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# Switching Times of the Current-Induced, Superconducting-to-Normal Transition in Filaments of Tin and Indium*

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The superconducting-to-normal switching time has been measured by comparing the electrical pulse incident on a filamentary superconductor with the pulse transmitted by it. The switching time was found to vary inversely with the excess of the current pulse over the critical current. In the limit of large current pulses, the switching time became less than about $5\times10^{-11}$ sec.

USING a microwave technique, Nethercot[1,2] and Nethercot and von Gutfeld[3] have inferred that a superconductor can be switched from the superconducting state to the normal state in times of the order of $10^{-10}$ sec or more. Using a sampling oscilloscope having a rise time faster than $10^{-10}$ sec, we have made direct measurements of the switching time as a function of current. We define the switching time, as the interval during which the current exceeds the critical value and the specimen remains in its superconducting state ($R=0$). It has been observed to vary from about $1\times10^{-7}$ sec at currents only slightly in excess of critical value to values shorter than $5\times10^{-11}$ sec at large currents. The latter value reduces by a half an order of magnitude or more an earlier attempt[4] to put an upper limit on the switching time using pulse techniques. The interval $\tau$, as defined above, can be thought of as composed of a fundamental time to form a normal nucleus plus a time for this nucleus to grow over the cross section of the specimen. If the normal nucleus formed over the entire cross section spontaneously, then $\tau$ would be identical with the fundamental time. Since this cannot be claimed, $\tau$ represents an upper limit to this time.

Measurements of $\tau$ were made using the arrangement shown in Fig. 1. In order to insure maximum current uniformity, the specimen cross sections were made as small as possible. The samples were evaporated tin and indium strips which varied in thickness from 500 to 1000 Å, in width from 5 to 15 $\mu$, and were 2 mm long. They had residual resistances varying from 50 to 100 Ω and resistance ratios between 3 and 10. They were made part of the center conductor of a 50-Ω coaxial line. The output of the pulse generator, which consisted of a pulse-forming line and mercury-wetted relay was fed through 100 ft of delay line to a "$T$" which split the pulse into two identical pulses. One pulse was fed directly to one channel of the scope; the other was fed through the sample to the other channel. Thus, the pulse incident on a sample and the pulse transmitted by the sample were displayed on the scope face. From these traces the pulse transmission coefficient and the normal resistance of a sample could be computed. When the specimen is superconducting the pulse transmission coefficient is 100%, so that the two pulses could be brought into exact coincidence on the scope face by adjusting the length of lines to channels A and B.

If the pulse height is increased until the current in the specimen exceeds its critical value, the two pulses (incident and transmitted) will be coincident until a normal bridge has formed over the cross section. As this normal bridge grows, and resistance is restored to the specimen, the transmitted pulse becomes attenuated, and the two pulses are no longer in coincidence on the scope face. In Fig. 2 the current exceeds the critical value by 22%, and the specimen resistance remains zero for about $1.7\times10^{-9}$ sec. The restoration of resistance can be measured by measuring the pulse transmission coefficient as a function of time.

In these measurements the resistance in the super-

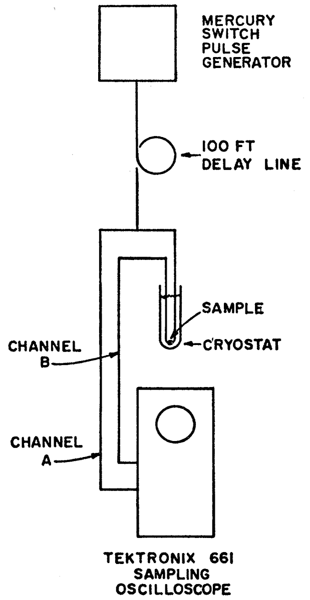

FIG. 1. Schematic of experimental arrangement.

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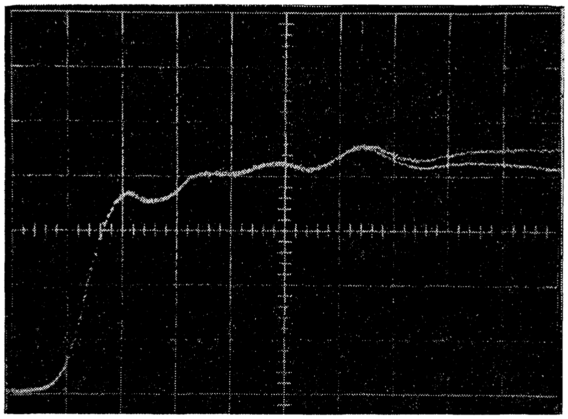

