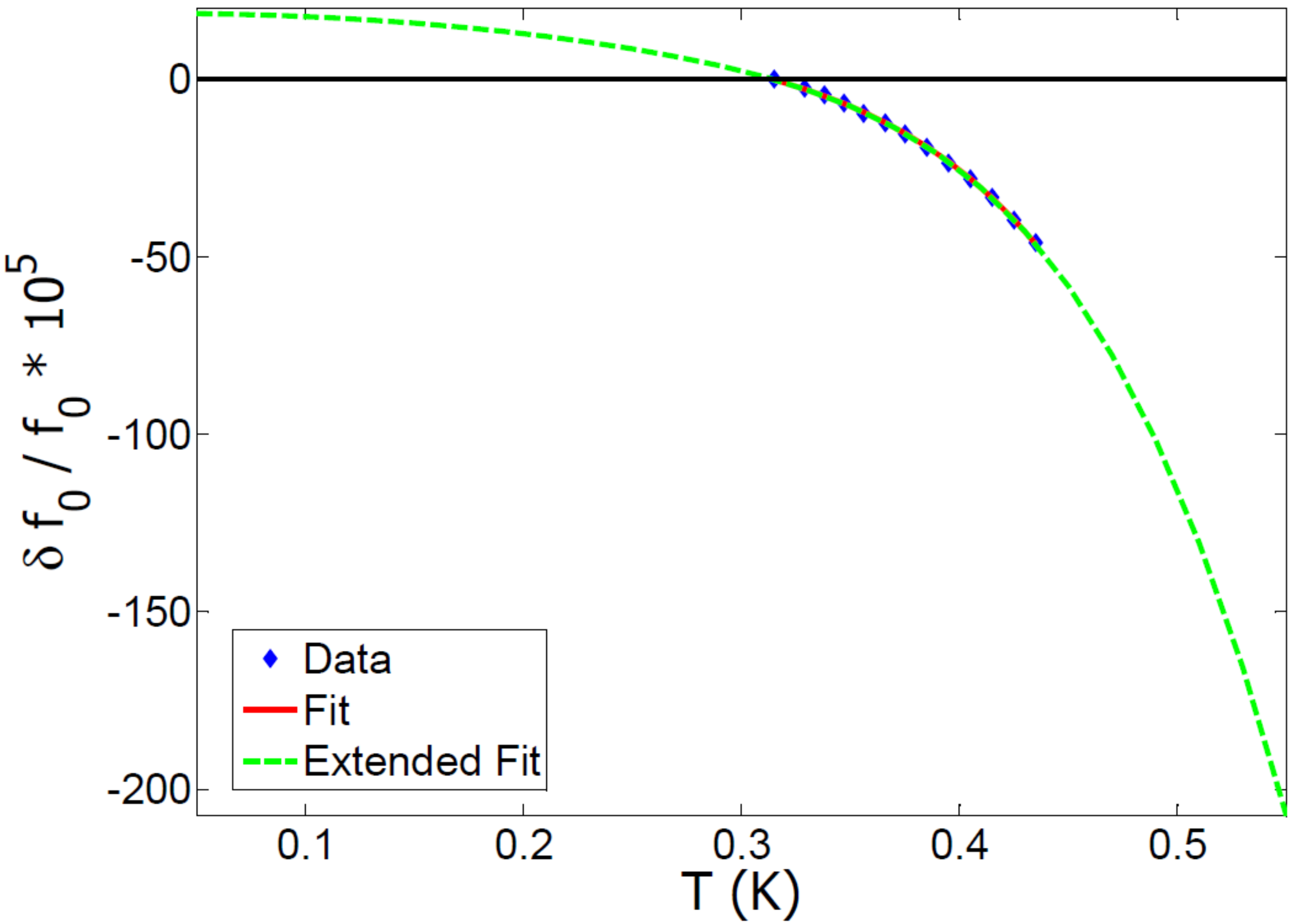
$E \rightarrow E - i\Gamma$ or $\Delta \rightarrow \Delta - i\Gamma$

Broadening of the BCS density of states



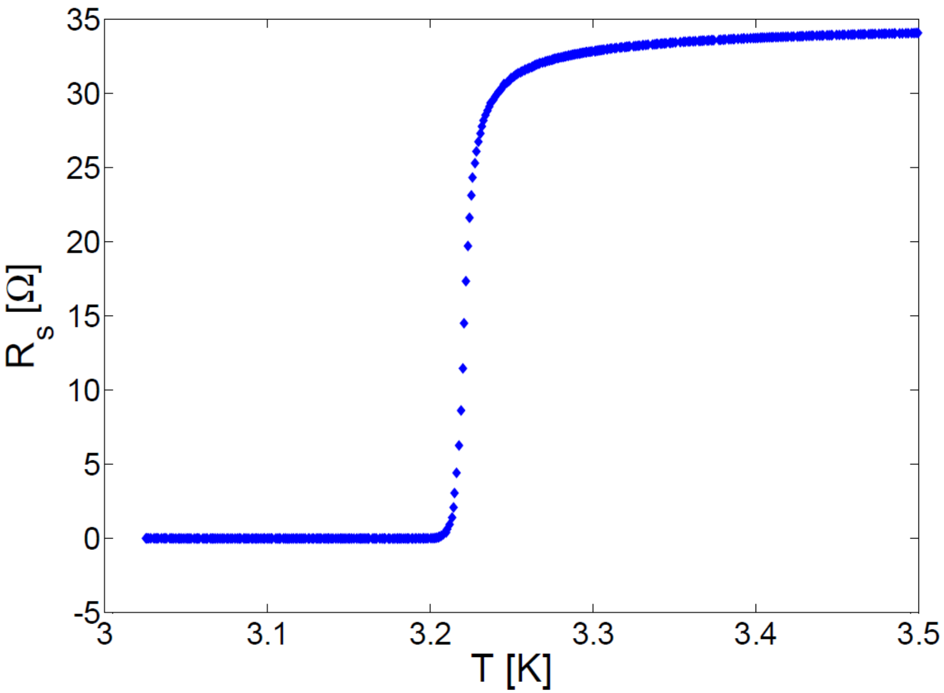
TiN - Low Disorder
London
$-\frac{\delta f}{f_0}(T) = \frac{\alpha}{2}\sqrt{\frac{\pi\Delta}{2T}}exp\left(-\frac{\Delta}{T}\right)$
data
fit: α = 1.2; Δ = 1.81 kT_c
δf_0/f_0 * 10^5
T (K)
TiN - High Disorder
data
fit: α = 0.62; Δ = 1.60 kT_c
δf_0/f_0 * 10^5
T (K)
NbTiN - Low Disorder
data
fit: α = 1.1; Δ = 2.09 kT_c
δf_0/f_0 * 10^5
T (K)
NbTiN - High Disorder
data
fit: α = 0.45; Δ = 1.34 kT_c
δf_0/f_0 * 10^5
T (K)

TiN High Disorder (ALD250)

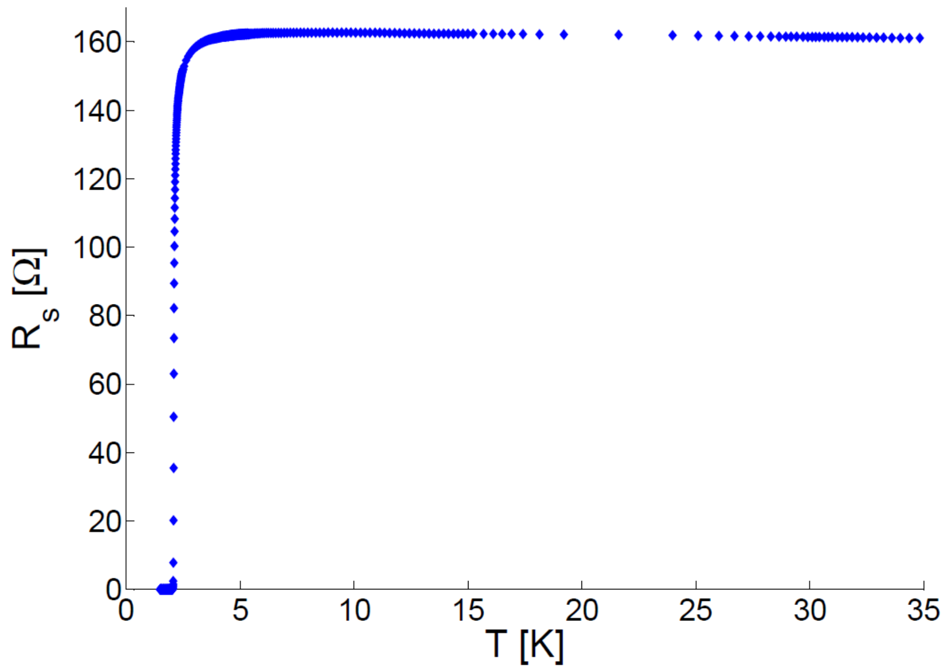


Resistance (T)

