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# Lattice Thermal Conductivity of a Neutron-Irradiated Copper-Aluminum Alloy*

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Low-temperature thermal-conductivity results are presented on two Cu+9-at.%-Al polycrystals which show that fast-neutron irradiation has two effects on a coldworked sample of this alloy. In the well-annealed specimen, irradiation produced defects which scatter long-wavelength phonons, giving a well-defined $T^{-2}$ contribution to the lattice thermal resistivity. Observations by other authors using electron microscopy suggest that the defects are planar-vacancy-generated dislocation loops 75–100 Å in diameter. The loop density is calculated from the thermal resistivity and is found to be in reasonable agreement with the electron-microscopy results. In the second sample, deformed in tension at room temperature and then annealed at 573 °K prior to irradiation, the same irradiation treatment produced a contribution to the lattice resistivity which was similar in temperature dependence but larger, by a factor of 3, than that produced in the well-annealed specimen. A model for this effect is suggested, based on two distinct contributions to the radiation-produced thermal resistivity: (i) dislocation loops of similar size and concentration as in the well-annealed sample; (ii) reformation of solute atmospheres around dislocations. These atmospheres had been thermally dispersed by annealing; their reformation is due to enhanced solute diffusion resulting from a large vacancy concentration produced by irradiation. The work of Mitchell *et al.* has shown that solute atmospheres in Cu+10 at.% Al enhances phonon scattering by dislocations.

## I. INTRODUCTION

Recent theoretical and experimental work has shown that the study of phonon scattering in alloys, using low-temperature thermal-conductivity measurements, can yield information about the equilibrium arrangement of solute atoms in the strain fields of dislocations, i.e., impurity atmospheres, and about the rate at which this equilibrium is attained. The theory of the modification of dislocation thermal resistivity at low temperatures by impurity atmospheres (Klemens,[1,2] Ackerman and Klemens[3]) was substantiated by Mitchell *et al.*[4] in a study of the annealing characteristics of the dislocation thermal resistivity in Cu+10-at.%-Al polycrystals. These experiments also indicated enhanced diffusion of the solute atoms during deformation, causing rapid formation of the impurity atmospheres. It was suggested that vacancies produced during plastic deformation could account for this enhancement.

In this paper we report on a series of low-temperature thermal-conductivity measurements which attempt to determine if fast-neutron irradiation can also produce the enhanced diffusion necessary for impurity-atmosphere formation. Two Cu+9-at.%-Al polycrystals were studied. One was irradiated in the well-annealed condition to determine if any extended damage was produced which would give rise to phonon scattering in the temperature range

of interest (1–4 °K). The second sample was subjected to an identical irradiation after being deformed in tension and annealed to 573 °K, i.e., after the impurity atmospheres were first produced during the room-temperature deformation, and then thermally dispersed, while leaving the dislocations unchanged.

## II. BACKGROUND

The thermal conductivity of a metal or alloy is the sum of the electronic thermal conductivity $K_e$ and the phonon or lattice thermal conductivity $K_g$. At low temperatures the electron thermal resistivity $W_0$ is dominated by elastic scattering due to impurities, and $K_e$ is well represented by the Wiedemann-Franz Law

$$K_e = (L_0/\rho_0)T = (W_0)^{-1} ,$$

where $L_0$ is the ideal Lorenz ratio ($2.445\times10^{-8}$ W $\Omega$ °K$^{-2}$) and $\rho_0$ is the residual electrical resistivity. The lattice conductivity at low temperatures in well-annealed alloys is limited by the electron-phonon interaction. The lattice resistivity $W_{pe}$ due to this interaction was obtained theoretically by Makinson[5]:

$$W_{pe} = 1/BT^2 .$$

This temperature dependence has been well verified by experiment. Large residual resistivities (> 10 $\mu\Omega$cm) lead to deviations from this $T^{-2}$ dependence (Pippard, [6] Lindenfeld and Pennebaker, [7] Zimmerman[8]). In deformed specimens, both the electron-phonon interaction and dislocation scattering are dominant in the low-temperature regime. Klemens[9] has derived the lattice-dislocation resistivity $W_{gd}$ for both edge- and screw-type dislocations in the long-wavelength limit, and for both cases

