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Current Transitions in Superconductive Tin Films*

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Except at temperatures just below the critical temperature the change of resistance of a superconducting film if the current through it is increased slowly takes place by a discontinuous transition, exhibits hysteresis, and is dominated by Joule heating effects. By applying current in short pulses, it has been possible to obtain isothermal transitions in films deposited on a flat surface. These transitions are smooth, do not exhibit hysteresis, and have a shape independent of film resistance. The critical current I in films of thickness about twice the penetration depth is proportional to film width and can be related to the critical field of the film H_C, and the bulk critical field H_{CB}, by the relation $IH_C=\text{const}H_{CB}^2$. It is also shown that by calculating the conditions of thermal equilibrium the dc transition curves with Joule heating can be derived from the isothermal transition results.

I. INTRODUCTION AND SUMMARY

THE study of current-induced transitions in thin films provides a test for theories of superconductivity. Attempts to account theoretically for the critical currents in thin films have been hindered by difficulties in observing current transitions which were not dominated by Joule heating effects. It has recently been shown that unless special precautions are taken any resistive region which appears in a current-carrying film will propagate spontaneously through the remainder due to Joule heating.[1] It has been possible to obtain current transition data without heating up the films appreciably either by using low currents very close to the critical temperature or by applying the currents in pulses which were short compared to the time required to heat up the film and substrate.

The transitions measured in this way will be called isothermal. They exhibit no discontinuities in contrast to the dc transitions with Joule heating which exhibit discontinuities and hysteresis. The current (measured isothermally) for which the resistance reaches half its maximum value can be expressed in terms of the critical field using an expression derived by Ginzburg.[2] It is also established that the form of the dc transition curve with Joule heating can be accounted for quantitatively in terms of the isothermal transition.

II. SAMPLE PREPARATION

The samples were prepared by vacuum deposition, and had the geometry shown in Fig. 1(a). Two types of substrate were used. The single crystal sapphire substrates were optically polished disks 2 cm in diameter and 1 mm thick. The glass substrates were 2.5 cm×1.25 cm×0.25 mm flame polished cover glass. The tin films were evaporated at pressures of 10^{-5} mm or less from a tantalum dimple boat mounted 15 cm away from the substrate, which was clamped to the back of a nickel or brass mask. The tin was 99.895% pure and was evaporated at approximately 50 A/sec. To obtain lower resistivity films, rolled tin was evaporated at approximately 1000 A/sec from a tungsten strip through a lavite mask.[3] Film thickness was controlled by evaporating a weighed charge to completion. The mean film thicknesses ranged from 3000 A to 5000 A and were determined by weighing a known area of film. The bulk density value for tin was used in the film thickness calculation.

Following the tin deposition, the masks were changed and between 1 and 10 microns of lead were evaporated over the ends of the tin strips, as shown in Fig. 1(a), to serve as superconducting contacts. Lead wires were soldered to the cheeks for connections.

The critical temperatures T_c of the films on both glass and sapphire substrates were approximately 3.85°K. The difference from T_c for bulk tin is similar to that obtained by Lock[4] and has been shown by him to be due to differential expansion between film and substrate.

The maximum substrate temperature during sample preparation did not exceed 45°C, which is known to be a safe annealing temperature for tin films of this thickness.[5]

III. EXPERIMENTAL PROCEDURE

The superconducting transitions were measured with the backs of the samples pressed against a plastic board immersed vertically in liquid helium. For dc

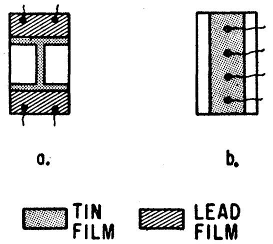

FIG. 1. Sample geometry. (a) Sample shape for current transition measurements. (b) Sample shape for magnetic field transition measurements.

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

[2] V. L. Ginzburg, Doklady Akad. Nauk S.S.S.R. **118**, 464 (1958) [translation; Soviet Phys. Doklady **3**, 102 (1958)].

[3] F. W. Reynolds and G. R. Stillwell, Phys. Rev. **88**, 418 (1952).

[4] J. M. Lock, Proc. Roy. Soc. (London) **A208**, 391 (1951).

