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FIELD REPLICATION AND FLUX SHIELDING IN ANNULAR SUPERCONDUCTORS*

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ABSTRACT

The phenomenon of flux trapping in type II superconductors can be exploited by fabricating simple, tubular assemblies of bulk or layered superconductors which then accurately preserve a wide variety of field configurations. The associated flux shielding properties can be used where field free regions are required. The results of flux trapping and shielding experiments on samples of vapor deposited Nb_3Sn, bulk Nb-Ti, Nb-Ti/Cu sheet-composite, and bulk Pb-Bi are reported. Measurements of the magnetic field in the vicinity of the samples as a function of position and applied field produce field profiles and magnetization-like curves. The experimental curves are related to critical state models and together with an appropriate model give estimates of critical currents in the materials. The occurrence and extent of the flux jumps, which often limit flux trapping and shielding capabilities, are compared with predictions of stability models. Heat- and surface-treatments which increase pinning strengths and trapped flux are described.

INTRODUCTION

Ideal superconductors can only trap magnetic flux in the holes of multiply-connected samples since the Meissner effect requires the field to be excluded from bulk materials. In practice nearly all superconductors exhibit some degree of irreversibility, and when cooled in a magnetic field do not completely expel magnetic flux. This behavior results from the pinning of fluxoids by inhomogeneities in the material such as phase boundaries,[1] precipitates,[2] or dislocation cell walls.[3] We have shown that irreversible materials can trap multipole magnetic fields of moderate strength.[4,5] In this paper we describe the results of further experiments on flux trapping and shielding by flat and tubular samples in uniform transverse fields of up to 2T. The samples were held within a dewar by a long, thin-walled stainless steel tube. Hall probes attached to a smaller concentric tube could be translated axially or rotated from above. The position of the probes was monitored by potentiometers coupled to the driving mechanism. With the probes in a fixed position adjacent to or within the sample, magnetization-like curves were obtained on which flux jumps were apparent as discontinuous changes in the field sensed by the probes. Moving the probes across the sample at successive field levels generated profiles which revealed the extent of the sample involved in, and the field shape before and after, a flux jump. Data were usually taken at 4.2°K with the samples immersed in liquid helium, although lower temperatures could be reached by reducing the pressure above the liquid helium.

STABILITY MODELS

Observations of flux jumping behavior in bulk materials may be compared to predictions based on the adiabatic critical state model, as described by Swartz and Bean.[6] They consider the case of a semi-infinite slab (with thermal diffusivity much smaller than magnetic diffusivity) in an applied field directed parallel to the slab's face, and develop an expression for H_{fj}, the lowest applied field at which small field perturbations result in massive flux penetration and a thermal runaway process

$$H_{fj}(A/m) = \left[\frac{-\pi}{160} C\,(J/cm^3\ {}^oK)\, J_c\,(A/cm^3)\left(\frac{\partial J_c}{\partial T}\right)^{-1}\right]^{\frac{1}{2}}$$

which, if $C = \beta T^3$ and $J_c(T) = J_c(0)(1-T/T_0)$ reduces to

$$H_{fj} = \left[\frac{\pi}{160}\beta T_0 T^3 (1 - T/T_0)\right]^{\frac{1}{2}} .$$

The expression, similar to one derived by others,[9] may be interpreted to mean that a sample will be stable if it is not thick enough to support field differences on the order of H_{fj}. The expression for this critical thickness is

$$d(cm) = \left[-\pi\ 10^{-5} C \left(4 J_c \frac{\partial J_c}{\partial T}\right)^{-1}\right]^{\frac{1}{2}} .$$

The effect of the field enhancement inherent in our geometries is to lower the value of H_{fj} and decrease stability.

The simple adiabatic model does not apply in cases where normal metal in proximity to superconducting samples damps flux changes.[7] Wilson et al.[8] consider the case of a composite with alternate layers of copper and superconductor, in which the speed of flux motion is limited by the effective resistivity of the composite (determined by the resistivity $\rho(\Omega\text{-cm})$ and volume fraction of the copper, $1-\lambda_s$), and in which the heat conduction is limited by the thermal conductivity $K_s\,(W/cm\text{-}^oK)$ and thickness d of the superconducting layers. The resulting criterion for dynamic stability of the material with respect to small temperature perturbations in the presence of a field applied parallel to the layers is

$$H \le \left[\frac{3\times 10^6}{4\pi^2}\ \frac{T_0 K_s}{\rho}\left(\frac{x}{d}\right)^2 \lambda_s (1-\lambda_s)\right]^{\frac{1}{2}}$$

