Conf-810809--35

CONF-810809--35

THERMAL PROPAGATION OF NORMAL-SUPERCONDUCTOR BOUNDARIES

DE83 009615

K. E. Gray, J. Zasadzinski and R. T. Kampwirth
Argonne National Laboratory, Argonne, Illinois 60439

The model of Newhouse for thermal propagation of long normal regions in thin superconducting films on good thermal conducting substrates has been verified. Measurements show much slower velocities for short regions, but the dependence is compatible with a new model calculation. Stable hot spots are found which agree semi-quantitatively with a modified hot-spot calculation.

One of the earliest studies of nonequilibrium superconductivity dealt with the thermal propagation of normal-superconductor (NS) phase boundaries [1]. Such propagation in a thin film on an electrically insulating, thermally conducting substrate is more easily analyzed and of practical interest. For a transport current driven transition, Newhouse [2] gives analytical expressions for the velocity as a function of current for specified thermal properties of the substrate (assumed to dominate the thermal conduction). To obtain an analytical solution, he ignores the temperature dependences of the substrate thermal conductivity K , specific heat C_V and boundary resistance to the helium α . However, since the NS boundary is always at the superconducting transition temperature T_C , use of the thermal properties at T_C might be expected to provide a reasonable value for its propagation velocity.

This calculation was published in 1964, but to date no detailed experimental verification seems to exist. This paper presents the first quantitative verification of this theory including a new, unexpected length dependence for short normal regions, which can be understood in terms of a simple model. In these experiments, as a NS boundary propagates, the current decreases due to a shunt resistor necessary for protection. Thus the propagation velocity decreases to zero, and the dependence of the size of the normal region on residual current can be understood by using the substrate thermal conductivity in the standard hot spot model [3].

The samples are 1×5 cm $\times$ 1μ m films of NbN or Nb₃Sn with nearly bulk values of T_C , normal state resistivity ρ_n of either 20 (Nb₃Sn) or 250 $\mu\Omega$ /cm (NbN) and critical current density J_C of $\approx 10^6$ A/cm². They are sputtered into $1.27 \times 5 \times 0.05$ cm sapphire substrates, which are then placed in liquid helium ($T_b = 4.2$ K) and propagation is initiated at one spot by a pulsed magnetic field. Dynamic measurements of current and voltage give the propagation velocity. The

high μ_n and small ratio of superconductor (d) to substrate (t) thickness insure that the substrate dominates heat flow.

Measurements of the propagation velocity v , relative to its maximum value (the substrate sound velocity s), are shown in Fig. 1, along with calculations based on Newhouse [2]. The experimental dependence on the length of the normal region L_n is striking, although it correctly approaches the calculation (valid for $L_n \rightarrow \infty$) as L_n increases. The agreement with no adjustable parameters is really quite good. To understand the L_n dependence, the minimum conditions for propagation at the sound velocity are calculated, neglecting heat transfer to the helium but including the temperature dependence of K and C_V . For $L_n \sim 2t$, the result is

$$\mu_n J^2 d L_n / 2t = 2sC_V (T_C - T_b) \approx 1.5 \times 10^4 \text{ W/cm}^2.$$

As L_n increases there is a snow plow effect until it approaches the thermal healing length η [3]. Then heat transfer to the helium must be included and Newhouse ($L_n \rightarrow \infty$) is valid: $\mu_n J^2 d = sC_V (T_C - T_b)$. If $\mu_n J^2 d$ is plotted against L_n for $v/s = 0.25$, the characteristic length for saturation is about 0.7 cm, in good agreement with estimates of the static $\eta = (Kt/\alpha)^{1/2}$; here α is the heat transfer coefficient per unit area across the boundary with the substrate.

As the current commutates into the shunt resistor, $\mu_n J^2 d$ decreases to a steady state value, v decreases to zero and thermal propagation stops. By varying the shunt resistor, stable hot spots are found for which $\mu_n J^2 d$ is proportional to $L_n^{-0.7}$ for $L_n = 0.02$ to 3 cm. It is reasonable that short L_n have higher $\mu_n J^2 d$ due to the better relative cooling by the sapphire. For very small L_n , v is negative and the hot spot collapses. However, why doesn't this dependence saturate for L_n significantly greater than η ? This static situation can be analyzed like the hot spot in Ref.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Figure 1: The velocity of propagation of a normal-superconducting boundary versus power dissipation per unit area and length of normal region, normalized to the sapphire sound velocity $s \sim 0.75 \times 10^6$ cm/sec. The calculation is based on Newhouse [2].

3 except K is for the substrate and the proper thicknesses must be used. Three boundary conditions seem (BC) possible: (I) $T = T_0$ at some distance from the middle of the hot spot (Ref. 3) as applied to microbridges of length L ; (II) infinite substrate; and (III) finite substrate with no heat flow from its ends. The prediction of BC I. is a minimum in $\rho_n J^2 d$ for $L_n = L/2$ while B.C. II and III show saturation for $L_n > n$. These are all incompatible with our measurements for the value of n inferred from the propagation velocity. In addition, these calculations show that $\rho_n J^2 d$ is proportional to L_n^{-1} instead of $L_n^{-0.7}$ indicating the model is too simple. One likely discrepancy comes from the heavy current leads which heat sink the ends of the substrate, increasing $\rho_n J^2 d$, especially for larger values of L_n .

Why are these results different from very small microbridges? The microbridge calculation [3] assumes the substrate is an infinite thermal sink. This is correct when the size scale (1-10 μ m for microbridges) is much smaller than t and the n calculated above. Then

propagation is only in the film and K_s and K_n for the film are used to calculate n_s and n_n for the superconducting and normal regions. Note that faster v is possible because the quasi-particle velocity is greater than s . However, when the film is almost as wide as the substrate and $L_n \sim t$, the substrate is not an infinite thermal sink and one dimensional diffusion in the substrate dominates.

The authors would like to acknowledge the assistance of Zenon Sungalia. This research was supported by the U.S. Department of Energy, Division of Electric Energy Systems and Division of Basic Energy Sciences.

REFERENCES

- [1] T. E. Faber, Proc. Roy. Soc. **A219**, 75 (1953).
- [2] V. L. Newhouse, *Applied Superconductivity* (Wiley, New York, 1964).
- [3] W. J. Skocpol, M. R. Beasley and M. Tinkham, J. Appl. Phys. **45**, 4054 (1974).

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER