SOVIET PHYSICS JETP VOLUME 13, NUMBER 6 DECEMBER, 1961

DESTRUCTION OF SUPERCONDUCTIVITY IN THIN TIN FILMS

A. M. KOLCHIN, Yu. G. MIKHAĬLOV, N. M. REĬNOV, A. V. RUMYANTSEVA, A. P. SMIRNOV, and V. N. TOTUBALIN

Leningrad Physico-Technical Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor December 3, 1960; resubmitted December 27, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) **40**, 1543-1550 (June, 1961)

It is shown that the destruction of superconductivity in thin tin films [of order $(1-8)\times 10^{-5}$ cm] by current pulses of different shape and duration is not isothermal because of heating of the sample by the measuring current and eddy currents. The destruction time of the superconducting state depends on the current pulse amplitude and at sufficiently large currents it is of the order of 5×10^{-9} sec. The first traces of resistance appear for currents which are much smaller than the values at which the resistance increases rapidly. Hysteresis, both of a thermal and nonthermal nature, has been detected in the transition from the normal to the superconducting state.

1. INTRODUCTION

IN line with the possibility of the use of superconducting phenomena for practical purposes,[1,2] the study of the destruction of superconductivity of thin films of superconducting metals by a current is of interest. In references 3 and 4, the values of the critical field and the currents were determined for films of tin in the form of discs and cylinders in measurements with direct current or with pulses of comparatively long duration. The effect of heat on the values of the critical currents was noted by the authors. This effect can be decreased considerably if the measurements are carried out with pulses of very short duration. Only recently have the first reports appeared in the literature[1,2,5,6] on a detailed study of the transition from the superconducting to the normal state with the use of short pulses.

The present research was undertaken with the purpose of making clear the laws of destruction of superconductivity by a magnetic field and by a current passing through a film, and also the study of the laws of return of the film to the superconducting state on removal of the field (current) over a wide range of temperatures for films of different thicknesses. The paper is limited to a statement of the results of investigation of the character of the destruction of superconductivity of tin films in the form of strips of thickness $(1-8)\times 10^{-5}$ cm under the action of current pulses of various shapes and duration, at temperatures close to the critical.*

2. SPECIMENS, APPARATUS, AND METHODS OF INVESTIGATION

Films for the investigation were prepared by the method of vacuum evaporation, for which a special apparatus was constructed. Eighteen films of different thickness and width could be obtained simultaneously in a vacuum chamber at a pressure of 10^{-6} mm Hg by use of nitrogen traps for the oil vapor.[7] The tin was evaporated from a long tantalum vessel, which guaranteed identical film thickness over the whole sample. The specimens were sputtered on the substrate through masks and had the shape shown in Fig. 1. Silver contacts were first imbedded in the substrate; lead conductors were later soldered to these. To make a satisfactory superconducting contact between the film and the leads at the silver contacts, a lead film was evaporated in a vacuum after application of the tin specimen. Glass or mica, was used as the substrate. It was first chemically cleaned, and was heated for a long time in the vacuum before evaporation.

The thickness of the film was estimated by weighing control glasses, evaporation on which was carried out simultaneously with obtaining of

*The results of the research were reported at the Seventh All-Union Conference on Low Temperature Physics at Kharkov in June, 1960.

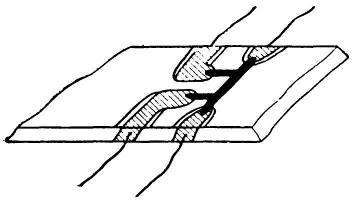


FIG. 1. Specimen with current and voltage contacts.

the specimens. The results given below were obtained on films of thickness $(1-8) \times 10^{-5}$ cm and width 0.10 — 0.25 mm. During the time of evaporation, which lasted from several tens of seconds to several minutes, the temperature of the base layers did not exceed 45° C. The films obtained under such conditions had a resistance of 30 — 130 ohm at room temperature.

The study at direct current at comparatively low currents through the specimen was carried out by means of a potentiometric system with a galvanometer or with a slide-wire resistor, which gradually changed the current in the circuit of the specimen. The values of the current through the specimen and the voltage on it were recorded by automatic potentiometer recorders of the type ÉPP-09M or ÉPP-11M.

