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Strong vortex matching effects in YBCO films with periodic modulations of the superconducting order parameter fabricated by masked ion irradiation

L.T. Haag [a], G. Zechner [a], W. Lang [a,*], M. Dosmailov [b], M.A. Bodea [b], J.D. Pedarnig [b]

[a] University of Vienna, Faculty of Physics, Electronic Properties of Materials, Boltzmanngasse 5, A-1090 Wien, Austria
[b] Johannes-Kepler-University Linz, Institute of Applied Physics, Altenbergerstrasse 69, A-4040 Linz, Austria

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ABSTRACT

We report on measurements of the magnetoresistance and of the critical current in thin films of the high-temperature superconductor $YBa_2Cu_3O_{7-\delta}$ (YBCO). A square array of regions with suppressed superconducting order parameter has been created in these films by introducing point defects via irradiation with He^+ ions through a silicon stencil mask. In such a structure distinct peaks of the critical current can be observed at commensurate arrangements of magnetic flux quanta with the artificial defect lattice. Concurrently, the magnetoresistance shows pronounced minima. Both observations demonstrate that the strong intrinsic pinning in YBCO can be overcome by a periodic array of ion-damage columns with 300 nm spacing.

1. Introduction

The interaction of magnetic flux quanta—or vortices—in superconductors with periodic arrays of holes in the material, so called “antidots” has been a topic of great interest since decades. On one hand, these investigations have been motivated by the rich landscape of different physical phenomena that result from the interplay of pinning, elastic, and thermal energies, the influences of the dimensionality, anisotropy, and spatial arrangement of vortices. On the other hand, the motion of vortices in a superconductor gives rise to dissipation that is detrimental for most technical applications. Consequently, many efforts have concentrated on the understanding of various mechanisms to block the mobility of vortices and to develop efficient strategies to pin them to local regions of suppressed superconducting order parameter. It is evident that the latter goal is particularly rewarding for the cuprate high-T_c superconductors (HTSC). In this paper we briefly review previous work on the pinning of vortices to artificially-created periodic defects in HTSC and the fabrication of point defects to suppress the superconducting order parameter by ion irradiation. Then we present our recent results on strong vortex pinning in a commensurate arrangement with a square defect array in the HTSC $YBa_2Cu_3O_{7-\delta}$ (YBCO) that was fabricated by masked ion irradiation.

* Corresponding author. Tel.: +43 1 4277 72624.
E-mail address: wolfgang.lang@univie.ac.at (W. Lang).

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2. Brief review of previous work

The pinning of vortices to natural defects that are randomly distributed or regularly arranged by self-organization, as well as to artificial defects, has been extensively investigated in metallic superconductors. Artificial defects can be created randomly or in regular patterns, too. The latter offer the chance not only to realize enhanced vortex pinning, but also many different ways of vortex manipulation, like for instance guided vortex motion, vortex ratchets and valves leading to the prospect of data manipulation and computing applications [1].

In HTSC, however, the anisotropic layered structure, strong thermal fluctuations and the *d*-wave symmetry of the order parameter render the mixed-state phase diagram more complex. Mainly the effects of columnar random defects created by heavy-ion irradiation have been investigated thoroughly [2] as well as the various structural point defects [3]. In contrast to clean metallic superconductors that are often used to study regular artificial defects, the typical average distance of random intrinsic defects in a prototypical HTSC, namely YBCO, is about 300 nm [4]. Therefore only with the emergence of advanced nanopatterning methods that allow for the fabrication of regular arrays of many thousands holes with (sub)-µm distance in a thin superconducting film it became possible that artificial structures can compete with the intrinsic pinning. Predominantly, this is demonstrated by the so-called “vortex matching” where at particular magnetic fields a commensurate relation exists between the vortex lattice and the lattice of holes imprinted in the sample. For a square array of holes the (first) matching field is given by

$$B_m = \frac{\phi_0}{d^2}, \quad (1)$$

where ϕ_0 is the flux quantum, and d the lattice constant of the defect array imprinted into the superconducting film. In principle, vortex matching can also occur at fields nB_m with n any rational number. The various arrangements of vortices with respect to the defect lattice for integer and fractional values of n have been demonstrated with Lorentz microscopy in a superconducting Nb film [5].

Vortex matching results in cusps of the critical current density j_c in YBCO films that were patterned with a square array of holes with spacing $d = 1$ µm [6]. The microscopic behavior of flux structures in a $d = 10$ µm array of antidots was visualized by scanning Hall probe microscopy and it was found that in increasing magnetic field, the vortices channel along the antidot rows to the inside of the sample [7]. Using periodic defect columns with distances of 120–180 nm fabricated by a combined e-beam lithography/ion irradiation technique strong minima in the magnetoresistance at the matching fields were demonstrated [8] and the interplay between random and periodic pinning investigated [9].

In HTSC with weaker intrinsic pinning, similar effects could be observed, too. In $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) single crystals with a triangular lattice of holes with $d = 1$ µm distance multiple minima in the magnetoresistance were observed at the matching fields [10]. In a related experiment but with a square lattice of $d = 0.5$ µm the minima were somewhat more pronounced. This confirms the expectation that artificial pinning arrays become operational around 1 µm lattice constant and improve for even narrower patterns.

