TECHNION
Israel Institute of Technology

Measuring the Stiffness and Coherence Length of 2D Superconductors

Nitsan Blau – Supervised by Prof. Amit Keren

Thesis Defense – 16/03/2020

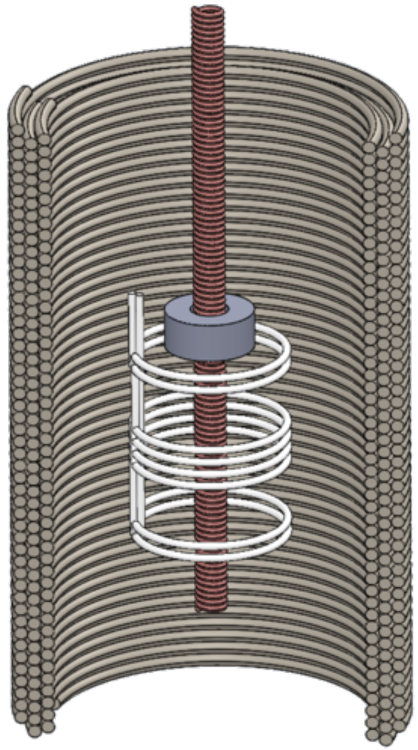
Outline

- Introduction & Motivation
- 2D Superconductivity – The Pearl equation
- The Stiffnessometer – Principle of Operation
- Experimental Setup & Samples Fabrication
- Stiffness Measurement
- Coherence Length Measurement
- Summary

The Stiffnesometer

Prof. Amit Keren

Dr. Itzik Kapon



Stiffnessometer, a magnetic-field-free superconducting stiffness meter and its application

Itzik Kapon,[1,*] Katrine Golubkov,[1] Nir Gavish,[2] and Amit Keren[1,†]

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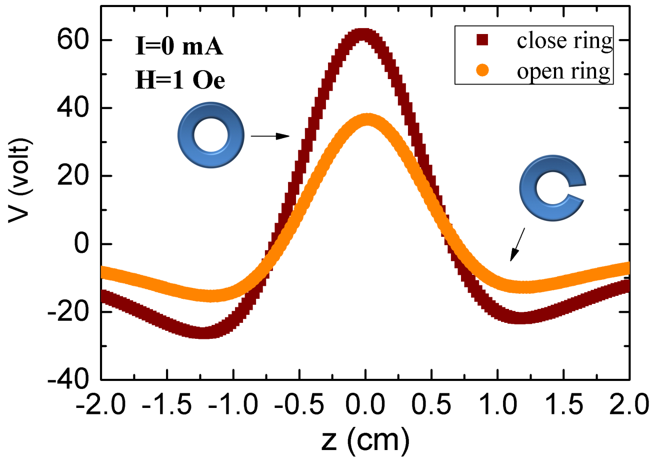
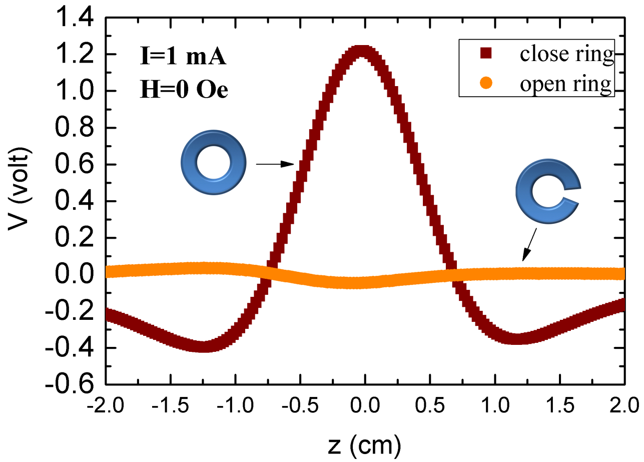
[2] *Department of Mathematics, Technion-Israel Institute of Technology, Haifa, 3200003, Israel*

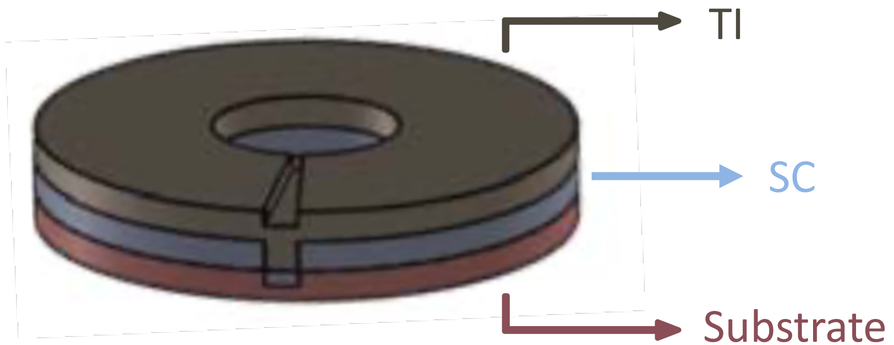
(Dated: November 10, 2017)



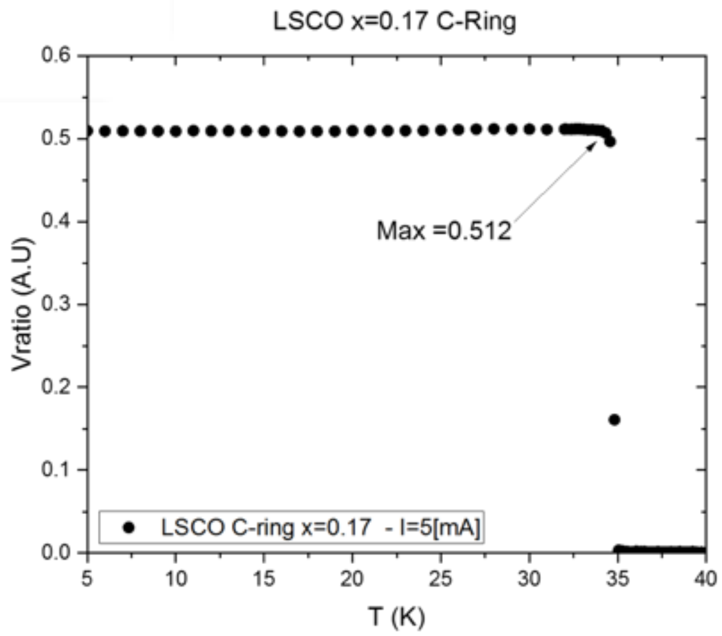


Motivations

- TI Proximity effect – how thin can we measure?



- Extracting absolute values of the Stiffness in 2D.



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London's Equation

- The superconducting stiffness is defined by:

$$\mathbf{J}_s = -\rho_s(\mathbf{A} - \frac{\hbar}{2e}\nabla\varphi)$$

- Where φ is the phase of the complex order parameter:

$$\psi = |\psi| e^{i\varphi(x)}$$

- When $\nabla\varphi = 0$ we get the **London's Equation**:

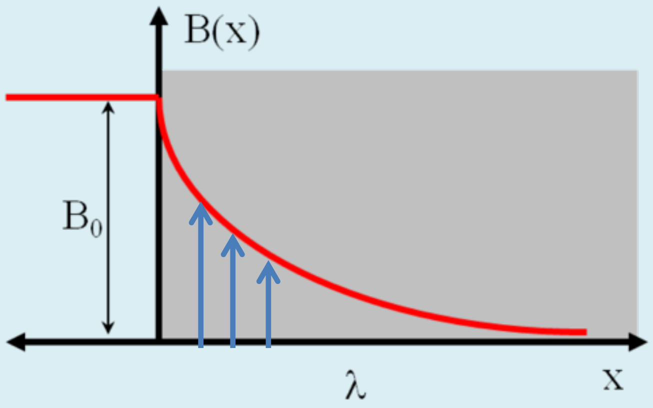
$$\mathbf{J}_s = -\rho_s \mathbf{A}$$

London's Equation

London's Eq. $$\mathbf{J}_s = -\rho_s \mathbf{A}$$ ρ_s is the stiffness

$\nabla \times$ Ampère's Law: $$\nabla \times \nabla \times \mathbf{B} = \mu_o \nabla \times \mathbf{J} = -\mu_o \rho_s \nabla \times \mathbf{A} = -\mu_o \rho_s \mathbf{B}$$

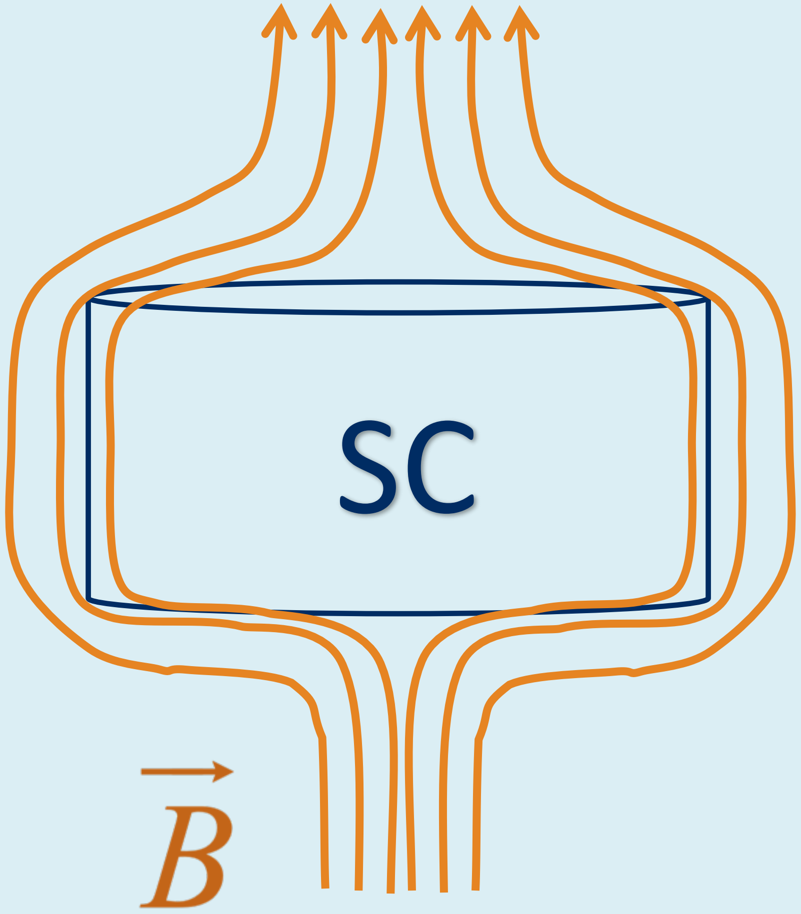
Solution $$B(x) = B_0 e^{-x/\lambda}$$ λ is the penetration depth



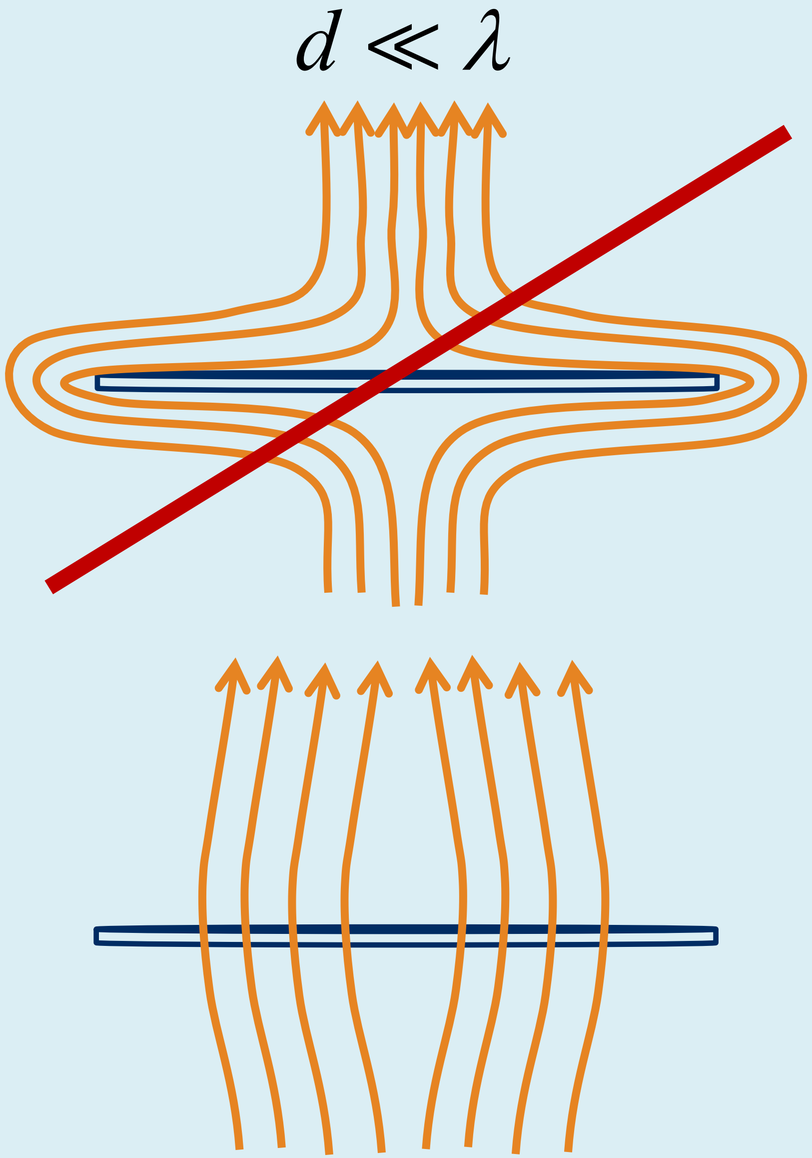
$$\rho_s = \frac{1}{\mu_o \lambda^2}$$

Currents on the wall prevent the field from penetrating, leading to the Meissner effect.