[5] J. Niebuhr, Z. Physik **132**, 468 (1952).

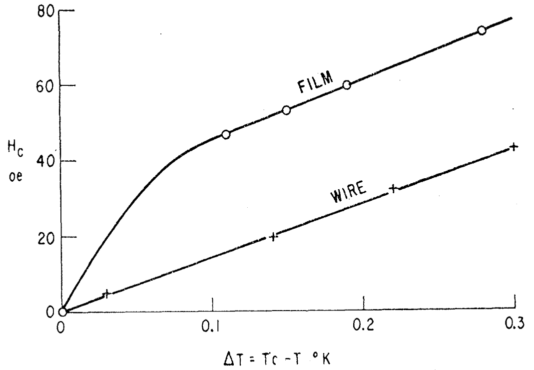

FIG. 2. Comparison of H_c *vs* T curve for typical film with that for bulk tin. ○, 0.3-micron annealed tin film on glass, $T_c=3.85°K$. +, 0.14 mm annealed tin wire, $T_c=3.75°K$.

measurements a known current from batteries and rheostats in series was passed through an opposite pair of leads [see Fig. 1(a)]. The film potential was measured across the other pair of leads with a Liston-Becker Model 14 breaker amplifier.

For film potentials above 100 μv a Kin-Tel Model 202B microvoltmeter was used. For the pulse measurements, Burroughs Model 3003 current drivers were used to supply pulses through coaxial lines. The potential generated across the film was observed with a Tektronix Model 541 oscilloscope, using a 53/54*L* plug-in unit, also connected through a coaxial line.

The critical field of a typical film was determined by measuring the resistive transition due to a field parallel to the plane of a film evaporated onto a glass substrate. The field was applied by means of a solenoid. The sample geometry used was that of Fig. 1(b). The current and potential probes were arranged as shown so as to avoid anomalous results due to measuring the current flowing through the film edge.[6]

IV. RESULTS AND DISCUSSION

A. Critical Field

The variation of the critical field H_C with temperature is shown for a typical film in Fig. 2. The critical curve for bulk tin is shown for comparison. The change in temperature necessary to alter the resistance of the tin film from 10% to 90% of its normal value was 0.04°K at values of $\Delta T=T_c-T$ between 0.1°K and 0.2°K, with constant field.

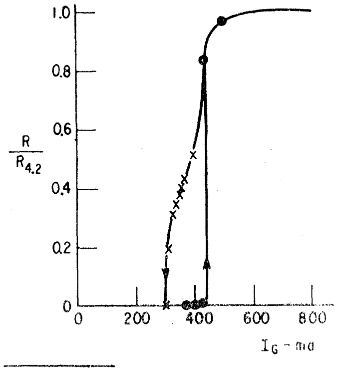

FIG. 3. Current induced transition for tin film on glass substrate. (Sample *A*, $\rho=1.28$ μohm cm, $T_c=3.74°K$. ●, increasing current; ×, decreasing current.

B. Dependence of dc Transitions on Substrate and on Film Resistivity

Figures 3 and 4 show the resistance changes which accompany a gradually increasing and then decreasing current for high-resistivity films on glass and sapphire, respectively. Figure 5 is for a lower resistivity film on sapphire. The resistance is plotted in terms of its ratio to the value at 4.2°K. Further sample details are shown in Table I.

Consider the transition for film *A* deposited on glass (Fig. 3). As the current is increased from zero, a measurable resistance (about 10^{-3} times the resistance at 4.2°K) appears at 370 ma. This will be called the critical current, I_c.[7] At 440 ma a discontinuous and irreversible jump to a high resistance occurs (I_{JU}). As the current is decreased, a gradual falloff in resistance occurs until, at 300 ma (I_{JD}), the resistance jumps back to zero. These jumps correspond to the spontaneous growth and collapse, respectively, of a resistive nucleus by thermal propagation.[1]

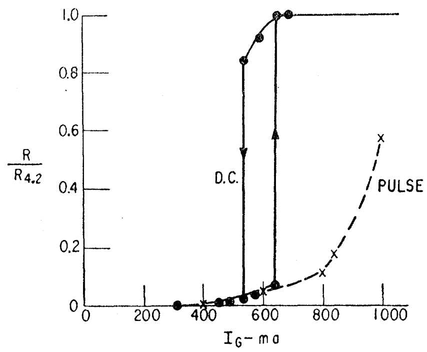

FIG. 4. Dc and pulse current-induced transitions for tin film on sapphire substrate. (Sample *B*, $\rho=1.1$ μohm cm, $T=3.77°K$.) ●, dc; ×, 4-μsec pulses.