(x = distance the field penetrates). This reduces to a condition on the thickness of the superconducting layers

$$d \le \left[\frac{8 T_0 K_s}{\rho}\ \frac{1-\lambda_s}{\lambda_s}\ \frac{1}{J_c^2}\right]^{\frac{1}{2}} .$$

The case of a field applied perpendicular to the layers is not explicitly treated but the same principles should apply, with the demagnetization factor leading to somewhat reduced stability. When the superconductor surrounds a space, increased susceptibility to flux jumps may result.[9]

RESULTS WITH BULK Nb-Ti

A 10.6-cm-long bulk sample of Nb-64at%Ti was machined to 6.1 cm diam and a .69 cm diam axial hole was drilled. The as-machined sample was able to trap and shield transverse dipole fields of approximately 0.3T. The trapping and shielding was limited by flux jumps which occurred when differences between the applied and interior field exceeded 0.25-0.35 T. The magnetization-like curves showed that the internal field changed only through flux jumps up to applied fields of 0.75T. The field profiles indicated that the flux jumps were partial, involving only one section of the sample at a time.

Nb-Ti has critical temperatures of approximately 7-10 °K.[10] Although reported values of its low temperature specific heat vary considerably, using $\beta = 10\times 10^{-6}\,J/cm^3\ {}^oK^4$ in $C = \beta T^3$, which gives a $C(4.2^oK) = 4.4\ mJ/cm^3\text{-}^oK$, is consistent with most data.[11,12] Using $T_0 = 9.5K$ then implies a flux jump field $H_{fj}(4.2^oK) = 0.27T$ on the basis of the adiabatic model. This result is consistent with our measurements as well as those of Boyer et al.[13] who found $H_{fj} = 0.3T$ on a smaller solid cylinder in an axial field.

EXPERIMENTS ON Nb-Ti/Cu COMPOSITE

A promising composite material containing Nb-70at%Ti and Cu in the form of a sandwich of three layers of Cu interleaved with 2 layers of Nb-Ti was obtained.[14] The sandwich had been roll-reduced until the layers were approximately

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. 005 cm thick and metallurgically bonded to each other. The magnetic behavior of this . 025 cm thick sheet composite material was observed in two different arrangements. In one, a rectangular strip with characteristic dimensions of a few cm was oriented normal to the applied field. Movable Hall probes sensed the field just above the strip. In the second arrangement one or more strips approximately 25.4 cm long by 4.8 cm wide were wound into a spiral on a 1.9 cm Cu tube. The inner end of the strip was soldered to the inner Cu tube and a larger Cu tube was fitted snugly over the spiral. A probe holder moved axially inside the tube while the whole assembly was suspended in a transverse magnetic field.

In shielding tests, the field above the center of the flat strip typically remained a few percent of the applied field for applied fields up to a certain level. When larger fields were applied, they began to penetrate to the center of the strip in a spatially nonuniform but repeatable manner. The greatest penetration was probably occurring in areas where the superconducting layer of the composite was the thinnest (micrographs of the composite showed that the thickness of a superconducting layer was reduced to below . 0005 cm in places). As the applied field was increased further, the field near the strip retained its nonuniform shape while increasing in magnitude, and generally maintaining its difference (with some decreases at higher field levels) from the applied field. Subsequent decreases in the applied field initially caused changes only in the outer regions of the samples, with larger and larger fractions of the sample subsequently being affected. In some cases the orderly evolution of the critical state was interrupted by flux jumps. In experiments with the flat composite, the jumps affected the whole sample and tended to result in nearly uniform fields approximately equal to the field applied at the time of the jump. During experiments with spiral configurations some flux jumps occurred in the outer layers without affecting the interior field at all; other times massive flux jumps apparently involving the whole assembly were seen. Samples prone to flux jumps during shielding tests at low fields often became more stable at higher fields.

The behavior in trapping tests was similar: if the initial field was not too large, the sample trapped the field with only small decreases in the field near the center of the strip or tube; if the field was too large, decreases and distortions of the trapped field near weak spots in the strip, or flux jumps, occurred before the applied field reached zero.

Effect of Low Temperature Heat Treatments

A flat strip sample was given a series of heat treatments in vacuum at approximately 355°C. Its trapping and shielding behavior was observed between treatments.

Maximum differences of . 0100-. 0200T were observed with the sample in the as-received state (no heat treatments after rolling to final thickness).

