Bi-Sr-Ca-Cu-O superconducting thin films: theory and experiment

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Abstract. The interest of this paper centers on fabrication and characterization and modeling of vortices in high temperature superconducting thin films. As a first step, the magnetic vertices of the superconducting matrix were modeled. As a second, Bi-Sr-Ca-Cu-O thin films were grown using Pulsed Laser Ablation (PLD) on single crystal MgO substrates as magnetic templates for the potential use for Nano and Microelectronic circuits, and were characterized by x-ray diffraction, electron, and atomic force microscopy. The third step (future work) will be observation and pinning of these vortices using Bitter decoration.

1. Introduction

The opportunity to self-assemble large arrays of magnetic particles into bio-sensors, bioscavengers of toxins and metastatic cells, as well as magnetic structures for quantum computing or spintronic circuits, lays a foundation for revolutionary new medical therapies, materials and technologies.

Based upon recent work from the nanoscale pinning research group at Texas A&M and Waterloo Universities [1-2], the focus of this paper is to demonstrate that magnetic vortices in thin-film type II Superconductors, with or without pinning could be (potentially) used as a magnetic platform either as a template itself, or to make templates, for self-assembly of mesoscale/nanoscale microcapsules, magnetic atoms, molecules, or mesoscale/nanoscale sensors. This could be an enabling technology for self-assembly centered on the ability of researchers at the above mentioned universities to place individual magnetic vortices or mass produce well organized arrays of vortices in equilibrium.

2. Physical Background

A type-II superconductor (SC) has the fundamental property that for an applied magnetic field, $H$, above a lower critical field, $H_{c1}$, but below an upper critical field, $H_{c2}$, super-current vortices appear inside the SC. Each vortex is also a magnetic flux tube containing a quantum unit of magnetic flux, $\Phi_0 = 2.07 \times 10^{-7}$ G cm$^2$, confined in a cylinder of characteristic radius $\lambda$, the magnetic penetration depth of the SC. Thus having a distribution of vortex lines inside a SC is a way for the external magnetic field to partially penetrate the SC, albeit non-uniformly. A vortex line also has a normal core of radius $\zeta$, the coherence length of the SC, in which superconductivity is suppressed. Thus over-population of vortex lines in a SC...
can lead to the suppression of superconductivity (at $H_c^2$). The ratio $\lambda/\zeta$ is the most important dimensionless parameter of a SC, known as the Ginzburg-Landau parameter $\kappa$ [3, 4]. According to the Abrikosov theory [5], a SC is type-II only if $\kappa$ is larger than $1/\sqrt{2}$. For a superconducting film or slab of thickness $d < \lambda$, $\lambda$ must be replaced by an effective value $\lambda_{\text{eff}} = \lambda^2/d$, which is greater than $\lambda$, and $H_{c1}$ must be replaced by an effective value $H_{c1}^{(\text{eff})}$, which can be very small if $d$ is very small. Thus vortices can easily appear inside a superconducting thin film or slab [6]. When two vortices in a SC are separated by a distance much larger than $2\lambda$ (or $2\lambda_{\text{eff}}$) the magnetic induction $B$ inside the SC drops to essentially zero between them. Thus $B$ is highly inhomogeneous inside a SC containing a distribution of vortices (unless their separation is $<< \lambda$ or $\lambda_{\text{eff}}$). Since $\lambda$ (or $\lambda_{\text{eff}}$) can range from less than 30 nm to well above 1 $\mu$m [7], and the vortex separation can be further varied, the resultant inhomogeneous magnetic field can have an even wider range of scales, that lends itself to a wide range of microencapsulation and nanoparticulate technologies. On the sample surface perpendicular to the vortex lines, the inhomogeneity of the magnetic field also extends outside the sample for a distance of the order of the vortex-vortex separation.

