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Stabilization of the dissipation-free current transport in inhomogeneous MgB_2 thin films

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ABSTRACT

In type-II superconductors at $T = 0$ the critical current density is determined by the pinning of flux lines. Considering an arbitrarily shaped energy landscape the pinning force at each pinning site is given by the derivative of the flux line energy with respect to the considered direction. At finite temperatures, in addition, thermal activation can lead to a depinning of flux lines. The governing property in this case is the depth of the corresponding pinning potential, i.e. the pinning energy. We show a detailed analysis of both pinning forces and pinning energies of MgB_2 films with inhomogeneous microstructure. We show that a pronounced increase of the pinning energy is responsible for the significantly enhanced stability of the dissipation-free current transport in thin inhomogeneous MgB_2 films. This is found even if the corresponding pinning forces are small.

The dissipation-free current transport in thin type-II superconducting films is one of the most interesting properties for technical applications. This loss-free electric transport is closely related to pinning of vortices. Therefore, a fundamental understanding of the underlying flux line pinning mechanisms is essential for technological progress [1]. The control of flux pinning can only be realized via the control of the defect structures in the material. The realization of an effective distribution of pinning sites of appropriate sizes and distances needs first of all an understanding of the mechanisms at individual defect structures. It is necessary to distinguish between the depth of an individual energy minimum of the vortex self-energy which forms a pinning potential and the gradient of the energy landscape giving rise to a finite pinning force density. Both properties usually have to be considered when a full picture is required. In all cases, the role of temperature is typically crucial which can be seen when looking at films of high-T_c superconductors (HTSC) [2]. In case of MgB_2, a metallic superconductor [3], the consideration of the flux pinning mechanism is usually less complicated compared to the HTSCs. In thin MgB_2 films pinning of vortices is found which originates from grain boundary pinning [4]. In absence of additional disorder this leads to a temperature dependence of $j_c \sim (1 - T/T_c)^{3/2}$ [5], with T_c being the critical temperature where superconductivity vanishes. We show that a systematic investigation of pinning forces and pinning energies can help to understand the observed properties of superconducting MgB_2 films. Here, we present experimental results where both pinning forces and pinning energies are extracted independently for superconducting MgB_2 films with different microstructure. We find that in particular inhomogeneous MgB_2 films can exhibit a significant higher stability of loss-free current transport against temperature and magnetic fields which can be understood when comparing the different contributions to the overall vortex pinning.

In this paper we use superconducting MgB_2 films which are fabricated by ex-situ annealing of an Mg/B multilayer precursor. For details see Refs. [6,7]. These films are approximately 300 nm thick and have lateral dimensions of $5 \times 5\ mm^2$. The typical critical current densities at $T = 10$ K are in a range of $7–9 \times 10^{10}\ A/m^2$. We were able to prepare combinatorial MgB_2 films where local variations of the microstructure were obtained within one sample [8]. A continuous homogeneous superconducting area is always found in the center of the film. Close to the edges a fractured inhomogeneous microstructure develops due to variation of the initial magnesium layer in the precursor [9]. It is important to note, that there is always a continuous superconducting layer adjacent to the substrate.

Such combinatorial films are ideal candidates to investigate the role of the microstructure on the superconducting transport properties. For the characterization of the electrical properties of

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the superconducting films we use four-point resistivity measurements using a Quantum Design PPMS system at temperatures between $T = 5$ K and 100 K. For this purpose small gold contacts are evaporated in different sections on top of different sections of the MgB_2 films with different microstructures as shown in Fig. 1.

Fig. 2 depicts the resistivity measurements of homogeneous and inhomogeneous sections at magnetic fields between $\mu_0 H = 0$ T and 5 T. The used detection current is $I = 1$ mA. Note, that this particular measurement geometry initiates supercurrent flow in all parts of the superconducting film. However, if vortex motion in one region sets in the corresponding voltage is only measured at the contacts in this area. There is no voltage drop at the contacts in the other area. This allows the precise extraction of the role of the microstructure on dissipative vortex motion without having any other variations to take care of. For displaying the results the color code from Fig. 1 is used where blue refers to the inhomogeneous part and red to the homogeneous. All results are normalized to the corresponding resistivity values at $T = 45$ K.

The results presented in Fig. 2 show a systematic behavior. It is found that in both cases the onset temperature T_c and the temperature T_0 where the resistance vanishes are reduced with increasing magnetic field H. This holds for both considered microstructures and is of course well known.