The transition of the specimens from the superconducting state to the normal one and back was also studied with the aid of an oscillographic apparatus which made it possible to observe visually and photograph the volt-ampere characteristics of the specimen. Two ÉNO-1 oscillographs were used, so connected that the vertical-deflection amplifier of one played the role of the horizontal-deflection amplifier of the other. Both sinusoidal current and triangular pulses with different rise times and repetition frequencies from several to hundreds of cycles per second, could be applied to the specimen. The minimum length of the rise time of the pulse in these experiments was 0.1 millisecond. The block diagram of this apparatus is shown in Fig. 2.

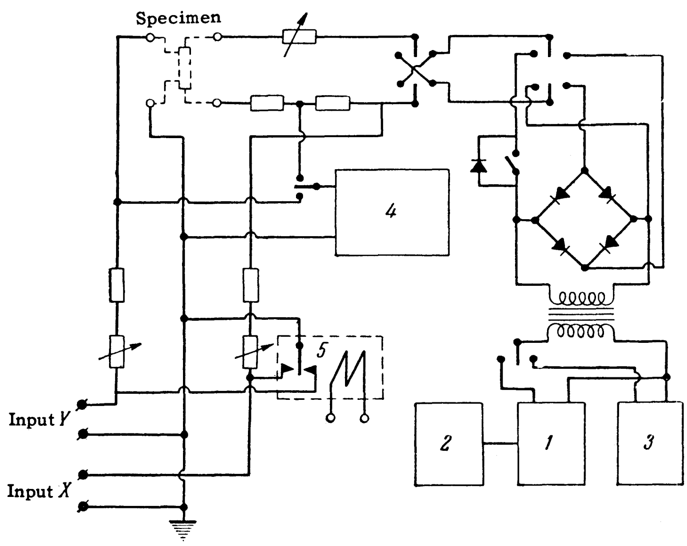


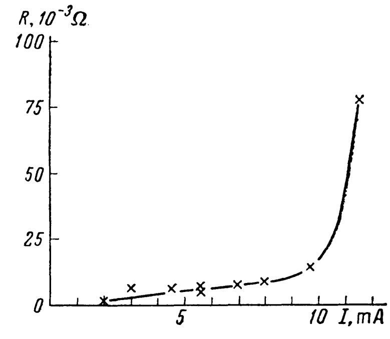
FIG. 2. Circuit for observation of volt-ampere characteristics: 1 – generator of triangular pulses, 2 – triggering generator, 3 – audio oscillator, 4 – millivoltmeter or oscilloscope for control of pulse amplitudes, 5 – polarized relay which serves to produce the coordinate axes on the screen of the oscilloscope.

For a study of destruction of superconductivity with much shorter pulses, generators of the type GIS-2 and GI-3M were used with a rise time of 0.15 and 0.05 microsecond, respectively. The lengths of the pulses were varied from 0.1 to 10 microseconds. The current through the specimen and the voltage across it could be recorded simultaneously by means of a two-beam oscillograph of the type DÉSO-1. To observe small signals, amplifiers of the type UR-1 were used. Studies on short pulses were carried out in a special cryostat with coaxial leads. The specimen on the substrate was mounted at the end of the coaxial lead so that together with the matching impedance it served as a continuation of the central conductor. Use of a superconducting lead screen located near the specimen made it possible to observe an undistorted picture of the transition of the specimen from the superconducting state to the normal one, since the lead screen decreased the inductance of the specimen (in our case, by a factor of 10).

3. RESULTS OF INVESTIGATIONS AND THEIR DISCUSSION

a) Direct current. At a temperature of 4.2° K, the resistance of the film studied amounted to 1 — 6 ohms, and the specific resistance to 0.4 — 1 microhm-cm. The transition temperature of the specimens from the normal to the superconducting state for a measurement current of 40 μa was in the region of 3.75 — 3.85° K, i.e., it was displaced in the direction of higher temperatures in comparison with the critical temperature for bulk specimens.

FIG. 3. Initial portions of the specimen resistance vs. current curve (direct current).



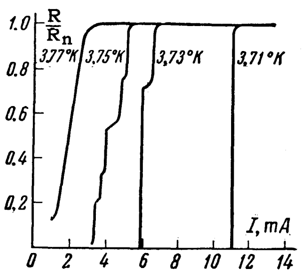


FIG. 4. Dependence of the resistance on the current in the transition of the specimen from the superconducting state to the normal (direct current).