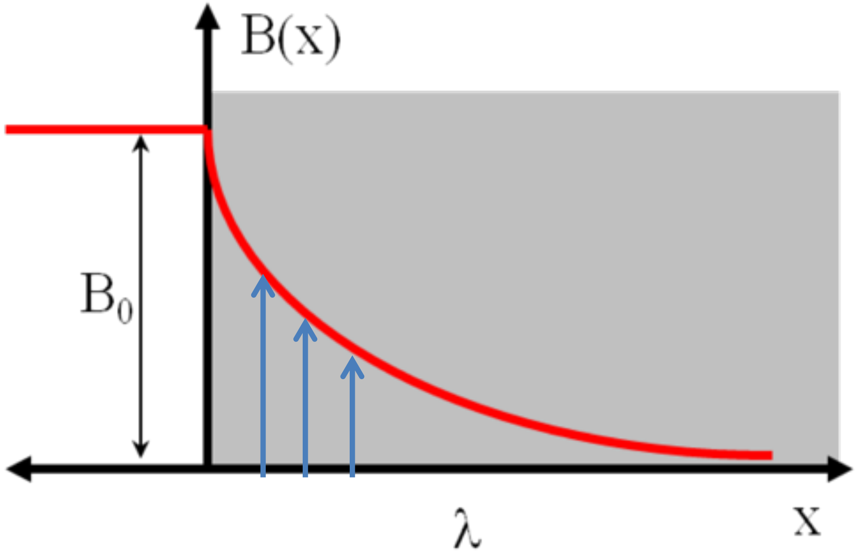
2D Superconductivity

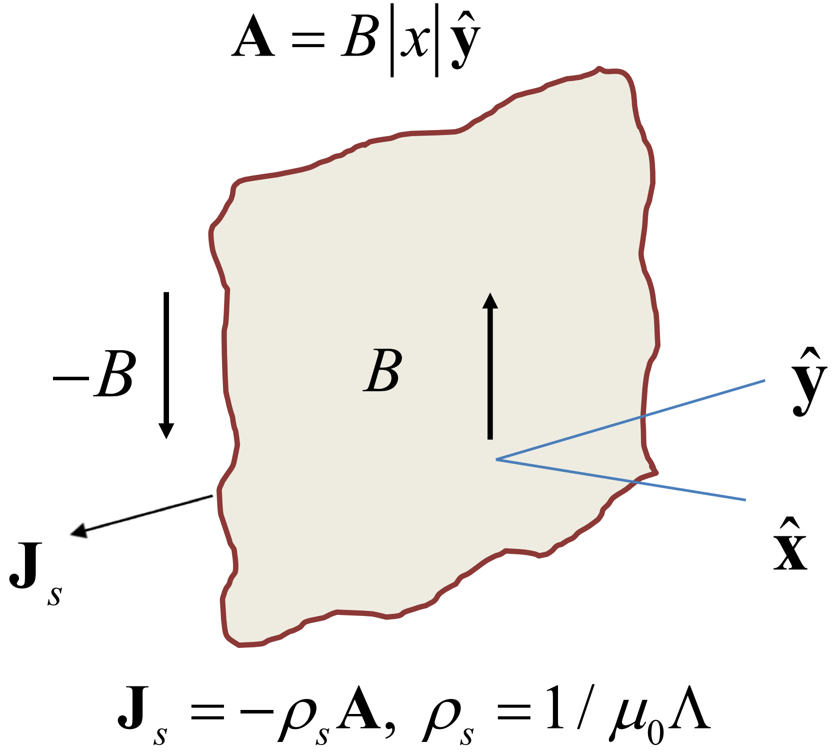


In **2D** even **type 1 SC** behaves like **type 2**



2D Superconductivity

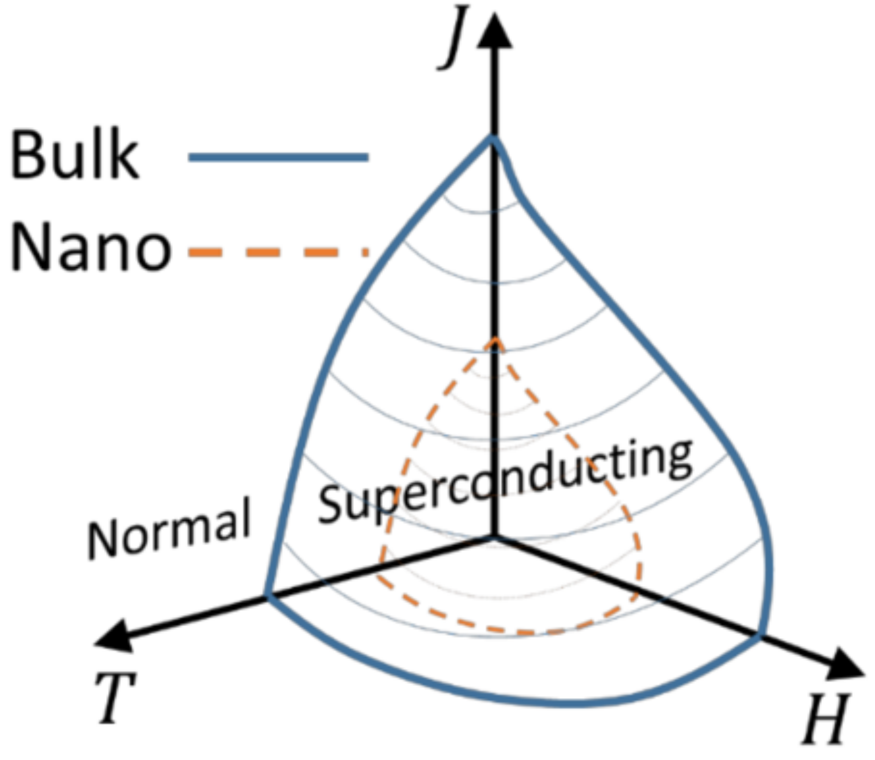




- In **2D** the question "what is the field inside the sample" is meaningless.
- In 2D the question "what are ***A*** and ***J***" is meaningful.

Superconductivity Suppression

- In **ultra-thin films**, superconducting properties often deviate from their bulk counterparts.
- In particular, the superconducting energy gap (Δ) and the magnetic penetration depth (λ) can get strongly affected by the **increased role of disorder, formation of vortex antivortex pairs, and thermal phase fluctuations.**



The Pearl Equation

- In 2D there is no wall and very weak Meissner effect.
- However there is Stiffness in 2D:

London in 2D $$\mathbf{J}_s = -\frac{d}{\mu_0 \lambda^2}\mathbf{A}\delta(z)$$ d is the **film thickness**

Pearl J - Appl. Phys. Lett. 5, 65 (1964);

- Ampere with $\mathbf{B} = \nabla \times \mathbf{A}$ $$\boxed{\nabla \times \nabla \times \mathbf{A} = \mu_0 \mathbf{J} = -\frac{d}{\lambda^2}\mathbf{A}\delta(z)}$$
- This is a PDE for $\boldsymbol{A}$ determined by $\frac{d}{\lambda^2} \equiv \frac{1}{\Lambda}$ where Λ is the **Pearl length**.

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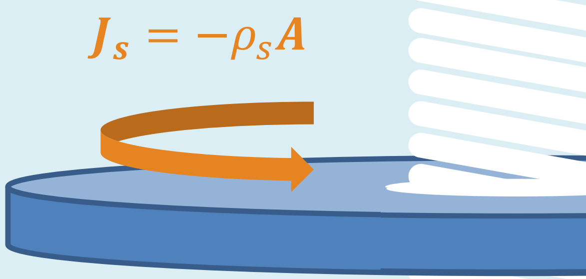
Principle of Operation

- Use **infinitely long coil** in the center of a **superconducting 2D ring**

$$(B_{coil}=0) \qquad A_{coil} \propto \frac{I}{r}\hat{\theta} \longrightarrow J_{ring} \longrightarrow A_{ring}$$

- The flux of the ring through a pickup loop (radius R_{PL}) is:

$$\boxed{\Phi(z) = 2\pi R_{PL} \cdot A_{ring}(R_{PL}, z).}$$



- By measuring $\Phi(z)$ we determine the solution of the **Normalized Pearl Equation** of our specific setup:

$$\boxed{\nabla \times \nabla \times \mathbf{A} = -\frac{1}{\Lambda}\left(\mathbf{A} + \frac{1}{r}\hat{\theta}\right)\delta(z)}$$

where $\Lambda = \dfrac{\lambda^2}{d}$ and $A = \dfrac{A_{ring}(r,z)}{A_{coil}(R_{PL})}.$

2D Simulation

- **Normalized Pearl Equation**:

$$\nabla \times \nabla \times \mathbf{A} = -\frac{1}{\Lambda}\left(\mathbf{A} + \frac{1}{r}\hat{\theta}\right)\delta(z)$$

$$\downarrow$$

$$\Lambda(A(R_{PL},0))$$

where $\Lambda = \dfrac{\lambda^2}{d}$ and $A = \dfrac{A_{ring}(r,z)}{A_{coil}(R_{PL})}$.

- Solve numerically (finite elements):

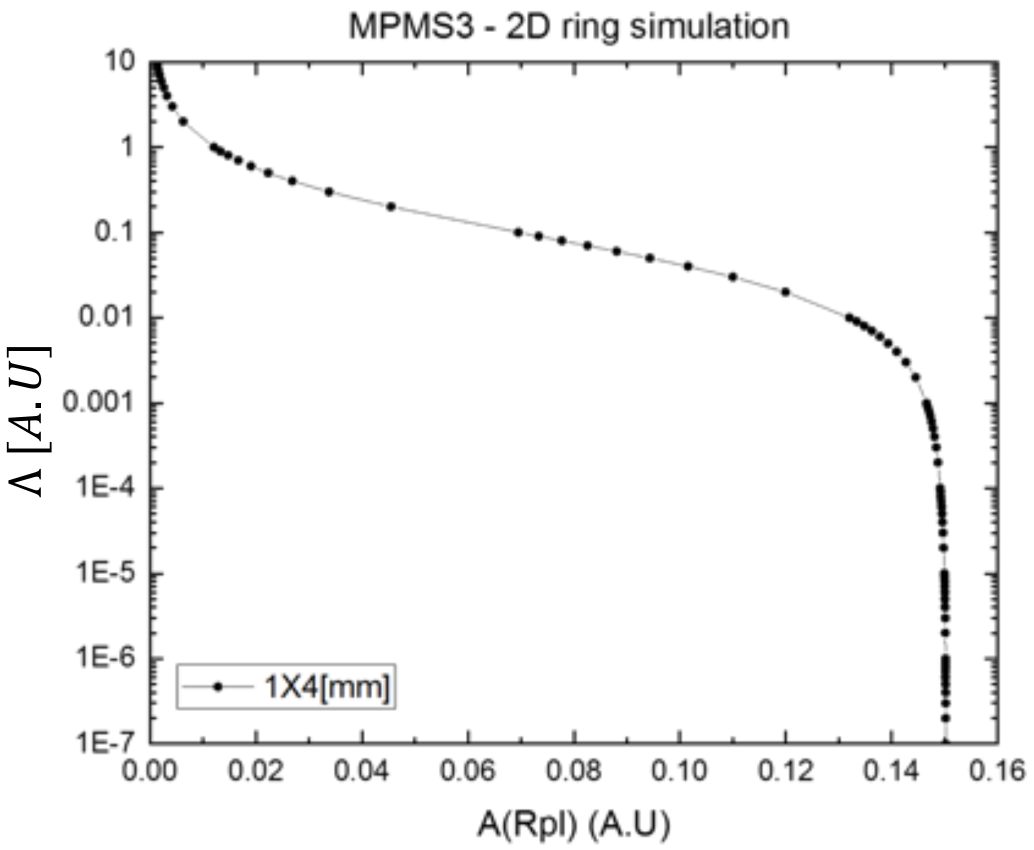
COMSOL $\nabla^2 A(r,z) = 0$

- In the box:

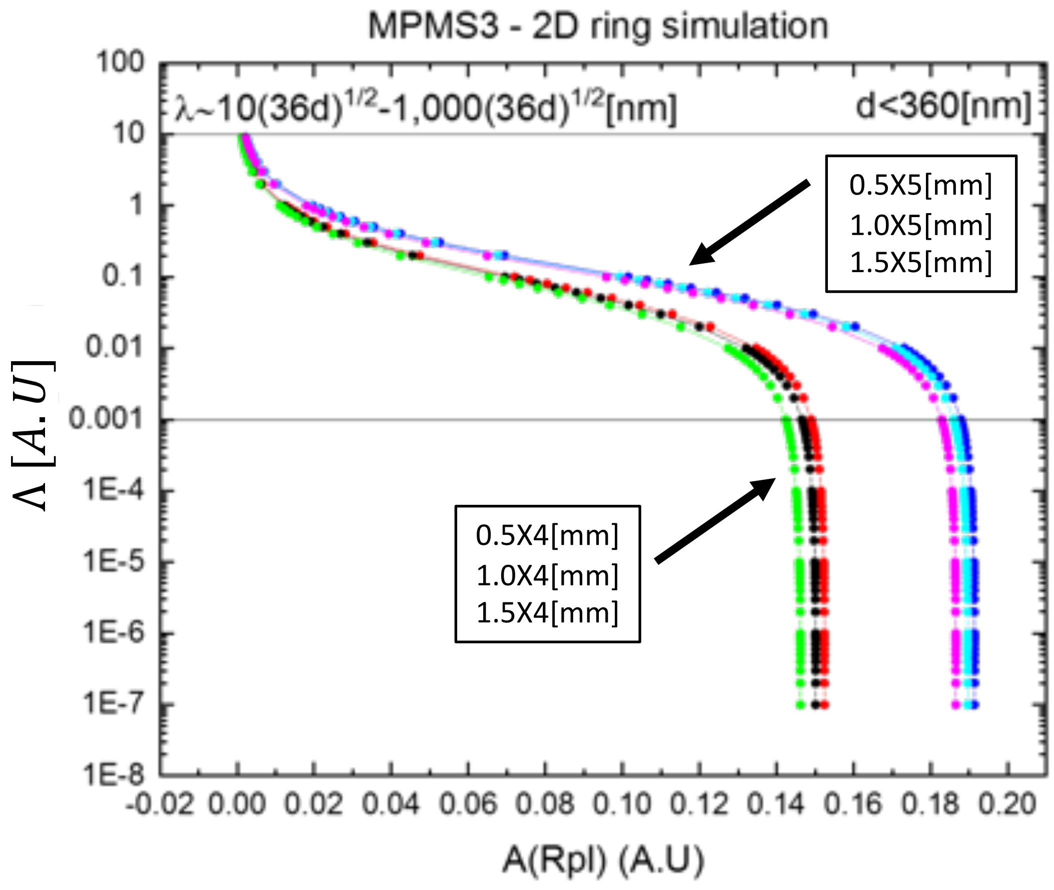
$0 < z < L$
$0 < r < L$

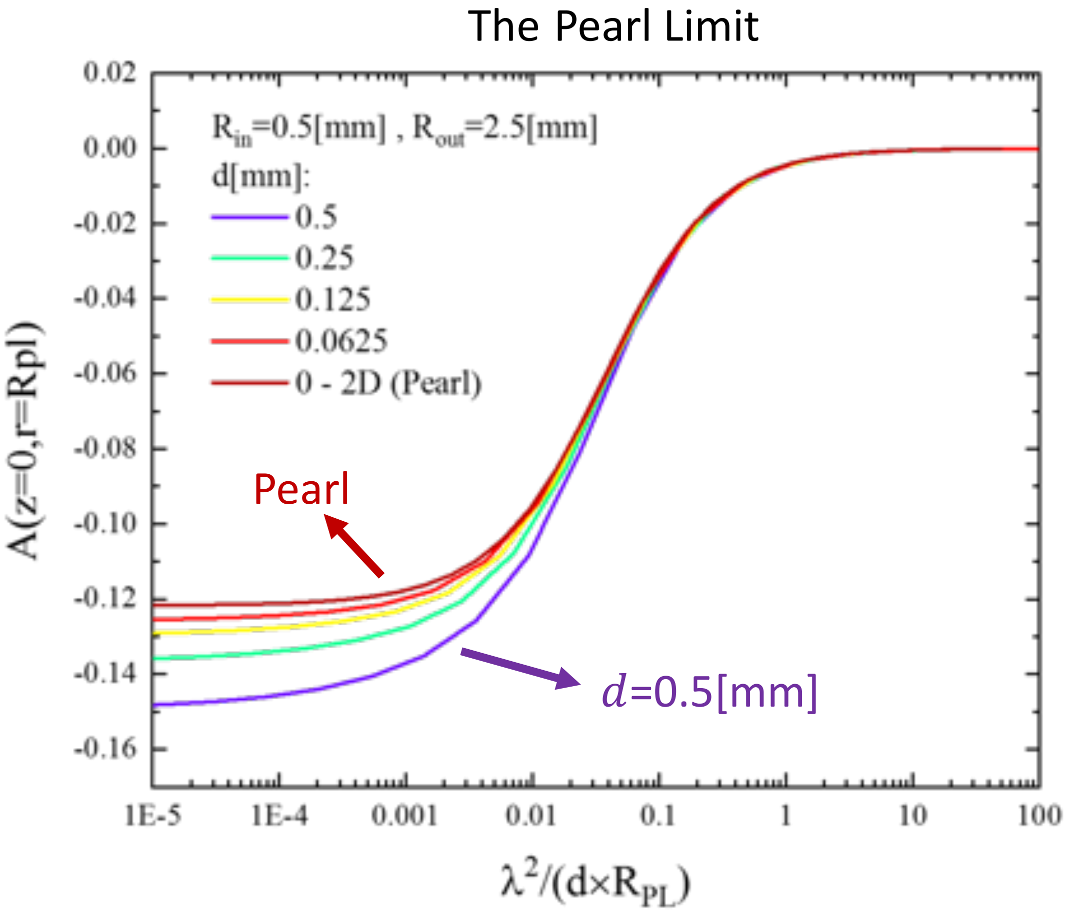
Boundary conditions:

$$\frac{\partial A}{\partial z} = -\frac{1}{2\Lambda}\left(\frac{1}{r} + A\right)$$

