Relaxation times in lead film, superconductive, storage elements

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Abstract.

An important factor in the performance of any thin film, superconductive, switching device is the speed with which superconductivity is restored after the film is driven into the normal conducting state. An experiment is described which measures the critical current of a lead film Crowe cell during the first microsecond after switching. The minimum writing time of such storage cells should be equal to the time required for the critical current to recover to one half of its initial value. Good correlation is found between the recovery times and the writing times for Crowe cells deposited on various substrates. Cells deposited on mica or sapphire recovered in 50 $m\mu s$*, while those on glass required approximately three times as long. Measurements were also made of the critical current as a function of temperature, and these are used to derive cooling curves during the recovery phase. The cooling curves are not related to the thermal conductivities of the substrates in any simple way, probably because the rate of cooling is determined primarily by the thermal resistance between film and substrate.*

1. Introduction

The growing requirement for increased speed in components for fast electronic computers has stimulated research on superconductive switching, and a number of devices, both of the active switching and the passive memory storage types, have recently been described in the literature. The invention by Buck(1) of the cryotron was the first example of the use of the superconducting transition in a practical electronic device. The original cryotron switch consisted of a niobium solenoid wound round a thin tantalum wire. This type of construction is restricted to comparatively low switching speed, and interest is now chiefly centred on thin film devices.

The operation of any superconducting device involves the transition of some part of the structure from the superconducting to the normal state, and *vice versa.* The speed of operation depends upon the rate of propagation of the superconducting phase transition, and this in turn depends in a complicated way on the geometry of the structure and the amplitude and rate of rise of the driving pulses. Two other time factors are, however, equally important; these are the L/R time constant and the thermal relaxation time following the almost instantaneous rise in temperature, when current flows in metal which has been driven into the normal state. Thin film construction tends to increase the normal resistance and the rate of propagation of the superconducting transition, but the very high current densities, which may reach values in excess of 10^7 A/cm^2, can cause transient temperature rises of several degrees, even when a film is in contact with liquid helium.

A great deal of work on the phenomenological properties of thin film superconductors will be needed before it is possible to predict the optimum design for any superconductive component. The object of the work described in this paper was to investigate one aspect of the problem, namely the relaxation of a thin strip of superconductor after it has been driven into the normal state by a current pulse. In order to apply the results to a case of practical importance, the thin films used were made in the form of Crowe(2) cells: it was thus possible to correlate the relaxation time directly with the switching speed of this kind of storage element. The conclusions are, however, relevant to any superconductive device employing thin films.

2. Experimental method

The Crowe cell, or trapped-flux storage device, consists of a thin film of a superconductor deposited on a flat substrate. In the present work lead was used as the superconductor and films were made by evaporation on to glass, mica or sapphire substrates. The film thickness was 600 Å and a single element consisted of a circular hole 2 mm in diameter bridged by a strip, called the cross-bar, of 0·1 mm width, Fig. 1. A drive wire located parallel to the cross-bar, and inductively coupled to it, can be used to induce a circulating current in the film, which flows through the cross-bar and returns round the outside of the hole. Under certain conditions a rectangular driving pulse can induce a permanent supercurrent in the film, and, since the sense of circulation is determined by the sense of the driving pulse, one bit of information is thereby stored. This can subsequently be recovered by interrogation.

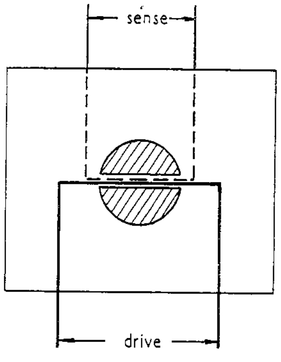

Fig. 1. Crowe cells used in the experiments. Lead film 600 Å thick, D-shaped holes 2 mm diameter, cross-bar 0·1 mm width. The drive and sense wires are detachable

The mode of operation of the device has been discussed by Rhoderick.(3) In order to store, the following conditions must be fulfilled. (i) The current induced by the leading edge of the driving pulse must exceed the critical current I_c required to drive the cross-bar from the superconducting into the normal state; (ii) the duration of the driving pulse must be long enough for the cross-bar to relax into the superconducting state; (iii) the falling edge of the driving pulse must not induce a current sufficient to drive the cross-bar normal a second time. The minimum pulse length for which these conditions are satisfied determines the maximum speed of the storage element.

The energy of the magnetic field of the supercurrent is dissipated by Joule heating in the cross-bar when it is driven normal, and consequently the temperature of the cross-bar rises. Since the critical current is a decreasing function of temperature, becoming zero at the transition temperature T_c, the condition (iii) requires the driving pulse to be long enough for thermal recovery to occur. Rhoderick's analysis shows that the writing time (minimum pulse length for storage), is determined by the time required for the critical current to recover to one half of its value at the beginning of the cycle.

The critical current of the cross-bar, measured as a function of time, can be obtained as follows. The lead film is scored as shown in Fig. 2, so that the secondary current loop is no longer continuous. The drive wire is removed and electrodes are attached to measure the current-voltage characteristics of the cross-bar. Very short current pulses are fed through the cross-bar with the wave-form shown in Fig. 3, at a repetition rate of about 1 kc/s, the voltage being displayed on an oscilloscope. So long as the cross-bar remains superconducting there can be no voltage drop across it. The first pulse is adjusted to an amplitude just sufficient to give a signal on the oscilloscope, i.e. the critical current of the cross-bar in equilibrium with the helium bath at 4·2° K. The critical current defined in this way depends on the pulse length of the driving current,[(4)] in these experiments the pulse length was always 20 mμs. The second pulse, delayed by an interval t, is also adjusted to the minimum amplitude $I_c(t)$ required to give a signal. Amplitude $I_c(t)$ is thus the critical current appropriate to the state of the cross-bar at an elapsed time t after the initial pulse. Fig. 4 shows the measured critical currents of three similar lead films of 600 Å thickness deposited on glass, mica and sapphire respectively, at times up to 1 μs after being driven normal by a 20 mμs current pulse.

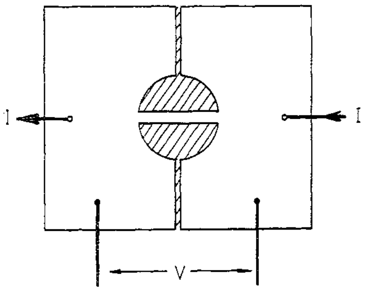

Fig. 2. Crowe cells with drive and sense wires detached, and lead film scored for measurement of I–V characteristic of the cross-bar

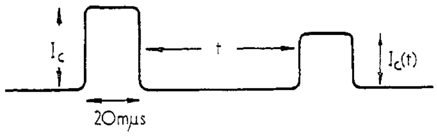

Fig. 3. Wave-form used for measurement of the I–V characteristic of the cross-bar. The repetition rate was 1 Kc/s

If the lead films were perfectly uniform, and at any given current density were either wholly superconducting or wholly normal, then the measurements of $I_c(t)$ shown in Fig. 4

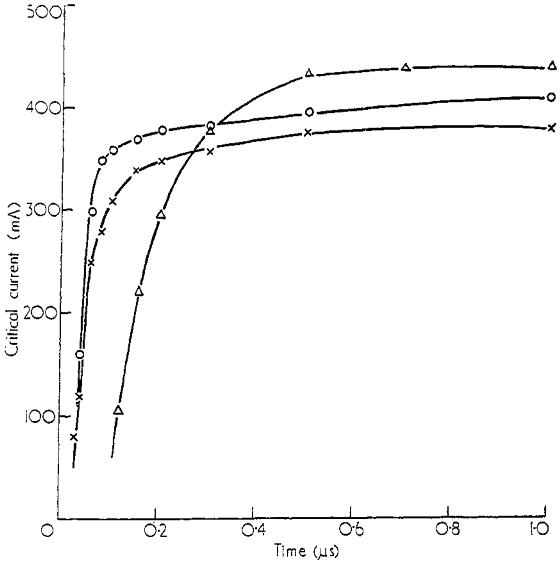

Fig. 4. Recovery of critical current of cross-bar following 20 mμs initial pulse

△ = lead film on glass substrate.
× = mica substrate.
○ = sapphire substrate.

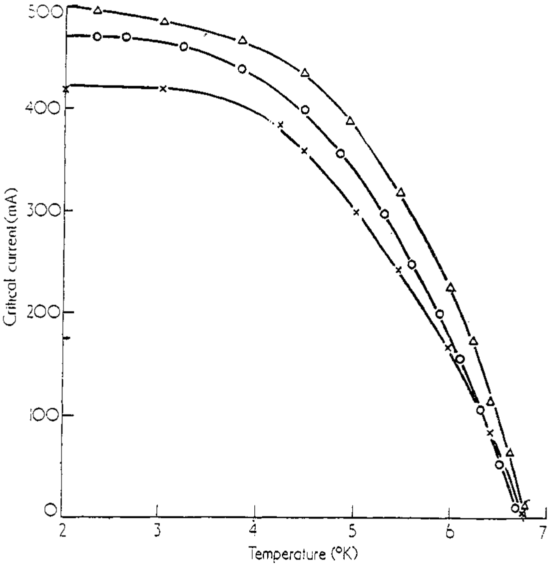

Fig. 5. Critical current of lead film cross-bar as a function of temperature

△ = glass substrate.
× = mica substrate.
○ = sapphire substrate.

could be used to determine the temperature of the cross-bar as a function of time. Fig. 5 shows the critical currents $I_c(T)$ of the same lead films measured in a separate experiment as functions of the bath temperature from 2 to 7° K. There is a spread of about 20% between the different substrates, which is reasonable for such thin films, and each has a critical temperature of about 6·8° K which is 0·3° K below the critical temperature of bulk lead. Using the curves of Fig. 5 to calibrate the previous results, the cooling curves shown in Fig. 6 are obtained.

3. Discussion

Considering first the results shown in Fig. 4, the films deposited on mica and sapphire substrates both exhibit a very rapid recovery of about 80% of the equilibrium critical current in less than 0·1 μs, followed by a slower recovery of the final 20%. The film on the glass substrate shows a rather different behaviour because, although recovery of the full critical current takes about 1 μs, which is comparable with the other substrates, the initial increase is very much slower than either. The times required to recover 50% of the equilibrium critical currents can be read off the curves of Fig. 4. These values of $t(\frac{1}{2})$ are tabulated in the table, together with the measured values of the minimum writing times t(write) of the same and similar films used as Crowe cells in a normal storing cycle. The writing time, though well defined for any one cell, was found to have rather a wide spread from one cell to another, and consequently a range of values representative of all the experimental cells made on each of the substrates has been given. The correlation between t(write) and $t(\frac{1}{2})$ is fairly good, and confirms Rhoderick's predictions which are based on the assumption that the current in the Crowe cell, when it is driven normal, decays almost to zero before the cross-bar returns to the superconducting state. This is equivalent to requiring the L/R time constant of the cells to be much less than $t(\frac{1}{2})$. Direct observation of the decay of the signal in the sense wire gives average values of 10 to 20 mμs for L/R.

Correlation of switching times with superconductive recovery times for lead films on various substrates

	glass	*mica*	*sapphire*
$t(\frac{1}{2})$ (mμs)	162	50	45
t(*write*) (mμs)	200–500	50–150	70–100
L/R observed	10–20 mμs in normal operation		
$K(4\cdot2° K)$ (W/cm° K)	10^{-3}	unknown	~ 1

The cooling curves in Fig. 6 will give a faithful representation of the temperature of the lead film only if the transition between the normal and superconducting phases occurs instantaneously throughout the strip. Recent work by Broom and Rhoderick[(4)] shows that in lead films the current-induced transition into the normal state is initiated at one or more weak points, and the consequent non-uniformity of Joule heating results in temperature gradients in the film. Since the experiment described in Section 2 measures the hottest part of the film, it is possible that the exact shape of the cooling curves in Fig. 6, and particularly the apparent existence of two decay components in the case of the mica and sapphire substrates, is the result of initial non-uniformity of temperature.

It is not possible to correlate the thermal decay rates with the properties of the various substrates, because little is known about thermal conductivities at liquid helium temperatures. Qualitatively sapphire is a very much better thermal conductor than glass, and mica is probably a good conductor also, although the effect of its anisotropy is unknown; this is in general agreement with the results in the table. The rates of cooling are not, however, necessarily determined by the thermal conductivity of the substrate, because at 4° K the phonon-mean free path is long compared with the thickness of both film and substrate. The thermal resistance at the interface between film and substrate is likely to be the controlling factor, in which case the optimum transfer of heat will occur when there is perfect acoustic matching between film and substrate.[(5)]

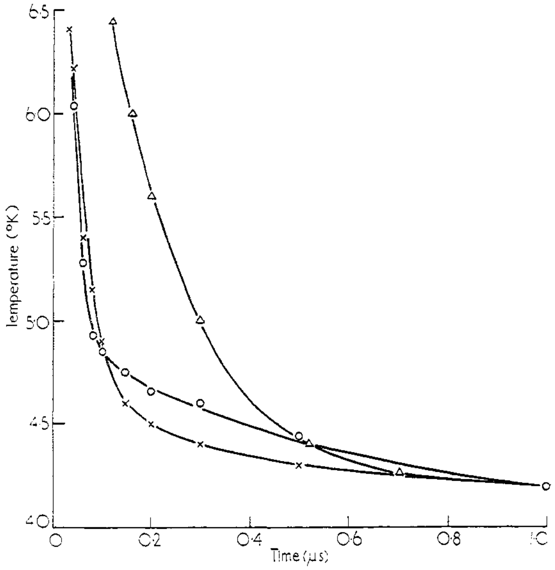

Fig. 6. Cooling curves of lead film cross-bars on various substrates

Δ = glass substrate.
× = mica substrate.
○ = sapphire substrate.

Acknowledgements

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