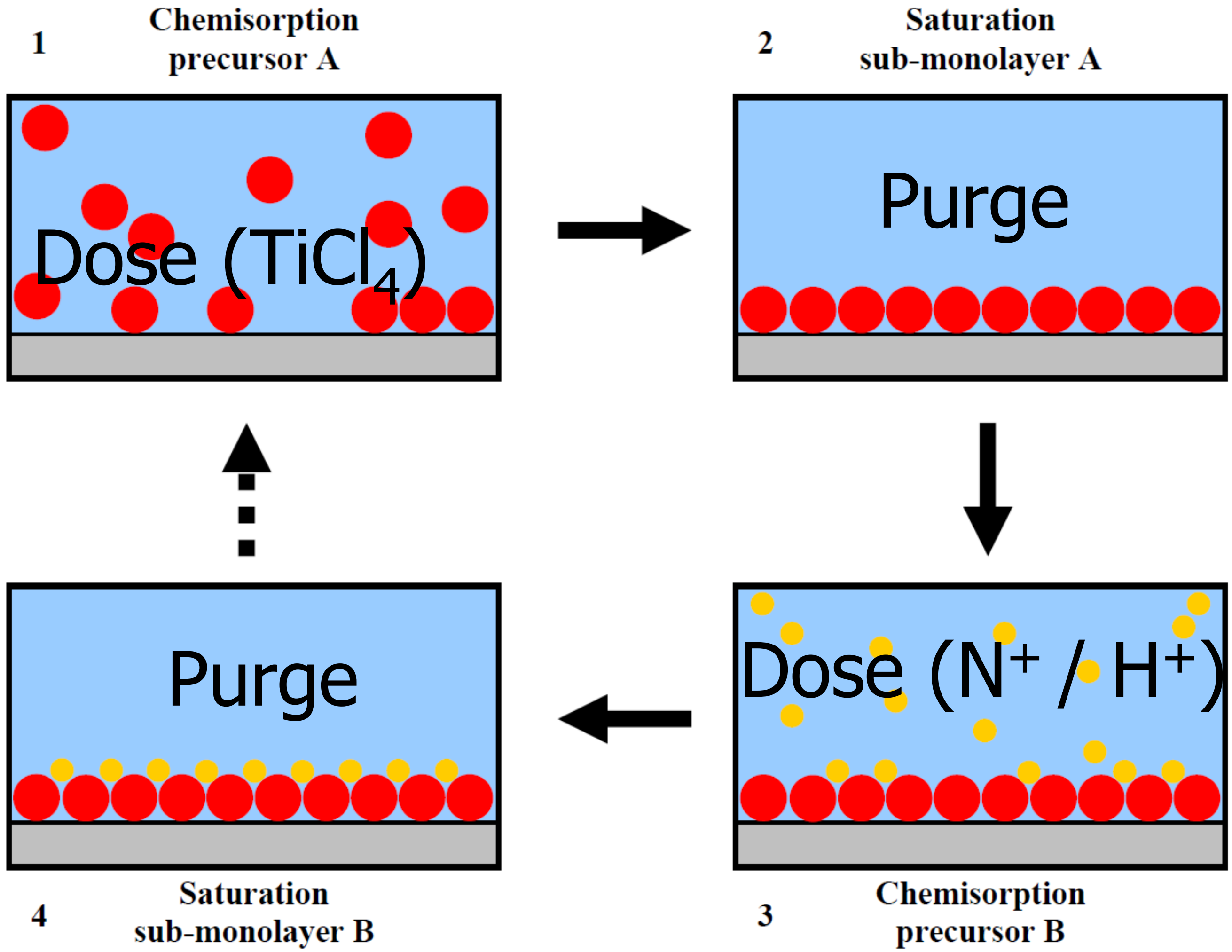
TiN Low Disorder (ALD021)



TiN High Disorder (ALD250)

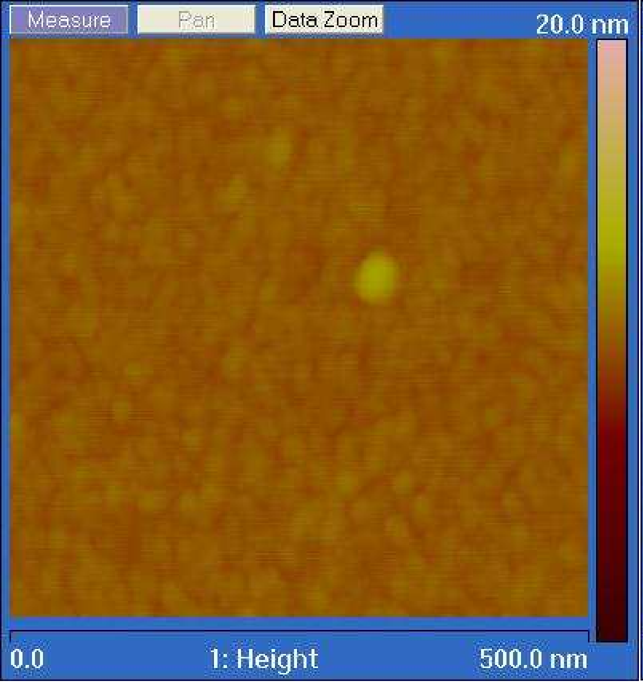


Atomic Layer Deposition

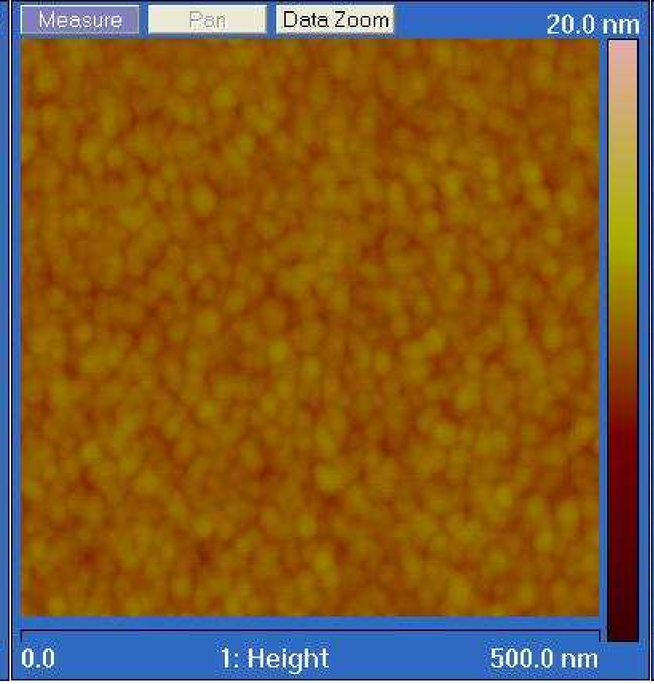


Why Atomic Layer Deposition?

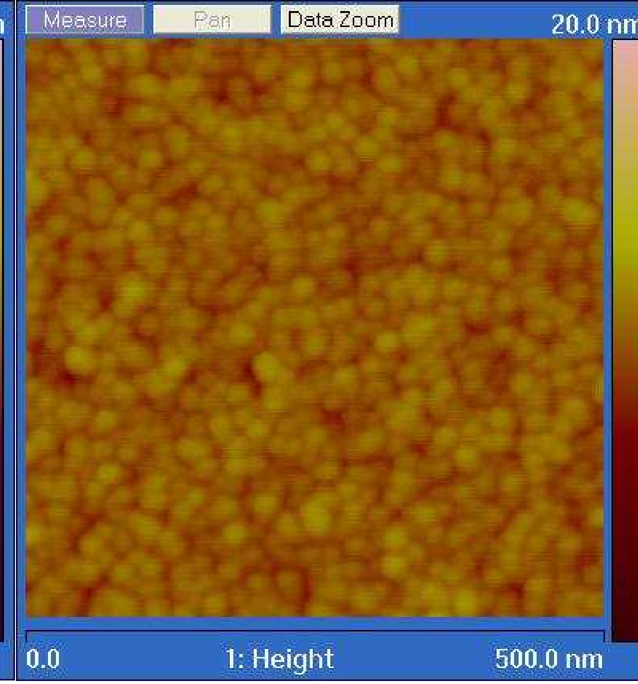
- Very thin layers of TiN
- High resistance per square
- High uniformity
- Possibly superior properties compared to sputtered materials



