subsequent processes which are dominant in establishing a spin temperature. It is shown that in the YIG resonance-modulation experiments,[9] the subthermal magnons are relaxed more effectively by the four-magnon exchange process than by the three-magnon processes for temperatures above $\sim 50°$K. In general, both the three-magnon dipole and the four-magnon exchange processes are important in the subsequent processes leading to a spin temperature. Finally, it is shown that these three- and four-magnon processes are more effective than the two-magnon–one-phonon processes, induced by magnetoelastic and exchange interactions, in relaxing all magnons which are important in the resonance experiments. These important magnons include the S magnons, the subthermal magnons, and the thermal magnons. This justifies the assumption made[5,16] in magnon-phonon calculations that a spin temperature exists. The calculations[5] of a magnon-magnon relaxation frequency averaged over all magnons to justify the assumption of a spin temperature is not sufficient for the relaxation scheme proposed in I.

ACKNOWLEDGMENTS

The authors would like to express their deepest appreciation to Professor C. Kittel for his invaluable advice and continued interest. We are grateful to Professor Y. Rocard and Professor P. Agrain for the hospitality of the Ecole Normale Supérieure, where this work was completed. One of us (M. S.) would like to thank the National Science Foundation for a pre-doctoral fellowship.

PHYSICAL REVIEW VOLUME 124, NUMBER 4 NOVEMBER 15, 1961

Use of Thin Films for the Study of Stress Effects on the Superconducting Transition of Indium

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(Received July 10, 1961)

Measurements on evaporated thin films of superconductors provide a powerful technique for studying stress effects on the superconductivity transition. Utilization of the differential thermal expansion of film and substrate by suitable choice of substrate and substrate temperature during evaporation provides a convenient way for controlling the stress in the films. In this manner, uniform tensile and compressive stresses of substantial magnitude can be obtained and are tolerable because of the great strength of thin films. To illustrate how this technique can be used, studies are shown of similarity effects in indium films under the influence of biaxial stress and a generalization of the usual similarity relations is suggested.

It is the purpose of this paper to suggest that studies of evaporated thin films of superconductors provide a powerful technique for studying stress effects on the superconductivity transition. Utilization of the differential thermal expansion of film and substrate by suitable choice of substrate and substrate temperature during evaporation provides a convenient way for controlling the stress in the films. In this manner, uniform tensile and compressive stresses of substantial magnitude can be obtained and are tolerable because of the great strength of thin films.[1]

TABLE I. Specimen characteristics.

	In 57	In 58
Substrate	fused quartz	high-expansion glass
Thickness	1253 A	1225 A
Residual resistivity	0.492 μohm-cm	0.473 μohm-cm
Critical temperature	3.473°K	3.437°K
Critical field at 0°K	836 oersted	840 oe
Tensile stress at 4°K	2.3×10^3 atm	1.0×10^3 atm
$H_c(\sigma,0)/T_c$	240.7 oe/°K	244.3 oe/°K
Bulk critical field[a]	285.7 oe	285.7 oe
Zero-stress critical temperature[a]	3.408°K	3.408°K
Ratio of weak-field penetration depth at 0°K to film thickness	0.600	0.605

[a] R. W. Shaw, D. E. Mapother, and D. C. Hopkins, Phys. Rev. 120, 88 (1960).

To illustrate how this technique can be used, studies are shown of similarity effects in indium films under the influence of biaxial stress and a generalization of the usual similarity relations is suggested.

Upon the application of hydrostatic pressures to bulk superconducting samples, in general, similarity is not obeyed. The term similarity usually implies the validity of two independent conditions[2]:

$$H_c(X,t)/H_c(X,0)=f(t), \tag{1}$$

and

$$H_c(X,0)/T_c(X)=\text{const}, \tag{2}$$

where H_c is the critical magnetic field, T_c is the critical temperature, t is the reduced temperature, T/T_c, and X is an independent variable such as pressure, or

[1] A. M. Toxen, Phys. Rev. 123, 442 (1961).
[2] M. Garfinkel and D. E. Mapother, Phys. Rev. 122, 459 (1961).