Ratchet and rectification effects have been also reported in YBCO with asymmetric antidots in square arrays [11], cylindrical antidots in an asymmetric geometry [12], and in BSCCO with cylindrical antidots in a trigonal lattice but asymmetric current excitation [13]. In a nanopatterned array of loops of the HTSC $La_{1.84}Sr_{0.16}CuO_4$ with 150 nm periodicity significant minima of the resistance were observed [14], whereas in an arrangement of alternating loops of different diameters large magnetoresistance oscillations with a period of $h/2e$ have been reported [15].

In summary, a significant impact of regular defect structures on the properties of HTSC, in particular on thin films of YBCO with their strong intrinsic pinning, was found to date in few experiments only that have employed patterning on the sub-µm scale.

Common techniques for the patterning of HTSC films are chemical etching or ion milling, where the structures are defined by a layer of photoresist on top of the HTSC. These processes potentially result in degradations after removal of the photoresist, but more importantly, etching away of parts of the sample inevitably leads to a highly textured surface. This is a major disadvantage for growing additional epitaxial layers of HTSC, a protection layer or other material on top of the processed area. Mechanical and environmental stability of the edges of the patterned film and the wavelength of the light used for exposing the photoresist limit the minimum size of device structures. In addition, such techniques involve several processing steps even for the fabrication of a simple sample structure.

As a different route, the reproducible and systematic change of the electrical properties of HTSC by irradiation with ions can be employed. The particular ion species used for irradiation plays a crucial role on the nature of defects created. The irradiation of YBCO thin films with either 300 keV protons or 600 keV Ar^{++} ions indicated different defect structures that were attributed to displaced oxygen atoms in the former and the overlap of insulating regions in the latter case [16]. Proton irradiation leads to small defects that are statistically distributed in the material, but the complete suppression of superconductivity in YBCO requires a dose of the order of several 10^{16} cm^{-2} that might be prohibitive for patterning applications. Irradiation of YBCO with 50 keV or 130 keV He^+ resulted in an orthogonal to tetragonal transition of the crystal lattice due to oxygen displacement at a fluence of about 5×10^{15} cm^{-2}, but below this threshold no extended defect clusters can be detected in TEM investigations [17]. Conversely, amorphous zones were reported after irradiation with 500 keV O^+ ions [18] in YBCO and after irradiation with 300 keV Ne^+ and 100 keV Xe^+ ions in the isostructural compound $GdBa_2Cu_3O_7$ [19]. These results and our investigations indicate that He^+ ions are a favorable choice as projectiles for irradiation since they create randomly distributed point defects, mainly by displacing the O atoms in YBCO, but still have a reasonable impact, as compared to protons.

He^+ ion irradiation with moderate energy leads to an increase of the room-temperature resistivity and a reduction of T_c while the transition remains sharp [20,21]. The resistivity at 100 K is increased by about two orders of magnitude upon irradiation with 75 keV He^+ ions at a fluence of 5×10^{15} cm^{-2}. Correspondingly, the critical temperature (defined at half-transition) is rapidly suppressed as shown in Fig. 1. A dose of 3×10^{15} cm^{-2} marks the crossover from superconducting material with a metallic-like temperature dependence to a semiconducting temperature behavior and the disappearance of superconductivity. Complementary resistivity and Hall effect measurements indicated that the mobility of carriers decreases almost linearly with ion fluence, whereas the carrier density remains nearly constant—an indication that no oxygen is depleted during irradiation [21] but rather that oxygen is reordered into different atomic positions [22].

The reproducible and systematic change of the electrical properties of HTSC by irradiation with He^+ ions of moderate energy can be used for **M**asked **I**on **B**eam direct **S**tructuring (MIBS) of HTSC that is schematically shown in Fig. 2. A film of a HTSC is prepared on a suitable substrate. The thickness of the HTSC film is small enough that the ions of the selected energy can penetrate through this film and implantation is avoided. A mask is placed at a small distance from the film and it protects selected areas of the HTSC film from being irradiated. After irradiating the arrangement with an ion beam with large cross-section and low beam divergence, selected parts of the film are converted to non-superconducting,

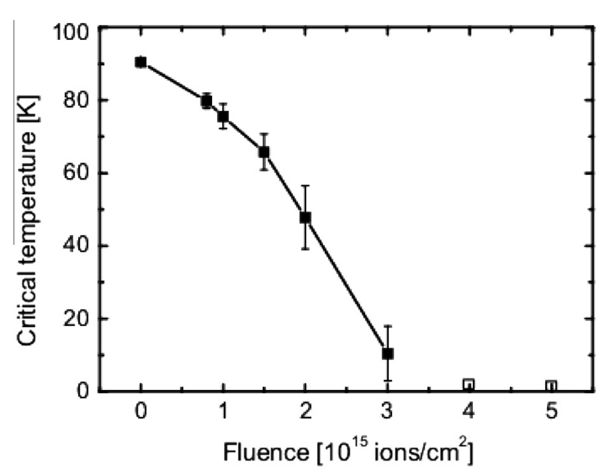

Fig. 1. Decrease of the critical temperature T_c of a thin YBCO film after cumulative ion irradiation. T_c is defined by the midpoint of the superconducting transition, the error bars indicate the width of the superconducting transition measured by the 10% and 90% resistivity levels. The line is a guide to the eye. Open symbols indicate that no superconductivity was found down to 4.2 K.

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