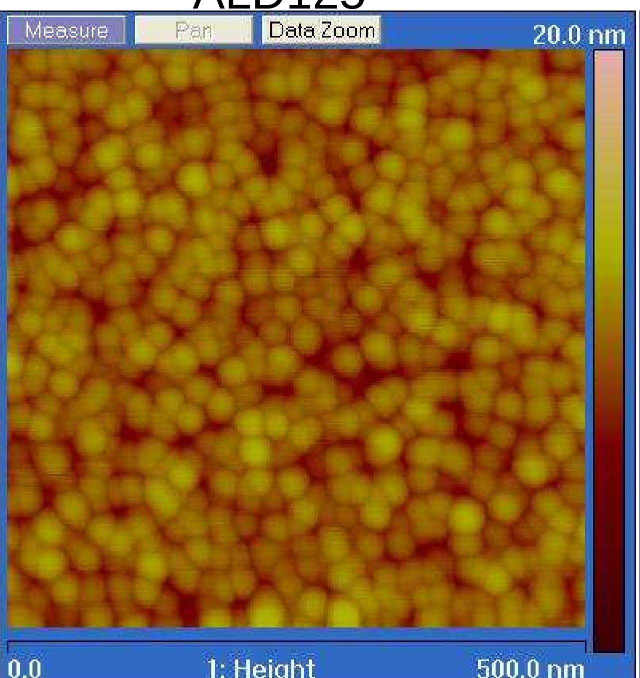
ALD125



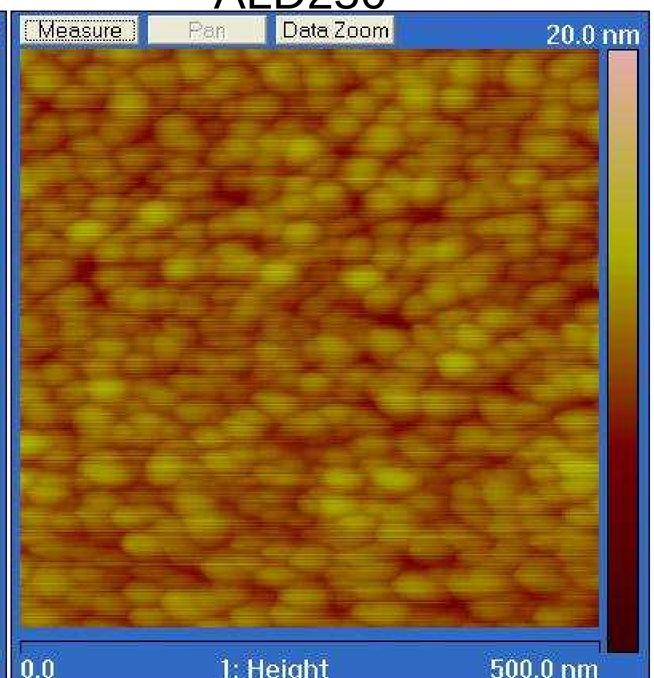
ALD250



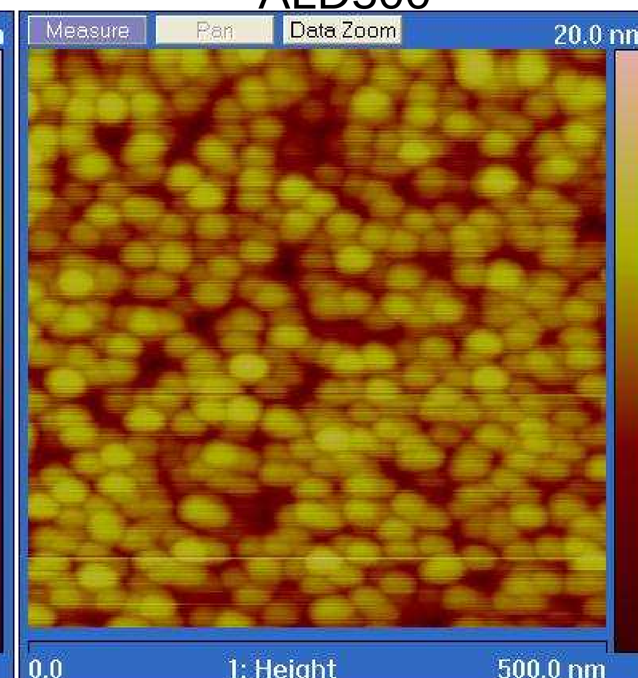
ALD500



ALD1000

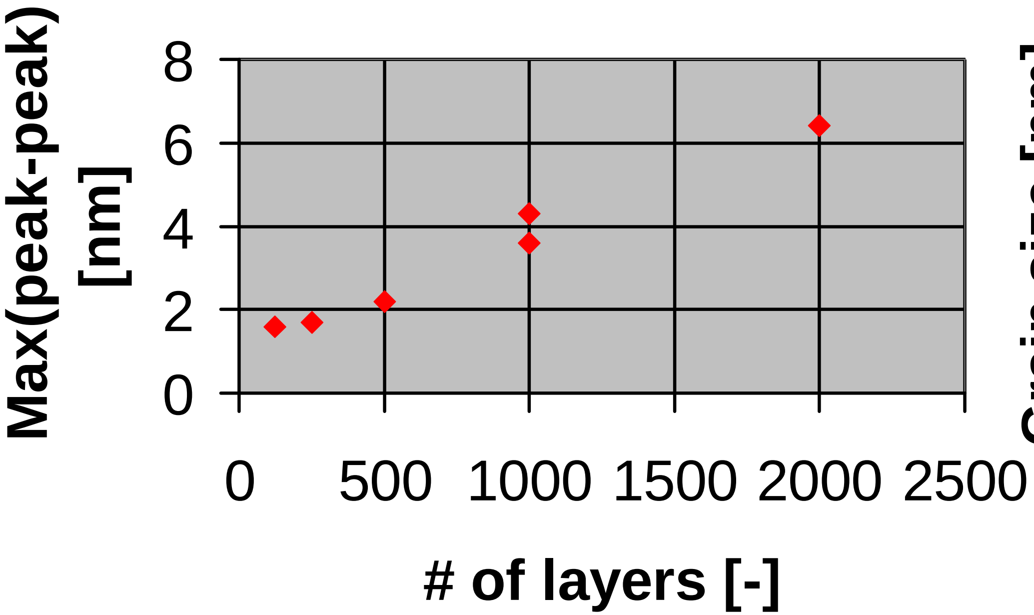


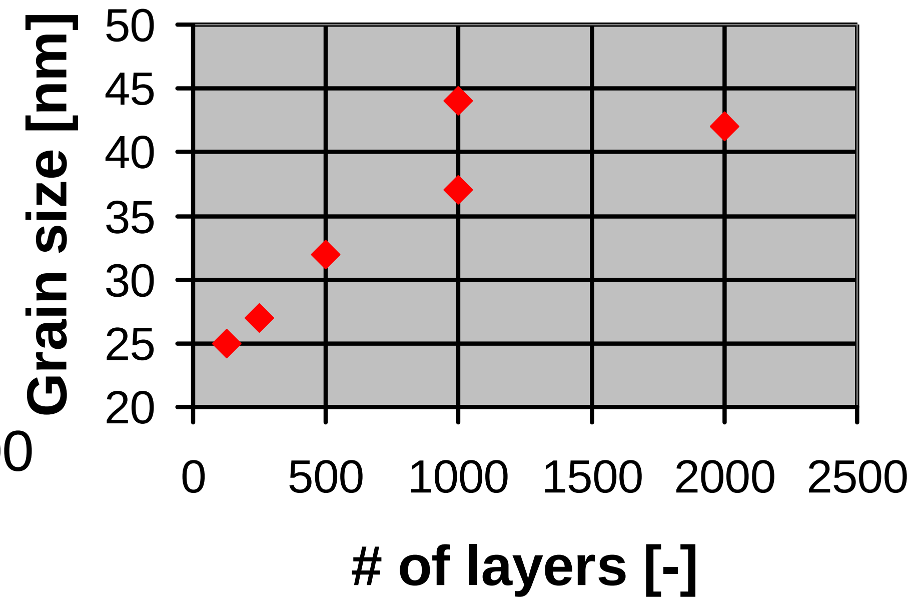
ALD021



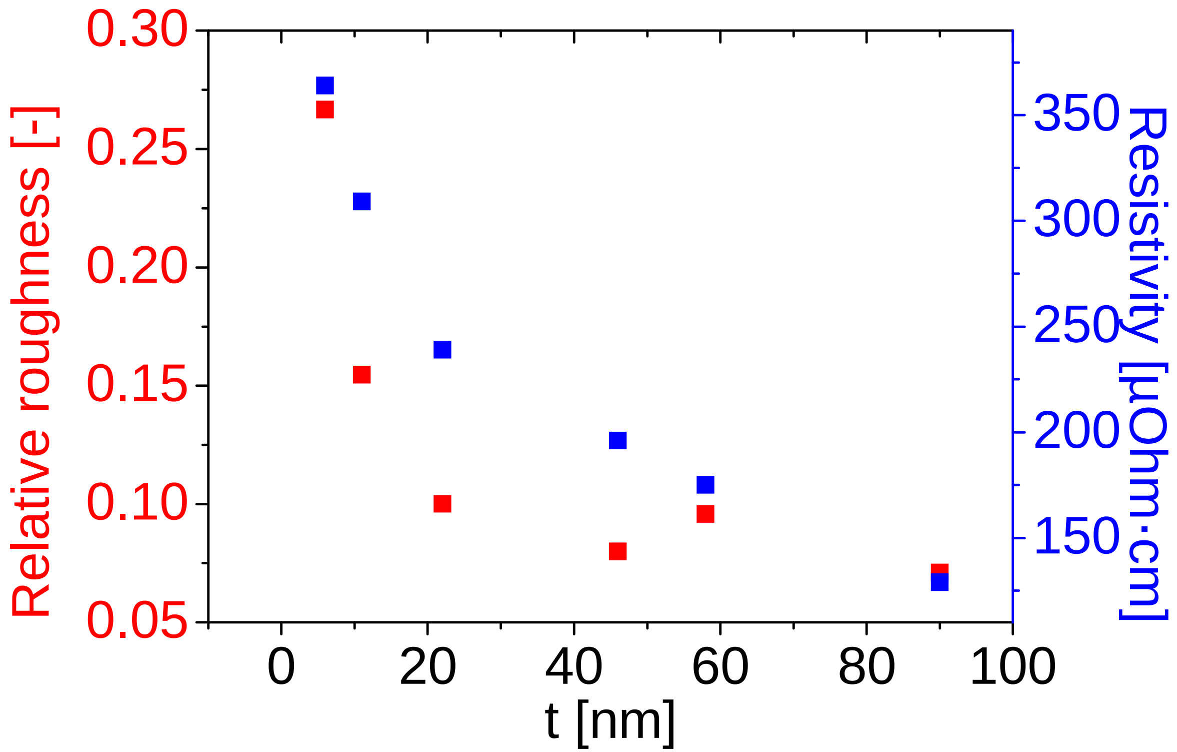
ALD2000

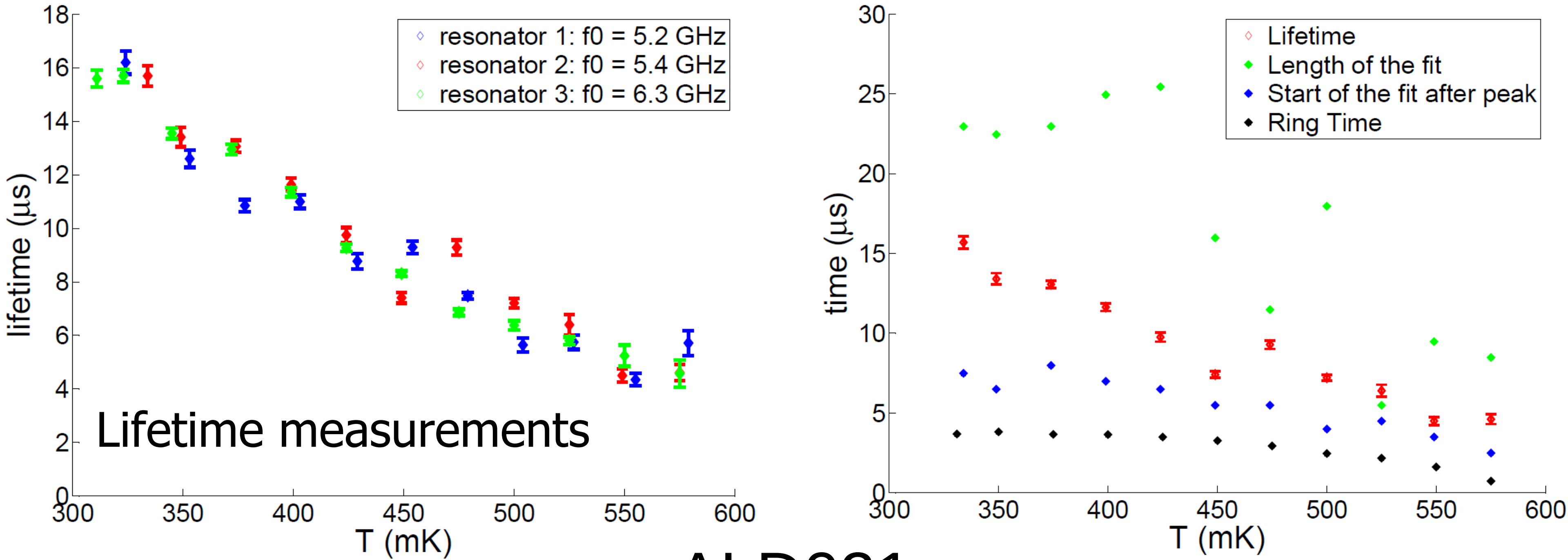
Roughness and grain size