$$W_{gd} \propto T^{-2}\gamma^2 N_d ,$$

where $\gamma$ is the Grüneisen constant and $N_d$ the dislocation density. In this theory most of the scattering occurs some distance from the core, allowing an elastic-continuum treatment, and for edge-type dislocations the dilatation $\Delta(r)$ at a distance $r$ from the core produces a local frequency change of a lattice wave of fixed wavelength given by

$$\omega = \omega_0[1 - \gamma\Delta(r)] .$$

At low temperatures and long wavelengths, point-defect scattering is negligible. A dilute impurity atmosphere in the strain field of an edge dislocation modifies the average properties of the strained region, thus modifying $W_{gd}$. The theory for this modification[1,3] considers substitutional impurities of mass difference $\beta$ and volumetric mismatch $\alpha$, where

$$\beta = \frac{1}{2}\left(\frac{m_0 - m_i}{m_0}\right) , \qquad \alpha = \left(\frac{V_i - V_0}{V_0}\right) ,$$

where the subscripts $i$ and 0 refer to the impurity and host, respectively, $m$ is the atomic mass, and $V$ is the atomic volume. It should be noted that $\alpha$ is the local distortion due to the impurity. The interaction energy between the strain field and solute used in this theory was first given by Cottrell and Bilby[10]:

$$U(r) = -\alpha K V_0 \Delta(r) , \tag{1}$$

where $K$ is the bulk modulus. They showed that this leads to a solute atmosphere in the strain field. The impurity concentration $c(r)$ for such an atmosphere is given by

$$c(r) = c_0^{-U/k_B T_a} \simeq c_0(1 - U/k_B T_a) . \tag{2}$$

Here $c_0$ is the impurity concentration prior to deformation, $T_a$ is the annealing temperature at which the atmosphere last attained equilibrium, and $k_B$ is the Boltzmann constant. The atmosphere then modifies phonon scattering by the strain field of its edge dislocation in three ways: (i) by changing the average mass of the dilated region away from the core; (ii) by changing the average dilation; (iii) by introducing a dependence on annealing temperature and time. The local frequency change near an edge dislocation with an atmosphere is

$$\omega = \omega_0\{1 - \gamma\Delta(r) + \beta[c(r) - c_0] - \alpha\gamma[c(r) - c_0]\} . \tag{3}$$

Substituting (1) and (2) for $c - c_0$ in Eq. (3), one obtains

$$\omega = \omega_0[1 - (\gamma + \gamma')\Delta(r)] , \tag{4}$$

$$\gamma' = (V_0 c_0 K/k_B T_a)(\gamma\alpha^2 - \alpha\beta) , \tag{5}$$

$$W_{gd} T^2 \propto (\gamma + \gamma')^2 N_d , \tag{6}$$

or

$$(W_{gd}/N_d)^{1/2} = I + M/T_a , \tag{7}$$

$$M = D^{1/2}(T_a/T)\gamma' , \qquad I = D^{1/2}(\gamma/T) , \tag{8}$$

where $D$ is a constant of dimension cm °K$^3$W$^{-1}$. The dependence of $W_{gd}$ on annealing time has also been considered. [2]

The dependence of $W_{gd}$ on solute concentration $c_0$ for the Cu-Al solid solution was investigated by Charsley *et al.*[11] by comparing measured values of $W_{gd}$ to dislocation densities determined by electron microscopy, and their results are in agreement with the above theory. Mitchell *et al.*[4] investigated both the dependence of $W_{gd}$ on annealing temperature and time, by a series of isochronal and isothermal annealing studies of deformed polycrystalline Cu + 10 at. % Al. The dependence on $T_a$ in Eqs. (7) and (8) was verified. The value of $M/I$ was found to be 183 °K, and $\alpha$ thus deduced was 0.23, in good

TABLE I. Sample history and resistivity data.