FIG. 2. Superimposed incident and transmitted pulses for indium filament. Time scale: $0.5\times10^{-9}$ sec/cm. Amplitude scale: 100 mV/cm.

conducting state due to the presence of high-frequency components in the pulse ($\omega_{\max}\doteq10^{10}$/sec) is completely negligible. In fact, if the current was assumed to be entirely contained in components near the highest available frequency, the heating would cause a temperature rise of less than 10 $\mu$deg. A more important source of heat might be the presence of a residual resistance due to flaws in a specimen which is slightly less than the minimum detectable resistance (less than about 1% of the normal resistance). In this case, conservatively assuming complete thermal isolation from the substrate and bath, a temperature rise of only 100 mdeg might be expected. Therefore, heating can be completely neglected during the interval $\tau$. Of course, for times greater than $\tau$, while the resistance is increasing to its normal value, the generation of Joulean heat may very well be dominant as has been shown by others.[5–7]

As the pulse height is decreased toward the critical value, $\tau$ changes by large amounts for extremely small changes in current. Thus, a reasonably precise value of the critical current was obtained using very long pulses (durations of $1.3\times10^{-7}$ sec). No measurable differences were observed for $I_c$, provided pulses longer than about $5\times10^{-8}$ sec were used. Measurements at dc were precluded by the risk of specimen burnout. Here the critical current is defined as the current for which $\tau$ becomes infinite.

Since the specimen current at any instant is equal to the instantaneous amplitude of the transmitted voltage pulse divided by the characteristic impedance (50 Ω), $\tau$ is measured from the instant the specimen current reaches the critical value to the instant an increase of specimen resistance can be observed. Until this instant the specimen resistance is zero and the transmitted pulse equals the incident pulse. If $\tau$ is plotted versus $(I/I_c-1)$, where $I_c$ is the critical current and $I$ is the specimen current at the instant the normal bridge is formed, a curve is obtained which, within the scatter of the data, is independent of temperature as is shown in Fig. 3. This figure is a composite of all data obtained from a tin specimen and an indium specimen. For values of $\tau$ less than about $3\times10^{-10}$ sec, which is the rise time of the incident pulse, the pulse is effectively a ramp function. Because of this ramp and the presence of a high-frequency ring, the current is not constant during the interval $\tau$. Since $\tau$ itself is a function of current, it will also depend somewhat on the length of time the current remains at a given value and hence on $dI/dt$. Because of this, the high-frequency ringing may very well be the major cause of the scatter in the data. Because the current does not reach its final value instantaneously, we believe the measured $\tau$ to be a conservative upper limit to the fundamental switching time.

For small values of $I/I_c-1$, $\tau$ is approximately given by $\tau=\tau_0[I/I_c-1]^{-1}$ where $\tau_0$ is about $3\times10^{-10}$ sec and varies only slightly from specimen to specimen. Figure 3 is typical of data obtained from several specimens of tin and indium. Reliable values of $\tau$ can be found in this fashion down to about $1.0\times10^{-10}$ sec. For $[I/I_c-1]$ equal to about one and greater, an estimate of $\tau$ can be obtained by measuring the rise time of the transmitted

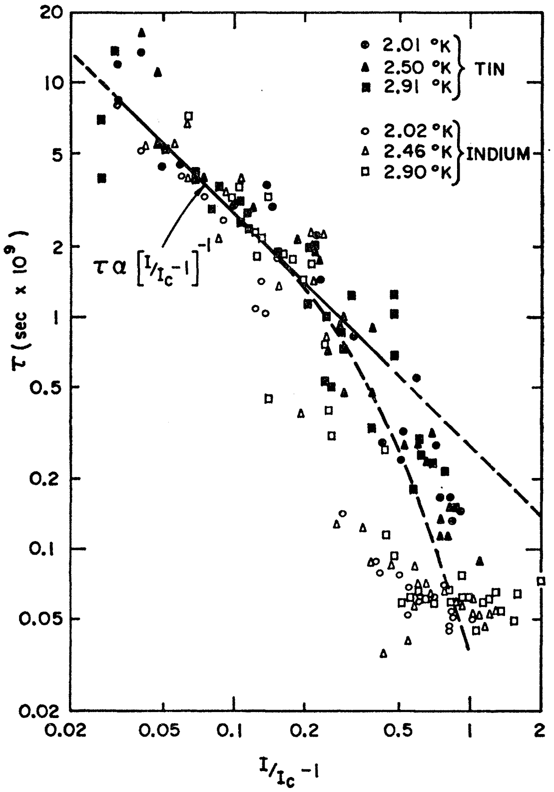

FIG. 3. Time to form a normal bridge $\tau$ versus fractional excess of current $I/I_c-1$.