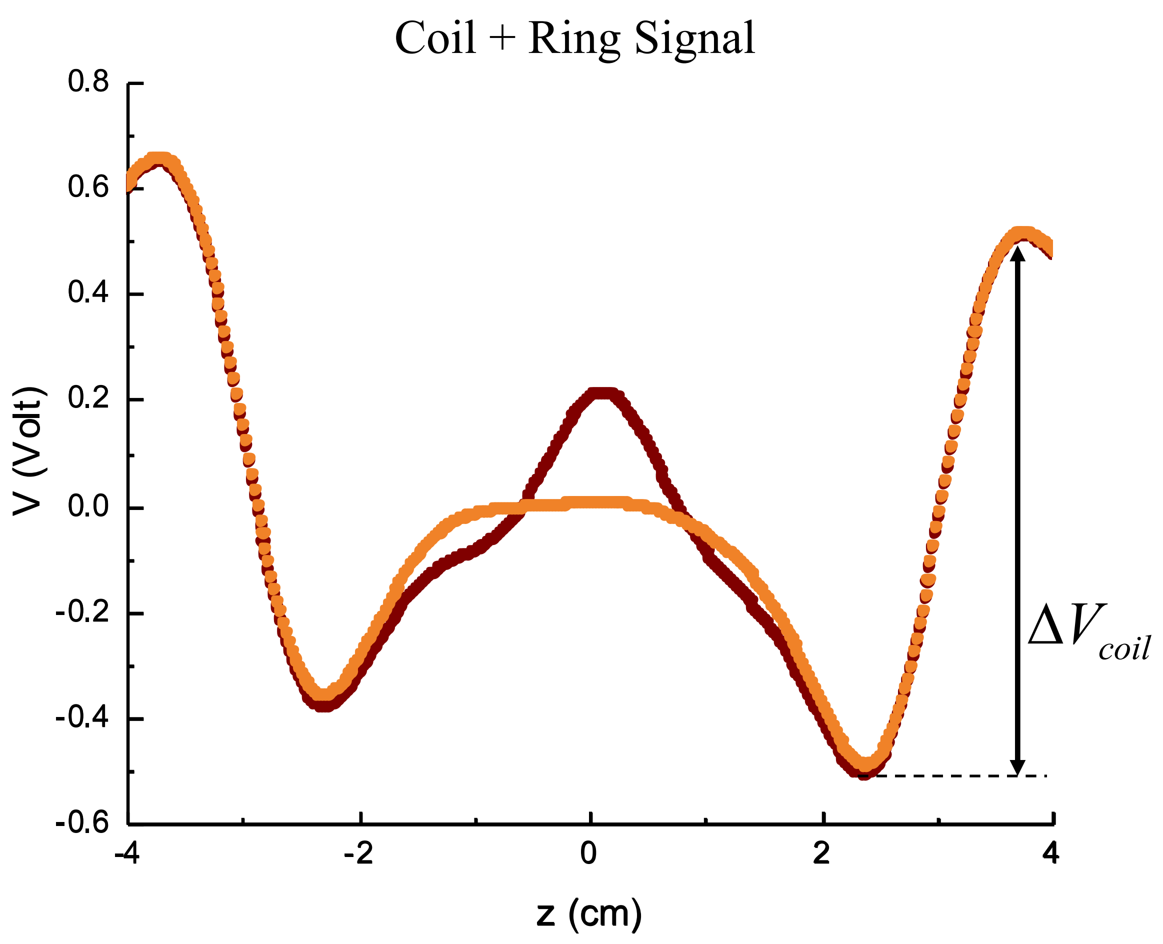


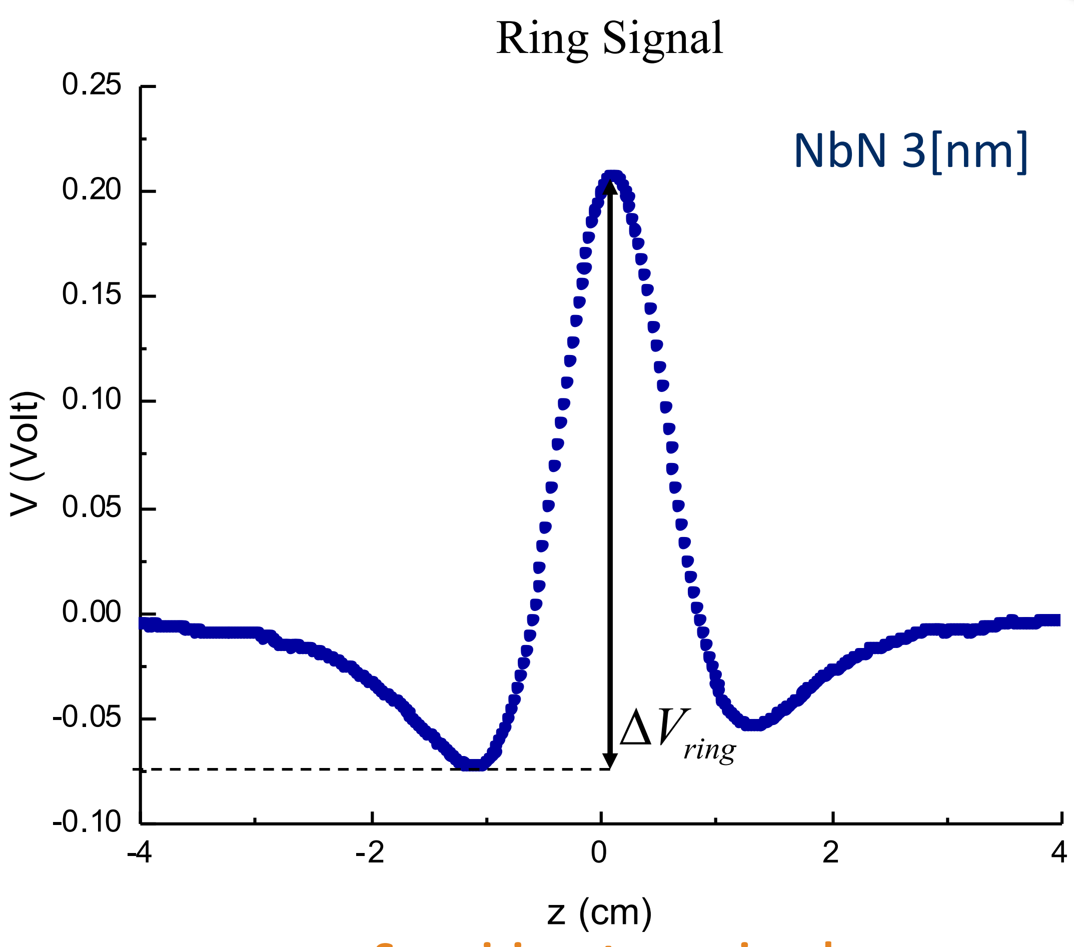
2D Simulation





Measurement





-Surprising strong signal-

~10 of sensitivity surplus

Data Analysis

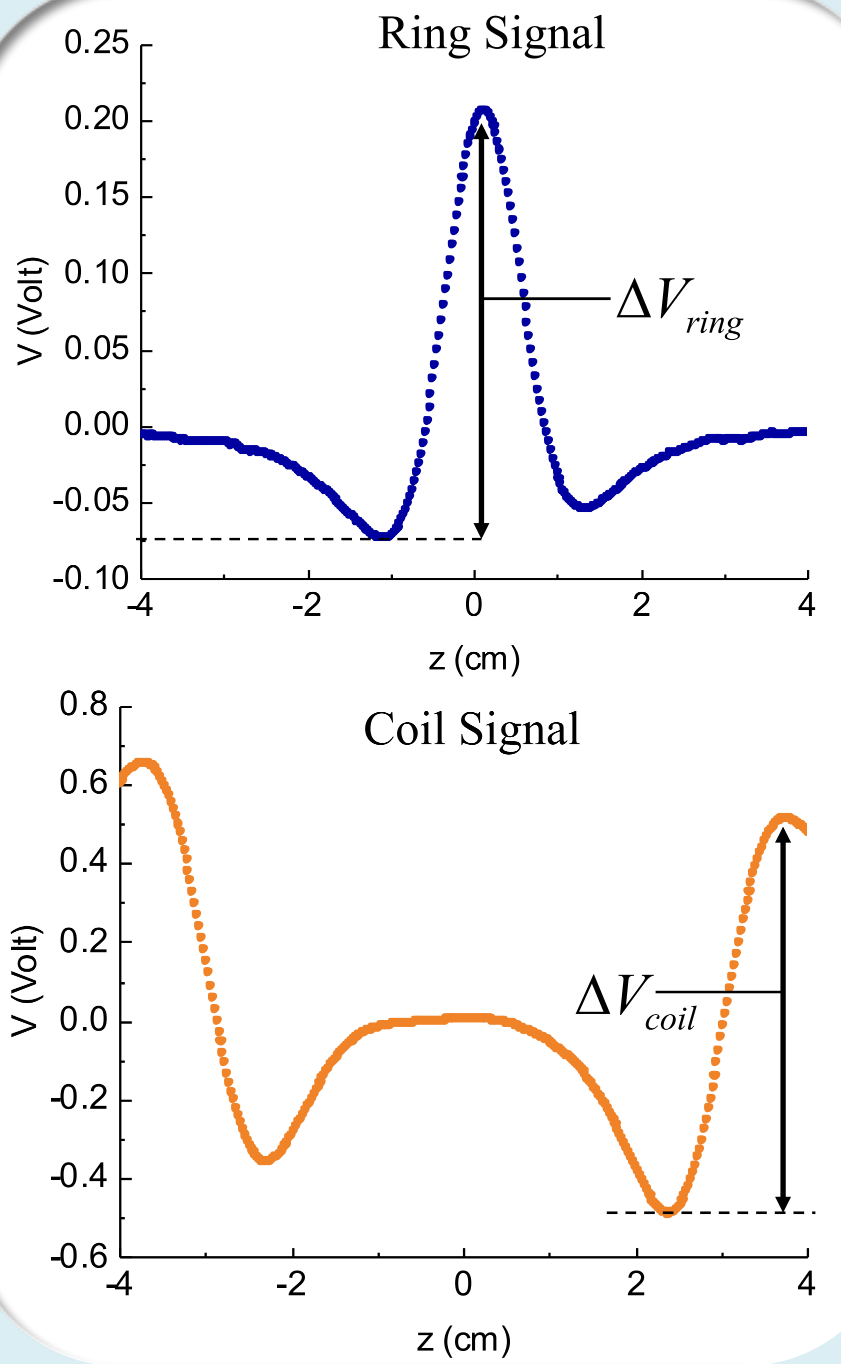
- The important relation is:

$$V_{ratio} \equiv \frac{\Delta V_{ring}}{\Delta V_{coil}} = G \cdot A(R_{PL}, z = 0)$$

- Where $A(R_{PL}, 0) \equiv \frac{A_{ring}(R_{PL}, 0)}{A_{coil}(R_{PL})}$.

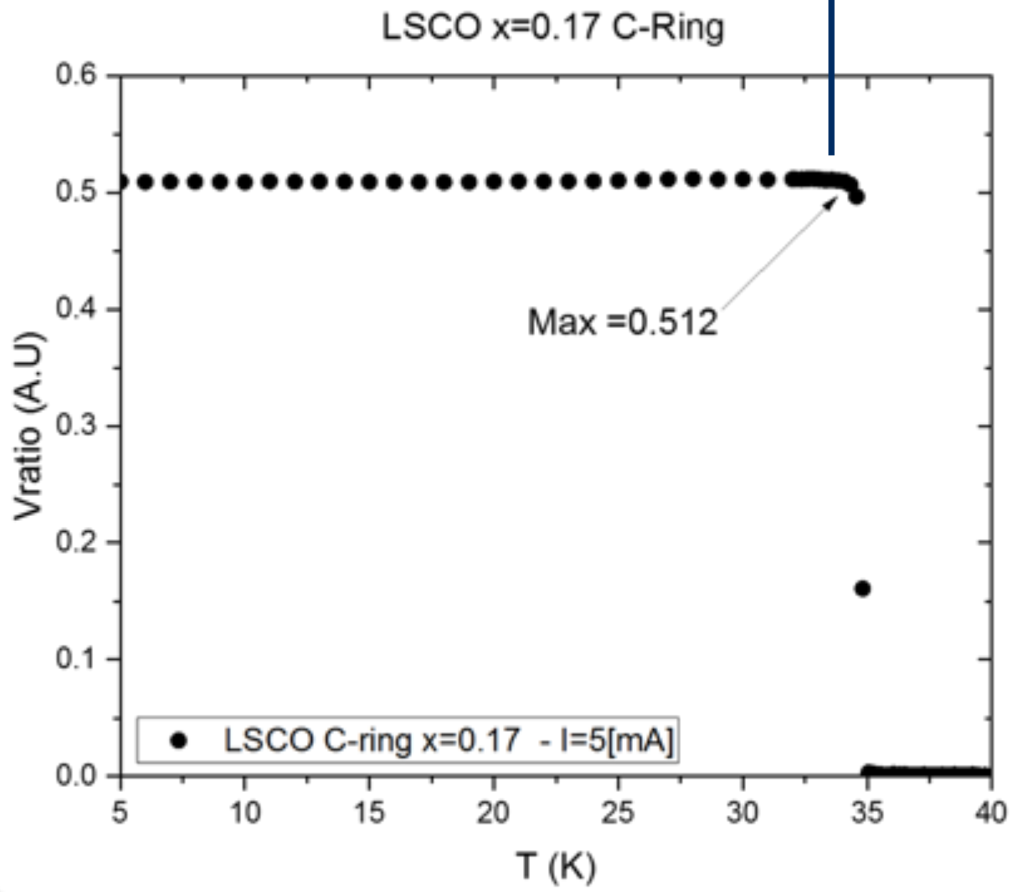
- G is a geometrical factor related to the Gradiometer $(G_{PL} = 1)$.

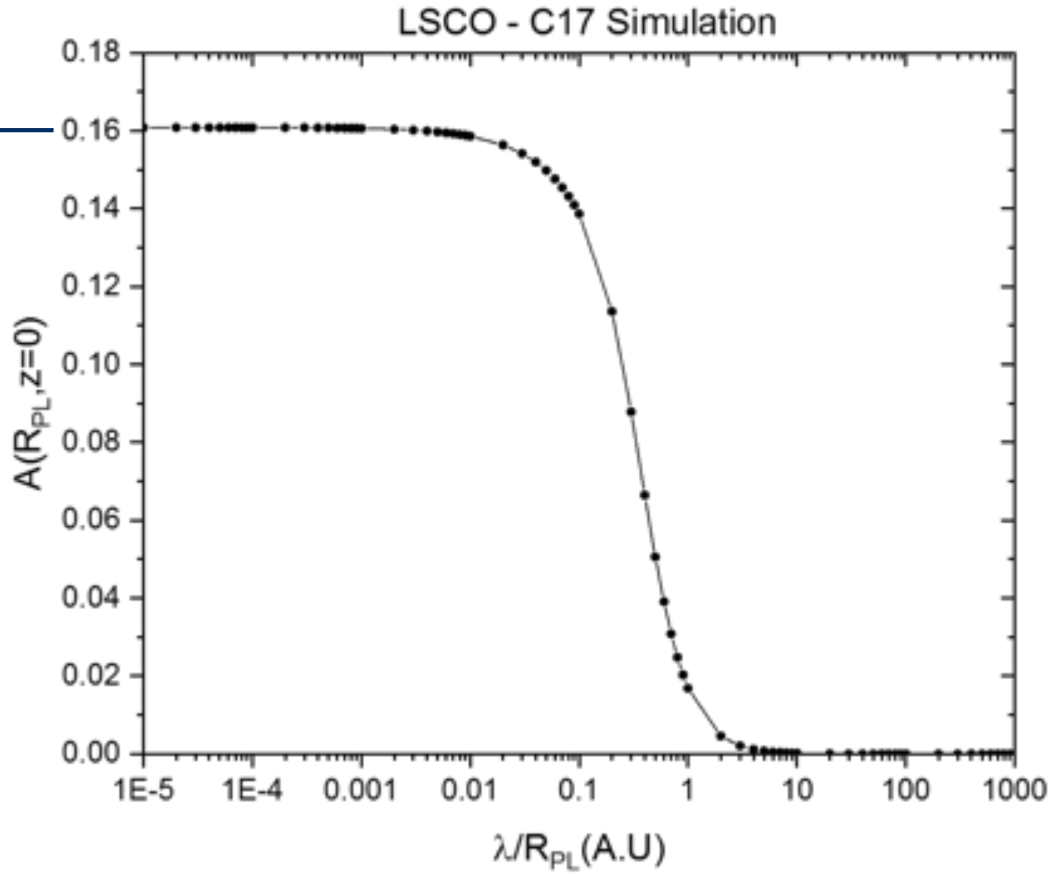
- We need to calculate $A(R_{PL}, z = 0)$ and fit the data, i.e. solve the Pearl equation.