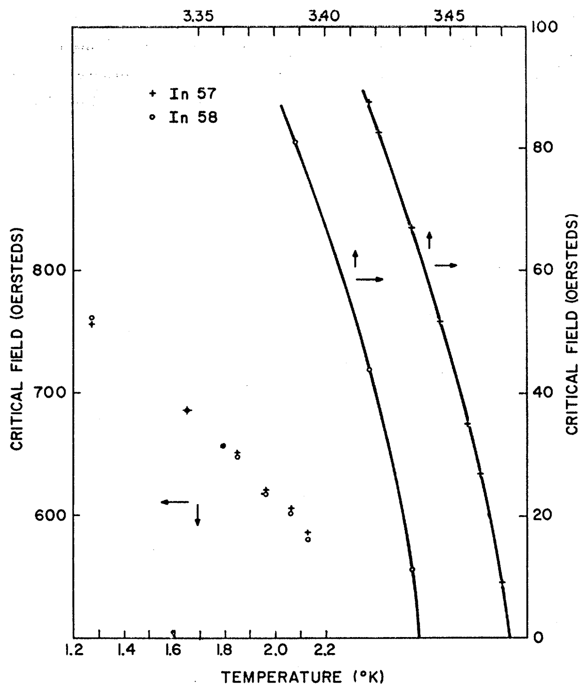

FIG. 1. Variation of critical magnetic field with absolute temperature.

isotopic mass, for which the concept was introduced.[3,4] Measurements by Muench[5] indicate that under the influence of hydrostatic pressure, tin satisfies similarity conditions (1) and (2), while indium satisfies (1) but not (2). More recent measurements by Swenson and co-workers[6] indicate that tin satisfies similarity condition (2), but not (1). Clearly, agreement or disagreement with similarity conditions (1) and (2) depends upon experimental precision and must be stated quantitatively. Measurements by Garfinkel and Mapother[2] of the influence of hydrostatic pressure upon the critical field of lead indicate that, just as in the case of indium, condition (1) is satisfied, while condition (2) is not.

The measurements we have made indicate that the critical fields of evaporated indium films under the influence of tensile stress, like those of bulk samples subjected to hydrostatic stresses, obey condition (1), but do not obey condition (2). This similarity between film and bulk material is particularly noteworthy in view of the fact that the critical fields of the films are three times greater than the bulk value because of size effects.[1]

Two indium films, In 57 and In 58, were evaporated simultaneously onto substrates of fused quartz and high-expansion glass, respectively, which were at a temperature of about 80°K. After evaporation, the films were annealed at room temperature for about a day and then their superconducting properties were measured. Some of the results are shown in Table I. The experimental details have been described elsewhere.[1]

Because the coefficient of expansion of indium is greater than that of either substrate material, when the films and substrates are cooled from 300°K to helium temperatures, the films are in a state of tensile stress, which is consistent with the observed increase in T_c over the bulk value (δT_c is positive for tensile stresses[7]). In fact, for In 57, the film on the fused quartz substrate, it is believed that the stress present in the film is the yield stress. Because the coefficient of expansion of the glass substrate is greater than that of the fused quartz and more nearly matches that of the indium, one would expect the tensile stress in In 58 at helium temperatures to be lower than that of In 57, which agrees with the observation that the critical temperature of In 58 is closer to the bulk value than that of In 57.

In Fig. 1 are shown the critical field curves for In 57 and In 58 plotted as a function of absolute temperature. In Fig. 2 the critical fields are plotted as a function of reduced temperature t. The actual critical fields of the two specimens at the same reduced temperature agree

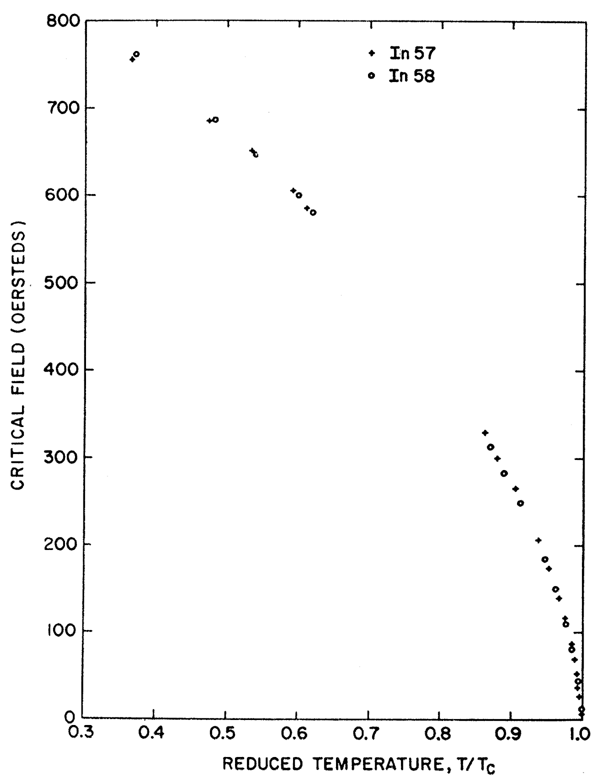

FIG. 2. Variation of critical magnetic field with reduced temperature.