Sapphire has a 10^3 times higher thermal conductivity than glass at 4°K. Therefore the heat produced by a small resistive region in a tin film will result in a much lower temperature rise near the resistive region, relative to the ends of the film, for a film on a sapphire substrate than for one on glass. This means that the spontaneous growth of the nucleus occurs at lower currents for films on glass substrates. On the other hand, a larger current is required to keep a film normal due to Joule heating in the case of a sapphire substrate. Consequently a film on sapphire should have a higher jump-up current and less hysteresis than a similar film on glass. This is confirmed by Fig. 4, which shows that the hysteresis loop for a film deposited on sapphire is

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[6] E.T.S. Appleyard *et al.*, Proc. Roy. Soc. (London) A172, 540 (1939).

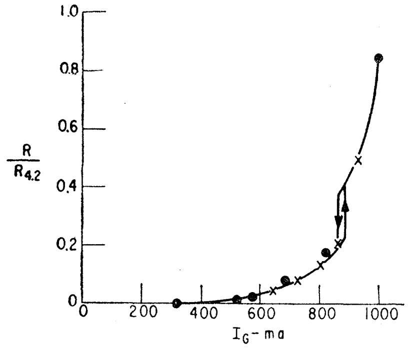

FIG. 5. Current-induced transition for low-resistivity film on sapphire substrate. (Sample *C*, $\rho = 0.30$ μohm cm; $T = 3.77$°K.) ●, increasing current; ×, decreasing current.

narrower relative to I_c than that for the similar resistance film *A* of Fig. 3 which is deposited on glass.

In vacuum deposition, the evaporated atoms tend to agglomerate on hitting the substrate because of surface tension forces. Agglomeration can be reduced by either cooling the substrate and thus restricting the mobility, or by increasing the rate of deposition[3] and hence reducing the time allowed for motion. The latter approach, which also has the additional advantage of reducing the amount of entrapped gas, was used for film *C* whose transition is shown in Fig. 5. Although the film has the same dimensions as *A* and *B*, its resistivity at 4.2°K is three times less, showing a much finer structure under the microscope. Compared with Fig. 4, the curve of Fig. 5 shows strongly reduced hysteresis and thermal propagation. This is clearly because of lower Joule heating due to the decreased resistivity.

C. The Use of Pulse Techniques for Obtaining an Isothermal Transition

When a current pulse is passed through a typical high-resistivity film on sapphire such as specimen *B*, the resistance rise occurs in two phases. One part of the resistance appears within the rise time of the pulse (approximately 0.5 μsec). The remainder of the resistance rises linearly with time. For specimens *B* and *D* this latter resistance increase occupied between 1 msec and 100 μsec, depending on the amplitude of the current pulse. These periods are of the order of magnitude of the calculated time required to heat up the sapphire from the bath temperature to T_c.

A typical isothermal curve of resistance *versus* current at constant temperature is the dashed curve of Fig. 4, which represents the resistance increase occurring during 4-μsec current pulses applied to *B* at 140-μsec intervals. The peak current amplitude for which a pulse measurement is shown in Fig. 4 corresponds to the point where the thermal contribution at 4 μsec is comparable to the experimental uncertainty of 10%. Hence the resistance increase shown is mainly electromagnetic in origin and represents the isothermal transition.[7]

TABLE I. Specimen description.

