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Intrinsic noise sources in superconductors near the transition temperature

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Abstract

The performance of Transition Edge Sensors (TES) is limited by excess noise that is not predicted by the current theory of microcalorimeters and bolometers. The nature of this noise is currently unknown, but is likely to be dominated by fundamental physics of supeconductors. The University of Miami has recently started a joint effort between the microcalorimeter group and the superconductivity group to study and characterize the noise in TES. In particular, we plan to investigate the effect of flux motion due to self-field and external field and the effect of fluctuating order parameter by measuring the para-conductivity due to fluctuations in the number of Cooper pairs near the transition. We also plan to characterize the fundamental physical parameters of the TES to better predict their properties. In this paper we report our preliminary qualitative assessment of the problem, based on the literature, and we illustrate the experimental techniques that we plan to use for the investigation.

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Keywords: Transition edge sensors; Excess noise; Magnetic flux penetration

1. Introduction

Understanding a superconductor transition process requires knowledge of basic physical properties of the material considered. In a thin film, intrinsic noise in addition to the Johnson noise near the transition temperature is expected. This noise is primarily due to magnetic flux penetration and to fluctuations in the order parameter. To understand and quantify this noise it is necessary to know the type of superconductivity. Most clean pure element superconductors are type I superconductors, but with disorder and impurities, they can evolve into type II superconductors.

2. Flux penetration in type II superconductors

Depending on the type of superconductor being investigated, magnetic flux will either be quantized to $\Phi_0 = hc/2e = 2.07 \times 10^{-7}\,\mathrm{G\,cm^2}$ (type II) or will be in the form of magnetic domains (type I) in bulk superconductors. In thin films, the flux is complicated and depends on the thickness of the film and magnetic penetration depth. In the presence of

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transport current J, the Lorentz force experienced by each individual vortex is $F = J\Phi_0/c$. Because of this force, flux lines or domains move transverse to the current. The appearance of a voltage in the superconductor has been associated with this motion. In the presence of pinning force F_P, which is a result of lattice defects, impurities, and voids, the average velocity is determined by

$$\eta v_\mathrm{L} = \frac{J\Phi_0}{c} - F_\mathrm{p} \tag{1}$$

where η is the viscosity coefficient. The electric field due to the motion of a single vortex is then given by

$$E = \frac{Bv_\mathrm{L}}{c}, \tag{2}$$

where B is the magnetic field inside the superconductor. Statistical fluctuations in the number of vortexes that cross the film are then a source of voltage noise.

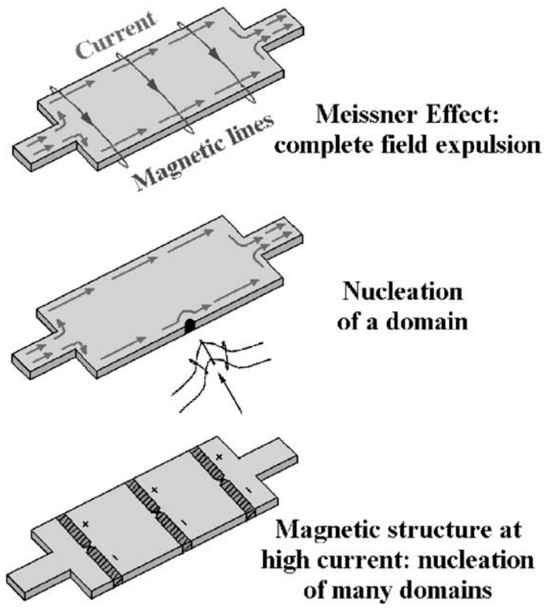

Fig. 1. Magnetic flux penetration in a type I superconductor. See text for details.

3. Flux penetration in type I superconductors

For a thin-film type I superconductors, the current and magnetic field profiles depend on the geometry, quality of the edges, and the magnitude of the current. For a long strip, the magnetic field at the edge of the film in the limit of Meissner effect (complete magnetic flux expulsions) is given by

$$H = \left(0.8\,\frac{\mathrm{G\,cm}}{A}\right)\frac{I}{2d}, \tag{3}$$

where I is the current and d is the thickness of the film. This result is derived assuming that the penetration depth λ is negligible compared to the thickness d. At a critical current for which this magnetic field reaches the value of the critical field, electrical resistance starts to appear. This result suggests that the critical current is only dependent on the film thickness. However, experimentally, the critical current on several thin film superconductor such as lead (Pb), or Indium (In), is found to be strongly dependent on the width of the film due to the effect of surface barriers against the magnetic flux entry at the edge [1–4].