Heating the sample for 4½ to 20 hours at 355°C improved the strip's trapping and shielding ability by a factor of more than 10. After heating 4½ hours, field differences of 0.10 - 0.15T were observed, and in one run a nonuniform field with a peak value of approximately 0.18T was trapped. The sample was nearly free of flux jumps at this stage, with only one flux jump in a decreasing field being observed (after 20 hours of heating).

With heating times longer than 20 hours, the sample became prone to flux jumping in decreasing applied fields. Heating for 43 or more hours actually resulted in lower remanent fields, 0.1400T after 60 hours and less than 0.1T after 130 hours. Flux jumping in increasing fields did not become a factor until aging times of approximately 60 hours or more (see Fig. 1). In shielding runs, samples aged 48-59 hours maintained field differences of over 0.35T, but were limited to 0.18-0.24T by flux jumping after 130 hours of aging.

Increases in flux pinning and critical current densities have been correlated with the precipitation of α-Ti (hcp) upon low temperature heat treatment of cold-worked Ti-rich Nb-Ti alloys.[2,15,16] Analysis of x-ray data showed an increasing proportion of α-Ti with heat treatment time in our

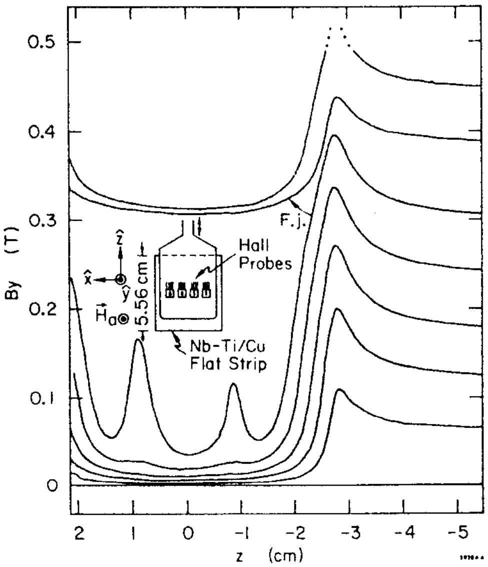

Fig. 1. Magnetic field profiles above the center of a flat Nb-Ti/Cu composite (heat-treated for 61 hr at 355°C) in increasing fields. Inset shows sample at approximately ¼ scale.

material, which paralleled increases in trapping and shielding of the composite until the material became limited by flux jumps. Comparison of flux jumping behavior with the dynamic stability model is difficult without actually measuring K_s and ρ, which can vary considerably.[17,18] With conservative values (K_s=11 mW/cm°K, $\rho = 2 \times 10^{-8}$ Ω-cm), flux jumping fields of over 0.7T and corresponding critical thicknesses more than . 065 cm are found for our material. Contrary to this calculation the material becomes unstable after heat treatments which should not adversely affect parameters such as T_0, K_s, and ρ.

Spiral Configuration

A strip approximately 25.4 by 4.6 cm was given an initial 43-hour heat treatment, and subsequently an 18-hour one. The strip was wound into a 4-layer spiral and tested in transverse fields.

The four layers were able to maintain a field difference of 0.7-1.0 T. The sample experienced a large flux jump for larger field differences. Peak fields of close to 1T generally remained after cycling the applied field to 2T and back to zero. The additional 18-hour heat treatment decreased the stability of the sample resulting in lower remanent fields and a lower field for the first flux jump in shielding runs.

Mineral oil was added to the space between the concentric Cu tubes containing the sample spiral in order to ascertain whether immobilizing the strip improved trapping and shielding behavior. The oil increased susceptibility to flux jumps and decreased the maximum attainable field differences by 0-50% depending on the type of test. Any advantage gained by immobilization with the oil was evidently more than offset by the elimination of direct contact between the sample and the liquid helium.

A specimen consisting of the above 4-layer spiral (heated 59 hours) with an additional 3-layer strip (heated 48 hours) wound around it flux jumped for the first time in a shielding test at 1.6T (see Fig. 2) and retained a peak field of 1.2T after cycling the field.