Sample	Substrate	Film width mm	Mean film thickness (microns)	Resistivity at 4.2°K (μohm cm)	Crit temp °K	Deposition rate A/sec
A (No. 33)	glass	3.75	0.3 ±0.03	1.28	3.859	50
B (No. 45)	sapphire	4.05	0.3 ±0.03	1.05	3.85	50
C (No. 57)	sapphire	3.90	0.5 ±0.05	0.30	3.827	1000
D (No. 50)	sapphire	3.75	0.3 ±0.03	0.83	3.860	50

The isothermal transition curve of Fig. 4 coincides, to within the experimental uncertainty, with the region between I_c and I_{JU} (the "toe") of the dc transition curve. This is to be expected, because the heat generated in this region of the dc curve is low (<1.5 mw). The toe of the dc transition for the low resistance film *C* shown in Fig. 5 can also be shown by calculation to be a good approximation to an isothermal. A criterion which establishes the condition under which a dc transition curve is a good approximation to an isothermal is developed below [Eq. (6)].

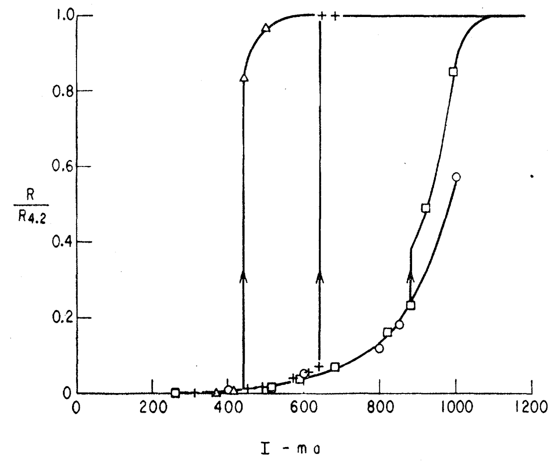

FIG. 6. Normalized current transition of specimens *A*, *B*, and *C* superimposed. △, Sample *A*, dc; +, Sample *B*, dc; ○, Sample *B*, pulse; □, Sample *C*, dc.

The regions of the dc transition curves of Figs. 3, 4, and 5 corresponding to increasing current, and the isothermal curve measured with pulse currents of Fig. 4, are plotted to the same scale in Fig. 6. It can be seen that the isothermal transition measured with pulsed current of specimen *B* superimposes excellently with the toe of the dc curve of the lower resistivity specimen *C* of Fig. 5, which is known itself to be a good approximation to an isothermal. This indicates that the details of the isothermal current-induced resistance transition are independent of the film resistivity over the 3:1 range measured.

The variation of the current I_c (corresponding to the onset of resistance) with the film width has been found

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[7] The specimen inductance does not contribute to the pulse voltage since this is measured after the pulse current has reached a steady value.

TABLE II. Critical current for 0.30-micron tin films. I_c is extrapolated current value at which resistance reaches zero.

Substrate	Sapphire	Glass
$I_c/w\Delta T$ $A/\mathrm{cm}-{}^\circ\mathrm{K}$	11.4	9.0

to be linear to within the experimental scatter of $\pm 30\%$ over the range of widths 0.01 to 0.4 cm. I_c was also found to be roughly proportional to $T_c - T = \Delta T$ for $\Delta T < 0.5^\circ\mathrm{K}$. $I_c/w\Delta T$ is shown in Table II. This gives the average for 15 sapphire samples and 12 glass samples made in different evaporators over a period of one year. The difference between the values of $I_c/w\Delta T$ for glass and sapphire may be due to a difference in the coefficients of expansion of these two substrates.

Pulsed current transition data for sample *D*, a high-resistivity film on sapphire, is plotted in Fig. 7 as the resistance variation with temperature for constant-height pulse current. Also shown is a transition measured with a steady current of 1 ma. This type of plot brings out the fact that the shape of the resistance variation with temperature at constant current is approximately independent of the current amplitude provided that the development of Joule heat is avoided.

D. Analysis of the Isothermal Transition

Most of the measurements reported here are for $\Delta T \leqslant 0.3^\circ\mathrm{K}$. In this range the calculated penetration depth for bulk tin is $\lambda \geqslant 0.1$ micron, which is comparable to the film thickness of 0.30 micron. Under these conditions the current should be nearly uniformly distributed throughout the film even when the film is completely superconducting.[8] It is not surprising therefore that I_c is found to vary linearly with width.

