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ScienceDirect
Physica C 460–462 (2007) 1251–1252
PHYSICA C
www.elsevier.com/locate/physc

Superconducting strip with ac current

E.H. Brandt [a,*], G.P. Mikitik [a,b], E. Zeldov [c]

[a] *Max-Planck-Institut für Metallforschung, D-70506 Stuttgart, Germany*
[b] *B. Verkin Institute for Low Temperature Physics and Engineering, Ukrainian Academy of Sciences, Kharkov 61103, Ukraine*
[c] *Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel*

Available online 12 April 2007

Abstract

A thin superconductor strip with perpendicularly applied dc magnetic field and longitudinal ac transport-current is considered. From the ac magnetic field profile measured across the strip by Hall probes, one can extract the voltage–current law in the bulk and the parameters of the edge barriers for flux-line entry and exit.

PACS: 74.25.Qt; 74.25.Sv

Keywords: Type-II superconductors; Edge barrier; Voltage–current law; Vortex pinning

In a novel method for mapping the distribution of the transport-current across a flat superconducting strip [1,2], an array of microscopic Hall sensors is used to measure the perpendicular component of the magnetic self-field H_z generated by an ac transport-current at various positions across the sample. By inverting the Biot–Savart law it was found that in contrast to the common assumptions the transport-current is highly nonuniform and its spatial profile varies significantly as a function of temperature T, applied dc field H_a, and of the phase of the vortex matter. Surprisingly, at high T over a wide range of the H–T phase diagram the current flows predominantly at the edges of the sample due to significant surface barriers, both in high-T_c and clean low-T_c superconductors [1–3]. At lower T, bulk vortex dynamics takes over, resulting in redistribution of the transport-current. So far, however, the experimental data thus obtained were not used for a quantitative study of vortex dynamics since a detailed theoretical description was absent.

In the present paper and in Ref. [4] we develop such a theory for extraction of voltage–current laws in the bulk and at the edges of superconductors. This ac method supplements the usual transport measurements of vortex dynamics.

We formally consider the strip as a set of two edge wires and of wires that form the bulk of the strip. The resistances of all these wires can be nonlinear functions of the currents flowing in them. The resistances R_l and R_r of the left and right edge wires characterize the edge barrier, they differ from the resistances of the bulk wires, and in general are different ($R_l \neq R_r$). We account for the mutual and self-inductances of the wires. This results in a set of coupled equations that can be solved numerically in the general case [4–6]. To get insight into the physics, we consider three special models.

In the *Ohmic model* the resistances of all the wires are assumed to be independent of the currents flowing in them, and hence the electric field in the strip is a linear function of these currents. Interestingly, even in the framework of this simplest model, one can reproduce the main features of the experimental data for $Bi_2Sr_2CaCu_2O_8$ [1,2] on the first harmonic of the ac magnetic field, $H_z^{(1)}$, measured in-phase with the applied ac current, Fig. 1. To describe this experiment, one has to assume that at T_c the resistance of both edge wires R_e is larger than the bulk resistance R_b, but with

* Corresponding author.
E-mail address: EHB@mf.mpg.de (E.H. Brandt).

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doi:10.1016/j.physc.2007.04.060