Critical State Model

Modeling the behavior of these strips has been partially successful. Currents of the critical current density were assumed to be flowing in specified parts of the specimen and

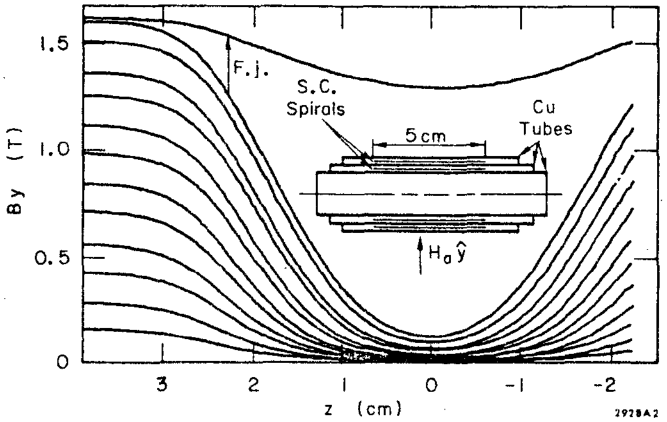

Fig. 2. Magnetic field profiles along the axis of a 7-layer spiral of Nb-Ti/Cu in increasing applied fields. Inset shows the sample assembly at approximately $\frac{1}{2}$ scale.

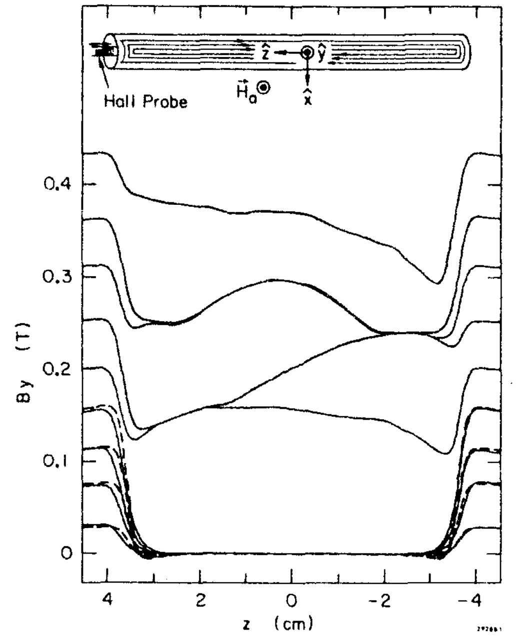

Fig. 3. Magnetic field profiles along the axis of a Nb_3Sn/Nb-Sn coated tube in increasing applied fields. Dotted curves were calculated by summing field contributions from a series of saddle-shaped current elements covering the tube surface.

the resulting field profiles computed. To date, fair agreement has been obtained between measured field profiles and profiles calculated on the basis of relatively simple current distributions. However, the assumed current distributions produce a field peak near the edge of the strip where no such peak is observed in practice. A calculation based on summing the field contributions from a distribution of magnetic dipole layers evidenced similar difficulties. The model is, however, useful for calculating approximate critical current density levels for our samples, and indicates that samples heat-treated for 40-50 hours have J_c values of close to 10^5 A/cm^2.

Nb_3Sn SAMPLES

The Nb_3Sn samples, kindly loaned to us by R. Howard of Stanford University, consisted of alternate layers of Nb_3Sn and Nb-Sn alloy or Nb_3Sn and Y, vapor deposited on a .64 cm Hastelloy tube. Total thickness of Nb_3Sn was 6-7 microns with individual layers on the order of 2000 Å thick.[19] Differences between the interior and applied transverse fields of over 0.2T were observed. Uniform fields of approximately 0.12-0.16T could generally be trapped in, or effectively shielded out of, the tubes. Below 0.3-0.6T field changes occurred through flux jumps. The jumps usually affected only a portion of the tube at a time and usually occurred in the regions of the tube supporting the largest field difference. At higher fields, flux jumps ceased to occur and the internal field, while still different from the applied field, changed continuously with the applied field. At lower temperatures (1.8-2.0°K) the samples became more prone to flux jumps and the changeover to smooth behavior occurred at higher fields. A model based on critical state theory with current flowing in saddle-shaped paths gave critical current values of 3-4 × 10^6 A/cm^2, in agreement with values measured in axial fields.[19] The model indicated that most flux jumps took place at field differences of roughly 50-100% of the maximum possible difference, given the thickness and critical current density of the material. Fig. 3 shows profiles taken during a shielding test on one of these tubes and also curves generated from the model. The discrepancy near the ends of the tubes could not be eliminated despite attempts using a variety of current distributions.

