PHYSICAL REVIEW VOLUME 116, NUMBER 2 OCTOBER 15, 1959

Time Delays in the Superconducting Transition of Lead Films

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(Received May 18, 1959)

Strips of lead between 500 A and 1000 A thick, evaporated onto mica substrates, were driven from the superconducting into the normal state by rectangular current pulses of 0.4 μsec duration. For current amplitudes just above the threshold value, there was an apparent delay of up to 0.4 μsec before resistance began to appear in the strip. A plausible explanation is that a minute portion of the strip in the neighborhood of a flaw is driven normal almost instantaneously, and that the Joule heating of this normal region eventually causes thermal propagation of the interphase boundary. The delay is the time that must elapse before the temperature of the nucleus rises sufficiently to initiate the thermal spreading process. Similar results were obtained with lead-indium alloys, but in the case of tin the delay was less than the instrumental resolution. The relevance of these results to the interpretation of dc critical currents is discussed.

In a recent communication, Woodford and Feucht[1] describe an experiment in which a thin film of an unspecified superconducting metal (probably tin), driven into the normal state by a radio-frequency magnetic field, was used to provide the nonlinear element in a superheterodyne mixer. From the fact that the conversion efficiency was unimpaired at a frequency of about 1000 Mc/sec, they conclude that the transition to the normal state induced by a magnetic field takes place within about 10^{-9} sec. In this paper we wish to report some experiments on lead and tin films which show that, in contrast, the current-induced transition may under certain conditions be relatively slow.

Lead strips 2.0 mm long×0.1 mm wide, with thicknesses in the range 500 A–1000 A, were prepared by evaporation onto mica substrates. Electron micrographs of the thinnest showed traces of "island" formation, but the thickest were devoid of macroscopic irregularities. The strips, immersed in liquid helium at 4.2°K, were driven normal by rectangular current pulses of 0.4 μsec duration, and the voltage developed across them examined with a "Tektronix" Model 545 oscilloscope (rise-time 12 mμsec).

Voltage wave forms corresponding to progressively larger current pulses through a typical strip are shown in A to D, Fig. 1. The small "pip" coinciding with the beginning of the current pulse is an induction signal caused by the rising edge. With the vertical sensitivity indicated in Fig. 1, the first sign of any return of resistance on increasing the current occurs at a time coincident with the end of the current pulse, as in A. As the current is increased, the delay in the first appearance of resistance decreases and its subsequent rate of growth increases (B and C). On increasing the current still further, a stage is eventually reached (D) where the delay is less than the resolution of the apparatus, but the resistance still increases throughout the duration of the pulse. On examining the voltage wave form with a current slightly smaller than that corresponding to A (about 500 ma for the strip of Fig. 1), and with a vertical sensitivity about twenty times greater, a rectangular pulse of 0.4 μsec duration and very small amplitude is observed. This rectangular pulse appears with no time delay within the resolution of the apparatus ($\sim$15 mμsec), and corresponds to a resistance of a few milliohms; if the current is varied, it does not show a sharp threshold, but increases smoothly in amplitude from zero to a value corresponding to about 10 milliohms just before stage A is reached. All the lead strips we have examined have shown qualitatively similar behavior, differing only in the absolute magnitudes of the currents involved.

We believe that a consistent explanation of the data can be given in the following terms. The very small rectangular pulse which occurs before stage A is reached is due to one or more flaws in the strip, which have smaller critical currents than the bulk of the film, being driven normal; the time delay involved in this process is not more than 15 mμsec. These flaws may be

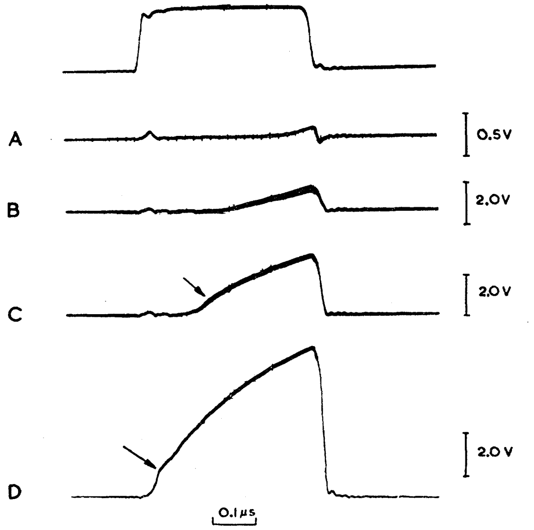

FIG. 1. Lead strip 2.0 mm. ×0.1 mm×500 A, driven normal by 0.4 μsec current pulse. Top trace: current wave form. Traces A to D: voltage wave forms. Current amplitudes: A, 0.64 amp; B, 0.70 amp; C, 0.74 amp; D, 1.30 amp.

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[1] J. B. Woodford and D. L. Feucht, Proc. Inst. Radio Engrs. 46, 1871 (1958).

physical imperfections or regions of local strain, and the normal region associated with them must fill the entire cross section of the film. The fact that the appearance of this rectangular pulse does not have a sharp current threshold suggests that a number of flaws are involved, with a range of critical currents. Immediately a flaw is driven normal, Joule heat is produced and its temperature rises, approaching an equilibrium value asymptotically. The rate at which it approaches this equilibrium value is determined by the same factors as control the rate at which it would cool if the current were switched off, the most important of these being loss of heat to the substrate. If we make the simplifying assumptions that the dimension of the normal region parallel to the length of the strip is negligible and that the ordinary thermal conductivity equations hold, it can be shown that the rise in temperature of the flaw is given by $\theta = AI^2 \operatorname{erf}[(t/\tau)^{\frac{1}{2}}]$, where A is a constant, I is the current, and τ is the thermal relaxation time which determines the rate of cooling of the entire strip. For lead strips on a mica substrate, the cooling curve shows two components,[2] an initial sharp drop in the first 0.1 μsec being followed by a tail which lasts for more than 0.5 μsec. Provided the equilibrium rise in temperature $\theta_\infty = AI^2$ is greater than the difference between the bath temperature and the critical temperature of the adjacent superconducting region (which is itself a function of I), the temperature of the flaw will eventually reach this latter value, and when this happens the superconducting region adjacent to the flaw will be forced into the normal state. This increases the rate of production of heat and in turn causes a further extension of the normal area. The process is unstable, and the normal region spreads until it includes the entire strip, as was observed for the case of tin films by Bremer and Newhouse.[3] The velocities of spreading observed in our experiments are much greater than those reported by Bremer and Newhouse, but the difference can be explained by the fact that our currents were much greater and our films much thinner than theirs. In traces C and D there are discontinuities (indicated by arrows) in the rate of growth of the resistance; the resistance at these points is about 1 ohm, which is the resistance of the strip just above the critical temperature. The initial steeply rising part of the trace therefore represents the growth of the normal region until it includes the whole of the strip, while the subsequent more slowly rising part represents the heating up of the entire strip. In D, the resistance of the strip at the end of the current pulse corresponds to a temperature rise of about 30°K.

The above explanation interprets the delay in the commencement of the thermal spreading process as the time taken for the temperature of the flaw to reach the critical temperature of the adjacent superconducting region. In our experiments there are clearly several flaws present, but it is reasonable to suppose that the spreading process begins at one of them, namely, the hottest. As the current increases, the delay decreases both because of the increase in θ_∞ and because the critical temperature is a decreasing function of I. For the strip quoted in Fig. 1, the dependence of delay on current is a surprisingly good fit to the error-function dependence mentioned above if τ is taken as 0.3 μsec, but we do not attach any great significance to this. On measuring the dc resistance of the strip with a potentiometer, behavior similar to that reported by Bremer and Newhouse[3] was found, namely, a "tail" with a resistance of a few milliohms which began at a current of about 500 ma and increased smoothly until the entire strip suddenly went normal at a current of 540 ma. The tail clearly has the same origin as the small rectangular pulse which appeared first in the pulse measurements, while the "apparent dc critical current" of 540 ma can be interpreted as that current which raises the temperature of the hottest flaw just sufficiently to make the thermal spreading process begin after an indefinitely long time. In the case of the pulse measurements, there is no sign in C of the strip being driven normal *en bloc*, though it is possible that this process is beginning to occur in D. The true critical current is therefore at least twice the apparent dc critical current.

A strip made from a 90% Pb–10% In alloy showed qualitatively the same behavior, except that the spreading process developed much more quickly with increasing current; a situation similar to that shown in D was reached with a current 1.4 times the apparent dc critical current, compared with a figure of 2.4 for the pure lead strip of Fig. 1. This alloy strip had a normal resistance thirty times that of the lead one, and the more rapid growth of the resistance can be explained in terms of the increased Joule heating. In the case of tin strips of the same thickness and dimensions, the behavior was qualitatively similar but with the important difference that there was no delay within the experimental resolution (~15 mμsec). Measurements similar to those quoted above[2] of thermal relaxation times of tin films on mica have shown that they are appreciably shorter than those of lead films, recovery to the bath temperature being complete in about 50 mμsec, so that any delay in the commencement of the thermal propagation process must be less than 50 mμsec. It is unlikely, however, that this is capable of accounting for the complete absence of any observable delay, and at the moment the difference in behavior of lead and tin remains partially unresolved.

ACKNOWLEDGMENTS

We are indebted to Dr. D. J. Oliver for the solution of the heat conduction problem, and to the Admiralty for permission to publish this paper.

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[2] R. F. Broom and O. Simpson, Brit. J. Appl. Phys. (to be published).

[3] J. W. Bremer and V. L. Newhouse, Phys. Rev. Letters 1, 282 (1958).