It is interesting that in both cases the onset temperature of the transition is the same for all magnetic fields. However, the transition to zero-resistance at T_0 is strongly different for the red and the blue curves, respectively. These results clearly support the used measurement method: whereas at $\mu_0 H = 0$ T both curves can hardly be distinguished a continuously developing difference between homogeneous and inhomogeneous areas is visible in increasing field. Finally, at $\mu_0 H = 5$ T a difference of more than 5 K appears. The transition temperature where the loss-free current of $I = 1$ μA collapses is significantly higher in case of the inhomogeneous superconductor.

The shape of a superconducting transition in resistivity measurements is governed by two mechanisms. The end of dissipation-free current transport with increasing temperature sets in when magnetic vortices in the superconductor leave their pinning centers and start to move. Following Faraday's law this creates finite electric fields and thus dissipative processes. Note, since depinning of vortices exhibits an exponential temperature behavior a threshold value for the resistance has to be used to define the temperature T_0. We use 1% of the resistance at $T = 45$ K to determine T_0. This onset temperature is a direct measure of beginning flux line motion.

A further increase of temperature further increases the resistance until the onset of superconductivity is reached. The collapse of the superconducting state is driven by fluctuations of the order parameter [10]. Since this transition is not affected by the microstructural variations addressed in this work we do not follow this results any further.

The large variations of the temperature T_0 are apparently related to the motion of vortices in the superconducting films. Further information on the dynamics of the vortex system can be obtained when addressing the magnetic signal generated by the ensemble of the magnetic flux lines. First, we try to access local properties of the film by quantitative magneto-optical measurements. Magneto-optical images are acquired using polarized light in a reflected-light microscope. A magnetic field sensitive iron garnet film which is put on top of the sample rotates the polarization plane of the reflected light depending on the local magnetic field. To obtain quantitative values of the field distribution, we record the relation between external field and light intensity above the superconducting transition temperature. As a result we can obtain a spatially resolved and calibrated gray scale representation of the flux density distribution in and around the superconducting film with high quantitative accuracy. Further processing of these data using a numerical inversion scheme of Biot–Savart's law in two dimensions for thin films finally yields a map of the critical current density in the film determined by the pinning force density acting on magnetic flux lines in the film. A detailed overview of the possibilities of this method is given in Ref. [11].

With this quantitative magneto-optical method we determine the temperature dependence of the critical current density j_c in the homogeneous and the inhomogeneous areas of a superconducting MgB_2 film. Since the temperature dependence of j_c allows the analysis of the underlying pinning mechanisms [2] we can distinguish between the roles of pinning force and pinning energy for the necessary inhibition of flux line motion. Since the flux-line self-energy exhibits a linear temperature-dependence and the pinning forces usually show a non-linear behavior we can use these results to acquire information on the underlying pinning mechanisms.

Fig. 3 shows the result of the temperature-dependent critical current density for MgB_2 film areas with homogeneous (red) and inhomogeneous (blue) microstructures. The curves have been extracted from magneto-optically obtained current density maps like the one shown in the inset of the figure. The process leading to these results has already been shown in Ref. [12]. Two regions exhibiting a constant critical current density each can be distinguished in the image. The homogenous section of the film exhibits

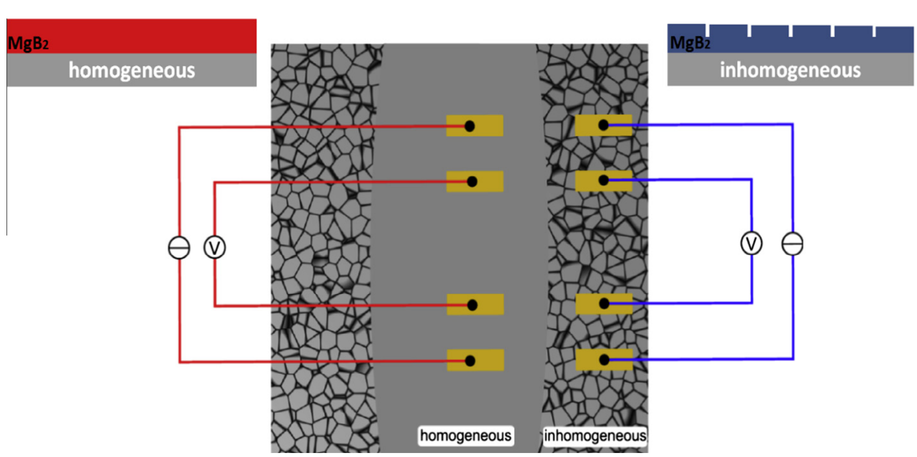

Fig. 1. Electric four-point measurements are performed at MgB_2 films with areas of different microstructures. Red and blue refer to homogeneous and inhomogeneous sections, respectively. A sketch of a representative cross section of the two superconducting structures is depicted in top left and top right part of the figure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)