G Factor Calculation

$$G = \frac{0.51}{0.16} \approx 3.18$$



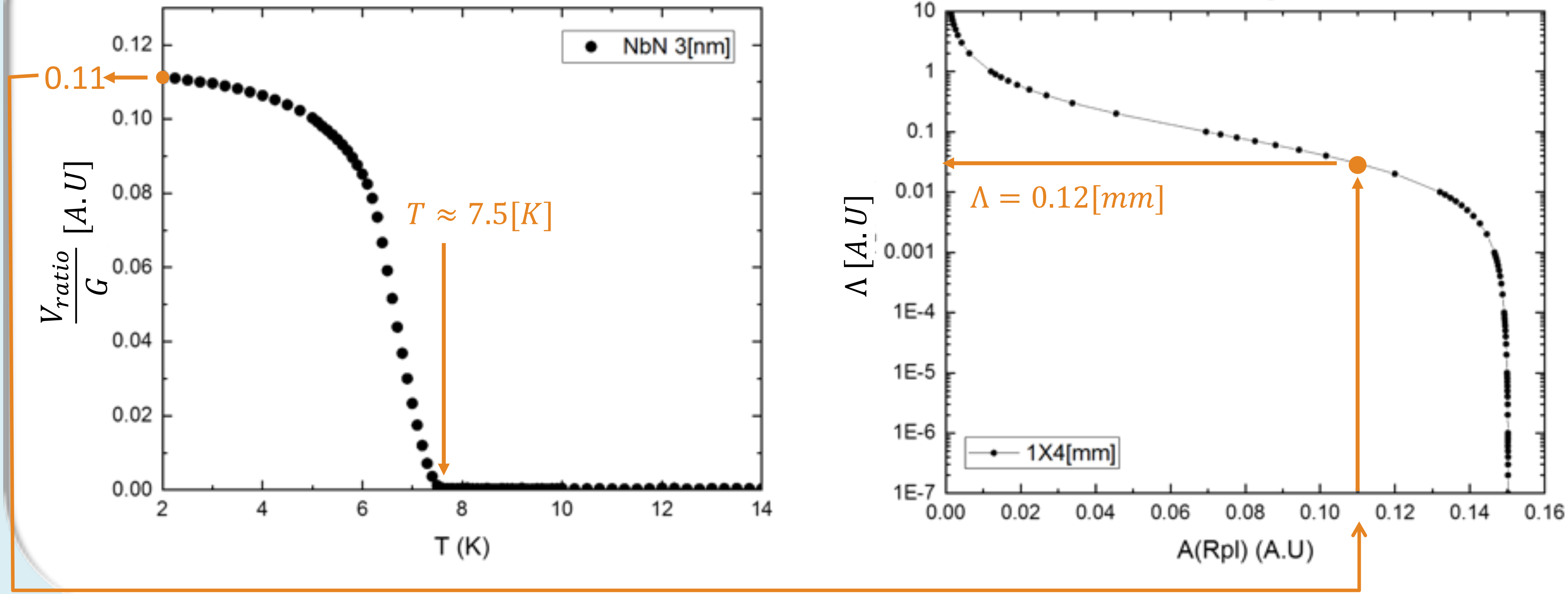


Data Analysis

$$\nabla \times \nabla \times \mathbf{A} = -\frac{1}{\Lambda}\left(\mathbf{A} + \frac{1}{r}\hat{\theta}\right)\delta(z) \longrightarrow \Lambda(A(R_{PL},0))$$

T dependence measurement

MPMS3 - 2D ring simulation



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Experimental Setup

SQUID Magnetometer - Quantum Design MPMS®3

(**S**uperconducting **QU**antum **I**nterference **D**evice)

- 7 [Tesla] Magnet.
- Temperature Range: 1.8 – 400 [K]

- The magnetic flux through the pickup loop is connected to the SQUID with a Flux Transformer and the measured voltage is:

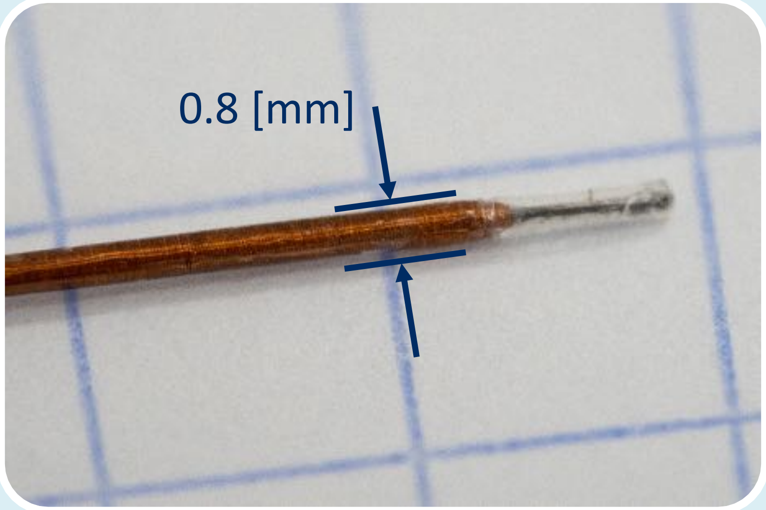
$$V_{SQUID} = K \cdot \Phi^{pl}$$

- This magnetic flux is proportional to the samples vector potential via:

$$\Phi^{pl} = \iint_{pl} B \cdot da = \int_{pl} A \cdot dl = 2\pi r_{pl} A(r_{pl})$$

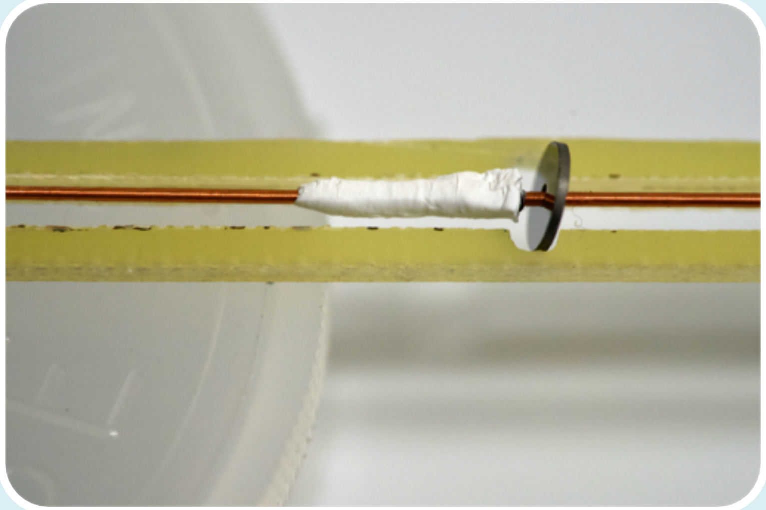
Since: Mar - 2019

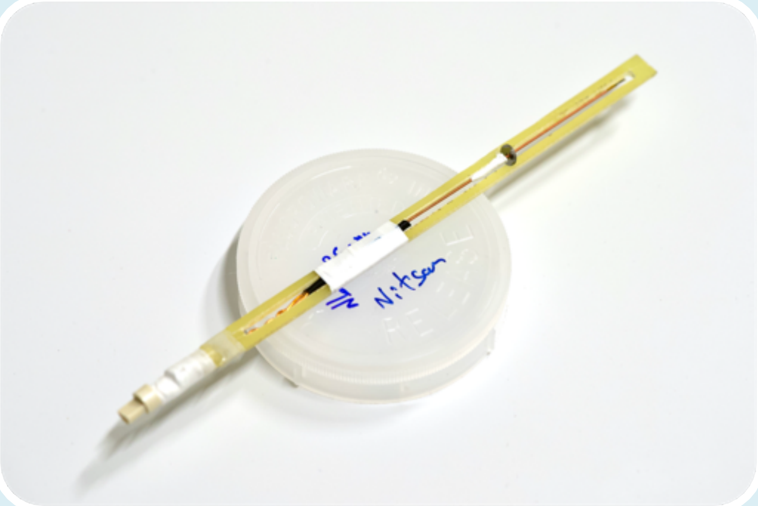
Experimental Setup

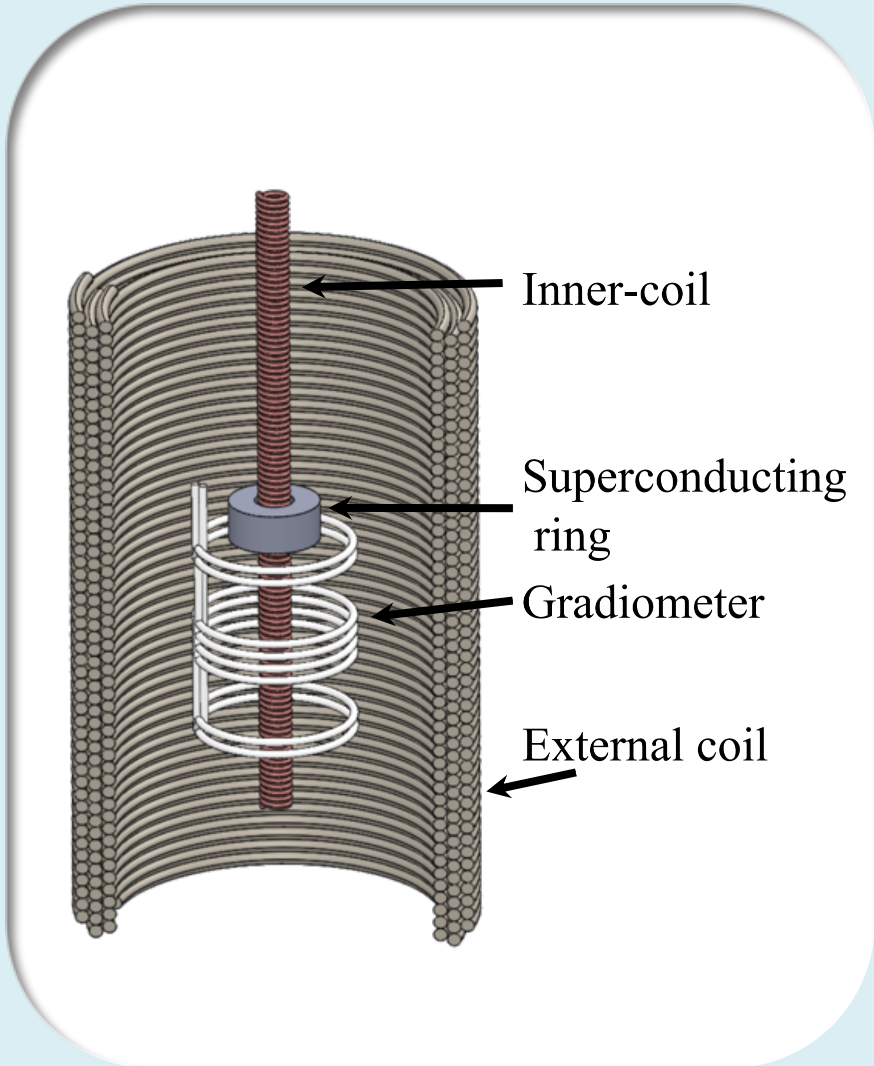


Cu Coil:

- Length - 6 [cm]
- Wire Thickness - 50 [μm]
- Outer Diameter - 0.8 [mm]
- 1940 turns (2 layers)





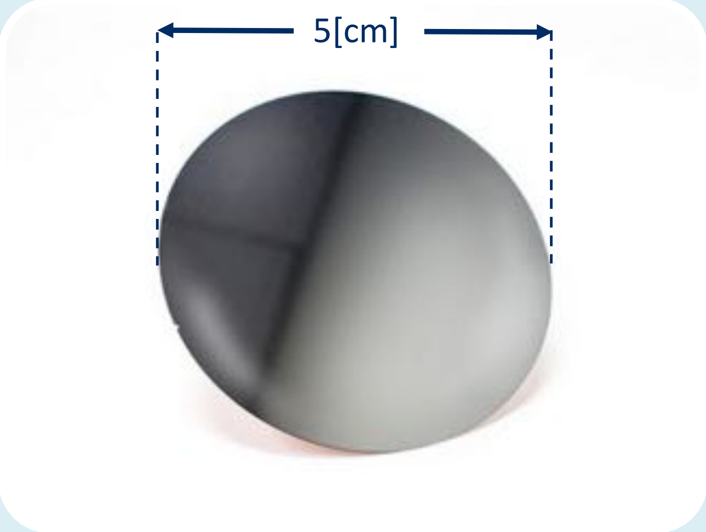


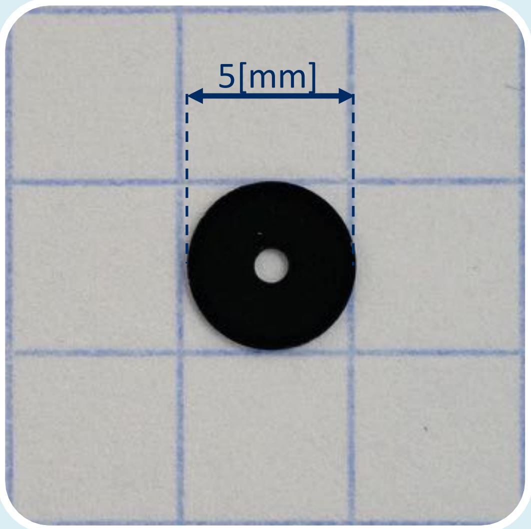
Si Rings Fabrication

Dr. Stanislav Stepanov

Specifications:

- Three possible wavelengths:
  1064[nm], 532[nm] and 355[nm].
- Pulse length 280 femtosecond.
- Power up to 10[W].
- Pulse rate between 44[KHz] and 200[KHz].
- Stage Precision ±1 [µm].
- Spot size 2[µm] at 355[nm], 30[µm] at 1064[nm].