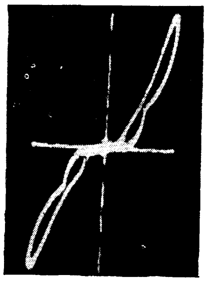


FIG. 6. Volt-ampere characteristic of a specimen for large current amplitude. The resistance of the specimen in the normal state changes as the result of heating.

The temperature interval of the transition was in the range 0.02 – 0.05°K.

Measurements have shown that with increase in the current in the specimen a very slow increase takes place in the resistance, up to a value of the order of 10^{-2} of the total resistance of the specimen (Fig. 3). A region of faster growth of the resistance with increase in temperature follows thereafter. A similar character of the initial stage of the transition was observed by Bremer and Newhouse.[5] At temperatures close to critical, and consequently at low currents, a non-monotonic increase in the potential on the specimen is observed, and consequently a similar increase appears in the resistance for a relatively large range of currents. A similar phenomenon was observed for thin tin wires by Galkin and others.[8]

For very low temperatures and, correspondingly, higher currents, the transition picture changes. The increase in current leads to a rapid appearance of a certain fraction of the resistance. Upon further increase of the current, the resistance is almost unchanged; thereafter, a second jump in the resistance takes place, etc. Sometimes, after a stage of smooth increase in the resistance, only one sharp jump is observed in the resistance, up to 0.95 of the full value; afterwards, a gradual increase to the total value occurs (Fig. 4).

A similar character for the change in the resistance can be explained by the inhomogeneity of the specimens. First traces of the resistance appear upon destruction of the superconductivity of the "weak points" of the specimen, which have a low value of critical current. Upon further increase in the current, resistance appears in regions which have a high critical current while the principal effect on the velocity and character of the transition is produced by the generation of heat in the normal parts of the specimen. The heating can be very pronounced and can lead to burning of the specimen.

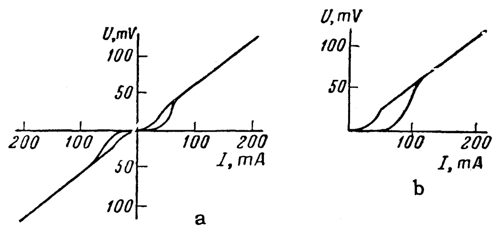


FIG. 5. Volt-ampere characteristics of the specimens: a – current of sinusoidal shape, b – current obtained as the results of half-wave rectification.

b) Pulses of triangular shape. The volt-ampere characteristics of specimens taken with the help of the apparatus whose circuit is shown in Fig. 2 make it possible to study in detail the character of the transition from the superconducting to the normal state upon increase of current through the specimen. The possibility of change within wide limits of the pulse repetition frequency, and of the rise times of the pulse and its amplitude allow one to elucidate the effects of thermal action on the character of the superconducting transition. The volt-ampere characteristics of a specimen obtained by passage of current of sinusoidal shape (Fig. 5a), and a current obtained as the result of half-wave rectification (Fig. 5b) show that the specimen has a much higher temperature in the first case, although the bath temperature was the same in both cases. Heating of the specimens by the current can be so great that a significant increase is observed in the resistance of the specimen in the normal state (Fig. 6).

To decrease the effect of heating, experiments were carried out on current pulses of triangular shape with the length of the leading front of 0.1 to 2 milliseconds. The repetition frequency of the pulses was set so that the specimen which was heated by the previous pulse managed to take on the temperature of the bath before the arrival of the following pulse. Thus the transition from the superconducting state to the normal can in first approximation be regarded as isothermal.[5] Even for the case of very short pulses (rise time 0.1 millisecond and decay time 0.1 millisecond) the specimen is heated during the time of transition from the superconducting to the normal state. Films mounted on a mica substrate made it possible to reduce the repetition frequency of the

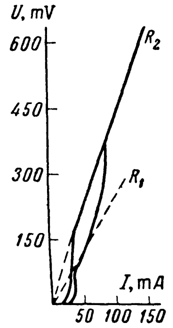


FIG. 7. Volt-ampere characteristics of a specimen. The stepwise character of the transition is seen.

pulses without change in the character of the transition to higher values, which is explained by the better thermal conductivity of the mica. In a number of specimens, a stepwise increase in resistance was also observed here (Fig. 7).