Pb-Bi CASTINGS

Experimental Results

As part of a series of measurements on Pb-Bi alloys, flux trapping experiments were carried out on hollow cylinders approximately 5.1 cm o.d. × 1.4 cm i.d. × 10.2 cm long, and on three spheres. Magnetization curves were measured on smaller 5.1 cm long × 1.4 cm diameter cylinders with rounded ends. A cylinder of approximately 50%-Bi composition trapped nearly 0.6T in the inner hole, although in cases where the trapped fields were larger than 0.44-0.46T, flux jumps were triggered by transients produced when the magnet power supply was turned off. When the applied field was cycled to 1T and back to zero, changes in the internal field generally occurred through flux jumps except above 0.8-0.85T where some smooth flux penetration was observed. In contrast, no flux jumps were observed during magnetization measurements on the smaller cylinder. A copper tube (with an estimated magnetic time constant of a few hundred milliseconds) placed around the large cylinder decreased flux jumping, although the maximum observed difference between the applied and the internal field did not change significantly. Bead-blasting the surface of the cylinder increased flux trapping by about 0.05T with approximately half of this improvement being lost after aging at room temperature for several months.

The three Pb-56%Bi spheres had narrow slits through their centers enabling the field profile to be measured along a diameter perpendicular to the applied field. The spheres were cast separately and so may have had slightly different compositions and structures. A 5.72 cm diameter sphere shielded up to 0.7760T and trapped 0.7040T in its center; the 3.96 cm diameter sphere trapped fields with peak values of up to 0.5940T and shielded the center from up to 0.5350T, while the 2.90 cm diameter sphere was able to shield up to 0.6350T and had a maximum remanent field of 0.6310T. No flux jumps were seen during testing of the spheres at 4.2°K or during one run at 2°K with the 3.96 cm diameter sphere. Fig. 4 shows typical field profiles obtained with the spheres.

Stability

A calculation of H_{fj} using appropriate values of the parameters for Pb-Bi alloys ($\beta = 210 \times 10^{-6}$ J/cm^3 °K^4 [20,21] and $T_0 = 8.6$°K) results in H_{fj} (4.2°K) = 0.4610T and H_{fj} (2°K) = 0.1850T. Agreement between the model and the results from the Pb-50% Bi cylinder is fairly good. That sample was prone to flux jumps initiated by field transients in the 0.44 - 0.46 T range, and spontaneous flux jumping at higher field differences in trapping runs. The smaller cylinder used in magnetization measurements was close to the

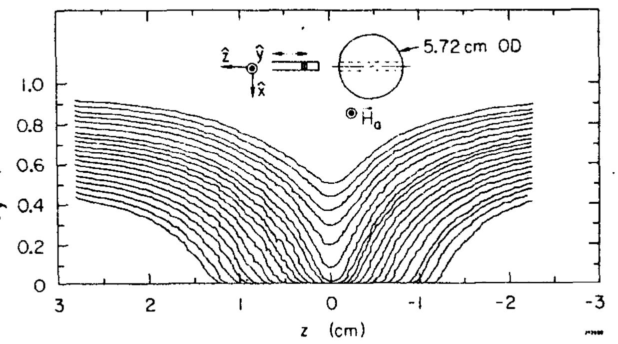

Fig. 4. Magnetic field profiles along a diameter of a Pb-Bi sphere during a shielding test.

critical size of .4 cm so that its lack of flux jumps is reasonable. After the bead-blasting treatment the large cylinder trapped 0.65 T, and when cooled to 2°K trapped 0.45 T stably and 0.66 T subject to flux jumping. While the sample did become more unstable with decreasing temperature the trapped fields at 2°K were more than twice the calculated value of H_{fj}. The results of the experiments with the spheres, which stably trapped and shielded fields of well over 0.70 T, also seem to be at variance with the model.

Critical Currents

Because of the unusual geometry, assumptions about the form of the current distribution must be made in order to simplify computations of critical current levels in these samples. For the large cylinder, calculations based on saddle-shaped current paths flowing throughout the cylinder wall with uniform current density require a $J_c = 4\times10^3$ A/cm^2 to generate 0.60 T in the center of the cylinder. Since the current density is actually a fairly strong function of field, peak current densities must be closer to twice this value. For a sphere there is a simple analytical expression for the field at the center assuming uniform azimuthal currents flowing throughout

$$B_z(T) = \frac{\pi\mu_0 J_c r}{400}$$

or

$$J_c = \frac{400\, B_z}{\pi\mu_0 r}$$

(where r = radius of the sphere). Applying this to the cases of the three spheres yields $J_c = 2.8$, 3.0, and 4.4×10^3 A/cm^2 for the 5.72, 3.96, and 2.90 cm diameter spheres, respectively. Introducing field-dependent current densities into the model approximately doubles the peak J_c values. For both the spheres and the cylinder, if the critical state currents flow only in a portion of the sample wall then the current densities are correspondingly higher. Examination of the microstructure of small samples from the same melt as the 50% Bi cylinder shows a reason for the low current densities. Rather than a sharp 2-phase structure consisting of Bi precipitates in a matrix of Pb-Bi (with critical currents in zero field of approximately $1 - 6\times10^4$ A/cm^2,[1,22,23] the samples have a complicated, fine intermixture of phases with varying concentrations of lead and bismuth. Pinning on boundaries between phases of varying composition is evidently not as effective as that between the strong superconducting Pb-Bi phase and normal Bi phase.[22]

