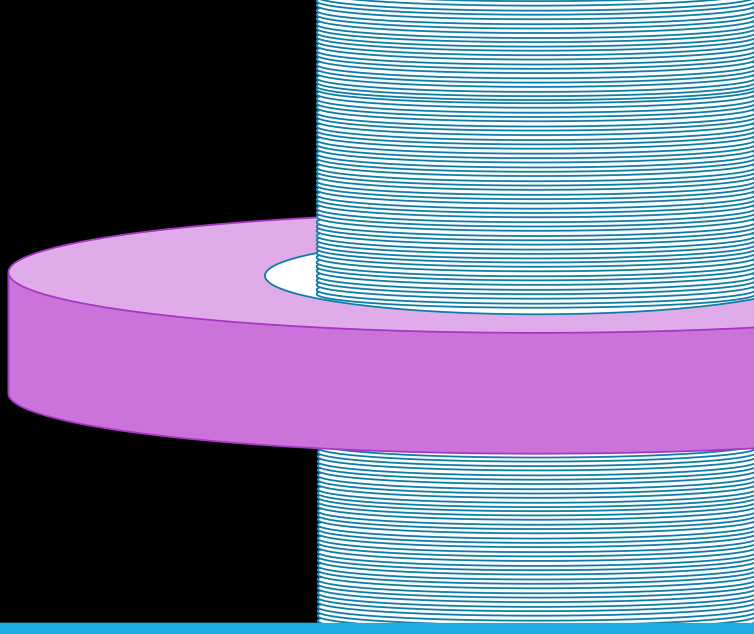
Measuring the Stiffness of 2D Superconductors



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Introduction & Motivation

- **Superconductivity** is a phenomenon of exactly zero electrical resistance and expulsion of magnetic fields (the Meissner effect) when superconductors are cooled down below T_c.
- **The Meissner effec**t means that magnetic fields only penetrate the superconductor on a small scale, called **the penetration depth (λ)**.
- The **stiffness** of a superconductor is defined by $\rho_s = \frac{1}{\mu_0 \lambda^2}$.
- In superconductivity, **the London equation** describes the relation between the current density and the vector potential (A):

$$J = -\rho_s A$$

- In 2D material, the Meissner effect is very weak and the currents can only run on the surface. Thus, the London equation becomes,

$$\mathbf{J}_s = -\frac{d}{\mu_0 \lambda^2} \mathbf{A} \delta(z)$$

where d is the thickness of the superconductor:

- Because magnetic fields can penetrate 2D superconductors, it is hard to measure their stiffness. We used a new mothed that doesn't apply magnetic field on the superconductor.
- Our goal is to measure the stiffness and the **critical temperature** of various thin superconducting ***NbN* (Niobium Nitride)** rings and studying the dependency of the above on the rings thickness.

The Method

- We have been using an “infinitely” long coil in the center of a superconducting 2D ring. There is zero magnetic field outside, and finite vector potential which produces current density.

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

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

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

- A is measured by moving the ring, which induces an electromotive force.
- The important relation is:

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

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

- $G \approx 2.7$ is a geometrical factor related to the gradiometer ($G_{PL} = 1$) .
- By measuring $\Phi(z)$ (Fig. 1) we determine the solution of the normalized **Pearl equation** of our specific setup:

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

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

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

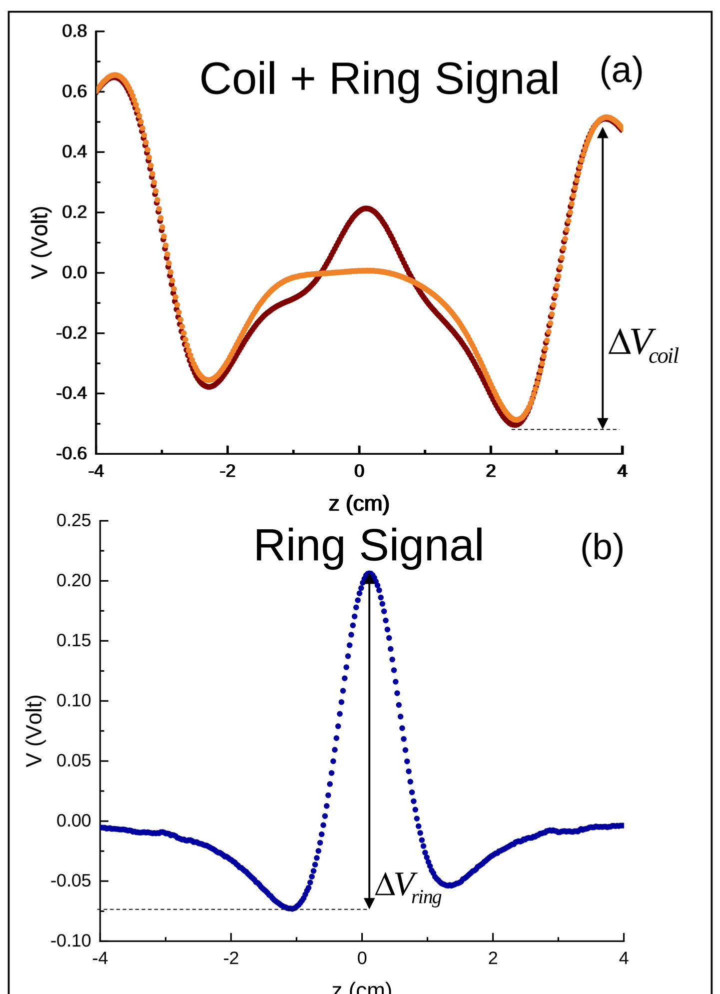
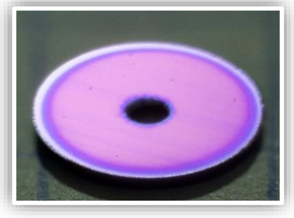


Fig. 1: The Voltages from the coil and ring signals, and from the ring signal

The Experiment

- Our samples are rings of NbN (Fig. 2), which is a superconducting material. The NbN is placed on a silicon ring, covered by silicon oxide (Fig. 3).



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

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

Fig. 2

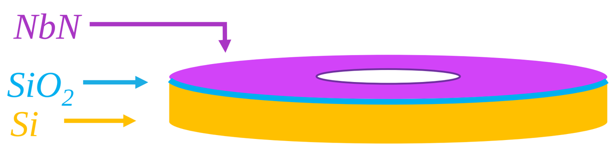


Fig. 3

- The measurements were made with ultra thin NbN rings: 3,5,10,15 [nm].

- When in bulk, the properties of NbN are: $T_C \approx 16[k]$, $\lambda \approx 200[nm]$.
- Cu coil: Length – 6 [cm]; Wire Thickness - 50 [mm]; Outer Diameter - 0.8 [mm]; 2400 turns (2 layers) , $R_{PL} = 8.5\ [mm]$ (Fig. 4).