3. Theoretical

The precise equilibrium arrangements of vortices of the fabricated films are quite intriguing and difficult to foresee. Large-scale simulations are necessary to determine these arrangements for a given sample geometry. In this regard the authors of this paper have collaborated to develop an efficient numerical algorithm for predicting such equilibrium vortex configurations. Initial results have demonstrated configurations having a lower symmetry than that of the sample, except at some values of the magnetic field [1-2]. The magnetization process inside a micron-sized superconducting grain in an external field was also studied by solving the time-dependent Ginzburg-Landau equation [8]. Figure 5 shows contour levels of $|\Psi|^2$, the density of Cooper-pairs, running from 0 to 1. The contour value of 1 corresponds to the superconducting state. Each isolated group of contours is called a "vortex" and represents the supercurrent density, $j$, circling around the vortex, that is zero at the vortex core. The two numerical simulations are identical except in the strength of the applied magnetic field, which was set at $H = 0.8$ and 1 (relative units). It has been assumed that the material is a very well-textured polycrystalline thin films of larger grains, each of which were acting as a single crystal of no defect such as grain boundaries or twins or impurities. Nevertheless, at steady-state conditions, the vortices settle at maximal distances due to mutual repulsion. In an infinite domain this would lead to a triangular lattice of vortices. However, an inherent characteristic is the dominant influence of the (confined) geometry, which is a perfect square. Thus, the vortex configuration reflects the square symmetry of the geometry (90 degree), with the $H = 1.0$ case displaying a perfect symmetry, while $H = 0.8$ case has a reflection symmetry (180 degrees). The reason for this difference is postulated to be that the $H = 0.8$ case is weaker, so the magnetic penetration in the form of vortices are weaker. Interestingly, there is a non-vanishing fluctuation of density in the vortices in the $H = 0.8$ case, which is close to a threshold value of $H$ at which new vortices are generated.

3. Experimental

The 2212 Bi-Sr-Ca-Cu-O polycrystalline, large grained, textured thin films for the vortex patterning were prepared using PLD on single crystal MgO substrates as mentioned by Yavuz et al [9]. There is also considerable amount of previous publication on PLD deposition of Bi-based thin films, which was summarized in a very well manner in the study of Rossler et al [10] and in references 11-15.

In this work, X-ray diffraction carried out on the specimen yields the result shown in Fig. 1. It shows that the peaks broaden out with increasing annealing time. There appears to be an optimum temperature and time of annealing which will yield a high $T_c$, sharp transition and single phase. Fig. 2 shows the AFM picture of a post annealed film. From the reference 9 it is readily seen from the surface morphology that
post annealing, or in-situ annealing is necessary to obtain a single phase. A SEM micrograph of the film is shown in Fig. 3, where there is some secondary phases present, with the largest size being less than 300 nm. Fig 4 shows the critical temperatures of as-grown films grown at various deposition temperatures. It is seen that film (b), grown at a temperature of 725°C shows the sharpest transition. Here, $\chi$ is the AC susceptibility. According to the reference 9, the post annealing increases the $T_c$, but the sharpness of transition is lost. This might be due to the fact that longer annealing time at higher temperatures results in the decomposition of the 2212 phase.

Figure 1. X-Ray Diffraction Pattern of film, (a) as-grown film deposited at 725°C (b) the film annealed at 825°C for 2 hours 835°C for 1 hour ($T_c$=63 K) (c) annealed at 825°C for 3 hours.

Figure 2. AFM image of a film annealed for 1 hour at 835°C, deposited at 725°C.

Figure 3. SEM Micrograph of as-grown film deposited at 725°C

Figure 4. $\chi$ vs T of various films grown at 700°C ($T_c$=43 K) (b) 725°C ($T_c$ = 58 K) (c) 735°C ($T_c$=63 K)(d) 750°C ($T_c$=63 K)
5. Future Work

To demonstrate programmed patterning methods for magnetic nanostructures, Scanning-Probe Microscopy (SPM)-based techniques will be used by the authors of this research to manipulate magnetic flux quanta and magnetic nanoscale structures. Once a vortex pattern is configured, Bitter patterning [16-18] methods will be employed to transfer this pattern to a magnetic nanoscale structure array. In this way, the superconducting magnetic vortices could be used as a means to place pre-set patterns of nanoscale magnets.

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