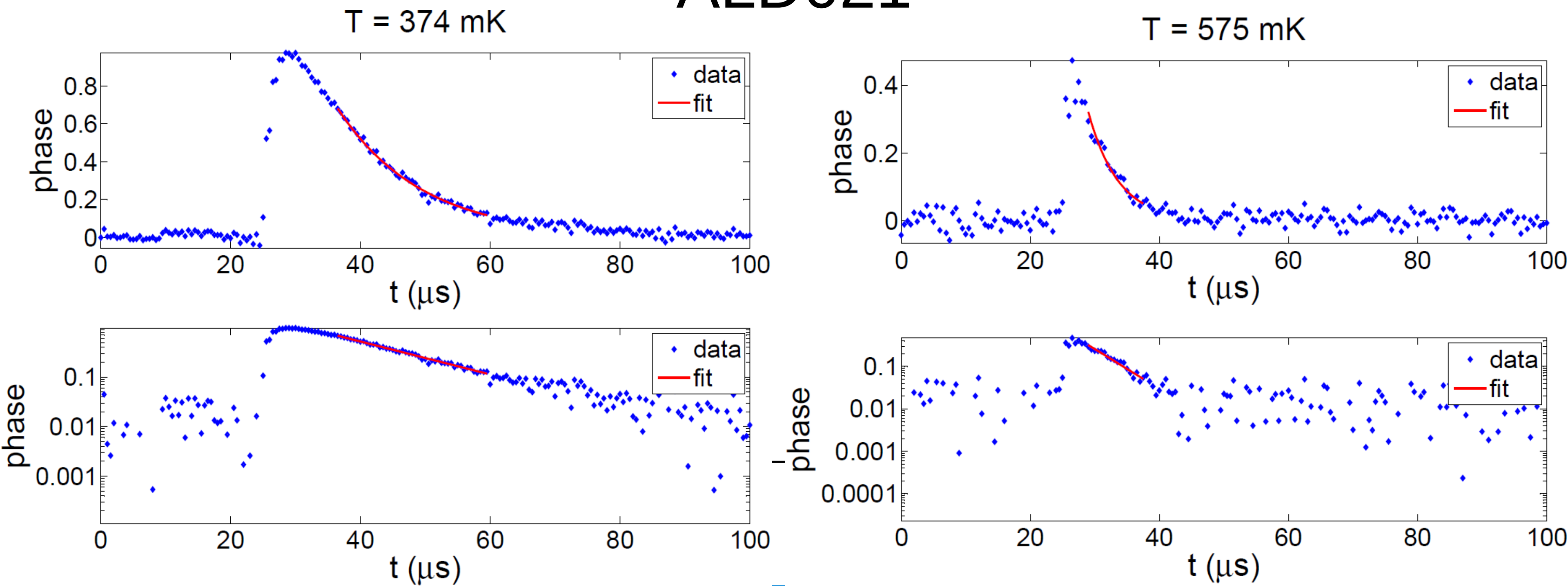
Relative roughness compared to resistivity





resonator 1: f0 = 5.2 GHz
resonator 2: f0 = 5.4 GHz
resonator 3: f0 = 6.3 GHz
lifetime (µs)
T (mK)
Lifetime measurements
Lifetime
Length of the fit
Start of the fit after peak
Ring Time
time (µs)
T (mK)

ALD021



T = 374 mK
T = 575 mK
data
fit
phase
t (µs)