The existence of hysteresis in the transition from the normal state to the superconducting state is partly due to the heating of the specimen;* moreover, the existence of hysteresis of a nonthermal origin was observed. The character of the transition of the film from a normal state to the superconducting state upon decrease in current through the specimen depends essentially on whether the specimen was completely transformed to the normal state. If only a part of the specimen is transformed to the normal state under the action of the current in the pulse, then the intermediate state which is formed is so stable that in the action of the next pulse the film still preserves the value of the resistance which appeared under the action of the previous pulse (Fig. 8a).

Only upon increase of the current pulse amplitude to a value sufficient for transition of the entire sample to the normal state does the specimen become superconducting before the start of the next pulse (Fig. 8b). The existence of hysteresis can even be due to the small content of superconducting phase in the layer when the resistance of the specimen differs slightly from the total value of the resistance in the normal state. This manifests itself on the branch of the volt-ampere characteristic (corresponding to the transition from the normal state to the superconducting state) in a decrease in the duration of existence of the normal phase with increase in the current amplitude of the pulse (Figs. 8b, c).

The rate of increase of current in the pulse has a significant effect on the character of the development of the intermediate state in the film. Upon decrease of the rise time from 2 to 0.5 milliseconds, the initially more rapid growth of the resistance shifted in the direction of higher currents as in the research of Alekseevskii and Mikheeva,[3] but upon further increase in the growth rate—for a change of the growth time of the current from 0.5 to 0.1 millisecond—the initially faster growth rate of the resistance shifts in the direction of smaller currents (Fig. 9).

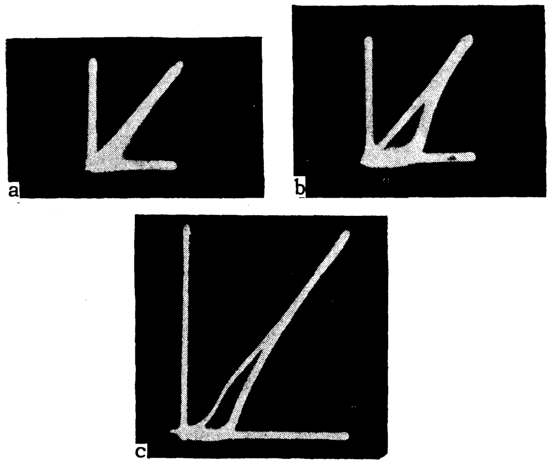


FIG. 8. Volt-ampere characteristics obtained by triangular pulses for different current amplitudes in the pulse. The rise time of the current in the pulse was 0.5 millisecond, the decay time was 0.1 millisecond, the repetition frequency of the pulses was 50 cps. a – I_{max} = 85 ma, b – I_{max} = 105 ma, c – I_{max} = 150 ma.

The character of this change makes it possible to assume the existence of two different mechanisms of propagation of the normal phase, depending on the growth rate of the current in the pulse. For a sufficiently slow growth of the current, the propagation of the normal phase is essentially determined by the motion of the heat front from the normal regions, which are heated by Joule heat.[6]

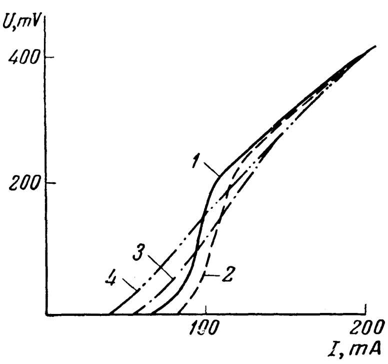


FIG. 9. Volt-ampere characteristics of specimens for different current rise times for constant amplitude (current pulses of triangular shape). Repetition frequency 50 cps. The curves correspond to the following rise times of current: 1 – 1 millisecond; 2 – 0.5 millisecond; 3 – 0.2 millisecond; 4 – 0.1 millisecond.

*A work recently appeared[9] which confirms these results.

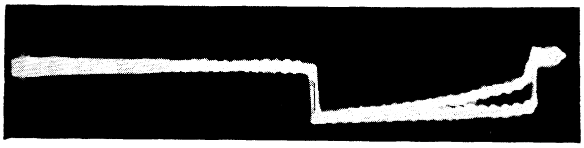


FIG. 10. Oscillogram of the transition of the specimen from the superconducting state to the normal under the action of rectangular pulse of 2 milliseconds duration. The upper curve is the current pulse, the lower is the voltage across the specimen.