CONCLUSIONS

The critical state model has been useful in understanding the qualitative behavior of the various samples in trapping and shielding tests, and has provided good estimates of critical current levels. Further work is required to explain the exact form of the field profiles. The utility of simple stability criteria seems more limited. The criteria have, however, correctly indicated methods of enhancing stability, i.e., the subdivision of a specimen into thin superconducting layers surrounded by high conductivity normal metal. This technique has proved useful in trapping and shielding, as it has in transport current applications. In any event we have found materials, the Nb-Ti/Cu composite and to a lesser extent the Pb-Bi alloys, which trap and shield fields at levels approaching those useful in high energy physics applications.

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REFERENCES

1. A. M. Campbell, J. E. Evetts, D. Dew-Hughes, Philos. Mag. 18, 313 (1968).
2. H. Hillmann, D. Hauck, Proc. 1972 Applied Superconductivity Conf., Annapolis, Maryland, p. 429.
3. D. F. Neal, A. C. Barber, A. Woolcock, J.A.F. Gidley, Acta Metall. 19, 143 (1971).
4. M. Rabinowitz, E. L. Garwin, and D. J. Frankel, Nuovo Cimento Lett. 7, #1, 1 (1973).
5. E. L. Garwin, M. Rabinowitz, and D. J. Frankel, Appl. Phys. Lett. 22, 599 (1973).
6. P. S. Swartz and C. P. Bean, J. Appl. Phys. 39, 4991 (1968).
7. R. B. Harrison, J. P. Pendrys, and L. S. Wright, J. Low Temp. Phys. 18, 113 (1975).
8. M. N. Wilson, C. R. Walters, J. D. Lewin, and P. F. Smith, J. Phys. D 3, 1518 (1970).
9. S. L. Wipf, Phys. Rev. 161, 404 (1967).
10. D. Grigsby, EPIC DS-148 (S-1) (1968).
11. Y. Iwasa, C. Weggel, D. B. Montgomery, R. Weggel, and J. R. Hale, J. Appl. Phys. 40, 2006 (1969).
12. B. Ya. Sukharevskii, A. V. Alapina, Yu. A. Dusheckkin, Zh. Eksp. Teor. Fiz. 54, 1675 (1968) [Sov. Phys.-JETP 27, 897 (1968)].
13. L. Boyer, G. Fournet, A. Mailfert, and J. L. Noel, Proc. Int. Conf. on Low Temperature Physics, Boulder, 1972 (LT 13), Vol. 3, p. 232.
14. Teledyne - Wah Chang Albany, Albany, Oregon.
15. A. D. McInturff and G. G. Chase, J. Appl. Phys. 44, 2378 (1973).
16. Yu. F. Bychkov, V. G. Vereshchagin, V. R. Karasik, G. B. Kurganov, and V. A. Mal'tsev, Zh. Eksp. Teor. Fiz. 56, 505 (1969) [Sov. Phys.-JETP 29, 276 (1969)].
17. L. Dubeck, K.S.L. Setty, Phys. Lett. 27A, 334 (1968).
18. N. Morton, B. W. James, G. H. Wostenholm, and S. Nuttal, J. Phys. F 5, 2098 (1975).
19. R. E. Howard, C. N. King, R. H. Norton, R. B. Zubeck, T. W. Barbee, and R. H. Hammond, to be published in J. Appl. Phys.
20. S. Ewert and W. Sander, Z. Phys. 247, 21 (1971).
21. R. Hultgren, R. L. Orr, P. D. Anderson, and K. K. Kelly, Selected Values of Thermodynamic Properties of Metals and Alloys (John Wiley & Sons, New York, 1963), p. 541.
22. S. A. Levy, Y. B. Kim, and R. W. Kraft, J. Appl. Phys. 37, 3659 (1966).
23. H. Voight, Z. Phys. 213, 119 (1968).