NbN Fabrication

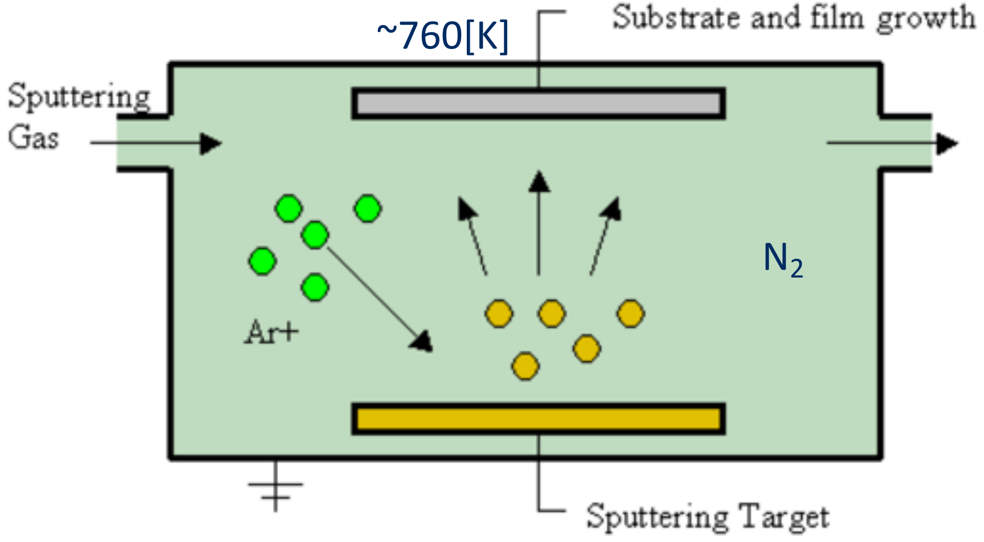
Prof. Yachin Ivry

Itamar Holzman

Dr. Guy Ankonina

ATC 2200 sputtering system (AJA International, Inc. USA)

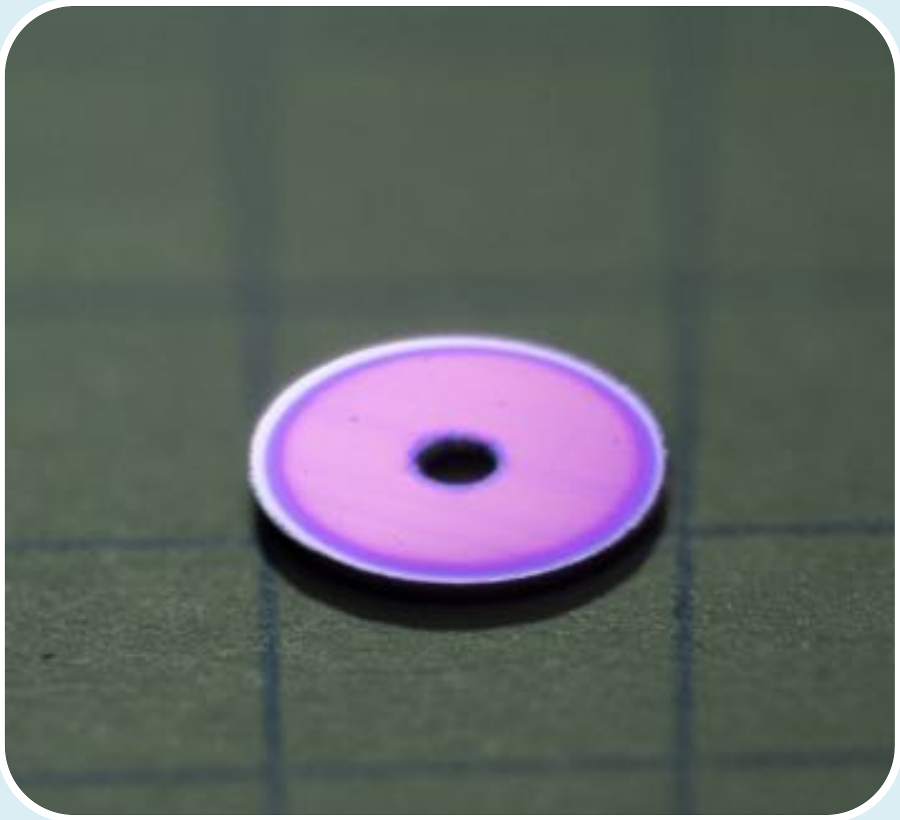
Nb → NbN



Deposition time is calibrated with Ellipsometry measurements.

arXiv: 1904.07739

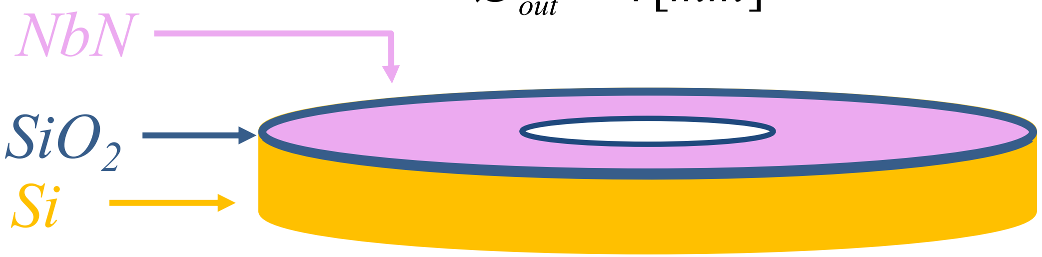
NbN Samples

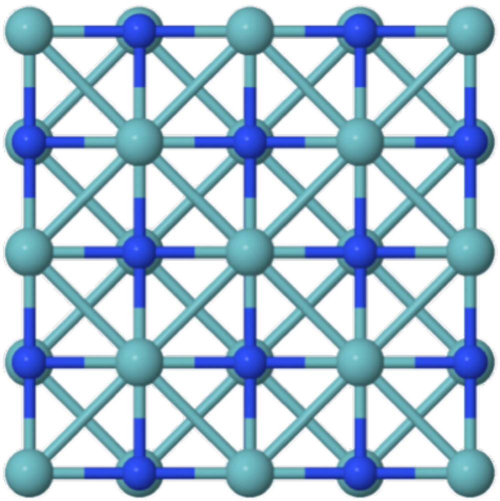


$d = 3\,[nm]$ (6 Unit Cells)

$\varnothing_{in} = 1\,[mm]$

$\varnothing_{out} = 4\,[mm]$





Polycrystalline

δ-NbN

Bulk properties:

$T_C \approx 16\,[k]$

$\lambda \approx 200[nm]$

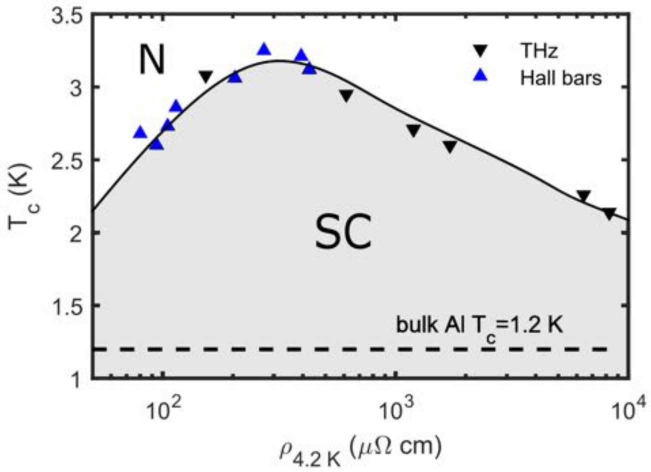
$\xi_0 \approx 6.5[nm]$

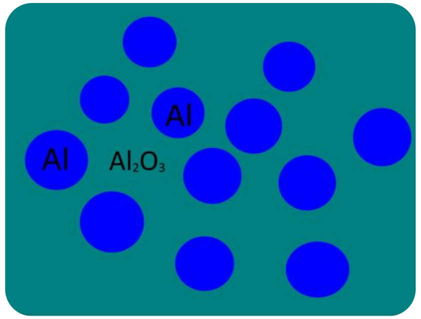
Granular Al Fabrication

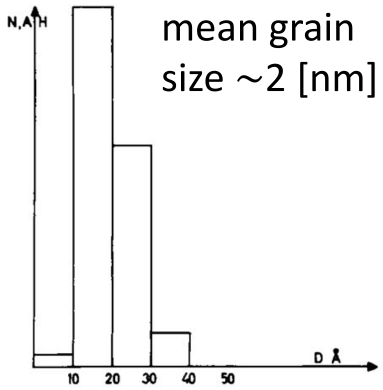

Prof. Guy Deutscher


Aviv Moshe

- Thermal Evaporation of Al in O_2 environment.
- Cooling the substrate down to $\sim 77\ [K]$ increases T_c up to $\sim 3.2\ [K]$.
- At higher substrate temperature the **grain size increases** and **Tc decreases**.
- Typical film thickness: ~100 [nm].
- Characterize of samples by ρ_{300K} or $\rho_{4.2K}$ which is related to T_c in a “dome like” shape.







mean grain size ~2 [nm]

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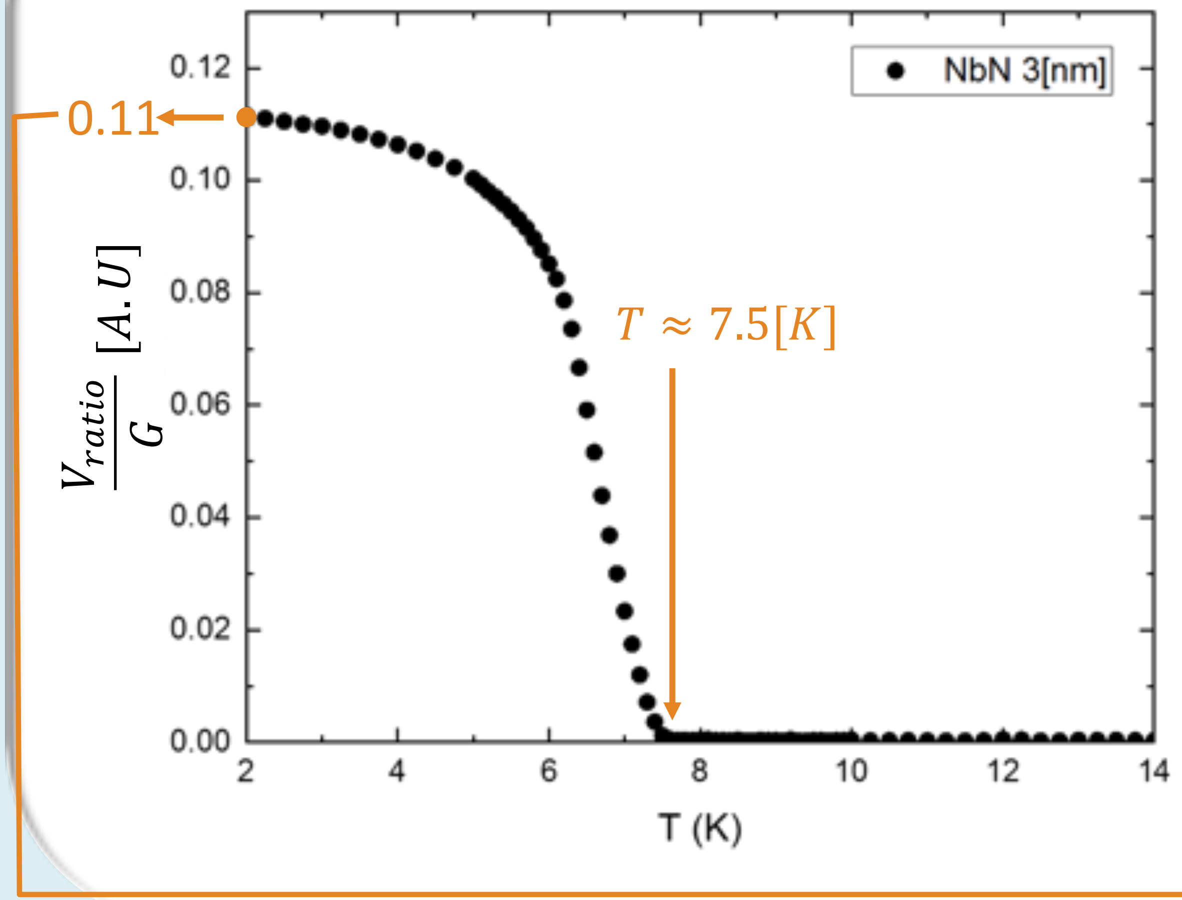
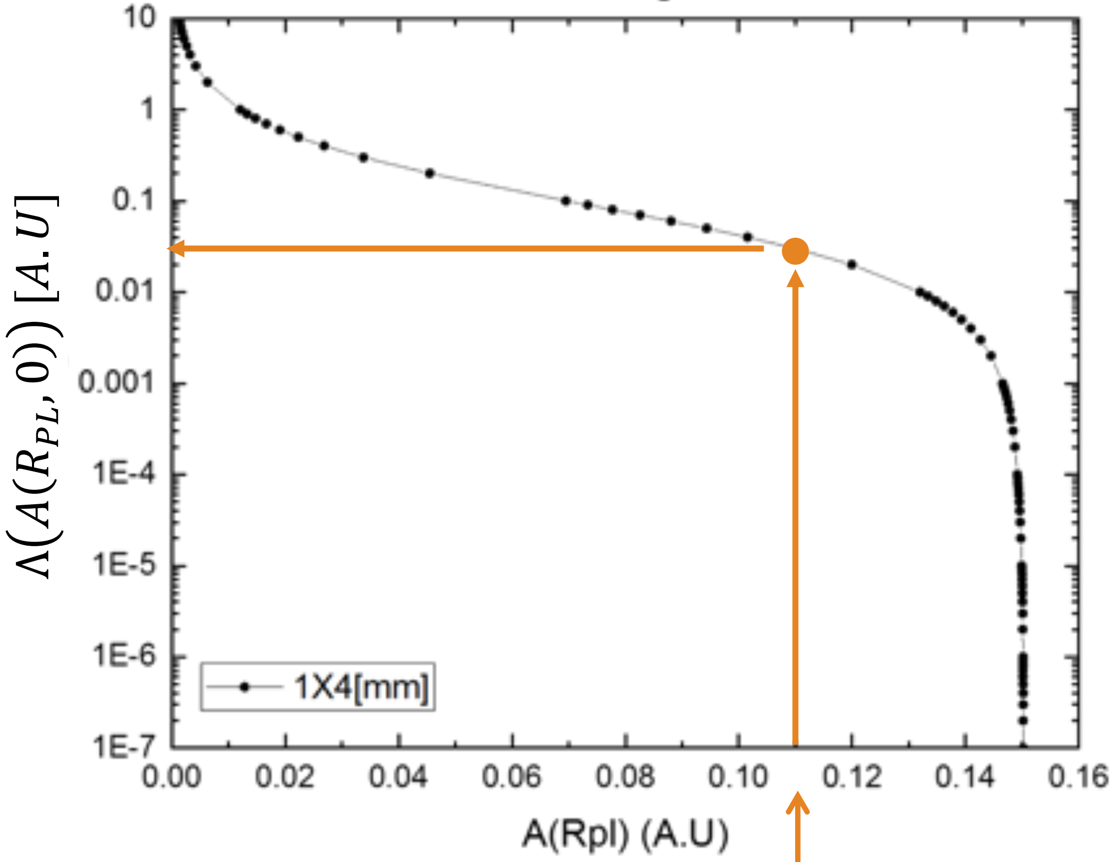
Reminder – Data Analysis

T dependence measurement

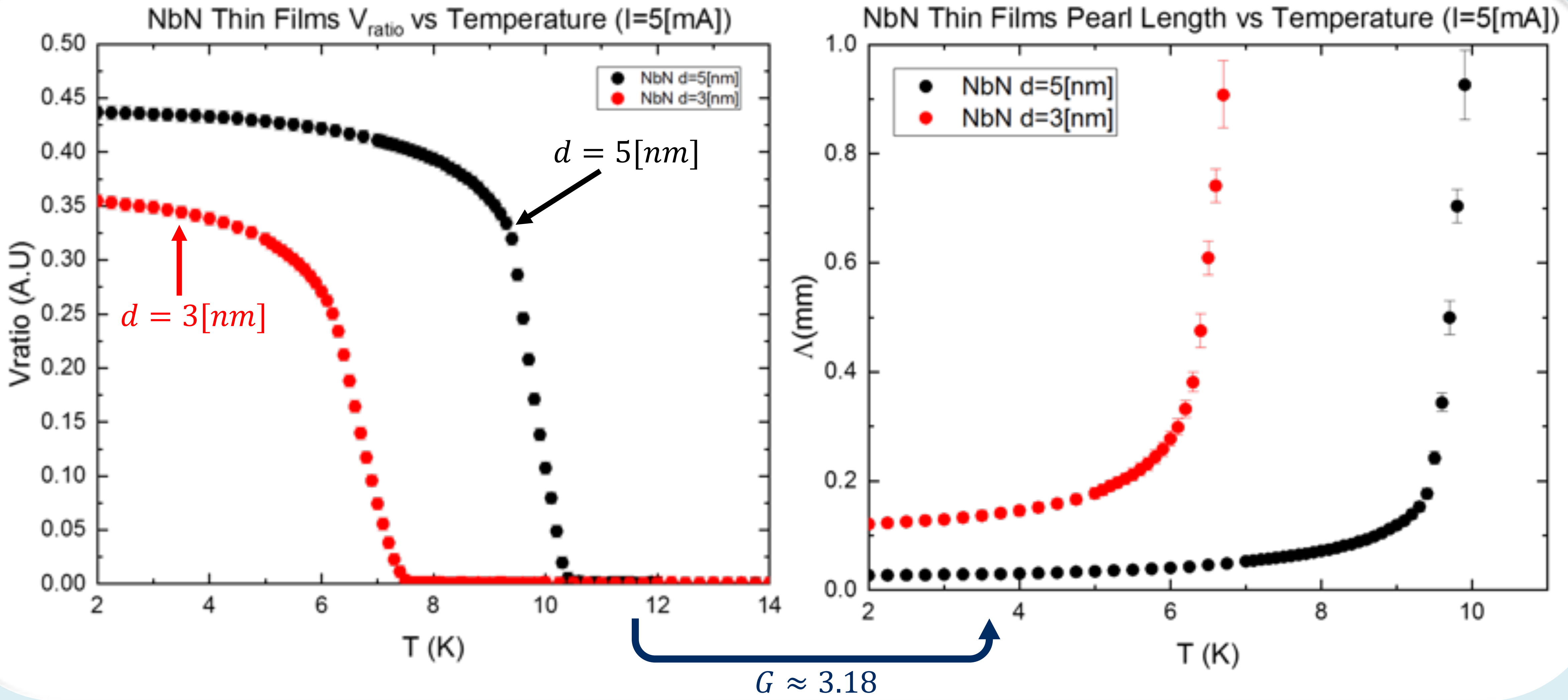


$$\nabla \times \nabla \times \mathbf{A} = -\frac{1}{\Lambda}\left(\mathbf{A} + \frac{1}{r}\hat{\theta}\right)\delta(z) \longrightarrow \Lambda(A(R_{PL},0))$$

