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THIN FILM SUPERCONDUCTING SWITCHES

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by

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THIN FILM SUPERCONDUCTING SWITCHES*

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ABSTRACT

Although thin superconducting films have been suggested for use in switching electrical power, virtually no experimental work has been reported. Our present research investigates thin films switched by applying a fast pulse of magnetic field perpendicular to the plane of the film. Short sections of niobium films, carrying approximately half of their critical current, were switched completely into the normal state upon application of pulsed fields as low as 0.02 T (200 gauss). The field pulse has a rise time and length of order 10 μsec, but switching was more rapid. It is shown that the magnitude of the field, and not its rise time, cause the switching. Recovery times, upon removing the current source, were also of order 10 μsec.

The use of superconductors for switches has been a subject of great interest in recent years. Generally, the difference between the zero resistance superconducting state and the resistive normal state provide the principle of operation, and many methods of switching between these states have been tried (heating, magnetic field, current). Bulk superconductors, including tapes are usually considered for high power applications, whereas thin films have been primarily reserved for low power applications (Josephson junctions and cryotrons). However thin film superconducting switches have advantages for certain high power applications,[1] although little experimental work has been published. This paper reports preliminary results in thin niobium films switched by applying a fast pulse of magnetic field perpendicular to the film. The idea is that the pulsed field creates a uniform dissipation along the length of the film which heats it to a temperature above its transition temperature T_c.

The problem with bulk superconductors, stabilized with a normal metal, is that long lengths are required to achieve sufficient resistance for high voltage applications. Additionally, the thermal recovery time is very poor due to the large volume to surface ratio. On the other hand, thin films without metallic stabilizers exhibit very high resistance per unit length as well as excellent thermal contact to the liquid helium coolant, resulting in thermal stabilization and extremely fast recovery time. The thermal relaxation time is $\tau_T = C_v\,RAd$, where C_v is the film's specific heat per unit volume (≈ 0.12 joules/cm^3-K for Nb), RA is the specific Kapitza boundary resistance (≈ 0.2 cm^2-K/watt for Nb), and d is the film thickness (≈ 1 micron in our samples). Hence $\tau_T \approx 2.4$ μsec.

However, because there is no alternative path (through the metallic stabilizer) for the current if a section of the superconductor prematurely becomes normal, hot spots in a thin film switch must be avoided and are the major problem. In many applications, this is avoided if a sufficiently large fraction of the superconductor is switched quickly to reduce the current. In a superconducting fault current limiter,[1] for example, this must occur within several microseconds, so very fast and uniform switching is required. The following reports on preliminary experiments designed to determine the feasibility of such a switch.

The samples of niobium were sputtered or evaporated onto sapphire, quartz or glass substrates to a thickness of about 1 micron. Photoresist was applied and the sample exposed through a pattern consisting of a strip 0.26 mm wide, 1.15 cm long and with various voltage probes (see Fig. 1). After etching, the sample is rinsed and leads are attached. The connections to the constant current source and shunt resistor are strip lines to reduce their inductance while coax cable is used for the voltage probes.

