

# Experimental Method to Measure Anisotropic Transport in 2D Superconductors

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*A two-coil kinetic inductance technique for measuring anisotropic response in two-dimensional (2D) superconductors is presented. Serpentine-shaped coils are lithographically patterned directly on top of the sample, separated by isolation layers. The drive and receive coils are positioned in a way that enhances signal from longitudinal currents and reduces transversal ones, maximizing the ratio. Anisotropic transport can be directly measured with this technique, even when anisotropy is induced by the transport current.*

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Many physical systems present an anisotropic character in their electrical properties. A usual procedure to measure this anisotropy is to lithographically pattern the sample into a star-like shape. Current can be applied and voltage measured in either direction, obtaining anisotropic ratio of the transport in a direct way. However there are cases where the anisotropy is induced by the current itself, therefore this approach can no longer be applied. The dynamical phases of vortex matter in superconductors are paradigmatic examples where vortex motion is induced by externally injected driving currents<sup>1,2</sup>. Many numerical simulations<sup>3</sup> and experiments<sup>4</sup> have studied these dynamical anisotropic phases. However none of these experiments directly measure the transport anisotropy.

In order to overcome the intrinsic difficulties of measuring transport anisotropy induced by the current itself, in a previous work we presented a variation of the kinetic inductance technique<sup>5</sup>, a contactless method that can be used while an external current is injected to the sample. The main improvement was the implementation of rectangular coils with high aspect ratio. Shielding currents induced in the sample by the primary coils are pre-

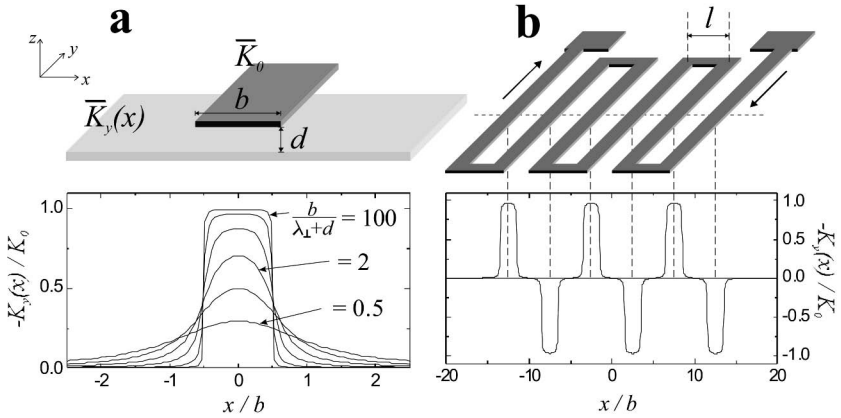


Fig. 1. **a.** Upper part: Schematic of a strip carrying uniform current above a superconducting film. Lower part: Screening current profile induced on the superconducting film. The different curves corresponds to the values of the ratio  $\frac{b}{\lambda_{\perp}+d}$ : 100, 20, 5, 2, 1 and 0.5. **b.** Upper part: Schematic of a serpentine-shaped coil. Lower part: Profile of the current density induced by this coil for a ratio  $\frac{b}{\lambda_{\perp}+d}=20$ .

dominantly parallel to the long side of the coil. As a consequence the voltage generated in the reception coil is originated by sample currents flowing in that direction. The relative angle between the coils and the injected current can be arbitrarily set, and the anisotropy can be directly measured. In this work we present a further improvement of that technique, in which the coils are lithographically fabricated on top of the sample, separated by isolation layers.