| Sample | Run No. | Sample history | $\rho_0(\mu\Omega$ cm)[a] | $L/A$ (cm$^{-1}$) |
|---|---|---|---|---|
| A | 1 | Vacuum annealed at 1273 °K for 18 h | 7.51 ± 0.02 | 37.50 ± 0.07 |
| | 2 | Vacuum sealed in quartz tube, irradiated for 6 h at the Brookhaven National Laboratory BMRR facility. Total fast-(> 1-MeV) neutron dosage $4\times10^{17}$/cm$^2$, total thermal dosage $1\times10^{15}$/cm$^2$, ambient temperature 25–60 °C. Sample remained at BNL for 4 weeks at room temperature. | 7.46 ± 0.02 | 37.57 ± 0.07 |
| B | 1 | Vacuum annealed at 1273 °K for 18 h | 7.60 ± 0.02 | 35.67 ± 0.07 |
| | 2 | Deformed in tension, 6.1%, at room temperature | 7.89 ± 0.08[b] | 47.4 ± 0.5 |
| | 3 | Vacuum annealed at 573 °K for 24 h | 7.90 ± 0.08 | 47.0 ± 0.5 |
| | 4 | Same irradiation treatment as sample A above | 7.83 ± 0.08 | 46.9 ± 0.5 |
| | 5 | Vacuum annealed at 573 °K for 24 h | 7.95 ± 0.08 | 46.6 ± 0.5 |

[a]Both $\rho(4.2)$ and $\rho(1.2)$ were measured, and had identical values.

[b]Larger uncertainty due to greater geometry-factor uncertainty after deformation.

agreement with x-ray results ($\alpha = 0.20$). The annealing-time results gave only fair agreement, due to experimental uncertainties. However, no dependence on annealing time at room temperature, after deformation at 77 °K, was found. Presumably the atmospheres formed to their room-temperature configuration faster than the samples could be mounted in the cryostat and cooled. It was suggested that vacancies produced during deformation substantially enhanced solute diffusion, allowing rapid formation of the atmospheres. Mechanisms for vacancy production during deformation are discussed by many authors (see, for example, Nabarro[12]).

## III. EXPERIMENTAL TECHNIQUES

### A. Samples

Two Cu + 9-at.%-Al polycrystals were studied. They were prepared by first making an homogeneous ingot of Johnsons and Mathey Specpure Cu(99.999% purity) and 4.07 wt% Al (99.99% purity) (supplied by the Jarrell Ash Co., Waltham, Mass.) in an evacuated quartz boat. Samples were obtained by casting pieces of this ingot into a precision-bore quartz capillary (0.1941-in. i.d., 6-in. length, supplied by the Wilmad Glass Co., Buena, N. J.) and quenching in an ice bath, which was agitated by a small ultrasonic cleaner. The resulting polycrystals had extremely uniform cross sections. The average grain size was about 1 mm. After the ends were threaded on a lathe, each sample was annealed *in vacuo* for 18 h at 1273 °K. Sample histories, geometry factors, and electrical-resistivity data are given in Table I.

### B. Conductivity Measurements

Both thermal- and electrical-conductivity measurements were made using standard dc techniques. Electrical resistivity was determined at 1.2, 4.2, 77, and 273 °K, using the method discussed by Gueths *et al.*[13] The probable error in these measurements was 0.2% for the undeformed cases and 1.2% after plastic deformation. This was determined primarily by the geometry factor $L/A$ ($L$ length, $A$ cross-sectional area). This factor had a larger uncertainty after deformation, due to some cross-section irregularities.

Germanium resistance thermometers were used as temperature sensors for all thermal-conductivity determinations. These were mounted to the same clamps used for resistivity-potential measurements. These clamps were removed from the sample during each treatment, and were replaced on the same positions by means of two reference scratches made prior to the initial 1273 °K anneal. This assured that determinations were made on the same sections for all treatments, the maximum variation being 1%. The 1–4 °K thermometers were calibrated against $He^4$ vapor pressure and were mounted directly in the bath during the calibration run. A total of 35 $R$-vs-$T$ points were taken for each thermometer and fitted to the standard equation:

$$\frac{1}{T} = A + \frac{B}{\ln R} + C\ln R + \frac{D}{(\ln R)^2} + E(\ln R)^2 .$$