MPMS3 - 2D ring simulation

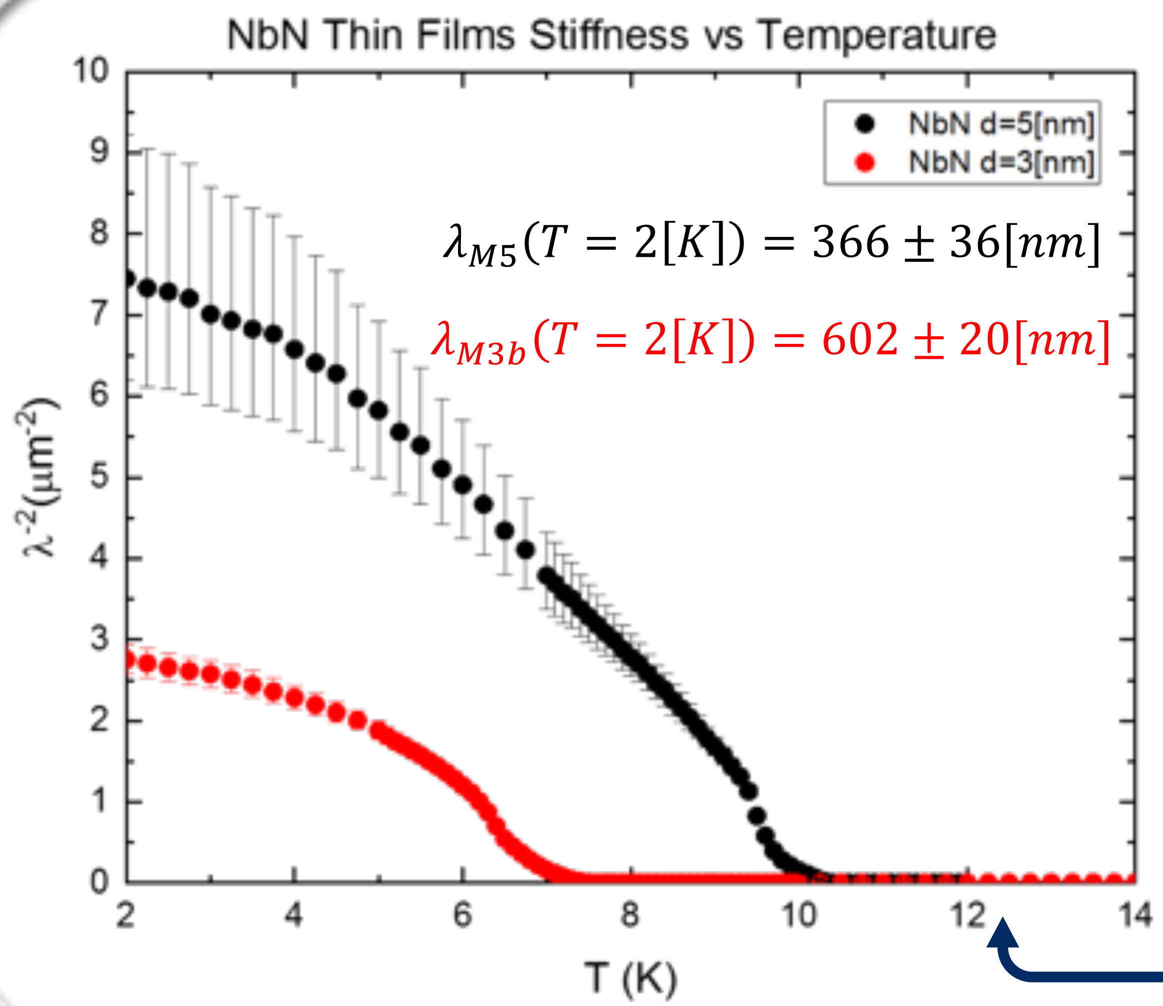


NbN – Results



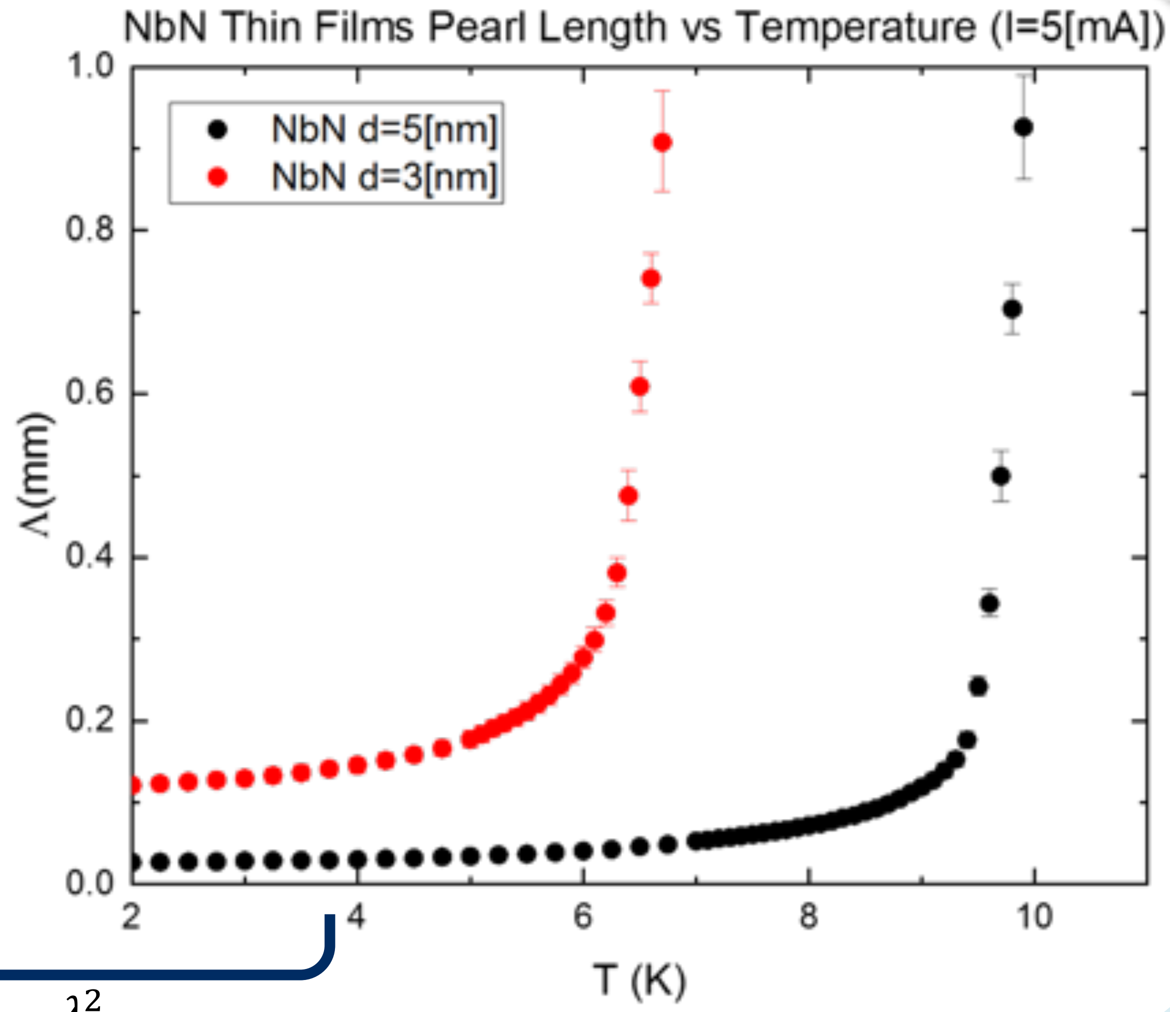
NbN Thin Films V_{ratio} vs Temperature (I=5[mA])
Vratio (A.U)
T (K)
NbN d=5[nm]
NbN d=3[nm]
$d = 5[nm]$
$d = 3[nm]$
NbN Thin Films Pearl Length vs Temperature (I=5[mA])
Λ(mm)
T (K)
NbN d=5[nm]
NbN d=3[nm]
$G \approx 3.18$

NbN – Results



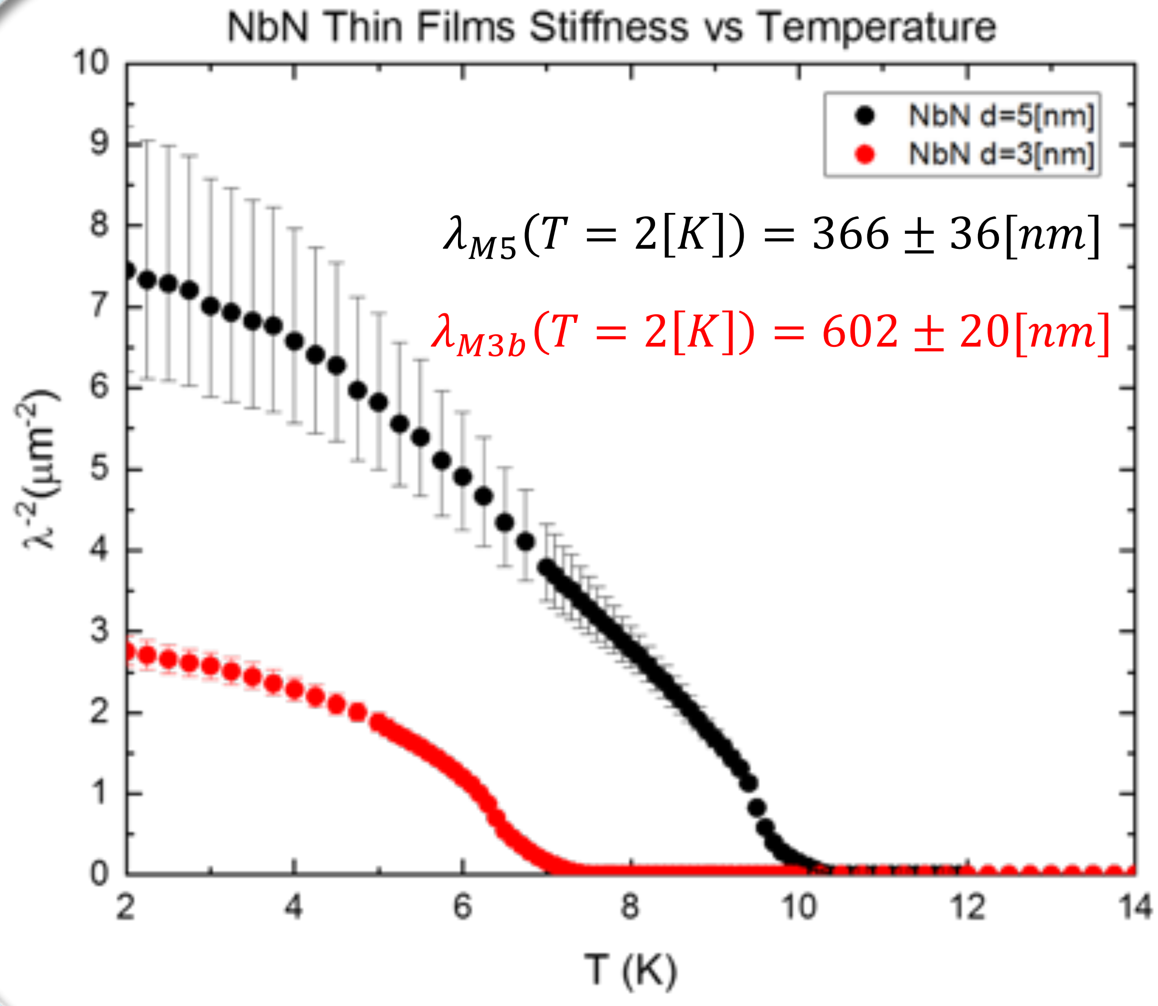
$\lambda_{M5}(T = 2[K]) = 366 \pm 36[nm]$

$\lambda_{M3b}(T = 2[K]) = 602 \pm 20[nm]$



$$\Lambda = \frac{\lambda^2}{d}$$

NbN – Results



$$\lambda_{M5}(T = 2[K]) = 366 \pm 36[nm]$$

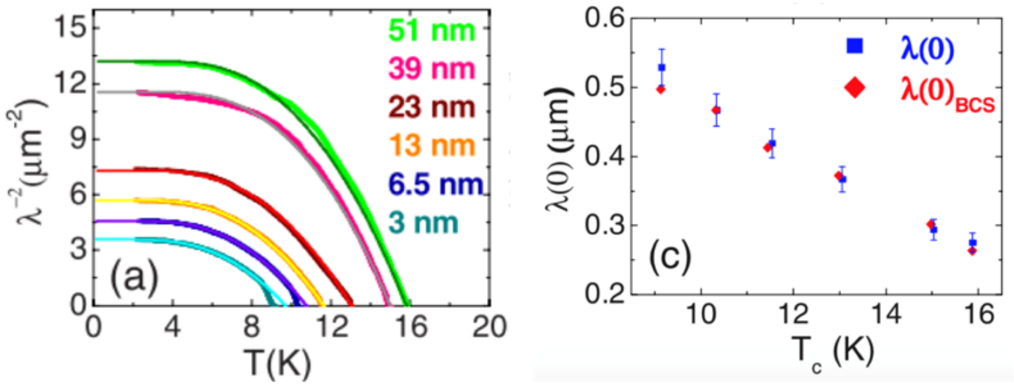
$$\lambda_{M3b}(T = 2[K]) = 602 \pm 20[nm]$$

In comparison with the work of **A. Kamlapure** and **P. Raychaudhuri** - *Measurement of magnetic penetration depth and superconducting energy gap in very thin epitaxial NbN films* - **Appl. Phys. Lett. 96, 072509 (2010)**

Measured for NbN 3[nm] epitaxial film:

$$\lambda(0) = 529[nm]$$

using a two coil mutual inductance technique.