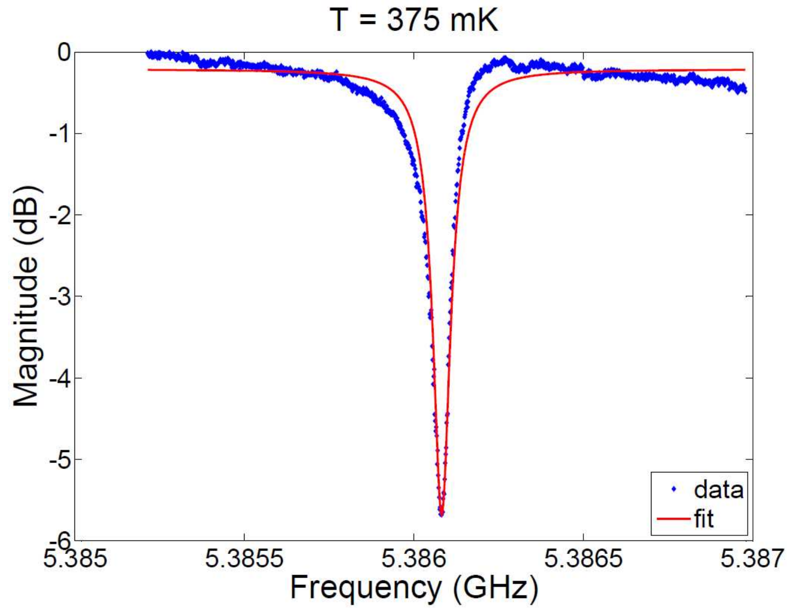
ALD021: bring it ON the carpet

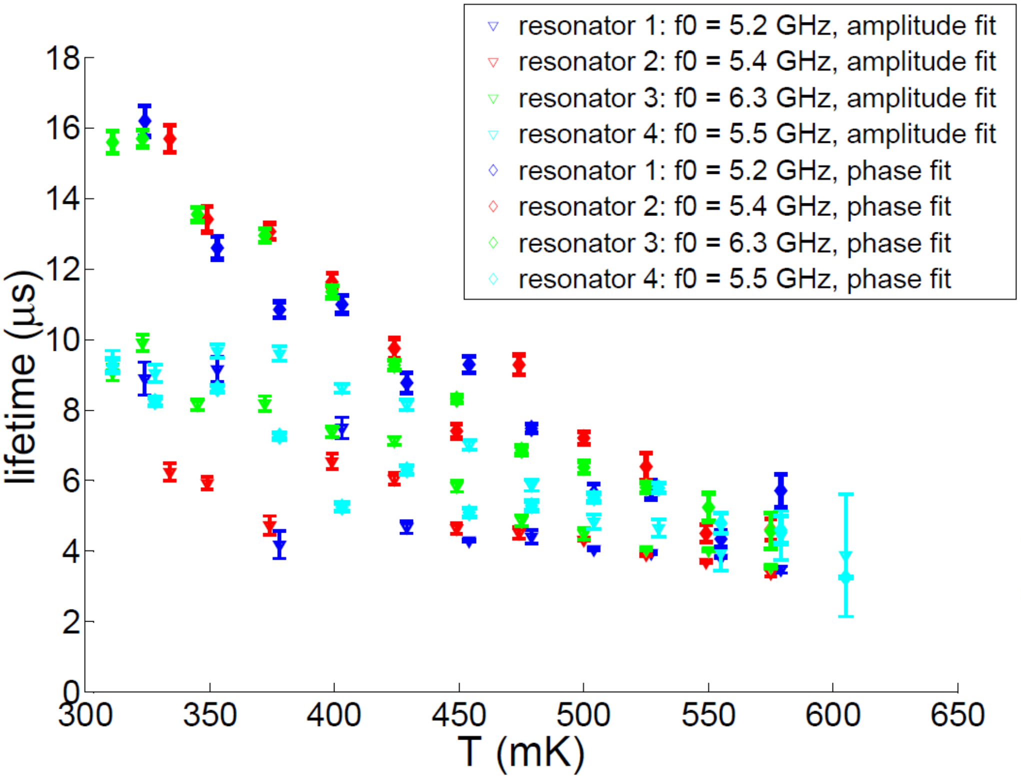
-Fitting the amplitude instead of the phase will give a different decay time, roughly a factor of 2 smaller.

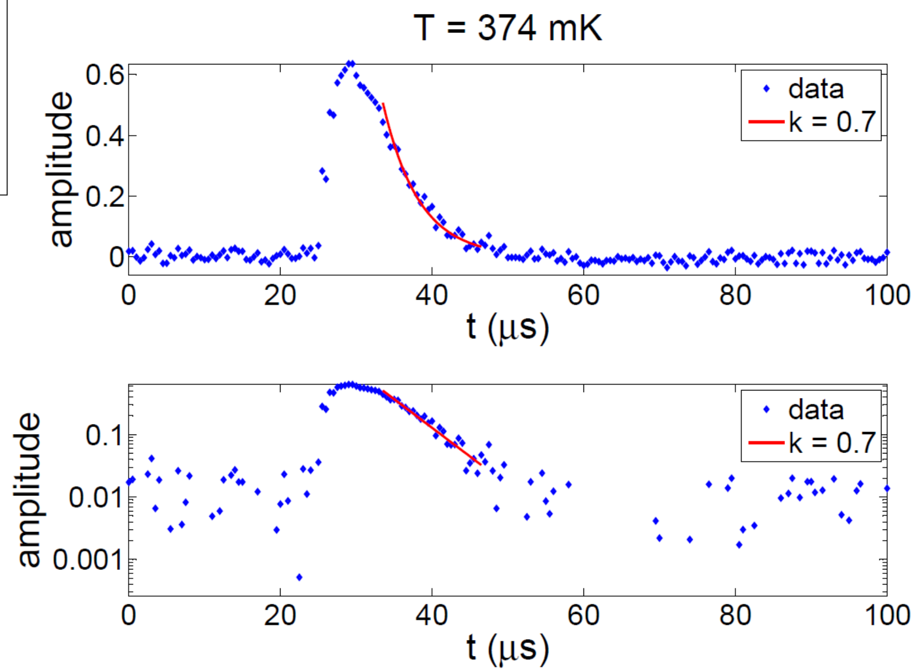
-The scatter in the lifetime deduced from the amplitude is very large, although the fits are reasonable.

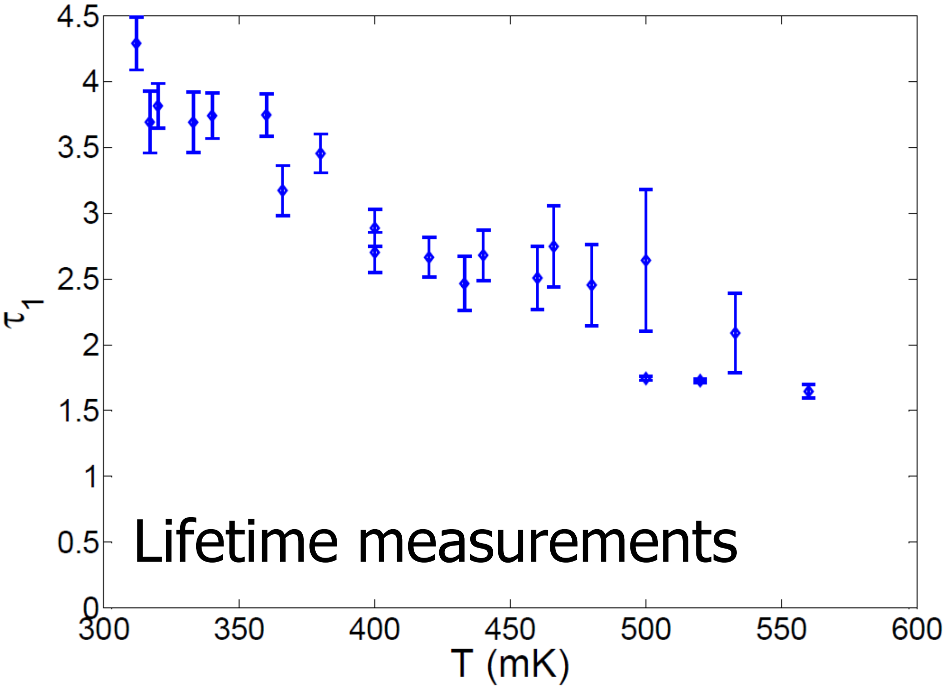
-Resonator 4 gives a large scattering in the lifetime (phase and amplitude), although the fits are reasonable.