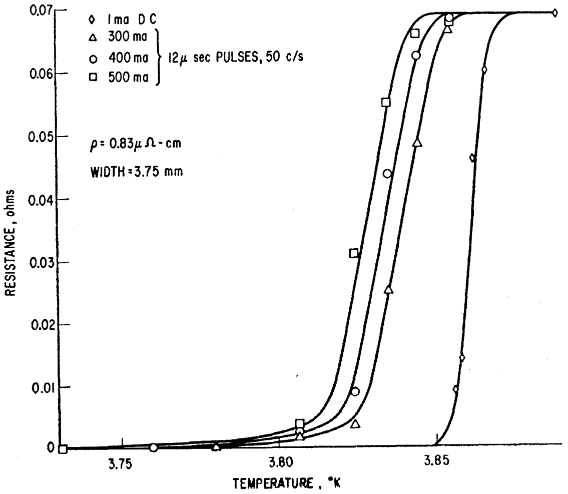

FIG. 7. Film resistance as a function of current and temperature in the absence of Joule heating (sample *D*).

The resistance transition with temperature has approximately the same width (0.02°K) as the resistance transition with temperature at constant field. This encourages us to attempt to relate the current required to restore half the resistance, with the *field* required to restore half the resistance at the same temperature.

Assuming uniform current distribution, the field associated with a current I passing through a film of width w is, in emu,

$$H = 2\pi I/w. \tag{1}$$

Ginzburg[2] has derived a relation which connects the field H_{IC} corresponding to the critical current of a film with the critical field H_C measured directly. This relation is

$$H_{IC}H_C = \tfrac{4}{3}H_{CB}^2, \tag{2}$$

where H_{CB} is the bulk critical field. This equation was derived for the limiting case of films much thinner than the penetration depth and should, therefore, only be true close to the critical temperature in the present experiments.

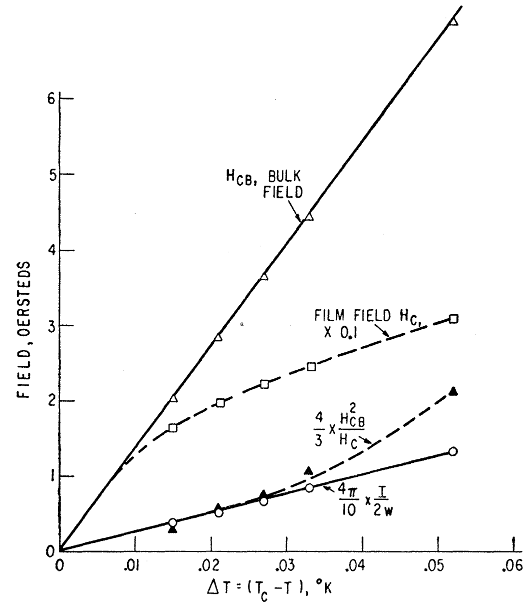

FIG. 8. Test of Ginzburg's relation for H_{IC}, the field associated with the critical current (sample *D*). □, H_C, Film critical field ×0.1; △, H_{CB}, Bulk critical field; ▲, $H_{IC} = \frac{4}{3}(H_{CB}^2/H_C)$; ○, Experimental values of $H_{IC} = (4\pi/10)(I/2w)$.

Experimental values of H_{IC} for specimen *D* are compared with those calculated from expression (2) in Fig. 8. Here H_{IC} is the field calculated from the (pulsed) current required to restore half the full resistance, using Eq. (1). Also shown are experimental values of H_C, the film critical field, and H_{CB}, the critical field for bulk material. It can be seen that the agreement between the theoretical and experimental curves of H_{IC} is good for $\Delta T < 0.03^\circ\mathrm{K}$.

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[8] D. Shoenberg, *Superconductivity* (Cambridge University Press, Cambridge, 1952).

E. Analysis of the dc Transition

An analytical technique will now be described with which it is possible to construct dc transition curves from experimental isothermal transition curves by establishing the condition of thermal equilibrium with the helium bath.

Consider a steady current I flowing through a film of resistance $R(I,T)$ at temperature T, immersed in a bath of temperature T_0. For thermal equilibrium

$$I^2R(I,T)=FA(T-T_0), \tag{3}$$

where F is the heat loss to the helium in watts/cm^2 °K and A is the area over which heat transfer to the helium occurs. This equilibrium can be represented graphically as in Fig. 9, which represents curves of $I^2R(I,T)$ *vs* T for a hypothetical film. The right-hand side of Eq. (3) is represented by the straight line passing through T_0. Current magnitudes increase from i_0 to i_4.