Deviation curves for this fit were very smooth

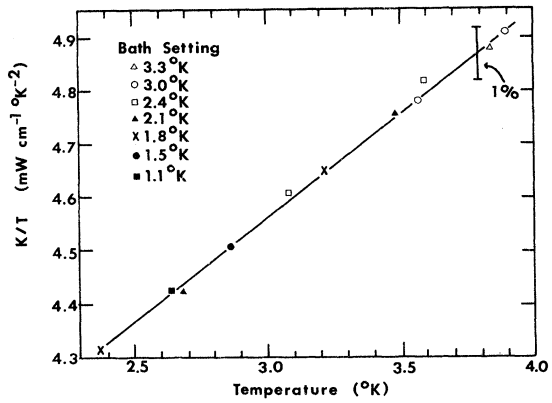


FIG. 1. $K/T$-vs-$T$ plot on exaggerated scales, showing typical consistency of the 1–4 °K thermal-conductivity data, as indicated by the close overlap of the low- and high-power points at successive bath settings.

through the $\lambda$ point, an indication of a good calibration. The calibration for the 4–77 °K thermometers is described by Karamargin.[14]

All thermal-conductivity determinations were of the steady-state longitudinal-heat-flow type, with one end of the sample thermally grounded to the bath (1–4 °K) or thermal platform (4–77 °K), and the sample enclosed in evacuated containers. The consistency of the data in the 1–4 °K range was extremely good, as evidenced by Fig. 1, showing the overlap for data taken at different bath settings on a typical run. The points are the low- and high-power determinations at a number of bath settings, and are displayed in the usual $K/T$-vs-$T$ format, with exaggerated scales. Since, for these samples,

$$K = K_e + K_g = AT + BT^2 \ ,$$

then a $K/T$-vs-$T$ plot yields a straight line. The scatter is seen to be small, indicating a good thermometer calibration, since the thermometers are reading considerably different temperatures at the low-power point of one bath setting and the high-power point of the next lower setting. Also, the excellent overlap indicates negligible errors due to thermal emf's and instrumentation. Data taken over the two ranges (1–4 and 4–77 °K) are very consistent, even though two separate cryostats and calibrations were utilized. All the 1–4 °K thermal-conductivity data for this work are shown in Figs. 2–4, in the usual $K/T$-vs-$T$ format.

### C. Lattice Conductivity

For these samples, in the range 1–30 °K, the lattice conductivity $K_g$ is about 30% of the measured total thermal conductivity $K$, and was obtained from $K$ by means of the Wiedemann-Franz Law

$$K_g = K - \frac{L_0 T}{\rho_0} \ .$$

The probable error in $K_g$ in the 1–4 °K range is 1.5% for the undeformed cases and 3% after plastic deformation, the geometry factor again being dominant. The deviation of the $K/T$ intercept from $L_0/\rho_0$ evident in Figs. 2–4 of all the data is believed to be a genuine effect, which does not affect the uncertainty in $K_g$, and is discussed in Sec. IV. The higher temperature determination of $K_g$ has a maximum experimental uncertainty of 3%; above 30 °K the present analysis breaks down, because of the ideal electronic thermal resistance.

The dislocation thermal resistivity $W_{gd}$ is determined experimentally by measuring the sample in the well-annealed state, thereby determining $W_{pe}$:

$$W_{pe} = (K_g)^{-1}_{\text{well anneal}} \ , \qquad (9)$$

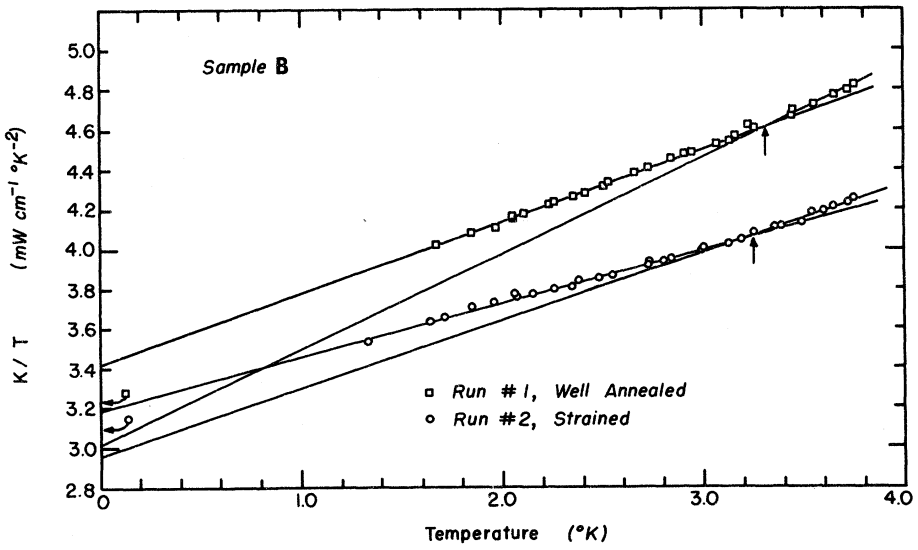


FIG. 2. 1–4 °K conductivity data for sample B in the well-annealed and deformed state. The Wiedemann-Franz Law should hold for this sample, the lattice conductivity should be proportional to $T^2$, and the $K/T$ intercept should be $L_0/\rho_0$. The value for $L_0/\rho_0$ for each run is indicated, as is the approximate temperature where there is some discontinuity or curvature. This behavior is characteristic of all the data of this work.

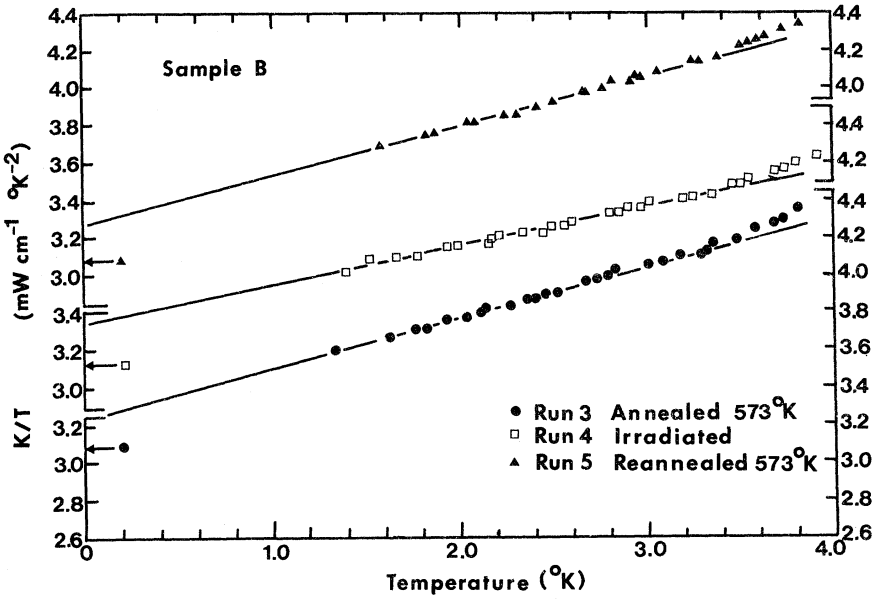


FIG. 3. $K/T$-vs-$T$ data for sample B, runs 3–5. The $L_0/\rho_0$ value for each run is indicated by the arrow on the $K/T$ axis.

and then in the deformed state:

$$(K_g)^{-1}_{\text{deformed}} = W_{pe} + W_{gd} \,. \tag{10}$$

Thus it is assumed that $W_{pe}$ is unchanged by cold-working and that the two lattice resistances are additive. This latter approximation is discussed by Klemens[15] and should be valid when the resistive mechanisms have similar frequency dependence, as is the case for the electron-phonon and dislocation scattering.

## IV. RESULTS AND DISCUSSIONS

### A. $K/T$ vs $T$

In Fig. 2 the total thermal conductivity for the first two runs on sample B, well annealed and deformed, is shown on the $K/T$-vs-$T$ format. Some discontinuity or curvature appears at about 3.3 °K in both cases. More important, however, is the fact that the $K/T$ intercept of the data below about 3.3 °K is always higher than $L_0/\rho_0$, predicted by the Wiedemann-Franz Law for a lattice conductivity proportional to $T^2$. This effect appears in all the $K/T$-vs-$T$ data of this work, as seen in Figs. 3 and 4. Mitchell[4] found the same effect on similar samples and attributed the anomaly to deviations from a pure $T^{-2}$ dependence in $W_{pe}$, due to the short electronic mean free path.[7] Leaver and Charsley[16] found no anomalies in well-annealed samples, and ascribed the effect to nonuniform arrays of dislocations, which become ineffective as phonon scatterers at low temperatures when the