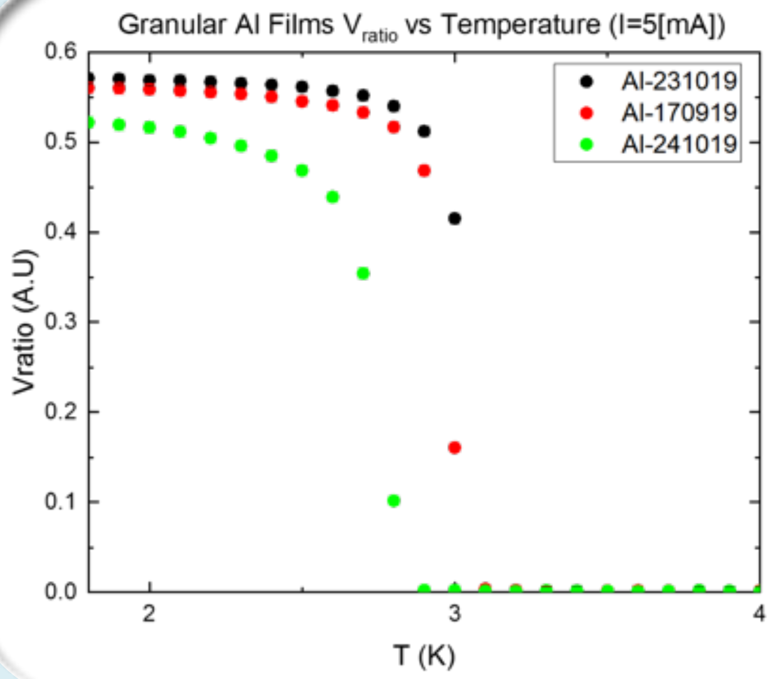


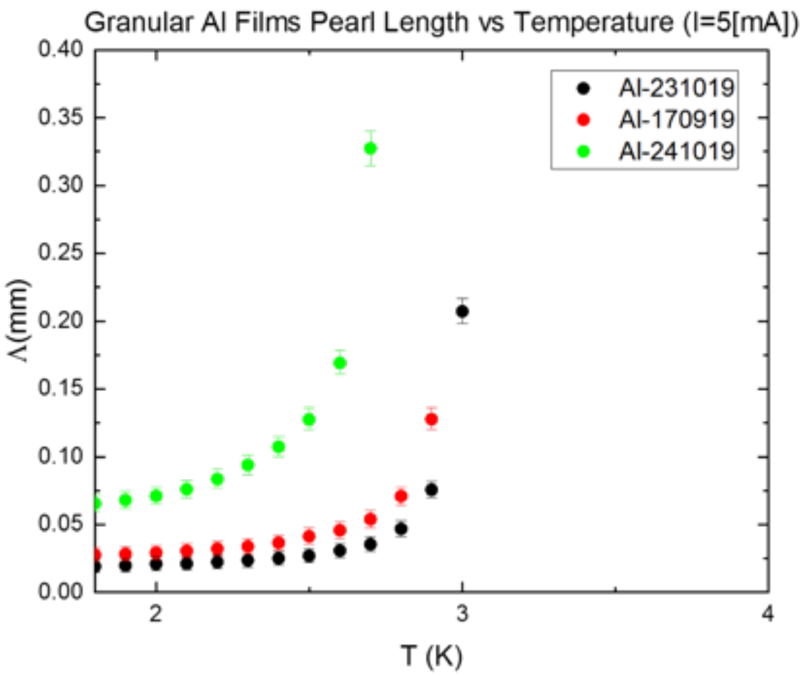
Granular Al – Results

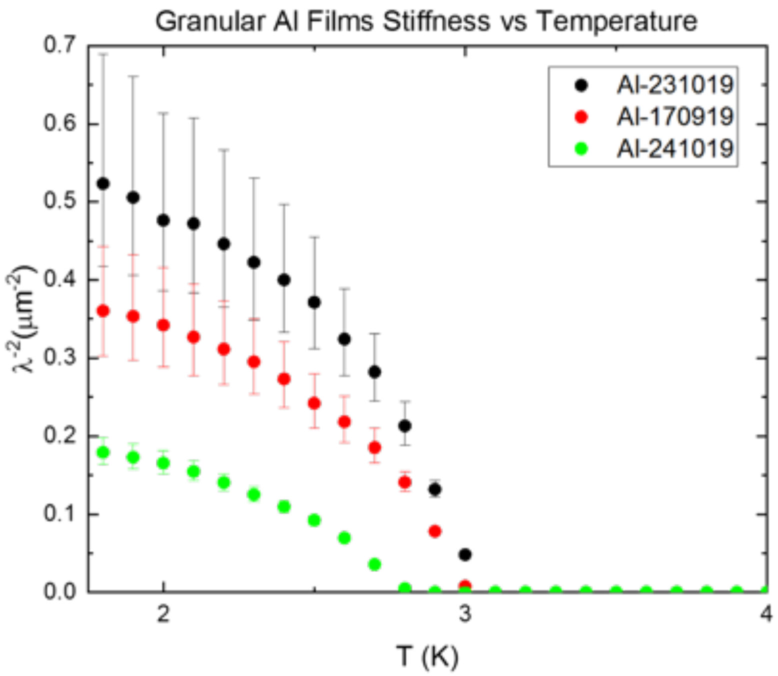
Al - 231019:
Thickness = **100 [nm]**
Room Temp. Resistivity = **238 [μΩcm]**
Tc = **3.0 [K]**

Al - 170919:
Thickness = **100 [nm]**
Toom Temp. Resistivity= **310 [μΩcm]**
Tc = **3.1 [K]**

Al - 241019:
Thickness = **85 [nm]**
Room Temp. Resistivity = **810 [μΩcm]**
Tc = **2.8 [K]**







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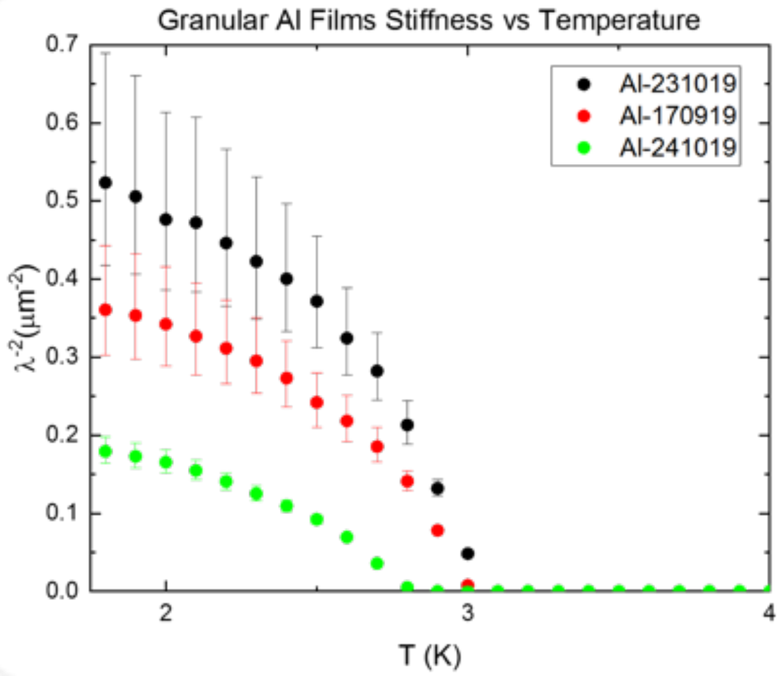
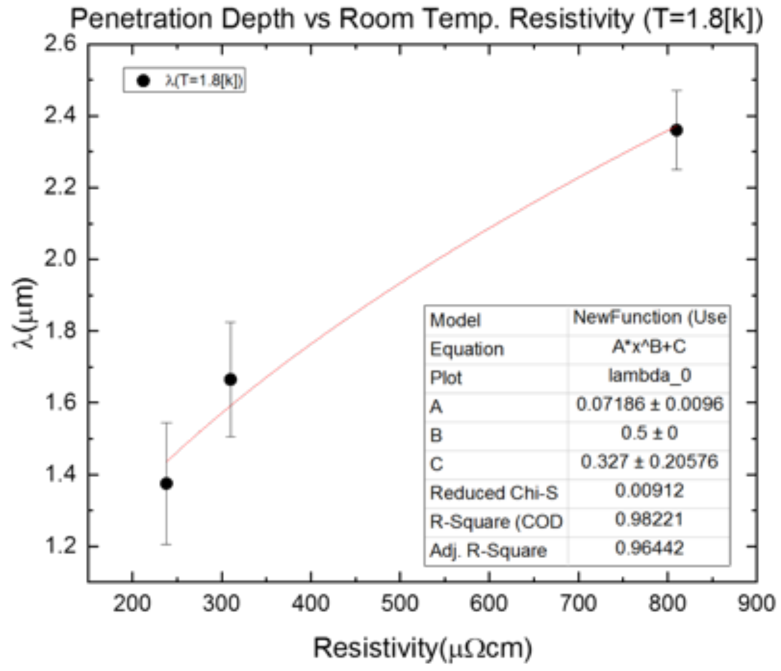


$$\lambda_{231019}(T = 1.8[K]) = 1.38 \pm 0.17[\mu m]$$

$$\lambda_{170919}(T = 1.8[K]) = 1.66 \pm 0.16[\mu m]$$

$$\lambda_{241019}(T = 1.8[K]) = 2.36 \pm 0.11[\mu m]$$



Granular Al – Results

Al - 231019:
Thickness = **100 [nm]**
Room Temp. Resistivity = **238 [μΩcm]**
Tc = **3.0 [K]**

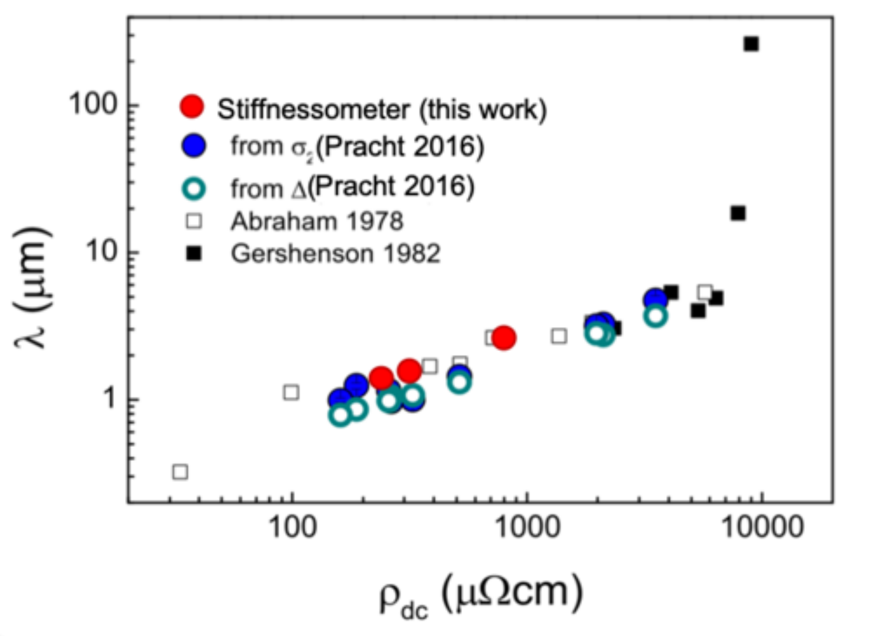
Al - 170919:
Thickness = **100 [nm]**
Toom Temp. Resistivity= **310 [μΩcm]**
Tc = **3.1 [K]**

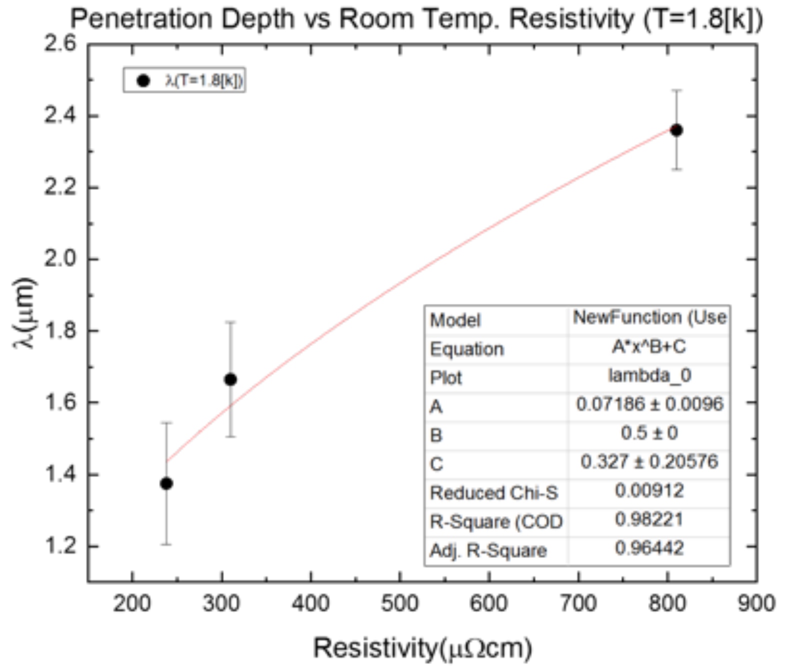
Al - 241019:
Thickness = **85 [nm]**
Room Temp. Resistivity = **810 [μΩcm]**
Tc = **2.8 [K]**

PhysRevB.93.100503

Enhanced Cooper pairing versus suppressed phase coherence shaping the superconducting dome in coupled aluminum nanograins

Uwe S. Pracht, Marc Scheffler *et. al.*





Intermediate Summary

- The measured values of λ in NbN and Al are in a good agreement with previous works.

- We showed that λ in the relation $\Lambda = \frac{\lambda^2}{d}$ is not a material property which is independent of the thickness.

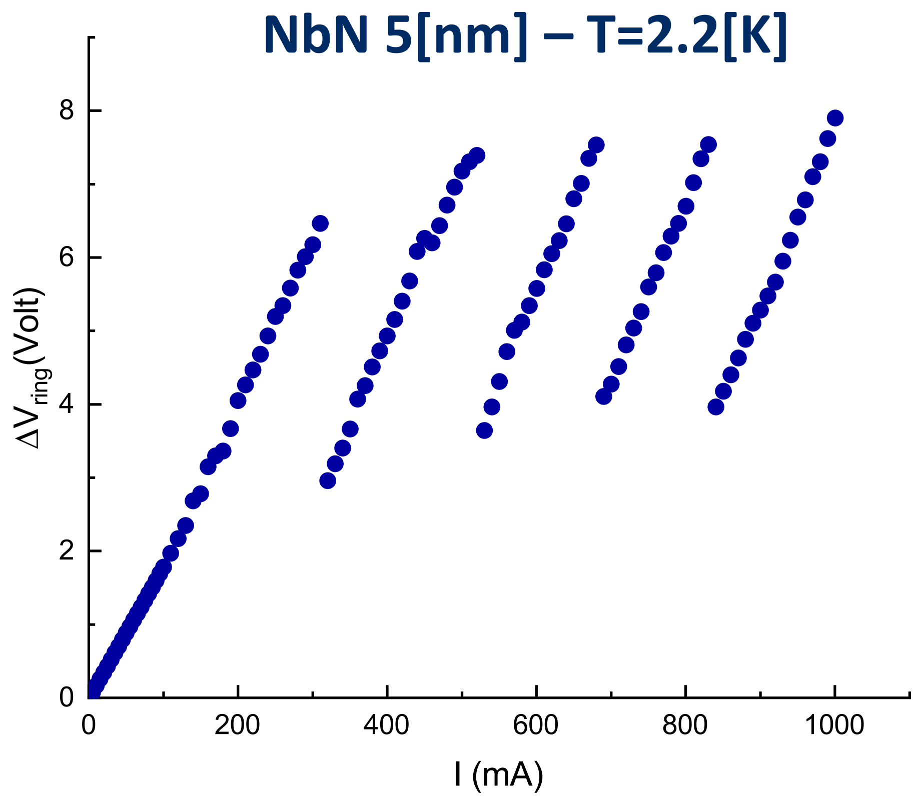
- Therefore, When $d \rightarrow 0$, Λ is a finite size, so we might be able to measure stiffness of surface states.

Outline

- Introduction & Motivation
- 2D Superconductivity – The Pearl equation
- The Stiffnessometer – Principle of Operation
- Experimental Setup & Samples Fabrication
- Stiffness Measurement
- Coherence Length Measurement
- Summary

Phase Slips

- When measuring the Stiffness as function of the excitation coil's current, we got surprising jumps that can be explained by **phase slips**.



