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Modeling superconducting vortices in high-T_c materials for TEM observations

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Abstract

In order to improve the model for the interpretation of transmission electron microscopy images of superconducting vortices in layered materials the number of representative layers should be increased. The upper limit of nine layers related to the computer performance has been more than doubled by approximating the screening layers above and below the layer containing a pancake vortex with a superconducting continuum.

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Recent transmission electron microscopy (TEM) observations of superconducting vortices interacting with columnar defects in high-T_c superconductors have been performed [1]. It was shown that the main features of the out-of-focus contrast could be consistently interpreted by assuming that the vortices are pinned along the tilted columnar defects and by using a layered or anisotropic model to calculate the phase shift of the electron wave. In particular, employing our Fourier space approach, we investigated the model of a tilted London vortex in a thin anisotropic slab and a pancake model with up to 7 layers [2]. The agreement between theory and experiments confirms the overall soundness of the models proposed for the interpretation of the experimental data and emphasizes the role played by the anisotropy of the material.

However, the number of layers in the pancake model is still insufficient to be truly representative of the actual specimen. As the contour line maps of the projected magnetic field and the simulated phase contrast images show a strong overall similarity with the continuous anisotropic case, apart from small cusps at each of the thin superconducting screening layers [3], in this work we investigate how the discrete pancake model can be approximated by a continuous stratified model composed of a single layer surrounded by anisotropic regions.

We essentially follow the approach proposed by Clem [4] and further developed by Coffey and Phipps [5], who replaced all the screening layers above and below the layer containing the vortex with a superconducting continuum that carries supercurrent only parallel to the layers.

The solution for the vector potential is found by Fourier methods, connecting the general solutions in the vacuum (where the potential satisfies the Laplace equation) with those in the superconducting regions (where the potential satisfies the London equation) by imposing the continuity of the vector potential and of its normal derivative. The presence of a vortex in the layer is taken into account by considering the layer as an additional superconducting region of negligible thickness.

Once the solution of the algebraic system for the unknown coefficients of the vector potential in the whole

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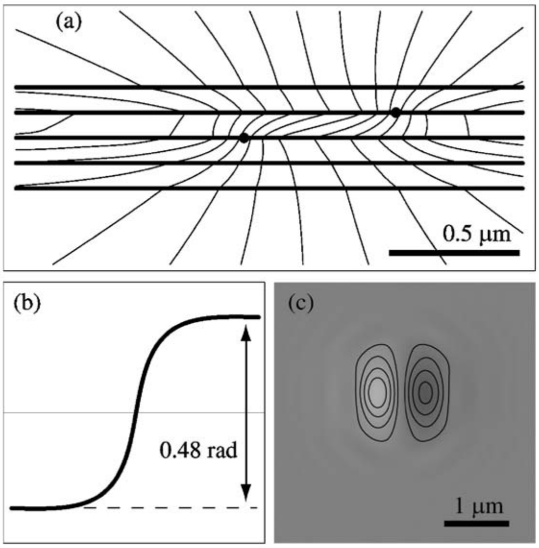

Fig 1. Pancake model: (a) projected field map; (b) phase shift line scan; (c) out-of-focus image. Each contour line in (a) represents a phase shift of $\pi/32$ rad, while each contour line in (c) represents a contrast variation of 3%.

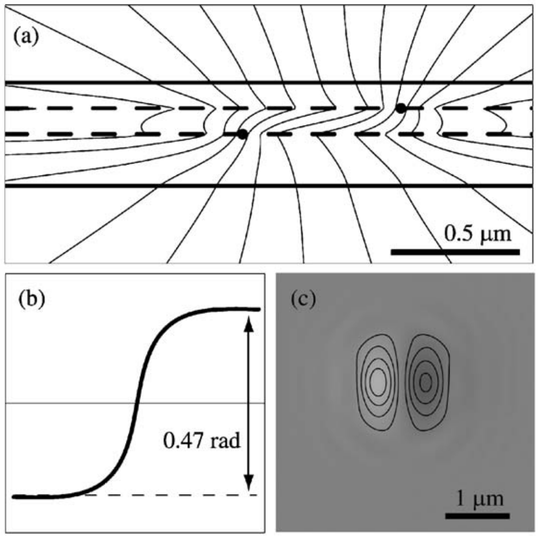

Fig. 2. Semi-continuous model: (a) projected field map; (b) phase shift line scan; (c) out-of-focus image. Each contour line in (a) represents a phase shift of $\pi/32$ rad, while each contour line in (c) represents a contrast variation of 3%.

space has been found, the electron optical phase shift is calculated by integrating the vector potential along a straight trajectory suitably chosen in order to take correctly into account the overall geometry of the experimental setup, including a tilt of the specimen with respect to the electron beam [1,2]. The field projected in other directions, useful for displaying its main features, is calculated according the same recipe. Finally, the Kirchhoff–Fresnel diffraction integral is used for the calculations of the out-of-focus images.

Figs. 1 and 2 show the comparison between the calculations carried out for two pancake layers (whose core is marked by a thick dot) in the case of a finite layered structure composed of five layers (Fig. 1) and within the new semi-continuous model (Fig. 2). In (a) the trend of the projected magnetic field is displayed, showing the overall similarity between the two cases. The higher magnetic screening power of the superconducting region is responsible for the curvature of the projected field lines in the region between the two layers.

The corresponding electron optical-phase shifts calculated for the same conditions of Ref. [1] are shown in (b). It should be noted that the total phase difference is only slightly different. However, this small difference is not detectable in the out-of-focus images (c), which are practically indistinguishable.

As the difference between the two models is rather negligible, we can now increase arbitrarily the number of layers to describe more accurately a real layered structure. The advantages are mainly in terms of computing time and analytical simplicity of the mathematical expressions. The semi-continuous model has been tested by simulations up to 20 layers, with room for further improvement. Another major advantage of this new model is the flexibility granted by the large number of layers, which can easily accommodate exotic structures such as kink vortices or distorted cores.

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