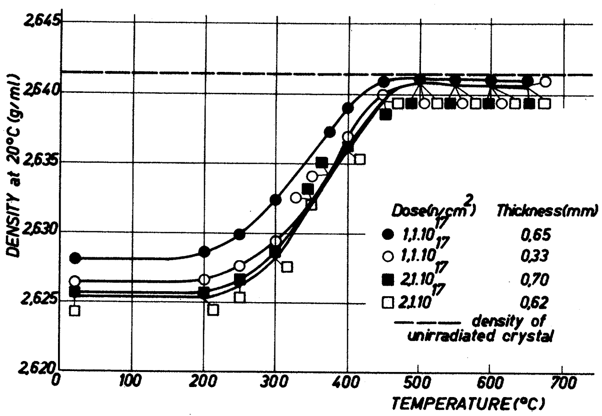

FIG. 2. Annealing behavior of density of neutron-irradiated lithium fluoride crystals: density at 20° C after annealing during 1 hour at the indicated temperatures.

chosen in the region of the maximum in the parameter curve are given in Fig. 2 (density after annealing during one hour at different temperatures).

A small fraction of the radiation-induced density change remains, even after annealing at 650°C. This fraction seems to depend upon the original density change induced by the irradiation. The values illustrate also the influence of thickness on the induced change.

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THERMAL PROPAGATION EFFECT IN THIN SUPERCONDUCTING FILMS

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The calculated magnetic field associated with a current-induced superconducting-to-normal (s-n) transition in thin films is known to be less than that associated with a field-induced transition.[1] This letter suggests one reason for this anomaly. It has been found that under conditions similar to those described in the literature,[1-4] current-induced s-n transitions in films involve thermal propagation, due to Joule heating, of normal regions which appear in parts of the film having a lower critical current than the remainder.

Thermal propagation of this type has been demonstrated in an evaporated tin film (Fig. 1) immersed vertically in liquid helium. It is also possible to demonstrate the propagation of resistive channels introduced by an external magnetic field generated by currents in the superconducting transverse wires.

The experimental results can be explained by the following model.

If a sufficiently large current is passed through a superconducting film crossed by a resistive channel the temperature at the channel edges will reach the critical value associated with the

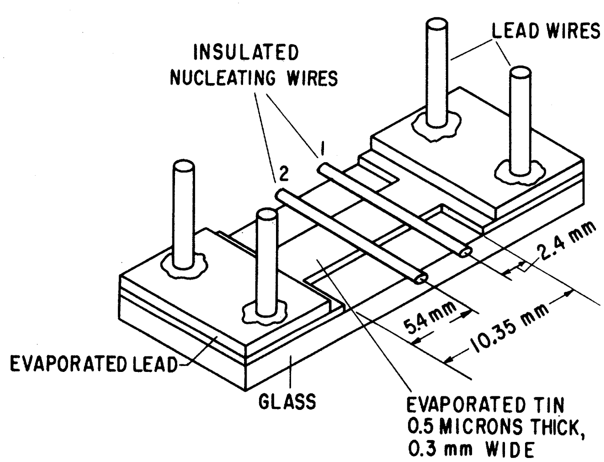

FIG. 1. Specimen structure. Substrate thickness= 0.25 mm; lead electrode thickness= 10 microns; diameter of nucleating wires = 75 microns. Tin film resistivities at 4.2° K= 1.1 ± 0.1 microhm cm; tin film critical temperatures = 3.85 ± 0.5° K. The lead wires and electrodes remain superconducting throughout, thus avoiding contact heating.

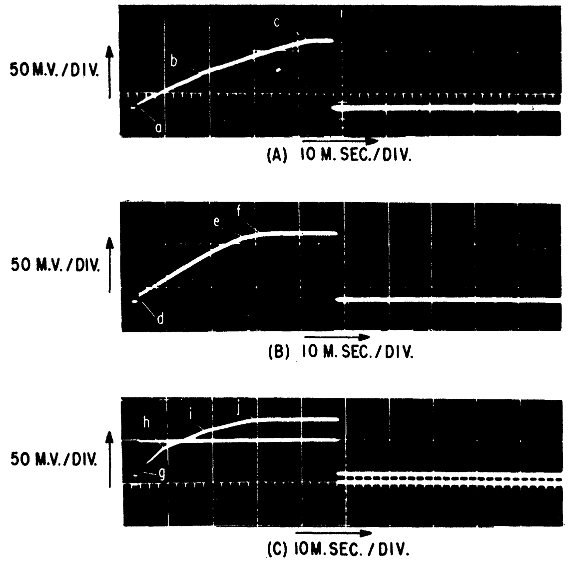

FIG. 2. The voltage across a film as in Fig. 1 associated with the growth of artificially nucleated resistive regions within it. (A) Nucleus initiated under wire 1. (B) Nucleus initiated under wire 2. (C) Nuclei initiated under wires 1 and 2 simultaneously (this is superimposed on the voltage across a $\frac{1}{2}$-ohm resistor carrying the maintaining current). The maintaining current pulse was 100 ma for 45 millisecs. The nucleating current pulse was 775 ma for 0.76 millisecs. The bath temperature was 3.57° K.