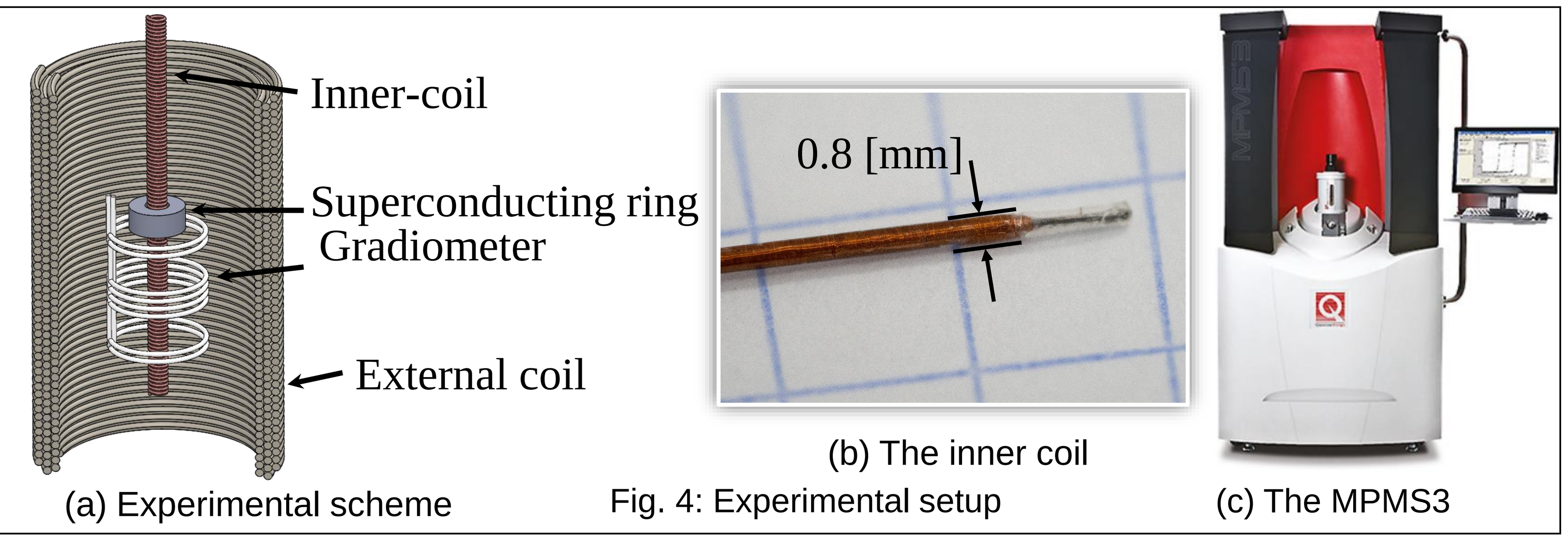


Fig. 4: Experimental setup

Results

We use the solution to the Pearl Equation, along with the magnetic potential A as function of T[K] (Fig. 5), to calculate the **Pearl length**, from which we can extract the penetration depth (Fig. 6). The results showed a surprising difference for A between opposite current directions (Fig. 7).