Beginning with a certain rate of change of the current in the pulse, the process of propagation of the normal phase takes place chiefly under the action of the magnetic field of the increasing current and the heat which is generated in the normal regions by the eddy currents due to the appearance of a field in this region.

The overheating of the specimen and the rate of its cooling are essentially determined by the thermal conductivity of the substrate which, in this case, is a heat radiator, since the heat removal through the helium is very small. It was shown in reference 1 that even putting the film specimens in He II has no significant effect on the dissipation of the heat released in the specimen during the action of the pulse.

c) Pulses of rectangular shape. Investigations with current pulses of rectangular shape of duration from 0.1 to 10 microseconds, with rise times of 0.05 and 0.15 microsecond, have made it possible to disclose new laws in the character of the transition from the superconducting to the normal state. On passage of the current pulse through the specimen, the change in the resistance during the time of action of the pulse takes place in double fashion. Initially, a sharp rise in resistance was observed in our specimens during the rise time of the current in the pulse. Analysis of the oscillograms shows that, for a given temperature, a definite value of resistance of the specimen corresponds to each particular value of the current amplitude in the pulse. With increase in the growth rate of the current, the start of the more rapid growth of resistance continues to be displaced in the direction of lower currents, which indicates the very large effect of the eddy currents. Moreover, although the current through the specimens is not changed, the resistance of the specimen continues to grow. Increase of the resistance of the film with time in this case takes place as a result of current heating of the part of the specimen, which is already in the normal state, and goes more slowly than according to a linear law (Fig. 10).

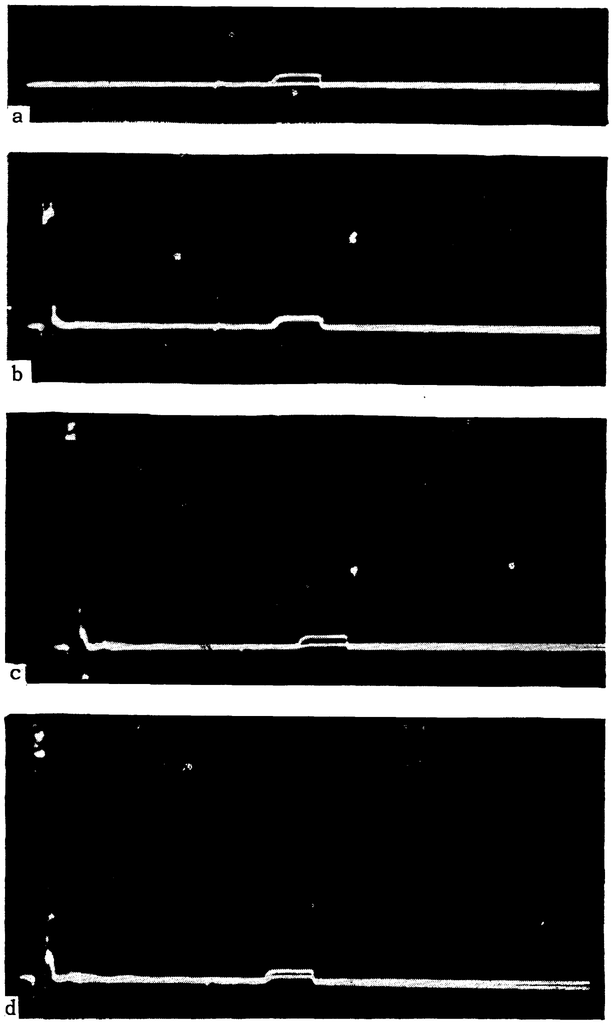


FIG. 11. Effect of the amplitude of the current in the pulse on the transition of the specimen from the normal state to the superconducting. The length of the pulses was 0.5 and 1.5 microseconds, respectively. a – $I_1 = 0$, b – $I_2 = 100$ ma, c – $I_3 = 190$ ma, d – $I_4 = 200$ ma.