local current density. Then the channel will grow, its velocity increasing from zero to an equilibrium value. The velocity increases because as the channel grows the rate of heat production increases faster than the rate of heat loss.

The propagation effect is indicated by Fig. 2. Shown is the rise in voltage across a tin film carrying a maintaining current pulse I_M, simultaneously passing a much shorter nucleating current pulse I_N through either or both nucleating wires. I_M is below the spontaneous s-n transition value.

In Fig. 2 (A), the resistive channel is formed under nucleating wire No. 1. Region $a-b$ corresponds to two boundaries moving outward at constant velocity from the nucleating site. One boundary stops before the other on reaching the nearer end of the tin strip. This corresponds to the break at b. Region b-c corresponds to the movement of the remaining boundary. When this reaches the other end of the strip, the resistance reaches its maximum.

In Fig. 2 (B) wire No. 2 is used to nucleate. The break e corresponds to the transition from double to single boundary propagation.

In Fig. 2 (C) both wires are pulsed simultaneously. In region $g-h$ four boundaries exist. Point h corresponds to the merging of the two between the nucleation sites. In region $h-i$ two boundaries exist. At i one boundary reaches the end of the strip. In $i-j$ only one boundary remains.[5]

The boundary velocity, deduced from the slopes of Fig. 2 and the number of boundaries predicted by the model, is shown in Table I.

Knowing the position of the nucleation sites and the resistance of the strip when completely normal, one can calculate the observed resistance at instants when the number of moving boundaries changes. Calculated and observed resistance values are compared in Table II.

The small scatter of the calculated velocity values and the close agreement between the calculated and experimental values of $R/R_{\max}$ in Table II indicate that the s-n boundaries are roughly normal to the direction of current flow, and move at a constant velocity.

If I_M is increased sufficiently in the absence

Table I. Velocity of the s-n boundaries calculated from dv/dt in Fig. 2 and the estimated number of boundaries.

Nucleation site	Waveform region	Boundaries present	$\frac{dv}{dt}$ volt/sec	Velocity cm/sec
1	*ab*	2	2.55	17.3
1	*bc*	1	1.60	21.6
2	*de*	2	2.83	20.5
2	*ef*	1	1.39	20.2
1 and 2	*gh*	4	4.72	21.1
1 and 2	*hi*	2	1.85	16.6
1 and 2	*ij*	1	1.25	22.3

Mean velocity: 19.5 cm/sec ± 15%

Table II. Comparison of the calculated and observed values of $R/R_{\max}$ at the waveform discontinuities in Fig. 2. $R/R_{\max}$ is (film resistance)/(maximum film resistance).

Nucleation site	Waveform discontinuity	$R/R_{\max}$ experimental	$R/R_{\max}$ calculated
1	*b*	47.3%	46.4%
2	*e*	92.8%	95.6%
1 and 2	*h*	48.2%	49.3%
1 and 2	*i*	75.0%	71.0%

of an external nucleating field, a spontaneous s-n transition will occur. By dynamic observations as above, these spontaneous s-n transitions have been shown to take place by the thermal propagation of two s-n boundaries starting near the midpoint of the strip, as in Fig. 2 (B).

Figure 3 shows the variation of R/R_{max} as I_M is varied cyclically with various nucleating currents through transverse wire No. 2. The value of I_M for which s-n transition occurs is seen to depend on I_N; but R/R_{max} after this transition is a function of I_M only. The irreversible s-n transition for $I_N=0$ is preceded by a "tail", i.e., a reversible rise of R/R_{max} to 1.3×10^{-4} ohm. This is not shown on the curve. As I_M is decreased below 2.6 amp/cm with the strip normal, R/R_{max} decreases reversibly to approximately 0.1; only the final transition to superconductivity takes place by an irreversible jump.

