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# Local Magnetometry of $Cu_{0.064}TiSe_2$

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Local magnetometry using miniature Hall-probe array was used to study vortex distribution in superconducting single crystal of $Cu_xTiSe_2$, with $x = 0.064$ and $T_c = 3.2$ K. We show that vortices after penetration into the sample move towards the center, resulting into a dome-shape field profile. Such a profile is a signature of relatively low pinning. We show that these measured profiles are consistent with a model proposed for the samples in the absence of bulk pinning. Modifications necessary to obtain quantitative agreement between the model and the data are presented.

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## 1. Introduction

$TiSe_2$, the charge density wave system, becomes a superconductor upon doping with copper [1]. The interplay between the two collective orders is interesting itself, but as for any superconductor of type-II, the behaviour of vortices is important to study in order to properly interpret the measurements in magnetic fields.

At magnetic fields below the lower critical field $H_{c1}$, a sample of type-II superconductor is in the Meissner state, expelling the field from its interior. The sample thus distorts magnetic flux lines from their linear course and bends them around the sample increasing their density in the vicinity of the surface. Due to this distortion, the sample is exposed to an effectively larger field compared to the applied one. The first vortex penetrates into the sample when this effective field reaches at least the value of $H_{c1}$ all around the sample surface, while the applied field reads the value $H_p < H_{c1}$, $H_p$ being the first penetration field. For fields lower than $H_p$ no magnetic field penetrates the crystal, thus the sensor located below the sample is shielded and no Hall voltage is detected. When the field increases above $H_p$, the sensor starts to read increasing voltage as the number of vortices grows. Once the vortex penetrates into the sample it is exposed to several forces and its further movement depends on their respective relation. First, there is an attractive force which keeps the vortex close to the surface. This is a result of the condition that no current circulation normal to the surface can occur. Next there is a repulsive force pushing the vortex from the surface towards the center of the sample. This force arises from the opposite orientation of the screening currents in respect to the vortex current, which makes the two to repel each other. While the attractive force dominates, the vortex remains trapped close to the surface. Once the repulsive force prevails, vortex may start to move. If there are no more barriers within the sample volume, it will be directed straight to the center. However, existence of macroscopic pinning sites may prevent vortices from moving. Even if they are pushed from the surface, they will remain pinned on such pinning centers. Measurements of the magnetic field profiles in the sample reveal the distribution of the vortices in the sample volume and thus may help to distinguish pinning in the material as being small or large.

## 2. Measurements

A crystal with dimensions of about 250 × 250 × 50 $\mu m^3$ was prepared via the iodine gas transport method [2]. The Energy-dispersive X-ray spectroscopy analysis yielded copper content of 2.09 at% which corresponds to $x = 0.064$ in $Cu_xTiSe_2$ formula. Critical temperature of the sample, $T_c = 3.2$ K was determined from the specific heat measurements performed on the same crystal. Magnetic field profiles have been measured using a Hall-probe array based on an epitaxial GaAs/AlGaAs heterostructure with a two-dimensional electron gas. The array is constituted of 7 Hall sensors, each of $10\times10$ $\mu m^2$ active area, arranged in a line. The probes were separated along the line with a distance of 35 $\mu$m between centers of two adjacent probes. The sample was placed on top of the sensor line and installed in the $^4$He flow cryostat regulated to 1.6 K. Prior to each measurement the sample was cooled in zero field. Then the magnetic field was applied perpendicular to the *ab* plane of the crystal via a superconducting coil. The sensors recorded a local magnetic flux density as the sample was exposed to an external field. The array was supplied with constant bias current and the voltage measured across each sensor was directly proportional to the magnetic field at the

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sensor's position. To obtain a full profile of the sample it was necessary to shift the crystal along the sensor line several times. In every position of the sample a partial profile was recorded. Final profile was then reconstructed as a superposition of all partial measurements.