When a specimen is subjected to currents increasing from zero, the thermal equilibrium positions are given by the lowest intersections of the corresponding current curve with the straight line. For a current just above i_3 an unstable equilibrium is reached and the equilibrium changes in a discontinuous fashion to the upper intersection B.

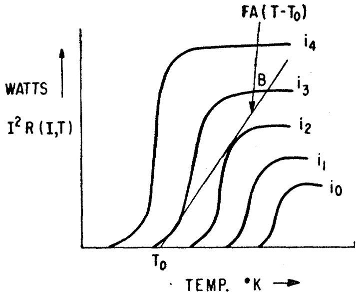

Fig. 9. Joule heat generated in film as a function of film temperature and current I. Straight line represents $FA(T-T_0)$, the heat loss to bath.

If the current is now decreased below i_2 the equilibrium again becomes unstable and the temperature returns discontinuously to a point close to T_0.

In general, discontinuous temperature transitions occur when

$$I^2(\partial R/\partial T)_I=FA. \tag{4}$$

On the other hand, for I increasing from zero, the resistance change due to Joule heating will remain negligible as long as

$$I^2(\partial R/\partial T)_I\ll FA. \tag{5}$$

The above analysis assumes that the temperature difference between the middle and ends of the film is at all times much smaller than the width of the temperature transition for constant current in the absence of Joule heating.[9] A straightforward calculation shows that this condition is fulfilled in the case of the tin films described here when deposited on sapphire.

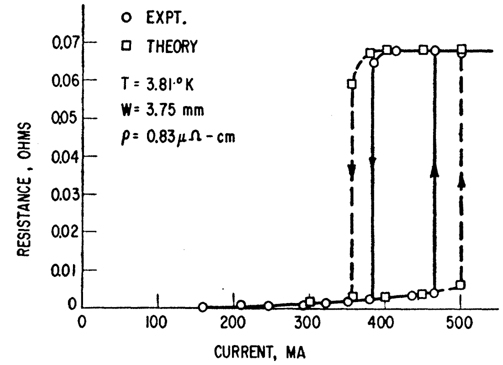

Fig. 10. Comparison of dc transition curve, constructed from isothermal data of Fig. 7, with experiment (sample D). $\Delta T=0.054$°K.

To compare (3) and (4) with experiment, a dc transition curve for $T=3.81$°K was constructed from experimental isothermal current transition curves for sample D some of which are shown in Fig. 7. The constructed dc transition curve and the curve obtained by direct measurement at the same temperature are compared in Fig. 10. The value of F used for the calculated curve was 0.2 w/cm^2.[10] The value of A, the effective area of heat loss to the helium, was chosen at 1.0 cm^2, intermediate between the area of the tin film (0.4 cm^2) and the total exposed area of the sapphire (3.0 cm^2). The width of the calculated hysteresis loop and the resistance before jump-up and after jump-down are quite insensitive to the choice of A. Using a value for A of 0.7 cm^2 gives coincidence of the calculated and experimental loops for I_{JU}; using a value for A of 1.25 cm gives coincidence at I_{JD}.

CONCLUSIONS

It has been established that close to the critical temperature the current transition for thin tin films in the absence of heating effects is smooth, shows no hysteresis, is independent of film resistivity and that the critical current is proportional to film width. The fact that the dc transition curve with its discontinuities and hysteresis can be constructed from the isothermal curves gives additional support to the conclusion that all of the hysteresis in these curves is due to thermal effects.

The linear variation of the critical current with film width suggests that in films whose thickness is comparable to the penetration depth the current is uniformly distributed over the film width as is to be expected on the basis of energy considerations. This interpretation is supported by the fact that the critical current (measured isothermally) sufficient to restore half the normal resistance is in good agreement with the value predicted by Ginzburg's phenomenological theory.[2] The factors which govern the width of the field and current transition curves remain to be investigated.

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[9] This does not imply that the whole film changes state simultaneously.

[10] A. Karagounis, Suppl. bull. inst. intern. froid Annexe 1956—2, Louvain Conference, 195 (1956).