The curve for $I_N=0$, typical of many published curves,[2,3] can be qualitatively accounted for by the model. For instance, the reversible rise in R/R_{max} preceding the s-n transition for $I_N=0$ (not shown in the curve), is believed to be due to resistive channels across thin portions of the film. When one of these heats up sufficiently, spontaneous propagation starts. Propagation starts in the middle of the strip because the temperature is highest there. Finally, the decrease of R/R_{max} below unity as I_M is decreased is thought to correspond to the retreat of the normal region to the hotter midpoint of the strip.

The above indicates that the current-induced s-n transition in films occurs by thermal propagation of a normal region starting from a high current density-high temperature location. The transition is therefore dependent, among other things, on the thermal properties of the substrate and the micro-structure of the film.

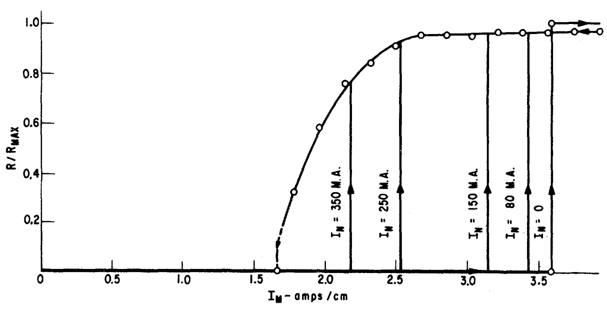

FIG. 3. Resistance variation in a film as in Fig. 1 as I_M is cycled slowly with various fixed values of I_N carried by wire No. 2. I_M is the maintaining current and is given in amp per cm of film width normal to the direction of current flow. I_N is the nucleating current. The bath temperature was 3.57° K. R/R_{max} is (film resistance)/(maximum film resistance).

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[5] Superimposed on Fig. 2 (C) is the waveform of the maintaining current pulse.

INTERPRETATION OF ELECTRON PARAMAGNETIC RESONANCE IN $BaTiO_3$

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There has recently appeared in this Journal a letter discussing the origin and interpretation of electron paramagnetic resonance (EPR) in single crystals of $BaTiO_3$.[1] Our work over the past few years has given us data which differ considerably from those presented in reference 1. Although a detailed account of this research has been submitted for publication elsewhere,[2] it seemed worth while to present here those of our results which differ from reference 1.

These results are:

(a) Five strong allowed transitions are observed, corresponding to a spin of 5/2. This is illustrated in Fig. 1, taken at 9.5 kMc/sec in the tetragonal ferroelectric phase, with the magnetic field parallel to the electric polarization. The spin Hamiltonian describing a spin of 5/2 in a tetragonal crystalline field is

$$\mathcal{H}=\beta\,\vec{H}\cdot g\cdot\vec{S}+DS_z^{\,2}+aS_z^{\,4}+b(S_x^{\,4}+S_y^{\,4}).$$

The strong lines of Fig. 1 labelled 1 through 5 have approximately the intensity ratios 5:8:9:8:5 of $S=5/2$. Weaker transitions due to slight

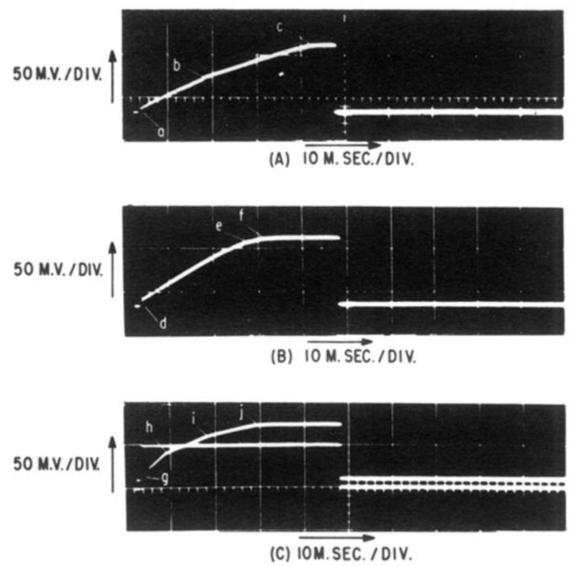

FIG. 2. The voltage across a film as in Fig. 1 associated with the growth of artificially nucleated resistive regions within it. (A) Nucleus initiated under wire 1. (B) Nucleus initiated under wire 2. (C) Nuclei initiated under wires 1 and 2 simultaneously (this is superimposed on the voltage across a $\frac{1}{2}$-ohm resistor carrying the maintaining current). The maintaining current pulse was 100 ma for 45 millisecs. The nucleating current pulse was 775 ma for 0.76 millisecs. The bath temperature was 3.57° K.