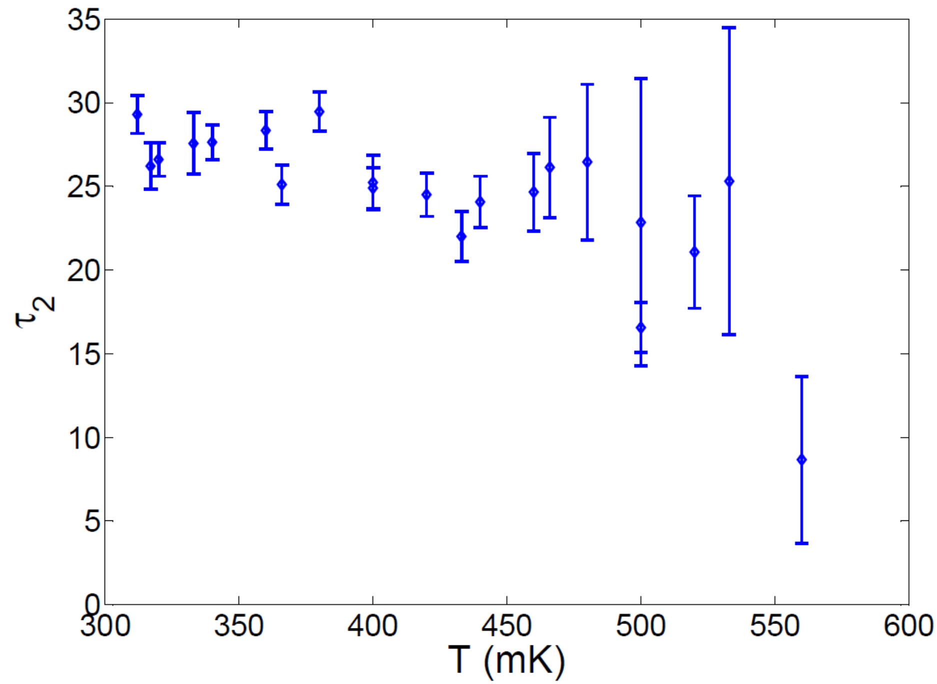
-We cannot really speak of an amplitude or phase response since the data is not properly normalized.

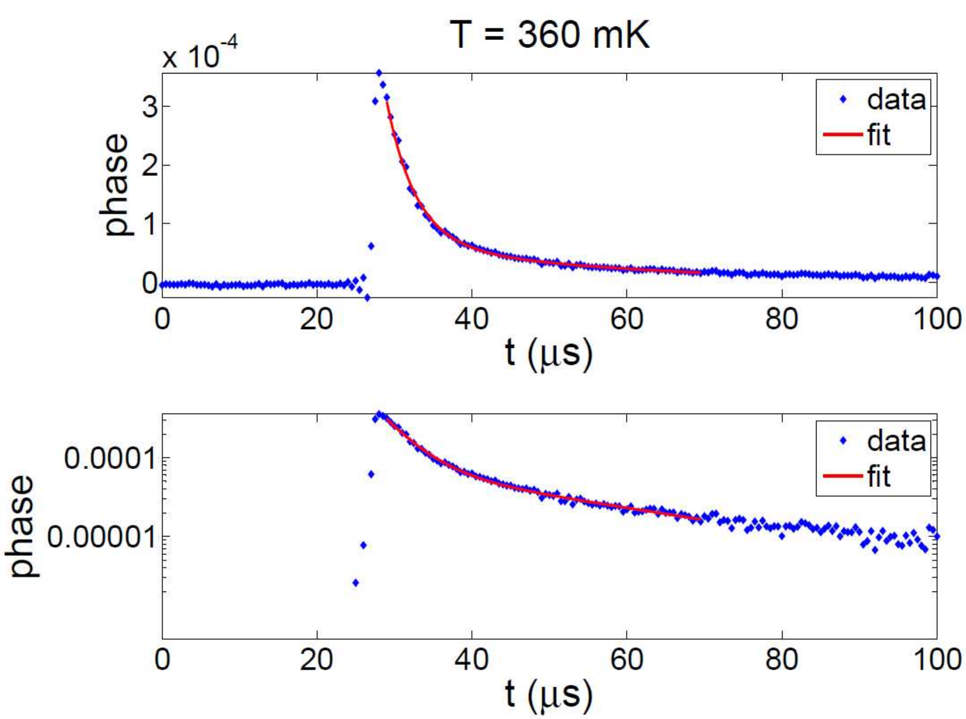












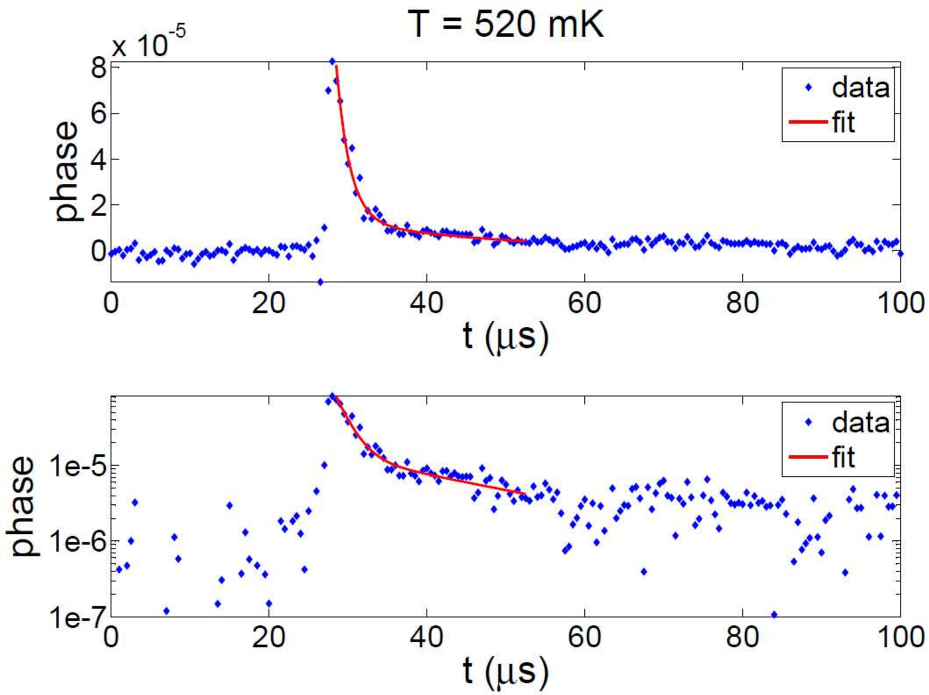
ALD250: two decay times! (unexplained)

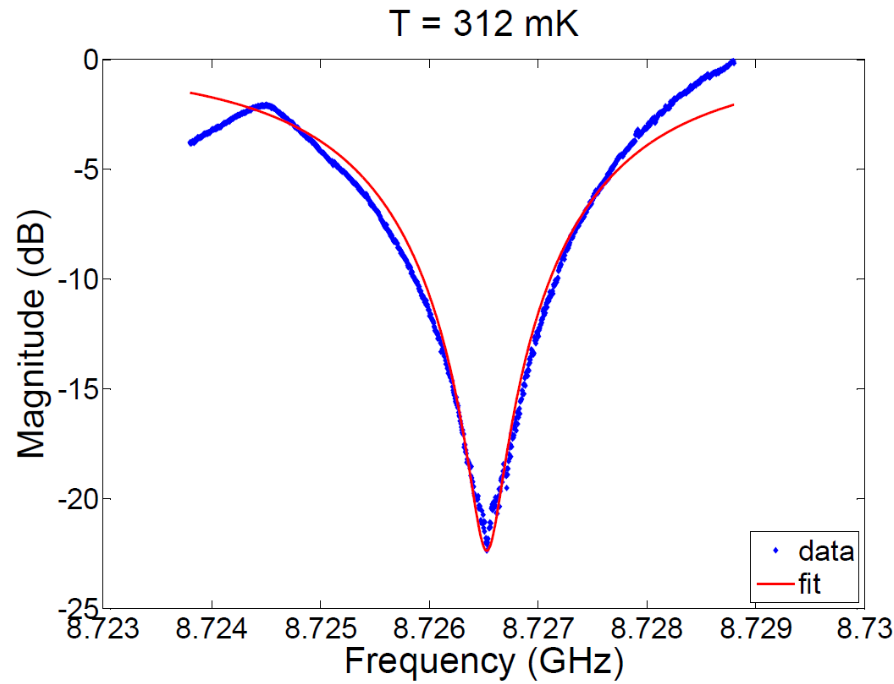
- Data is fitted with a double exponential function:

  $r_1*\exp[-t/\tau_1] + r_2*\exp[-t/\tau_2]$

- The short time scale is temperature dependent

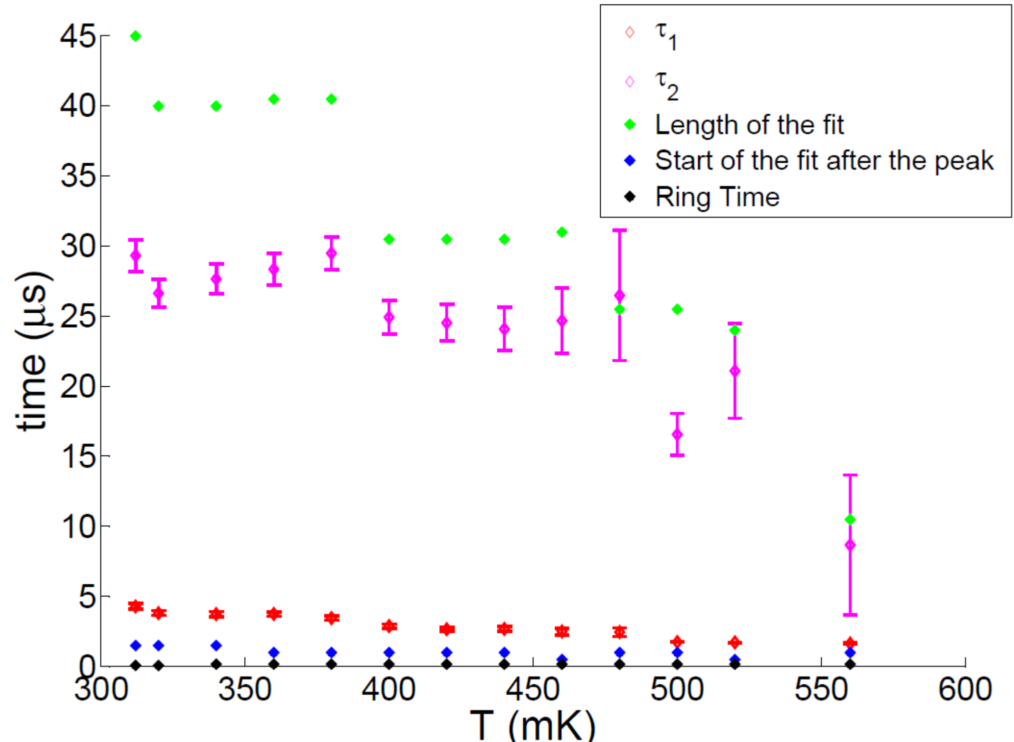
-The long time scale is roughly temperature independent

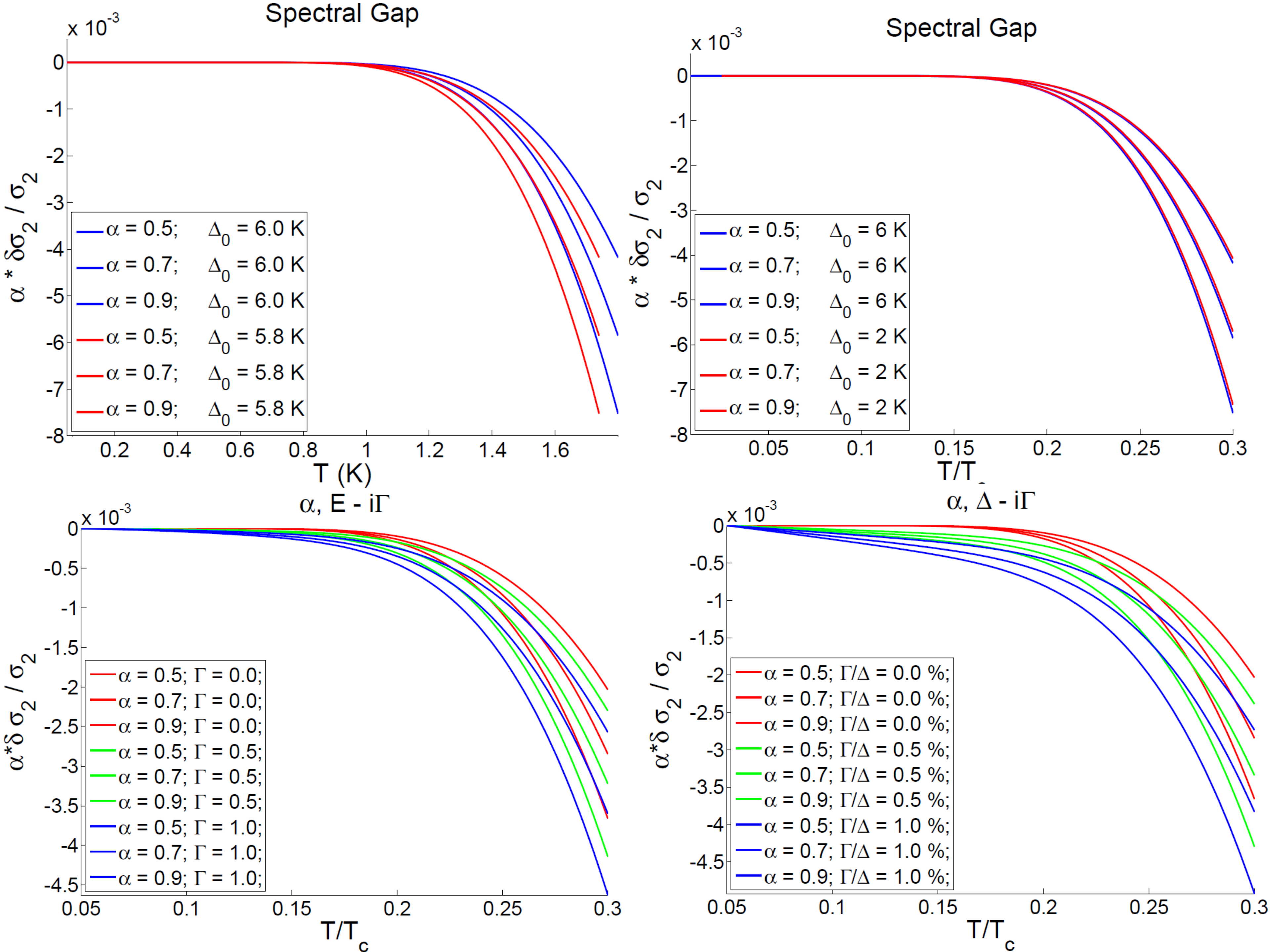




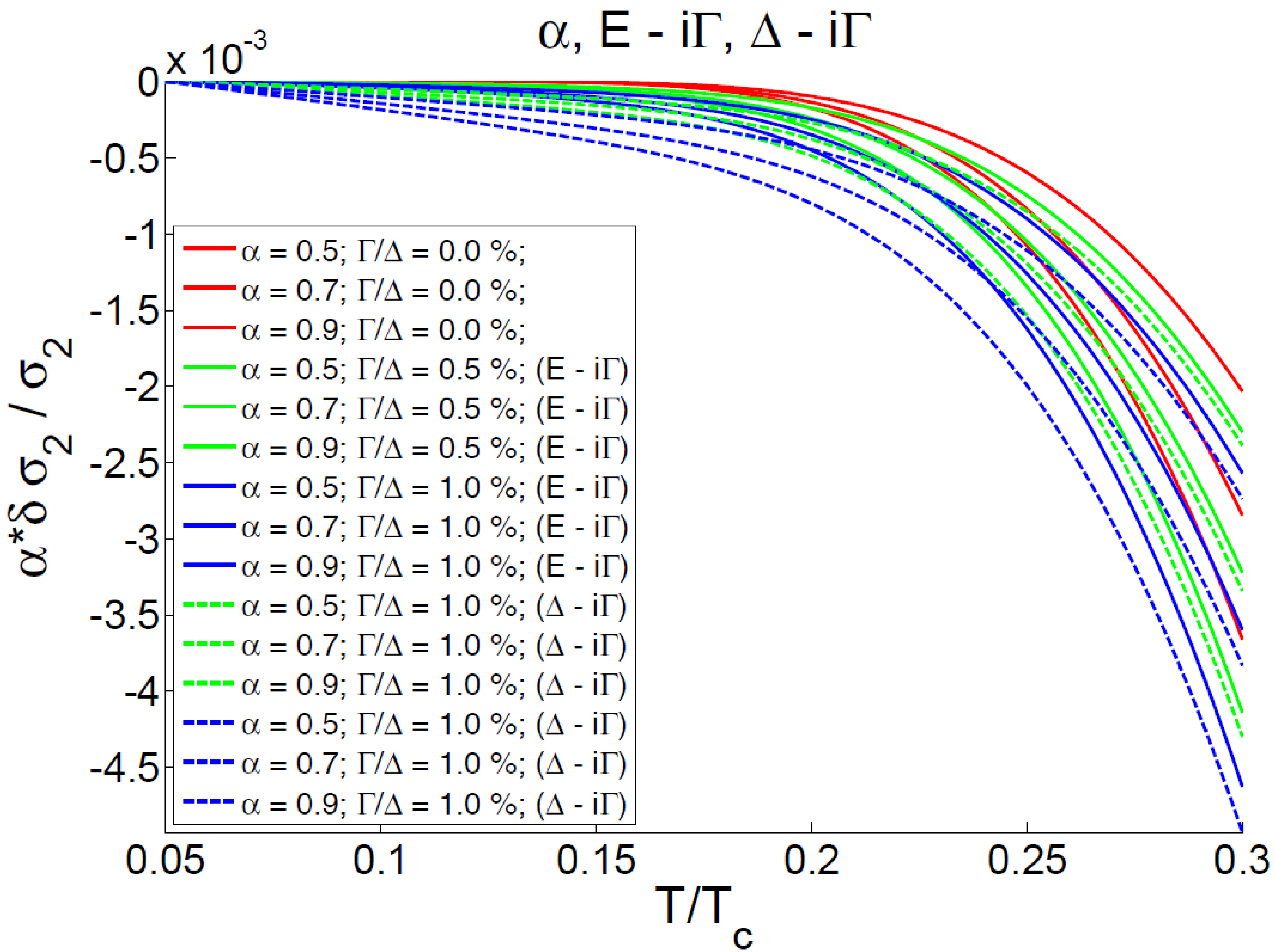
ALD250: additional plots

- I have only data of one resonator
- Further, I have only analyzed the ‘phase’ data and no proper normalization was possible