[3] J. M. Lock, A. B. Pippard, and D. Shoenberg, Proc. Cambridge Phil. Soc. 47, 811 (1951).
[4] R. W. Shaw, D. E. Mapother, and D. C. Hopkins, Phys. Rev. 121, 86 (1961).
[5] N. L. Muench, Phys. Rev. 99, 1814 (1955).
[6] C. A. Swenson, IBM Superconductivity Conference (unpublished).
[7] H. Rohrer, Phil. Mag. 4, 1207 (1959).

within about 0.5%, and the reduced fields, $H_c(t)/H_c(0)$ agree within 0.2%. Hence it follows that the films deviate from similarity condition (1) by less than 0.2%, which falls within experimental error. However, from Fig. 1 (lower curves), one can see that similarity condition (2) is not satisfied. The $H_c(T)$ curves for In 57 and In 58 actually cross, and the quantity $H_c(\sigma,0)/T_c$ is 240.7 oe/°K for In 57 and 244.3 oe/°K for In 58, a difference of (1.5 ± 0.2)%.

If one makes the assumption that the deviations of the film critical temperatures from that of bulk are entirely the result of tensile stresses in the films, one can calculate the tensile stresses. (This assumption is discussed in reference 1.) The change in critical temperature with applied uniaxial stress can be related to the change in critical field with stress and the change in critical field with temperature, i.e.,

$$\frac{\partial T_c}{\partial \sigma}=-\left(\frac{\partial H_c}{\partial \sigma}\right)_{T_c}\Big/\left(\frac{\partial H_c}{\partial T}\right)_{T_c}$$
$$=(4.0\times10^{-5}\cos^2\theta+0.2\times10^{-5}\sin^2\theta)\,°\mathrm{K/atm}, \quad (3)$$

where θ is the angle which the uniaxial stress σ makes with the tetragonal axis. In Eq. (3), $\partial H_c/\partial\sigma$ was obtained from the measurements of Rohrer,[7] and $\partial H_c/\partial T$ was taken to be 156 oersted/°K (see for example Reeber[8]). The convention followed in Eq. (3) is that tensile stresses are positive in sign so that T_c is raised by tensile stresses. Since the indium films are highly oriented, with the (111) planes parallel to the substrates,[9] the expected change in critical temperature is just given by[10]

$$\partial T_c/\partial\sigma=2.8\times10^{-5}\ °\mathrm{K/atm}. \quad (4)$$

[8] M. D. Reeber, Phys. Rev. **117**, 1476 (1960).

[9] M. G. Miksic (private communication).

[10] Since indium has a tetragonal structure with an axial ratio, c/a, equal to 1.082 at helium temperatures [J. Graham, A. Moore, and G. V. Raynor, J. Inst. Metals **84**, 86 (1955)], the biaxial stress in the plane of the film can be resolved into two independent uniaxial stresses making angles of 90°, and 37° 22′, respectively, with the c axes of the indium grains.

Under the assumption that the observed shift in T_c from the bulk value is all due to stress, it follows from Eq. (4) that the stress in In 57 at helium temperatures is 2.3×10^3 atm; similarly, the stress in In 58 is 1.0×10^3 atm. Therefore, the difference in stress in the films is 1.3×10^3 atm. One can obtain some idea of how strong thin films are by comparing the above stresses to the tensile yield stress of bulk indium at helium temperatures, which is approximately 10 atm.[11] Thus a 1200 A indium film will withstand a tensile stress 230 times greater than the bulk yield stress. Similar effects are observed in thin tin films.[12]

Calculations of penetration depth from the critical field data[1] of In 57 and In 58 indicate that, within experimental error, the two films have the same ratio of penetration depth to film thickness, δ_0/d, at every temperature. The values of this parameter extrapolated to 0°K are shown in Table I.

The results of this experiment suggest that similarity condition (1) can be generalized to hold for superconductors whose critical fields depend upon an additional parameter such as the penetration depth. In the case of thin films, this might be

$$H_c{}^f(\delta_0/d,\sigma_i,t)/H_0{}^f(\delta_0/d,\sigma_i)=f(\delta_0/d,t), \quad (5)$$

where $H_c{}^f$ is the film critical field, $H_0{}^f$ is the value of the critical field at 0°K, $\sigma_i(i=1,\cdots,6)$ are an arbitrary set of stresses, δ_0/d is the ratio of penetration depth to thickness, and where the function f is independent of the applied stresses.

ACKNOWLEDGMENTS

The author would like to express his appreciation to M. T. Burns, R. E. Horstmann, and R. J. Parker for the film measurements, and to Dr. P. M. Marcus for many helpful suggestions for presenting these results.

[11] D. P. Seraphim (private communication).

[12] R. Blumberg and D. P. Seraphim, J. Appl. Phys. (to be published).