The magnetic behavior of a superconducting strip is schematically shown in Fig. 1. For small current values the current flows mostly along the edges of the strip, and the magnetic field is completely expelled, except for a surface layer of thickness λ. As the magnetic field due to the current approaches a value of the order of the critical field at the sample edge, a normal region will be created locally (domain nucleation). The transport current will try to avoid this region by flowing around it. Because of the magnetic field enhancement at the inside of this current loop, this configuration is magnetically unstable, and the normal region will grow abruptly until it reaches the center of the strip. At higher current levels, the current-induced magnetic structure consists of many channels of the normal phase, which have grown from both edges. The current-induced magnetic structure and its dynamics have been studied and verified in classical low-temperature superconductors [1–4]. Time fluctuations in the number and size of normal phase channels generate a resistance noise in the superconducting strip.

4. A test to quantify the noise due to flux penetration

To quantify the contribution of magnetic channels motion to TES noise we propose a critical test that employs a superconductor/insulator/superconductor sandwich structure. The result should unambiguously support or reject the flux motion model. In this structure, two superconducting films are separated by a thin insulating layer. The same magnetic domains cross both superconductors and the excess noise in the two films is correlated. By measuring the level of correlation in the noise from both films it is therefore possible to clearly identify and quantify the contribution due to flux penetration (see Fig. 2).

For thin film type I superconductors, assuming the noise is from the fluctuation of the number of magnetic domains, one can qualitatively model the contribution to the noise spectrum. For example, if the fluctuations ΔN in the number of domains are statistically independent of each other and have constant magnitude and constant lifetime τ_o, the noise power spectrum can be derived to be [4]

$$P(\omega) = \frac{8\Phi_0^2\langle(\Delta N)^2\rangle_{av}}{\tau_0\omega^2}\sin^2\frac{\omega\tau_0}{2}.$$

The contribution due to fluctuating number of magnetic domains to the noise power spectrum has been studied in Pb and In superconductors [4]. The experimental results showed maximum noise power when the resistance first appeared. The power spectrum showed very weak frequency dependence for small frequency and ω^{-1} to ω^{-2} dependence at higher frequencies. The noise spectrum was also found to be strongly dependent on the quality of the sample. The similarities in the noise dependence in the transition region (large noise for small resistance and weak frequency dependence) between TES and thin films of Pb or In prompt us to believe that a very similar physics is at work.

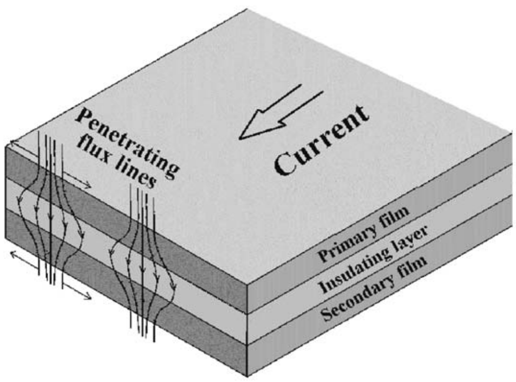

Fig. 2. Flux penetration in a sandwich structure.

5. Superconducting fluctuations near the transition

There are other possible sources that could contribute to the total noise spectrum. One such source is the fluctuation in the number of superconducting pairs or superconducting order parameter near the transition temperature.

The physics near the superconducting transition can be well described by the celebrated Ginzburg–Landau theory since the order parameter is small and varies slowly in space. The free energy can be then expanded in series of the order parameter ψ. In the absence of magnetic field, the number of superconducting pairs n_s can be calculated by minimizing the free energy

$$n_s = |\psi_0|^2 \propto (1-t), \quad \text{where } t = T/T_c.$$

The superconducting pair density near and below T_c increases linearly with decreasing T.

This result does not consider thermal fluctuation effects. At a finite temperature, the system can sample states with energy $k_B T$ above the ground state. This leads to a fluctuation in the order parameter and consequently in the number of superconducting pairs that are responsible for a voltage noise in the superconductor. A detailed description of this noise term can be found in Refs. [5,6].

The magnitude of this noise term is biggest at the transition temperature, and decreases symmetrically both above and below it. The generation of noise above the transition offers a test to quantify the magnitude of this mechanism, by comparing the noise spectrum just above and below the transition temperature.

Acknowledgements

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