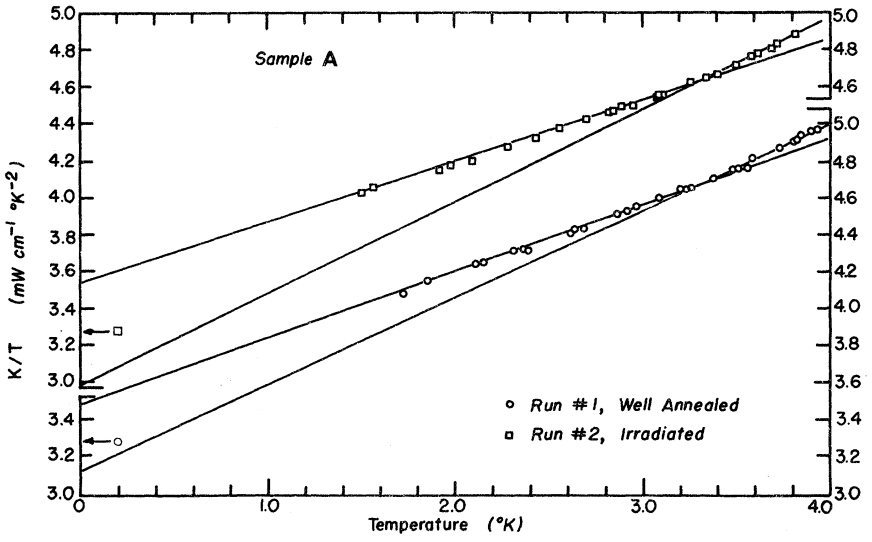


FIG. 4. $K/T$-vs-$T$ data for sample A, runs 1 and 2, in the range 1–4 °K. The $L_0/\rho_0$ value for each run is indicated by the appropriate arrow on the $K/T$ axis.

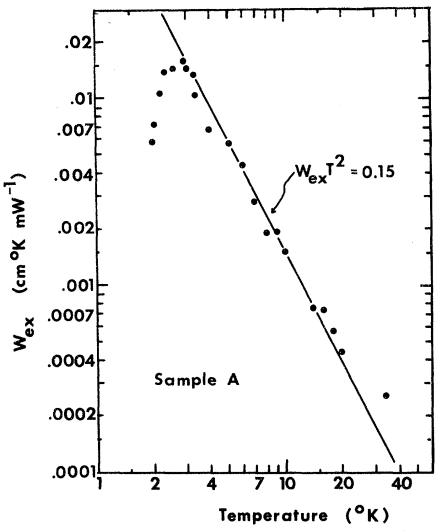


FIG. 5. Extra lattice thermal resistivity $W_{ex}$, defined by Eq. (6), produced in the well-annealed sample A by neutron irradiation.

dominant phonon wavelength becomes comparable to the size of the array. The present data support the $W_{pe}$ explanation, since also the well-annealed $K/T$-vs-$T$ data for both samples cannot be adequately fit with a single straight line, which has a $K/T$ intercept of $L_0/\rho_0$, and since an explanation involving dislocation scattering would not apply in that case.

### B. Sample A (Annealed and Irradiated)

In Fig. 5 the extra lattice thermal resistance $W_{ex}$ produced by neutron irradiation in the well-annealed sample A is plotted, where

$$W_{ex} = \left(\frac{1}{K_g}\right)_{\text{irrad}} - \left(\frac{1}{K_g}\right)_{\text{well anneal}} . \qquad (11)$$

This resistivity corresponds to a decrease in lattice conductivity of 5% in the range 3–40 °K. Data for this temperature range were obtained using two separate cryostats and thermometer calibrations, so this effect, even though it is small, must be considered genuine. At 2.5 °K the decrease is 3%, and becomes even smaller at the lowest measurement temperatures. While changes in lattice conductivity less than 3% are difficult to resolve, it is clear that the temperature dependence of the extra resistance from 40 down to 3 °K is not continued below 3 °K.