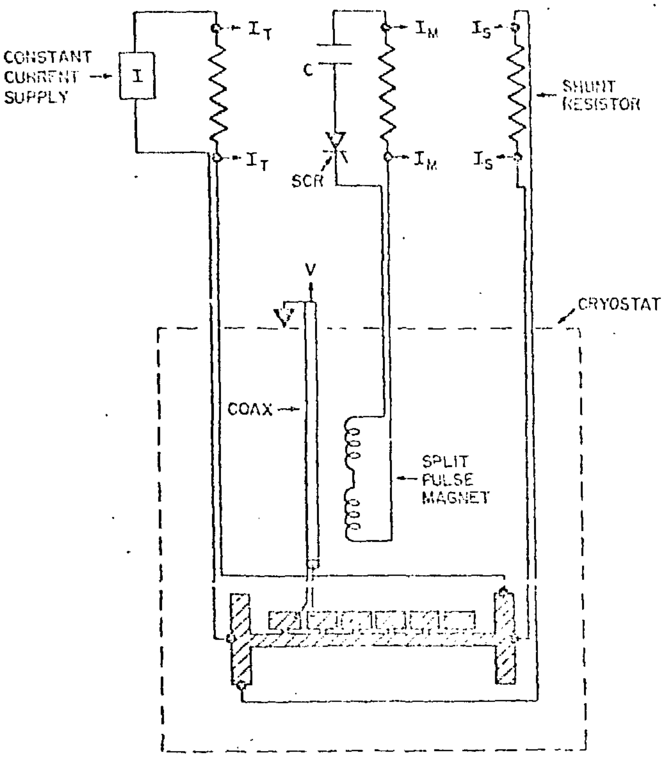

Figure 1. The experimental setup. The constant current source supplies the sample with current I_T, some of which I_S is commutated into the shunt resistor upon switching. The magnet is pulsed by discharging capacitor C with a gated SCR. The sample voltages V are measured on coax lines.

Low inductance coils are placed symmetrically above and below the film to provide a uniform magnetic field perpendicular to the sample. Strip lines are also used to connect the magnet to the pulse supply—a capacitor discharged through a gated SCR. Up to 100 Amps corresponding to 0.2 T are available with a rise time of 7 μsec. Longer rise times, and correspondingly lower fields are obtained by placing room temperature inductors in series with the magnet. The shunt resistors were also low inductance to assist in the rapid commutation of the current. No delays due to the cryostat leads have been observed.

Figure 2 shows the sequence of events (repeated at ~ 30 Hz during an experiment). A short time after a constant current I_T is applied to the superconductor, the magnet current I_M is pulsed, switching the superconductor into the normal state and commutating some of the current into the room temperature shunt resistor. A voltage V is seen across the sample until the current I_T is turned off.

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For currents I_T of about one half the critical current, pulsed fields as small as 0.02 T (200 gauss) are sufficient to cause switching. This is considerably smaller than the critical field for niobium (several kilogauss) and is important because the small field reduces the cost of a practical switch.

In order to establish if eddy current heating was responsible, the minimum magnetic field for switching was measured while varying its rise time. Since the rise times τ are greater than τ_T, it should be the input power which determines the switching point. For eddy current heating, the power is B^2/τ^2 so that B should be proportional to τ. However, the switching field is found to be constant for τ between 7 and 40 μsec, in complete disagreement with eddy current heating. In fact switching occurs in d.c. fields of similar size, confirming that it is the magnitude of the field and not its time dependence which cause switching.

Another conclusion is that the magnetic field penetrates the film on a time scale short compared to 7 μsec. Otherwise there would be a buildup of flux at the film edges due to the large demagnetization factor of thin films in a perpendicular field and switching should occur at lower values of applied field. This field amplification would be similar to a type I superconductor exhibiting the Meissner effect in static fields.