Since the fabrication is a sequential process (one layer at a time) the simplest geometry is making single layer 2D planar coils. The loss of sensitivity due to the use of only one turn is compensated by the close proximity of the coil to the sample. This leads us to focus on the effect of one single current strip on a 2D superconductor. The screening currents on a superconducting film induced by a strip carrying uniform current was calculated by Pearl<sup>6</sup>. The results are shown in the lower part of Fig.1a, where  $K_y(x)/K_0$  is the sheet current density in the  $y$  direction, normalized by the applied current density on the strip  $K_0$ , the position  $x$  is normalized by the width of the strip  $b$ ,  $\lambda_{\perp}$  is the effective penetration depth of the magnetic field in the film, the geometric parameters of sample and strip are shown in the schematics in upper part of Fig.1a. If the width of the strip  $b$  is larger than

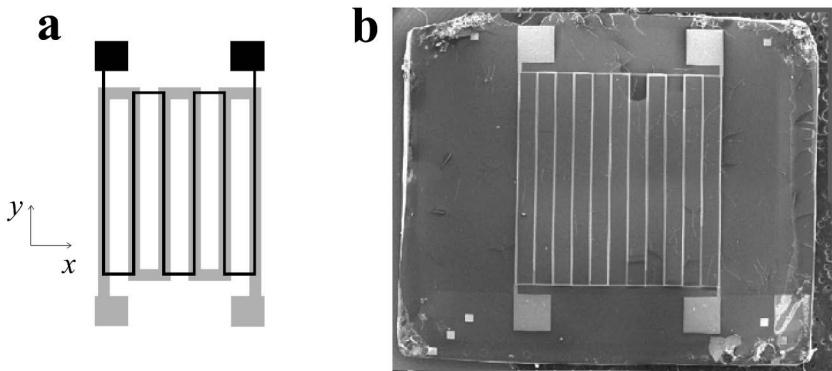


Fig. 2. **a.** Schematic of the two coils. **b.** Photograph of the serpentine coils fabricated on a sample.

the thickness of the isolation layer  $d$  and the effective penetration depth  $\lambda_{\perp}$ , the current geometry induced on the film nearly mirrors the strip. For values of  $b$  smaller than  $\lambda_{\perp} + d$ , the shape is rounded off. Typical design values are:  $b \approx 50 \mu\text{m}$ ,  $d \approx 1 \mu\text{m}$ . In the case of superconducting films and Josephson Junctions Arrays,  $\lambda_{\perp}$  is temperature dependent. At low temperatures  $\lambda_{\perp}$  is usually smaller than  $b$ , and diverges near  $T_c$ . In kinetic inductance techniques, sensitivity drops when  $\lambda_{\perp}$  is bigger than other characteristic lengths of the measuring system and sample.

The induced currents in the film spread up to a distance of the order of  $\lambda_{\perp} + d$  away from the strip border. Hence when adding parallel strips separated a distance  $l$  greater than  $2\lambda_{\perp} + d$  the respective shielding current profiles are nearly independent. Therefore several of these strips connected in a serpentine-shaped coil can be regarded as one long strip. The shielding current density profile for this geometry is shown in Fig.1b.

To complete the setup of kinetic inductance technique a second detection coil is fabricated. The two coils (excitation and detection) are built one on top of the other, separated by isolation layers. To achieve maximum sensitivity the distance of the receive coil to the sample is needed to be as small as possible. This is the reason to choose the lower coil to be the detection coil. For the same purpose the isolation layers are made as thin as possible.

Its interesting to observe that in these kind of flat, one-turn coils, the amplitude of the measured signal is proportional to the length of the coil, instead of enclosed area. The basic reason is that the shielding currents are induced along and close to the drive coil, unlike in a semi-infinite coil where

magnetic field is present in the whole area enclosed by the coil.

The two serpentine coils are rotated  $180^\circ$  as depicted in Fig.2. In this way, the long  $y$  strips of the secondary coil are under the primary coil, while the short  $x$  parts are not. The small distance between the receive coil and the sample causes the most significant contribution to the generated voltage is produced by currents flowing in the sample directly beneath the receive coil. The contribution to the total voltage in the secondary coil of the currents flowing in  $x$  direction is negligible.

The induced current density can be obtained analitically, solving Pearl equations for this geometry. The vector potential and voltage generated in the secondary coil can be calculated, establishing an expression of the measured voltage as a function of the effective penetration depth. Inverting this relation,  $\lambda_\perp$  can be numerically obtained following a similar procedure as in Ref. 7.

In conclusion, anisotropic inductance technique is presented, which opens the possibility for investigating the anisotropic transport properties of two-dimensional superconducting samples.

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