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pulse. For large values of $[I/I_c-1]$, the growth of the normal phase over the length of the specimen becomes too fast to observe. This is probably the result of the formation of many normal bridges plus a very large velocity of normal phase propagation. Thus, the specimen, which has a pulse-transmission coefficient typically in the range of 30 to 60% when normal, effectively clips the incident pulse "long" before it reaches full amplitude. Although the rise time of the incident pulse is about $3\times10^{-10}$ sec, transmitted-pulse rise times have been measured in the range $1.0-1.1\times10^{-10}$ sec. Since the rise time of this particular oscilloscope has been measured by the manufacturer to be $9.5\times10^{-11}$ sec, values of $\tau$ less than $5\times10^{-11}$ sec are indicated. This follows if one makes the usual assumption that the square of the rise time of the observed pulse is the sum of the squares of the actual-pulse rise time and that of the oscilloscope.

Therefore, we must conclude that, in the limit of large values of $(I/I_c-1)$, the time required to create a primordial normal nucleus is not more than $5\times10^{-11}$ sec and perhaps considerably less.

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The authors would like to note that since this paper was submitted for publication, other pulse measurements have been reported[8] which also indicate switching times of the order of tens of picoseconds or less.

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# Bulk Absorption of Radiation in Superconductors†

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Perturbation theory is applied to calculate the spectral shape of the bulk absorption of radiation in a superconductor. The second-order processes involving one photon and one phonon are considered. The resulting spectrum exhibits a spike near the frequency corresponding to the energy gap. This is attributed to the large values of the BCS density of states at the gap edges.

## I. INTRODUCTION

It has been shown that the bulk absorption due to the second-order processes, each involving one photon and one phonon, contribute significantly to the infrared absorption of normal metals at very low temperatures.[1–3] That the contribution of these processes may be significant in a superconductor which has large electron-phonon interaction has been pointed out by Richards and Tinkham.[4] While calculations on both the bulk radiative[5] and nonradiative[6] recombination rates and of the absorption associated with the anomalous skin effects[7,8] have been offered previously, similar studies on the bulk absorption processes (unpairing) have not been reported.

In the present paper, the bulk absorption rate is calculated as a function of the radiation frequency. As a result, it is shown that the absorption spectrum exhibits a spike (i.e., a maximum) near the gap frequency. The previous calculations of the *skin* absorption by Mattis and Bardeen[7] and Miller[8] do not exhibit such a structure.

The subject matter is of considerable current interest in view of the suggestion, made by Burstein *et al.*[5] on possible use of a superconducting sandwich of metals as a radiation detector, and particularly in view of the recent experimental development in this direction reported by Dayem and Martin.[9] The observations by Dayem and Martin on a superconducting sandwich composed of two superconducting metals and a dielectric layer between them, indicate that, upon absorption of radiation quanta, the paired electrons in one metal are unpaired, being taken, across the barrier, to the unpaired band of the other metal. This, admittedly, is not quite the same as what happens in an absorptive unpairing in a single superconducting metal. The physical explanation for the absorptive tunneling processes, however, is yet unavailable. It is hoped, therefore, that the calculations presented here on a single supercon-

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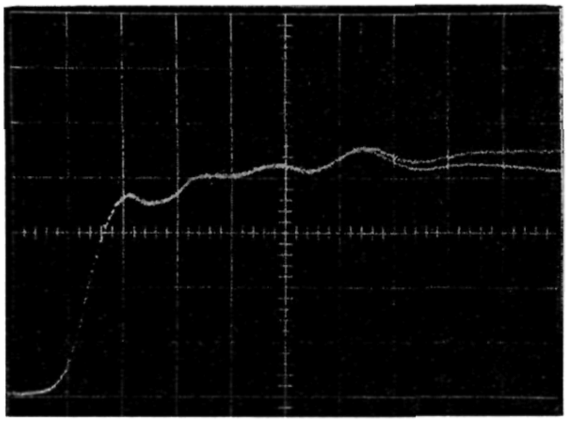

FIG. 2. Superimposed incident and transmitted pulses for indium filament. Time scale: $0.5\times10^{-9}$ sec/cm. Amplitude scale: 100 mV/cm.