Manifestation of room-temperature superconductivity in thin films fabricated of YBa$_2$Cu$_3$O$_{7-\delta}$

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Abstract. We present manifestations of room temperature superconductivity in thin films fabricated of YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) on the substrate of NdGaO$_3$ (110). We show that the static magnetic susceptibility measurements demonstrate the Meissner effect in weak magnetic fields at room temperature. In addition, the oscillations of the magnetic susceptibility are revealed in external magnetic field, which can be interpreted as the quantization of magnetic flux through inclusions, with superconducting domains around them and the observation of the field-dependent steps that seem to be of evidence the second-order phase transition of domains. The results obtained are in a good agreement with the data of tunneling I-V curves. Finally, we suggest few further experiments that could confirm our hypothesis.

1. Introduction
There are few methods of high-temperature superconducting (HTSC) films growing [1,2]. And one of the most common is magnetron sputtering [3]. However, it is very hard to fabricate homogeneous thin HTSC films by this method. The presence of about 1 µm size inclusions (copper oxide or yttrium oxide particles) on the surface is a distinctive feature of the inhomogeneous sputtering [4].

Recently, the great interest has been caused by the influence of different geometrical factors on the superconductivity, such as interfaces, matrix superconductivity, inclusions and so on. There is hope that it may lead to the increasing of critical temperature, what determines the relevance of this work.

The goal of this work is to find out, how inclusions, described above, are able to effect on the magnetic properties of samples, particularly, on the static magnetic susceptibility.

2. Samples
Thin films of YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) on the substrate of NdGaO$_3$ (110) were fabricated by magnetron sputtering. The average thickness of such films is about 500 nm. Figure 1 demonstrates that samples are very inhomogeneous, because there is a lot of inclusions with typical diameter of 800 nm.
3. Static magnetic susceptibility
In this section, we present the results of the static magnetic susceptibility measurements by the Faraday method [5]. All measurements were performed at room temperature.

3.1. Different orientation of magnetic field

3.1.1. First orientation
If we apply the external magnetic field perpendicularly to the sample plane, then the diamagnetic response that is a basis of the Meissner effect is observed in the interval of weak magnetic fields (see figure 2). The negative magnitude of $\chi$ corresponds to ideal diamagnetism of film, because the thickness of film ($\sim 0.5 \mu m$) is match less than the thickness of substrate ($\sim 1 \text{ mm}$).

![Figure 2](image2.png)

**Figure 2.** The field-dependent static magnetic susceptibility. Magnetic field is perpendicularly to the sample plane. Subsequent arrows show the magnetic field scanning from zero magnetic field to the right and opposite to the left with changes of the magnetic field direction and finally to zero magnetic field. $T=300 \text{ K}$.

3.1.2 Second orientation
If we apply magnetic field in parallel to the sample plane, then other behaviour of the field-dependent static magnetic susceptibility is observed (see figure 3). The diamagnetic – paramagnetic conversion of the response of the static magnetic susceptibility is not observed by scanning the external magnetic field, thereby dumping the hysteresis that is caused by the Meissner effect.

![Figure 3](image3.png)

**Figure 3.** SEM-Image of the sample surface (left) and the sample edge (right).
Figure 3. The field-dependent static magnetic susceptibility. Magnetic field is in parallel to the sample plane. Subsequent arrows show the magnetic field scanning from zero magnetic field to the right and opposite to the left with changes of the magnetic field direction and finally to zero magnetic field. \( T = 300 \text{ K} \).

3.2. Oscillations of the field-dependent static magnetic susceptibility
Field-dependent oscillations of the static magnetic susceptibility are predominantly observed in the geometry, when magnetic field is perpendicularly to the sample plane, (see figure 4).

Figure 4. The field-dependent oscillations of the static magnetic susceptibility. Arrows correspond to the direction of the magnetic field scanning, vertical lines – positions of peaks. \( T = 300 \text{ K} \).

This can be explained according to the Bayes-Young theorem \([6]\), i.e. due to the quantization of magnetic flux through inclusions. But in this case, taking into account the oscillation period, \( \Delta H = 25 \text{ Oe} \), and the inclusion size, the flux value results in the flux unit of \( \Phi_0 = \hbar / 2e \), i.e. superconducting flux unit that is evidence of the presence of superconducting domains around inclusions at room temperature.

It should be noted also that there is no dependence between the peak position and the direction of magnetic field scanning.
3.3. Steps in the static magnetic susceptibility

The steps of the static magnetic susceptibility are observed in the range of 2.3-3 kOe (see figure 5). Orientation of magnetic field is perpendicularly to the sample plane.

We assume that it is the second-order phase transition of domains described above from superconducting state to normal state at critical magnetic field. Hysteresis that accompanies this transition is evidence of the second-order phase transitions.

Figure 5. The field-dependent steps of the static magnetic susceptibility. Arrows correspond to the direction of the magnetic field scanning. \( T = 300 \) K.

4. Scanning tunnelling microscopy (STM) and local I-V curves

Also, using STM-tip technique, we have measured local I-V curves at room temperature. The spot, in which we have found the gap-type I-V curve (see figure 6(right)) is shown in figure 6 (left).

Figure 6. STM-Image of the sample surface (left) and the local I-V curve (right) at the spot, marked in the left figure by arrow. In the right figure arrows correspond to the direction of voltage scanning. \( T = 300 \) K.

This figure demonstrates the presence of gap \( 2\Delta = 126.7 \) meV in spectra of elementary excitations. We interpret the peaks around \( \pm 0.05 \) V as Andreev reflection. Hysteresis may be associated with recharge phenomena. Note that the presented I-V curve is different from the standard SIN I-V curve, hence more detailed analysis of presented I-V characteristic is required.
5. Summary and conclusions
In this paper, we have presented few experimental results, that seem to indicate the presence of superconducting domains in thin HTSC film at room temperature. In order to confirm our assumption, we suggest the following experiments:

1) The period of magnetic susceptibility oscillations at different angles between magnetic field and sample plane is required to be measured. Trigonometric angular dependence has to be revealed, which appears to confirm the flux quantization.

2) The heat capacity measurements have to identify the phase transition above room temperature. The critical temperature from calorimetric measurements followed by the gap from I-V curve is necessary to be in agreement.

References
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