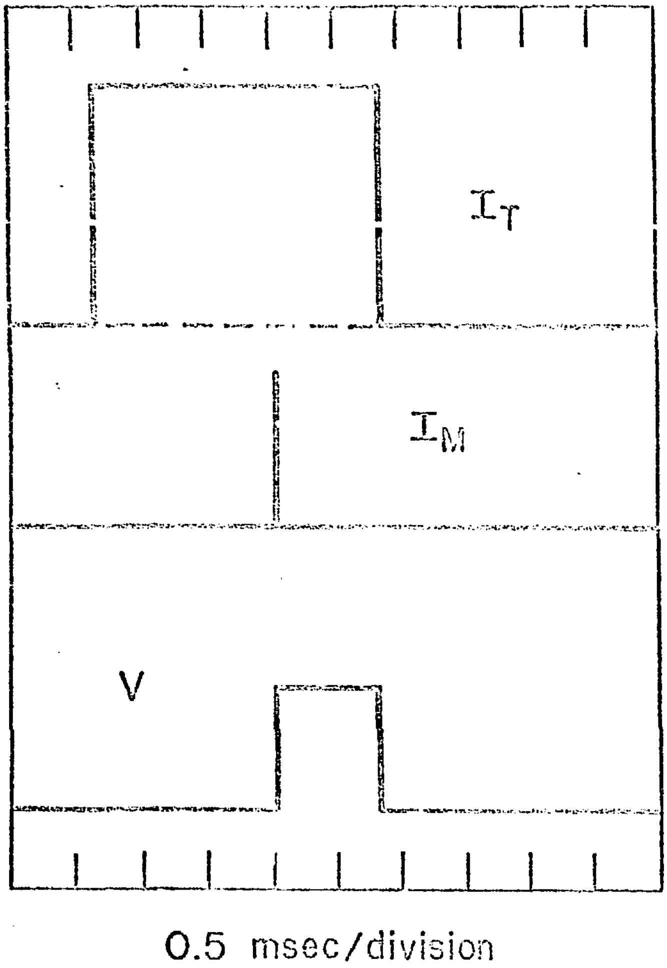

Figure 2. The sequence of events during an experiment; they are repeated at about 30 Hz. Shortly after the sample current I_T if terned on, the magnet is pulsed causing the sample to switch into the normal state and show a voltage V. Thereafter I_T is turned off returning the system to the orignal state.

Previous studies[3] of perpendicular flux penetration rates in thin films are not directly applicable to our samples. They used type 1 superconductors in high static fields so that a flux flow conductivity could be determined; then the flux penetration rates were shown to agree with theory. In the present case the conductivity cannot even be estimated. Nonetheless, the penetration times found in the previous studies (∿ 10 μsec- 100 μsec) are similar to the penetration time required for our explanation. While it would be advantageous on the one hand to have a slower flux penetration time and amplify the applied field, this apparently requires a superconductor with higher normal state conductivity--which is a distinct disadvantage in a switch.

Our earlier discussion of hot spots clearly shows that the field must be switched as fast as possible. Figure 3 shows an oscilloscope trace of the magnet current pulse and sample voltage. The fastest rise time measured is 3 μsec, which is comparable to the 7 μ sec rise time of the magnetic field. It is important to know whether the film is switching uniformly or by thermal propagation from a single weak spot.[4] This is because thermal propagation is not fast enough to switch the much longer lengths of superconducting film necessary for practical applications before a hot spot fuses. One indication of thermal propagation comes from a comparison of sample voltage rise time with the time to thermally propagate a normal boundary between the voltage probes (∿ 0.15 cm). A 3 μsec rise time indicates a propagation velocity of 5×10^4 cm/sec which is the order of the sound speed. Such a velocity is compatible with thermal propagation. In addition, it is sometimes found that only one section switches (see Fig. 1); this could occur because the propagation is halted at the voltage probes where the film is necessarily wider.

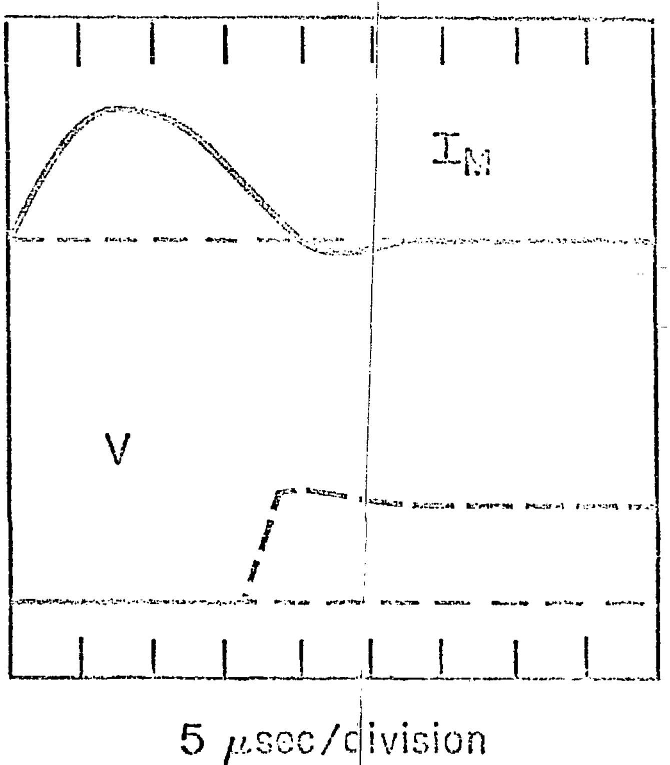

Figure 3. The magnet current and sample voltage on expanded time scale, showing rise times and the switching point.

Further measurements on longer samples without voltage probes are necessary to settle this question. However, even if there is non-uniform switching in these films, the much wider films necessary for a practical device should switch more uniformly. This is because the non-uniformities in the edge will be a considerably smaller fraction of the film width.