Spectral Gap
x 10^-3
0
-1
-2
-3
-4
-5
-6
-7
-8
α * δσ2 / σ2
α = 0.5; Δ0 = 6.0 K
α = 0.7; Δ0 = 6.0 K
α = 0.9; Δ0 = 6.0 K
α = 0.5; Δ0 = 5.8 K
α = 0.7; Δ0 = 5.8 K
α = 0.9; Δ0 = 5.8 K
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
T (K)
Spectral Gap
x 10^-3
0
-1
-2
-3
-4
-5
-6
-7
-8
α * δσ2 / σ2
α = 0.5; Δ0 = 6 K
α = 0.7; Δ0 = 6 K
α = 0.9; Δ0 = 6 K
α = 0.5; Δ0 = 2 K
α = 0.7; Δ0 = 2 K
α = 0.9; Δ0 = 2 K
0.05
0.1
0.15
0.2
0.25
0.3
T/Tc
α, E - iΓ
x 10^-3
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
α*δ σ2 / σ2
α = 0.5; Γ = 0.0;
α = 0.7; Γ = 0.0;
α = 0.9; Γ = 0.0;
α = 0.5; Γ = 0.5;
α = 0.7; Γ = 0.5;
α = 0.9; Γ = 0.5;
α = 0.5; Γ = 1.0;
α = 0.7; Γ = 1.0;
α = 0.9; Γ = 1.0;
0.05
0.1
0.15
0.2
0.25
0.3
T/Tc
α, Δ - iΓ
x 10^-3
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
α*δ σ2 / σ2
α = 0.5; Γ/Δ = 0.0 %;
α = 0.7; Γ/Δ = 0.0 %;
α = 0.9; Γ/Δ = 0.0 %;
α = 0.5; Γ/Δ = 0.5 %;
α = 0.7; Γ/Δ = 0.5 %;
α = 0.9; Γ/Δ = 0.5 %;
α = 0.5; Γ/Δ = 1.0 %;
α = 0.7; Γ/Δ = 1.0 %;
α = 0.9; Γ/Δ = 1.0 %;
0.05
0.1
0.15
0.2
0.25
0.3
T/Tc



α, E - iΓ, Δ - iΓ
x 10^-3
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
α*δ σ2 / σ2
α = 0.5; Γ/Δ = 0.0 %;
α = 0.7; Γ/Δ = 0.0 %;
α = 0.9; Γ/Δ = 0.0 %;
α = 0.5; Γ/Δ = 0.5 %; (E - iΓ)
α = 0.7; Γ/Δ = 0.5 %; (E - iΓ)
α = 0.9; Γ/Δ = 0.5 %; (E - iΓ)
α = 0.5; Γ/Δ = 1.0 %; (E - iΓ)
α = 0.7; Γ/Δ = 1.0 %; (E - iΓ)
α = 0.9; Γ/Δ = 1.0 %; (E - iΓ)
α = 0.5; Γ/Δ = 1.0 %; (Δ - iΓ)
α = 0.7; Γ/Δ = 1.0 %; (Δ - iΓ)
α = 0.9; Γ/Δ = 1.0 %; (Δ - iΓ)
α = 0.5; Γ/Δ = 1.0 %; (Δ - iΓ)
α = 0.7; Γ/Δ = 1.0 %; (Δ - iΓ)
α = 0.9; Γ/Δ = 1.0 %; (Δ - iΓ)
0.05
0.1
0.15
0.2
0.25
0.3
T/Tc

Characterization

Level of disorder

- How close to localization are our TiN films?
  - Anderson localization at $k_F\ell \sim 1$

$$D = \tfrac{1}{3} v_F \ell$$

$$v_F = k_F^2 / \hbar\pi^2 N(0)$$

$$\rho^{-1} = e^2 N(0) D$$

$$k_F = \sqrt[3]{3\pi^2 n}$$

$$k_F \ell = \frac{3\pi^2}{e^2} \frac{\hbar}{\rho \sqrt[3]{3\pi^2 n}}$$

Critical field (D)

R – T Curve (ρ)

Hall effect (n)

- Blue Oxford Cryostat
  - Base temperature 1.5 K
  - Magnetic field up to ~13.5 T

Dynes *et al.*, PRL **53** (1984)

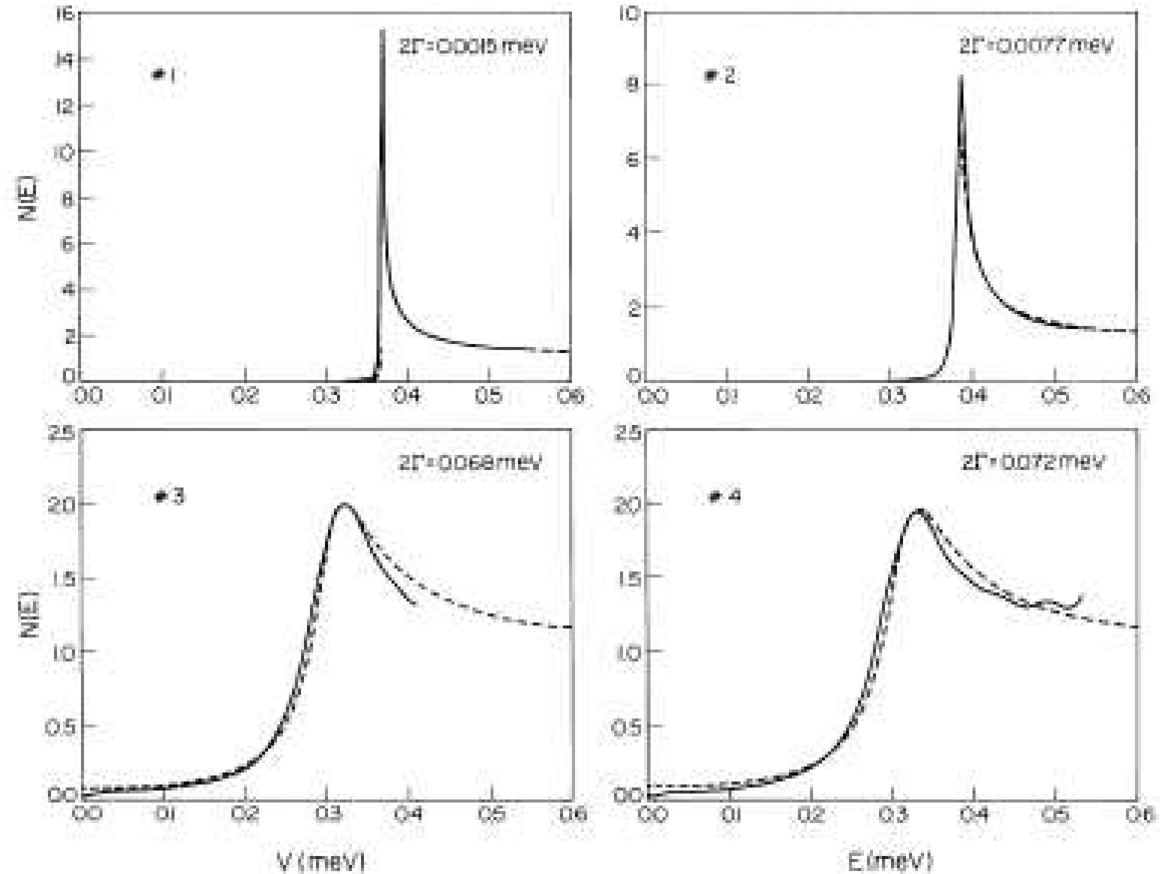


FIG. 3. The density of states $N(E)$ deconvoluted from the data of Fig. 2 (solid line). The dashed line is a BCS density of states broadened by the value of Γ shown in the figure for each case.