## 3. Results and discussion

Figure 1 presents magnetic field profiles of the sample in various applied magnetic fields. The sample is centered around the probe position 0, covering the positions $x$ from $x = -3$ to $x = 3$. Remaining probes are outside of the sample. Points of magnetic flux density corresponding to the same applied field are marked with the same colour. The right-most and left-most points (far from the sample) in every profile correspond to the value of the applied field. Connecting thin lines are shown only to guide the eyes.

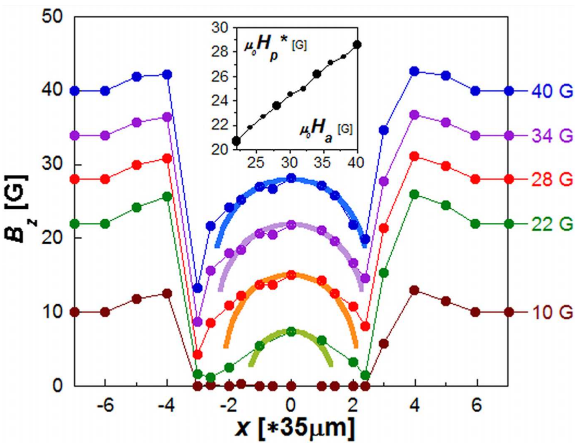


Fig. 1. Magnetic field profiles measured at 1.6 K in and around the sample for increasing field. The crystal covers 7 probes – positions from -3 to 3. Thin lines are shown to guide the eyes. Thick lines are the fits to the modified model (see text for details). Inset: effective values of $H_p$ needed to obtain agreement of the model and the data.

The lowest (brown) curve is a profile for applied magnetic field $H_a$ lower than $H_p$. Probes located under the sample read no voltage since no flux penetrates the sample. On the other hand probes in the exterior of the sample sense a higher density of the magnetic field – the closer the probe to the sample edge, the higher the flux density value. This is in agreement with magnetic flux lines distortion, resulting in their increased density around the sample surface.

For applied fields larger than $H_p$, all sensors including those below the sample read the voltage adequate to local magnetic field. The shape of each profile for $H > H_p$ is dome-like with maximum of the magnetic flux density in the center of the sample. For increasing field, more and more flux lines penetrate into the sample, thus the height of the dome is gradually increased. This dome-shape field profile may be described by a simple model proposed by Zeldov et al. [3] for superconducting samples in the absence of bulk pinning and for significant influence of geometrical barriers. With the model, knowing the dimensions of the sample and the penetration field $H_p$, one can estimate magnetic flux density inside the sample for any given value of applied field as

$$B_z(x) = H_a\sqrt{(b^2 - x^2)}/\left(w^2 - x^2\right);$$

$$b = w\sqrt{1 - (H_p/H_a)^2}; \quad -w < x < w.$$

Here, $B_z$ is a component of the magnetic flux density in the direction perpendicular to the sample plane and $w$ is a half-width of the sample. When fitting the data we found that the flux density in the center region of the sample is lower compared to the value expected from the model. This discrepancy is due to the existence of non-zero pinning in the sample, while the model describes samples absent of any pinning. Pinning sites act as barriers and stop some of the vortices from moving towards the center. This results in higher magnetic flux density close to the edge and lower in the center of the sample than expected from the model. To simulate the existence of the non-zero pinning we replaced the constant $H_p$value in the equation with a field dependent effective value $H_p^*$. The main panel of Fig. 1 shows the modified model fit curves (thick lines) corresponding to specific values of the applied field. As can be seen, we could reproduce the dome height in the profiles very well. Also consistently, an excess of magnetic flux density, compared to the constructed curves, is visible close to the edges. The evolution of $H_p^*$ with the applied field is plotted in the inset of the figure.

## 4. Conclusions

Magnetic field profiles of $Cu_{0.064}TiSe_2$ single-crystal were determined using miniature Hall-probe array. The dome-shape of the profiles suggests very low pinning. The evolution of the profiles is in a good agreement with the model of Zeldov et al., modified to simulate the existence of non-zero pinning in the sample. Thus we conclude that the pinning in the crystal is present, but is very low.

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