Finally, the recovery time has been measured. Figure 4 demonstrates the technique; instead of turning the current I_T off, shortly after switching, a smaller current in the opposite direction is applied. Under these conditions, a negative voltage appears until the superconductivity has recovered, i.e. the film temperature has dropped below T_c. In the example shown a reverse current of about 10% is used and the recovery time is less than 1 msec. For smaller reverse current this time decreases, indicating that one must take the limit of very small reverse currents in order to avoid heating. Recovery times of < 10 μsec have thus been observed, consistent with the calculated τ_T. This is much faster than necessary for envisaged applications.

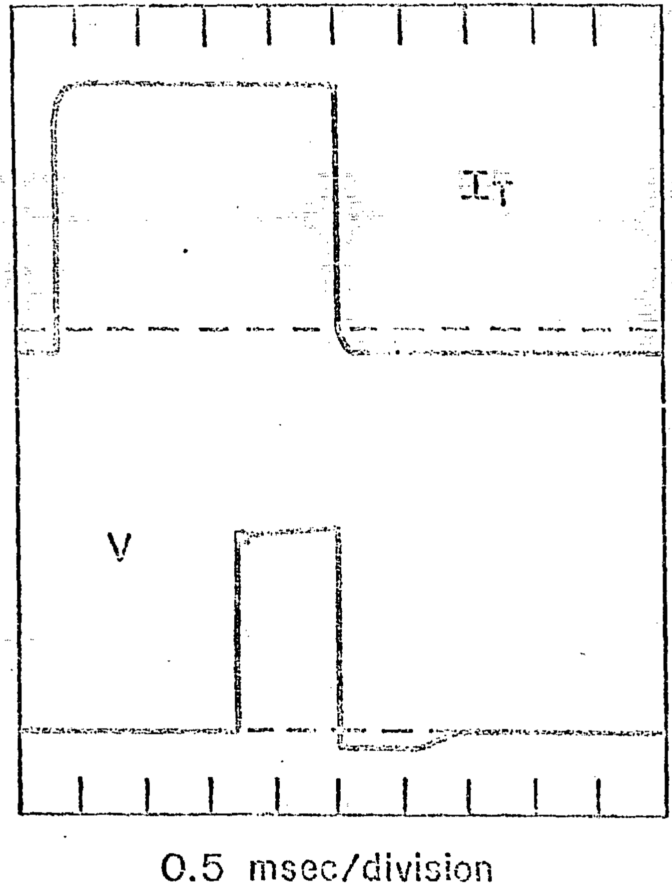

Figure 4. Recovery time studies are accomplished by using a small negative d.c. offset to the sample. After I_T is reduced a negative voltage remains on the sample until it recovers its superconductivity.

We have not made a complete investigation of materials nor preparation conditions. In the one sample of Nb_3Ge measured, switching was observed in pulsed fields of about 2 k gauss; however, it was erratic, and showed the characteristics of thermal propagation[4] with a rise time of 80 μsec. These samples as well as the most successful niobium samples were made in a magnetron sputtering system.[5] Several niobium films evaporated on glass showed no switching up to their critical current, although one evaporated on sapphire produced clean switching.

In one of the better niobium films, the normal state resistivity, ρ_N, was ≈ 12 x 10^{-6} Ωcm and the critical current density J_c was ≈ 2.8 x 10^6 A/cm^2. While J_c is sufficient for switching applications, ρ_N is too small.[1] Sputtering niobium onto a room temperature substrate produced switching in a film with ρ_N ≈ 40 x 10^{-6} Ωcm and approximately the same J_c. In the future we hope to investigate NbN in an attempt to increase ρ_N to ≈ 100 μΩcm.

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REFERENCES

1. K. E. Gray and D. E. Fowler, J. Appl. Phys. 49 2546 (1978).

2. K. Mittag, Cryogenics 13, 94 (1973).

3. R. P. Huebener, L. G. Statford, and F. E. Aspen, Phys. Rev. B5 3581 (1972).

4. V. L. Newhouse, Applied Superconductivity (Wiley, New York, 1964), p. 132.

5. C. T. Wu, R. T. Kampwirth, and J. W. Hafstrom, J. Vac. Sci. Technol. 14 134 (1977).

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