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

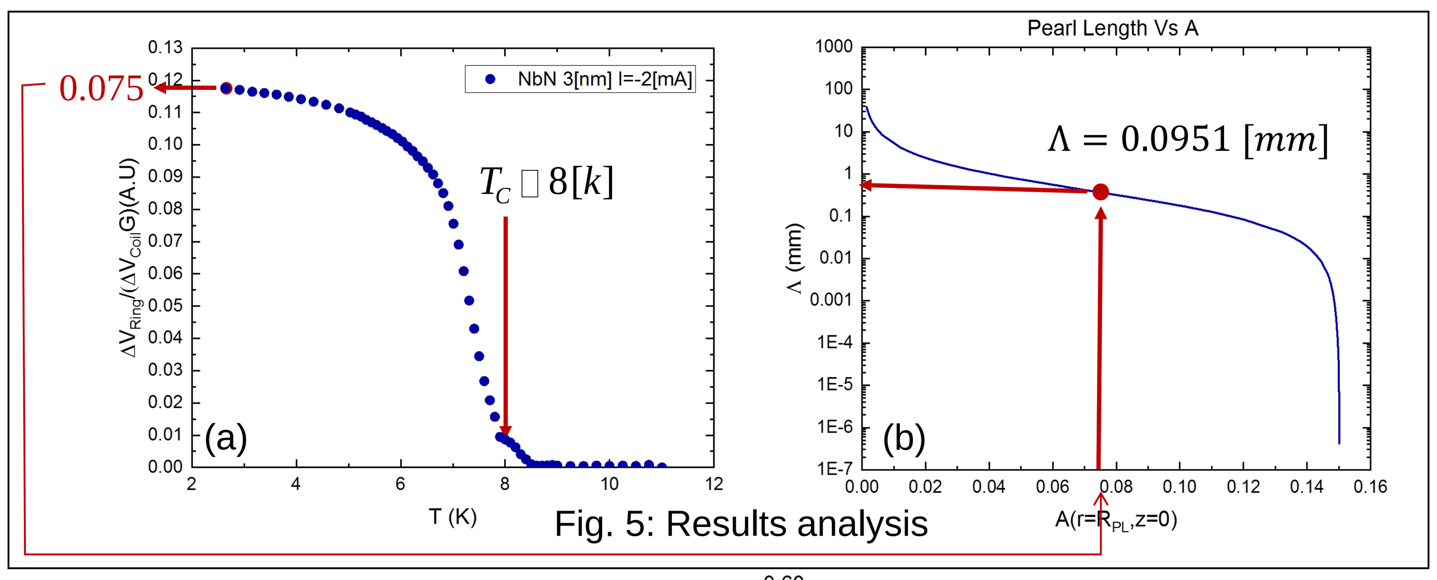


Fig. 5: Results analysis

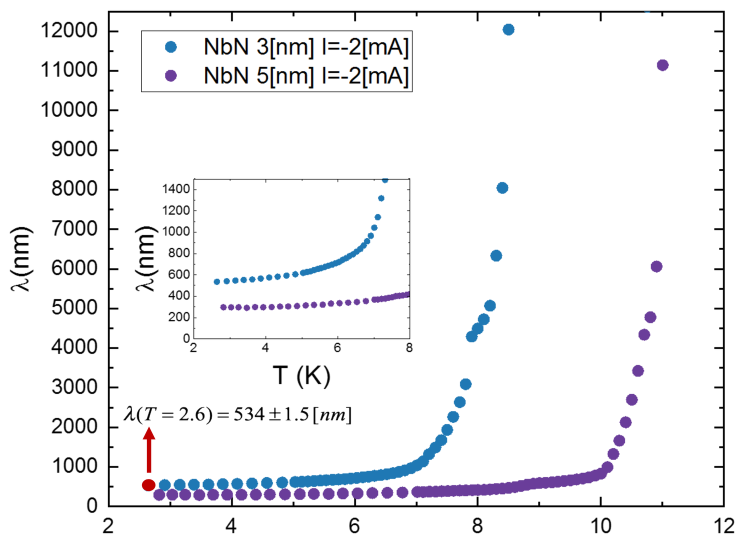


Fig. 6:The penetration depth

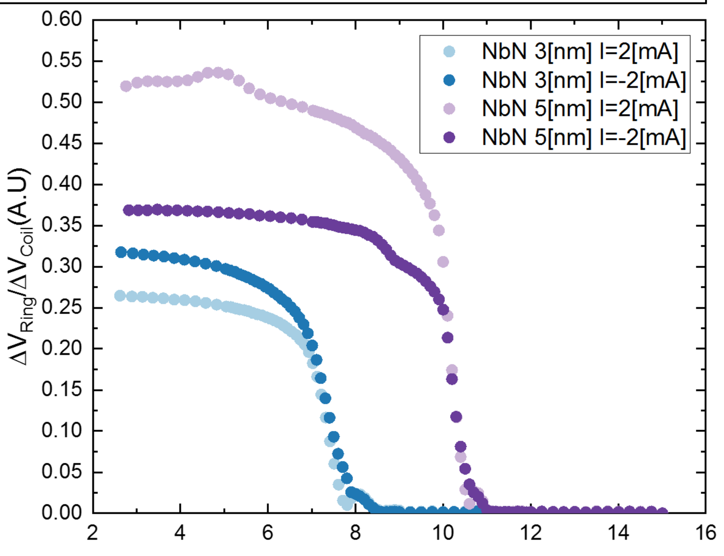


Fig. 7: Voltage ratio

Concluding Remarks

- We used a new method of measuring the stiffness of 2D superconductor films, and compared the stiffness of a 3nm NbN ring, and a 5nm NbN ring.
- We found a surprising difference between the measurements of the same NbN ring when the current applied has an opposite sign. We assume the difference is because of a remnant magnetic field inside the measurement chamber.

Acknowledgments

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