The data above 3 °K are seen to be adequately represented by

$$W_{ex}T^2 = 0.15 \text{ cm °K}^3\text{mW}^{-1} .$$

Only dislocations and electrons give rise to a $T^{-2}$ thermal resistivity in the long-wavelength limit. Koppenaal *et al.*[17] have observed the defect structure in a series of neutron-irradiated Cu-Al $\alpha$-phase solid solutions using electron microscopy. Two types of defects were found in pure Cu: large dislocation loops up to 500 Å in diameter, and smaller loops 75–100 Å in diameter. Specimens of Cu with 5 at.% Al and 14 at.% Al exhibited defects of the second type only, which they identified as planar-vacancy loops, that is, dislocation loops produced by the collapse of vacancy platelets. Using the complete expression[9] for $W_{gd}$, we find that $W_{ex}T^2 = 0.15$ corresponds to a line density of $1\times10^9/\text{cm}^2$, or to a total dislocation line length per volume of $2\times10^9$. If the loops are 75–100 Å in diameter, then the average loop length is 300 Å, giving $6\times10^{14}$ loops/cm$^3$ in this sample. Since each loop may be thought of as a partial collapse of a platelet of vacancies 100 Å across, then each platelet contains about $10^3$ vacancies, and the observed loop density corresponds to a vacancy concentration of $6\times10^{17}/\text{cm}^3$ or $0.6\times10^{-5}$. Each platelet of vacancies is thought to be produced at the center of a displacement spike, and the larger loops in pure Cu grow by migration of single vacancies or other clusters.[18] In pure Cu, Silcox and Hirsch[18] observed defect concentrations of $3\times10^{15}$/cm$^3$ (large and small loops) for fast-neutron dosages of $6\times10^{17}/\text{cm}^3$. Our estimate of $6\times10^{14}$ loops/cm$^3$ for a fast dosage of $4\times10^{17}/\text{cm}^3$ is deemed reasonable. It is of interest to note that the decrease of $W_{ex}$ below 3 °K may in part be due to the increasing ineffectiveness of defects of this size as phonon scatterers, since the dominant phonon wavelength in Cu at 3 °K is about 300 Å, so that opposite sides of the loop would interfere in the scattering.

### C. Sample B (Deformed and Irradiated)

After measuring sample B in the well-annealed state, it was deformed in tension at room temperature, which introduced a dislocation density of about $5\times10^{10}/\text{cm}^2$, as estimated from $W_{gd}$. In addition, each impurity atmosphere attained an equilibrium concentration characteristic of room temperature. Annealing to 573 °K presumably left the dislocation structures unchanged (since recrystallization begins at over 700 °K in this system[4]) but reduced $W_{gd}$, by Eq. (2), using $M/I = 183$ °K$^4$:

$$W_{gd}(573) \simeq 0.7\,W_{gd}(300) .$$

The sample was then subjected to the identical irradiation treatment as sample A. In Fig. 6 the extra thermal resistivity produced by irradiation in both samples is shown in the range 2–4 °K, where for sample B we have

$$W_{ex} = \left(\frac{1}{K_g}\right)_{\text{irrad}} - \left(\frac{1}{K_g}\right)_{573\ ^\circ\text{K anneal}} . \qquad (12)$$

The resistances are similar in temperature dependence, but the radiation-produced resistance in sample B is 2–3 times larger than in sample A. Figure 7 indicates the essential features of the measurement series on sample B. It is evident that after reducing $W_{gd}$ by the 573 °K anneal, neutron irradiation increased $W_{gd}$ to its value after deformation in the 1.5–2.5 °K range, and caused a further increase in $W_{gd}\,T^2$ of about 0.15 cm °K$^3$ mW$^{-1}$ in the 2.5–4.0 °K range. Since this extra resistance of $(T^{-2})$ 0.15 cm °K$^3$ mW$^{-1}$ is the same as the loop resistance produced in the well-annealed sample A, we suggest that the effect of irradiation on sample B after the 573 °K anneal was to (a) permit reformation of the impurity atmospheres to their strength after deformation via enhanced solute diffusion due to vacancies, and (b) introduce the same concentration of 75–100-Å-diam vacancy loops as in the well-annealed sample A. Additional evidence for enhanced solute diffusion during irradiation is found in the values of the ice-point electrical resistivities for both samples. A decrease of 0.07 $\mu\Omega$ cm was observed after irradiation in each case. Similar decreases, measured in-pile, have been observed by Wechsler and Kernohan[19] in Cu-Al samples for similar dosages. Their results are analyzed in terms of enhanced diffusion of the Al impurities, leading to short-range order and a resistivity decrease.