The existence of phase delays of the normal state was again confirmed with the help of two successive current pulses also with short pulses in the case of a decrease in the current. Upon passage of two pulses through the specimen, the amplitude of the second pulse was so set that this pulse did not transform the specimen to the normal state in the absence of the first pulse (Fig. 11a). The presence of resistance in the film in the case of the second pulse was detected when the amplitude of the current of the first pulse only was increased (Fig. 11b). If now the amplitude of the first pulse is increased so that the specimen goes over entirely into the normal state during the time of action of the pulse, then the normal phase is not observed in the specimen in the second pulse and the specimen continues to remain superconducting

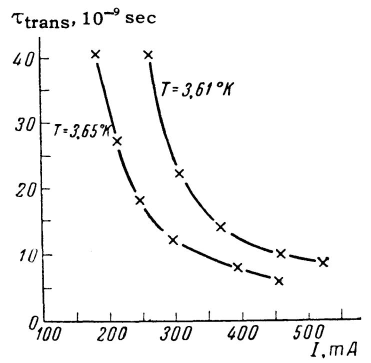


FIG. 12. Dependence of the times of transition from the superconducting state to the normal on the amplitude of the current in the pulse at different temperatures of the helium bath.

(Fig. 11c). Upon further increase in the amplitude of the first pulse, the amplitude of the second pulse is shown to be sufficient for transformation of the specimen to the normal state (Fig. 11d).

Analysis of the oscillograms shows that the reasons for the appearance of the normal phase during the time of action of the second pulse are different in the cases shown in Figs. 11b and d. In the first case (Fig. 11b), this is brought about by retardation of the normal phase in the specimen after cessation of the action of the first pulse. The time of existence of the normal phase is shown to be appreciable and reaches tens of microseconds. If the same specimen were completely transformed to the normal state, then the transition to the superconducting state is completed in a time less than the decay time of the current, i.e., 0.05 microsecond. In the second case (Fig. 11d), the increase of amplitude of the first pulse led to heating of the specimen to a temperature at which the amplitude of the second pulse was sufficient for appearance of the normal phase in the specimen. It then followed that the structure of the intermediate state, which is formed upon destruction of the superconductivity by the current, differs essentially from the structure of the intermediate state in the spontaneous formation of the superconducting phase.

Measurements of the transition times of the specimen from the superconducting state to the normal state were carried out with these same pulses as a function of the amplitude of the current in the pulse. The transition time was determined as the time between the instants of achieving half-maximum by the current through the specimen and the voltage across it. The character of the dependence of the transition time on the current amplitude (Fig. 12) is the same as in references 1 and 10. The time of transition for the specimens from the superconducting to the normal state for sufficiently high current amplitudes in the pulse was $\tau < 5 \times 10^{-9}$ sec.

4. CONCLUSION

The results set forth above were obtained on films of such thickness for which the values of the currents which destroy superconductivity depend weakly on the thickness of the specimens. For thinner films, one can expect other laws[1] both for destruction of superconductivity by the current and for the transition of specimens from the normal to the superconducting state.

Recording of the first traces of resistance upon increase in the current depends significantly on the sensitivity of the measuring apparatus.

In the action of very short current pulses, the principal effect on the character of the transition is supplied by Joule heat and the heat generated by eddy currents.

In addition to hysteresis of a thermal character, which is brought about in the transition from the normal to the superconducting state, a hysteresis was observed which was brought about by the existence of superconducting regions in the normal phase. The time for spontaneous transition to the superconducting phase is appreciably less than the time for destruction of the intermediate state formed in the destruction of the superconductivity by the current.

For films of the thickness investigated, the transition time from superconducting to normal state depends materially on the current amplitude in the pulse. For sufficiently large current amplitudes in the pulse, the transition time is $\tau < 5 \times 10^{-9}$ sec.

[1] Crittenden, Cooper, and Schmidline, Proc. IRE **48**, 1233 (1960).

[2] Newhouse, Bremer, and Edwards, Proc. IRE **48**, 1395 (1960).

[3] N. E. Alekseevskii and M. N. Mikheeva, JETP **38**, 292 (1960), Soviet Phys. JETP **11**, 211 (1960).

[4] N. I. Ginzburg and A. I. Shal'nikov, JETP **37**, 399 (1959), Soviet Phys. JETP **10**, 285 (1960).

[5] J. W. Bremer and V. L. Newhouse, Phys. Rev. **116**, 309 (1959).

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

[7] Borovik, Lazarev, and Fedorova, Ukr. Phys. J. **2**, 182 (1957).

[8] Galkin, Kan, and Lazarev, JETP **20**, 865 (1950).

[9] Smallman, Slade, and Cohen, Proc. IRE **48**, 1562 (1960).

[10] F. W. Schmidlin and E. C. Crittenden, Proceedings of the 5th International Conference on Low Temperature Physics and Chemistry, p. 234 (Madison, 1958).

Translated by R. T. Beyer
267