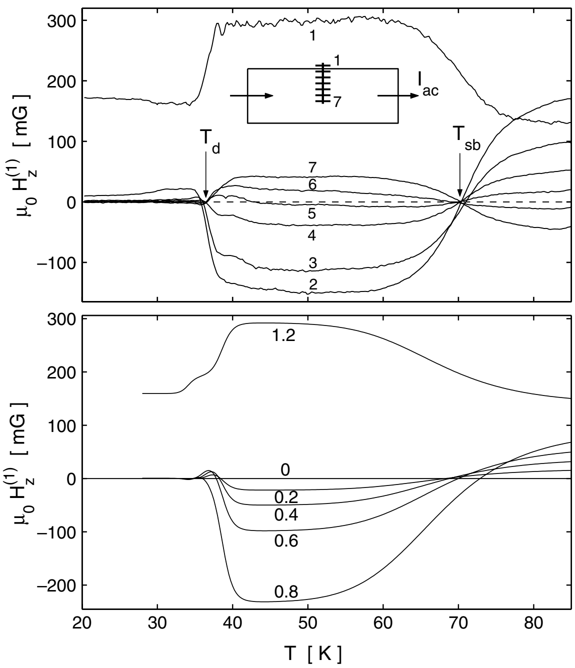

Fig. 1. Top: Temperature dependence of the first harmonic of the ac self-field, $H_z^{(1)}$, measured in-phase with the applied ac current of 4 mA amplitude by an array of 7 Hall probes at the surface of a $Bi_2Sr_2CaCu_2O_8$ strip in a constant applied dc field of 1000 G [2]. T_d and T_{sb} mark characteristic temperatures. The inset shows the geometry of the experiment and the positions of the sensors. Bottom: The same temperature dependence calculated in the Ohmic model for the same parameters as in the experiment and for $-x/w = 1.2, 0.8, 0.6, 0.4, 0.2, 0$, where w is the strip half width, and x is measured from the strip axis. The dependences $R_e(T)$ and $R_b(T)$ are chosen as Arrhenius laws with exponents that reproduce the measured temperatures T_{sb} and T_d.

decreasing temperature, R_e decreases sharper than R_b. Then, at temperatures near T_c, the bulk current I_b exceeds the edge current I_e, and the profile $H_z(x)$ is characteristic of the normal conducting state. Since with decreasing T the role of the edge current increases, one has $I_b = I_e$ at a temperature $T = T_{sb}$ defined by $R_e(T_{sb}) = R_b(T_{sb})$, and the contributions of I_b and I_e to H_z practically compensate each other for x inside the strip. With further decrease of T, the x-dependence of H_z is mainly determined by the edge current, $I_e > I_b$. But below a temperature T_d defined by $R_b(T_d) \approx \mu_0\omega$, the ac magnetic field is expelled from the strip due to the skin effect, and the applied current spreads over the sample again.

Our calculations presented in Fig. 1 (bottom) describe the experimental data sufficiently well, but for this we had to assume that the model functions $R_e(T)$ and $R_b(T)$ decrease with decreasing T more sharply than the appropriate data [7] obtained from usual transport measurements. This problem is overcome by nonlinear models.

In a *model with nonlinear* R_e, the edge resistance R_e is a nonlinear function of the current I_e flowing in the edge wires. We assume that if I_e exceeds a critical current characterizing the edge barrier, the edge wires do not differ from those in the bulk. But this critical current is implied to increase with decreasing T, and when it exceeds I_e, the resistance R_e sharply drops. Thus, in contrast to the Ohmic case, in this model a sharper decrease of $R_e(T)$ than of $R_b(T)$ is explained by the nonlinear dependence of R_e on I_e. The temperature T_{sb} is now near the temperature at which the above-mentioned critical current reaches I_e, but the temperature dependence of the first harmonic $H_z^{(1)}$ near T_{sb} remains qualitatively similar to that of the Ohmic model.

In a *model with nonlinear* R_b, the resistance R_b is assumed to be a nonlinear function of the currents flowing in the bulk of the strip, namely: When the critical current for bulk pinning, $I_c(T)$ (increasing with decreasing T), exceeds the bulk current I_b, the resistance R_b sharply drops. Within this model the temperature T_d is not due to the skin effect as it occurs for the Ohmic case, but now T_d is close to the temperature T_j at which the critical current in the strip $I_c(T)$ reaches the amplitude I_{a0} of the applied current, $I_c(T_j) = I_{a0}$. The temperature dependence of the first harmonic $H_z^{(1)}$ near T_d is mainly determined by the dependence $I_c(T)$. This enables one to extract information on the critical current in this temperature region from the measured $H_z^{(1)}(T)$.

Acknowledgement

This work was supported by the German Israeli Research Grant Agreement (GIF) No. G-705-50.14/01.

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