London's Eq. (ZGFC)

$$\mathbf{J}_s = -\rho_s \mathbf{A}$$

$$\mathbf{J}_s = -\rho_s (\mathbf{A} - \frac{\hbar}{2e} \nabla \varphi)$$

The Full GL Equation

Dr. Oded Kenneth

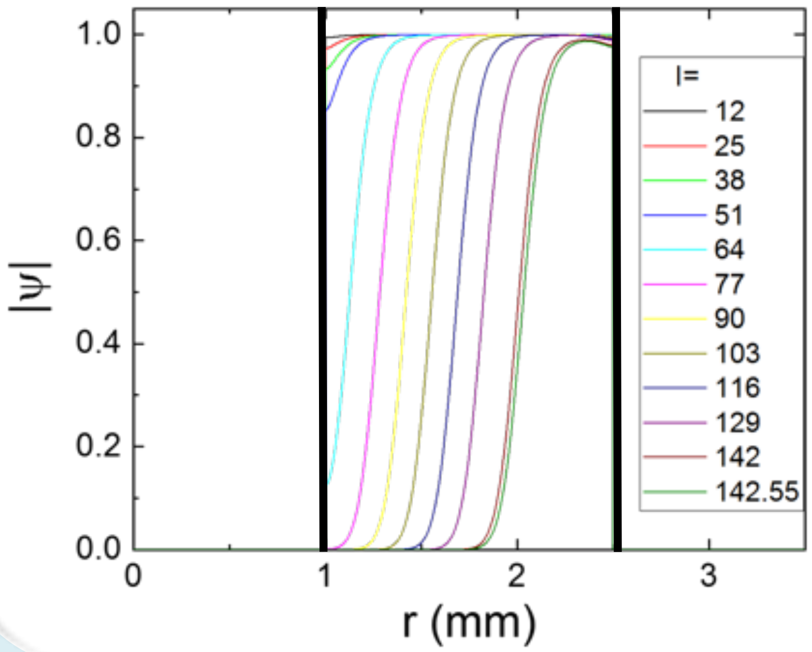
Prof. Nir Gavish

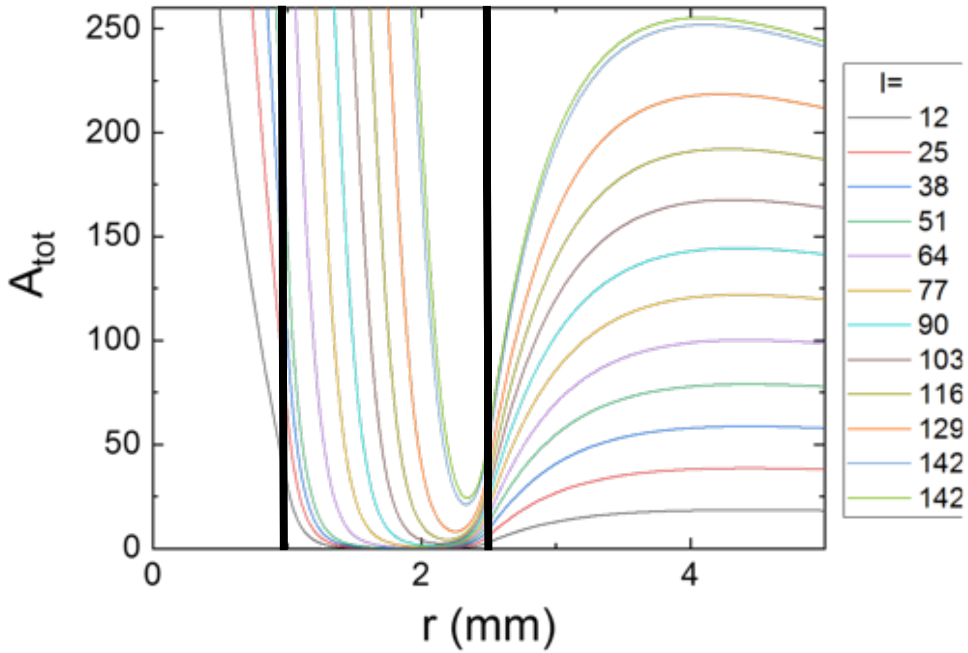
$$\nabla\times\nabla\times A\hat{\theta} = -\frac{|\psi|^2}{\lambda^2}\left(A+\frac{J-l}{r}\right)\hat{\theta}$$

$$-|\psi|_{rr} - \frac{|\psi|_r}{r} - |\psi|_{zz} + \left(A+\frac{J-l}{r}\right)^2|\psi| = \frac{1}{\xi^2}\left(|\psi|-|\psi|^3\right)$$

GL Free Energy minimization

Combined Solutions





$$\xi \ll \lambda$$

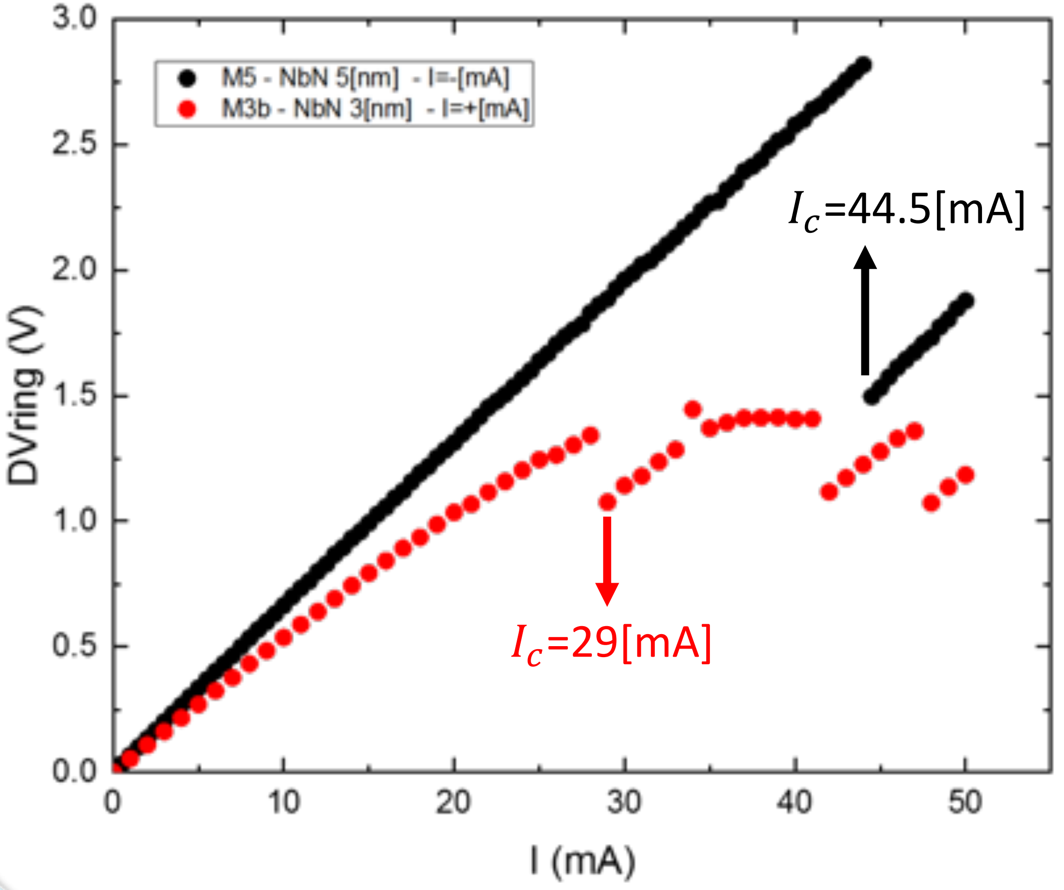
$$\boxed{\frac{\Phi_c}{\Phi_0} = \frac{r_{out}}{\xi}}$$

a la Oded Kenneth

As long as $|\psi| = 1$ in the ring, the SC will expel the flux entering it so that $A_{ring} \propto A_{coil}$ Consequently, r_{out} is important.

NbN – Results

NbN Critical Current ($T = 2[K]\,; r_{out} = 2[cm]$)



$$\xi = \frac{\Phi_0}{\Phi_c} r_{out} = \frac{\Phi_0 r_{out}}{\tilde{\Phi} I_c}$$

- $\tilde{\Phi}$ is the magnetic flux per current of the Cu Excitation coil.
- In our case: $\tilde{\Phi} = 1.031 \cdot 10^{-11} \left[\frac{Wb}{mA}\right]$

$$\frac{\tilde{\Phi}}{\Phi_0} = 4986[mA^{-1}]$$

- Therefore:

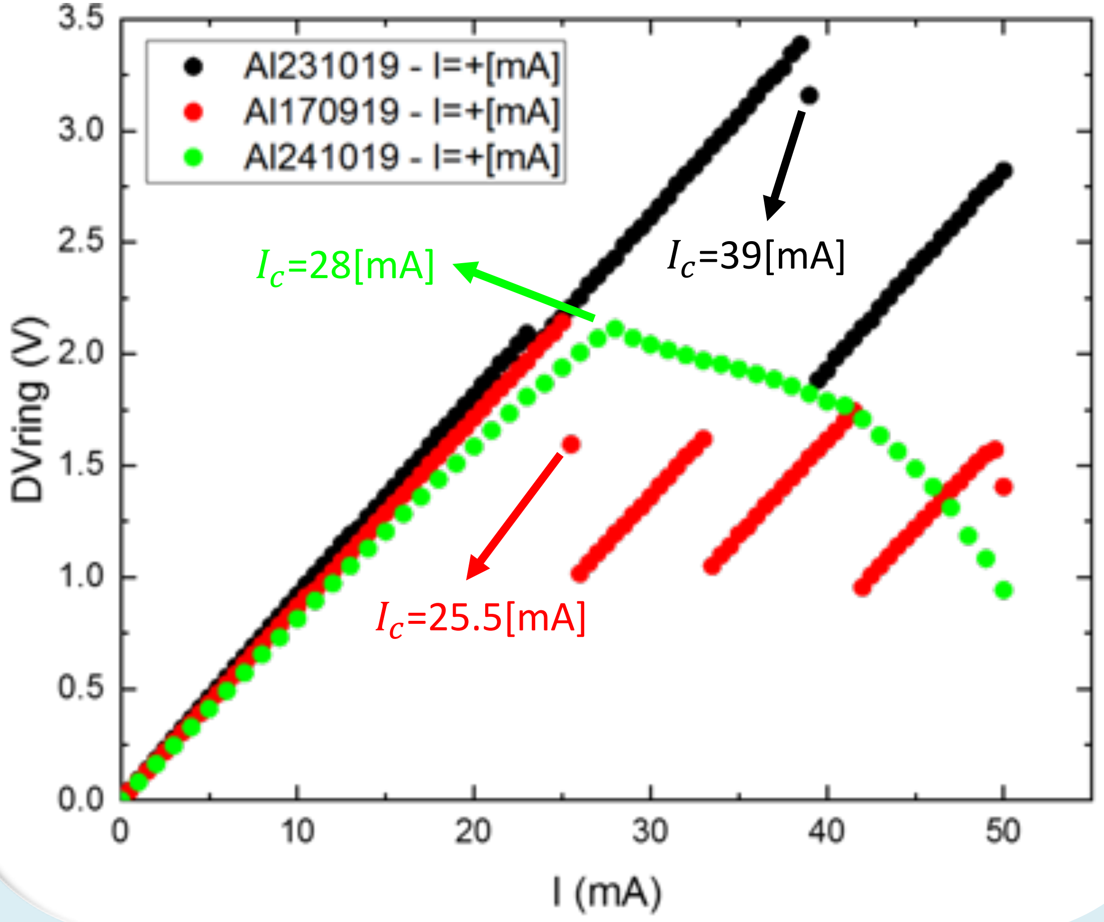
$$\xi_{M5} = 7.07 \pm 0.36[nm]$$

$$\xi_{M3b} = 10.84 \pm 0.66[nm]$$

- *The role of Coulomb interaction in superconducting NbTiN thin films* **Hazra, D.** *et. Al.* PhysRevB.97.144518 – H_{c2} measurement of 10[nm] NbN film: $\xi_0 \approx 6.5[nm]$

Granular Al – Results

Granular Al Critical Current $(T = 1.8[K]\,; r_{out} = 2.5[cm])$



$$\xi = \frac{\Phi_0}{\Phi_c} r_{out} = \frac{\Phi_0 r_{out}}{\tilde{\Phi} I_c}$$

Al - 231019: ξ_{231019}=$10.08 \pm 0.31[nm]$

Thickness = **100 [nm]**

Room Temp. Resistivity = **238 [μΩcm]**

Tc = **3.0 [K]**

Al - 170919: ξ_{170919}=$15.42 \pm 0.53[nm]$

Thickness = **100 [nm]**

Toom Temp. Resistivity= **310 [μΩcm]**

Tc = **3.1 [K]**

Al - 241019: ξ_{241019}=$14.04 \pm 0.64[nm]$

Thickness = **85 [nm]**

Room Temp. Resistivity = **810 [μΩcm]**

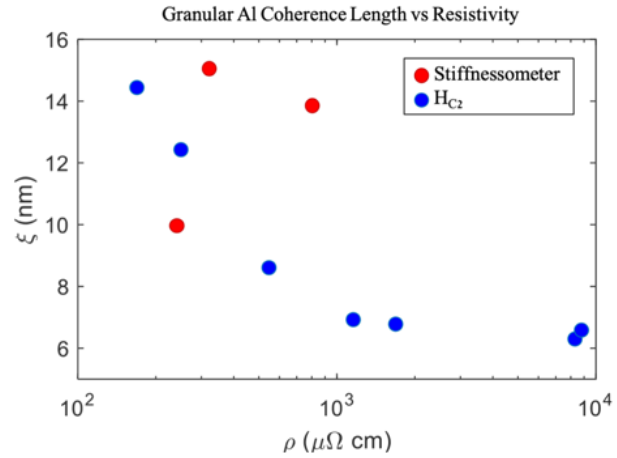
Tc = **2.8 [K]**

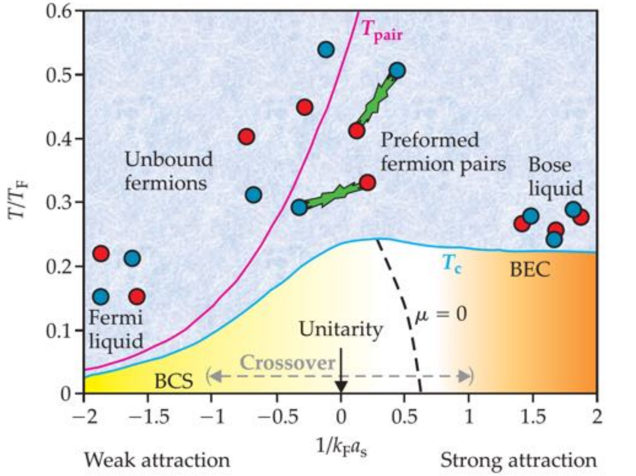
Granular Al – Results

H_{c2} measurement of Granular Al films

Prof. Guy Deutscher

Aviv Moshe





$k_F\xi_{pair} \gg 1$ $\quad k_F\xi_{pair} \sim 1$ $\quad k_F\xi_{pair} \ll 1$

$$\xi = \frac{\Phi_0}{\Phi_c} r_{out} = \frac{\Phi_0 r_{out}}{\widetilde{\Phi} I_c}$$

Al - 231019: ξ_{231019}=$10.08 \pm 0.31[nm]$
Thickness = **100 [nm]**
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Thickness = **85 [nm]**
Room Temp. Resistivity = **810 [μΩcm]**
Tc = **2.8 [K]**

Summary

- We introduced a new method to measure penetration depth & coherence length of **ultra-thin SC films**.
- We have enough sensitivity to measure **single layer SC**.
- Our extraction of the penetration depth agrees with the literature. in a good agreement with previous works.
- **Next Steps:**
  - TI/SC device fabrication.
  - Phase slips mechanism.

Special Thanks


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Prof. Guy Deutscher


Aviv Moshe


Oded Kenneth


Prof. Nir Gavish

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Thanks for Listening!