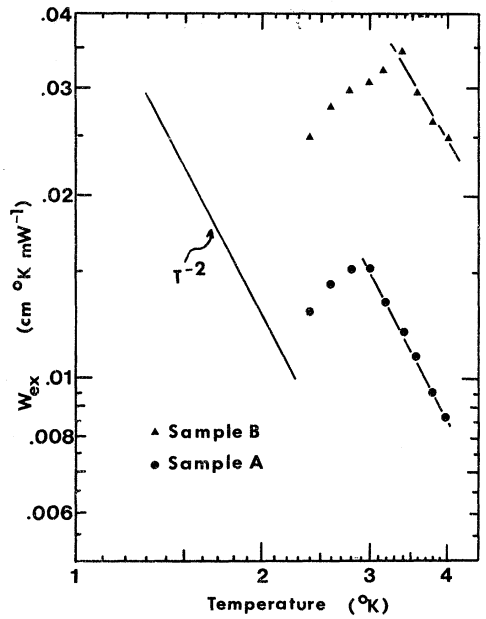


FIG. 6. Comparison of the extra lattice thermal resistivity $W_{ex}$, defined by Eq. (7), produced by neutron irradiation in sample B, after being deformed at room temperature and annealed at 573 °K, with that produced by the same radiation treatment in the well-annealed sample A.

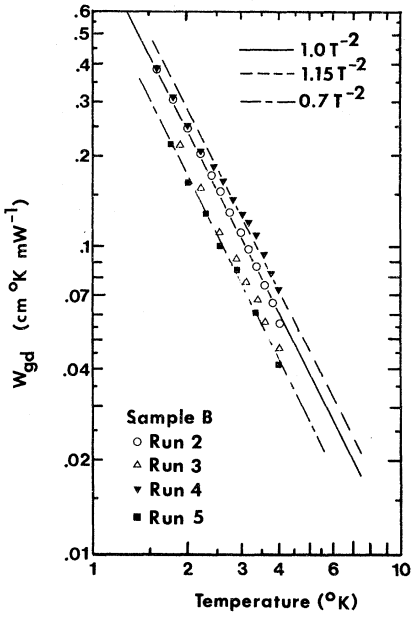


FIG. 7. Dislocation thermal resistivity $W_{gd}$, defined by Eqs. (4) and (5), of sample B after deformation at room temperature (run 2), annealing for 24 h at 573 °K (run 3), irradiation (run 4), and reannealing at 573 °K (run 5).

The second 573 °K anneal produced essentially the same $W_{gd}$ as did the first, indicating that, in addition to dispersing the atmospheres, this annealing treatment might have been sufficient to remove many of the loops. Silcox and Hirsch[18] reported that after annealing their irradiated Cu samples for eight hours at 623 °K, the loop concentration, initially $3\times10^{15}$/cm$^3$, was reduced by better than an order of magnitude, and that some areas of the samples were free of detectable defect densities.

## V. SUMMARY

Using low-temperature lattice-thermal-conductivity determinations on bulk specimens measured out-of-pile, we have detected two effects due to neutron irradiation in Cu + 9-at.%-Al polycrystals: (i) Extended defects are produced, which scatter phonons like dislocations above 3 °K, but are increasingly ineffective below 3 °K, and which have been identified by other authors in the same material as planar-vacancy loops, 75–100 Å in diameter. (ii) Solute diffusion is enhanced by the excess vacancy concentration due to irradiation, permitting reformation of solute atmospheres in the long-range strain fields of edge dislocations.

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# Elastic Moduli and Magnetic Susceptibility of Monocrystalline $Nb_3Sn$

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The elastic moduli $c_{11}$, $c_{12}$, and $c_{44}$ and the magnetic susceptibility $\chi$ of single-crystal $Nb_3Sn$ have been measured as a function of temperature below 300 K. Detailed comparison is made between the experimental results and the predictions of simple one-dimensional band models. It is found that the behavior of the elastic moduli $c_{11}$ and $c_{12}$ above and below the cubic-tetragonal transformation at 45 K is well accounted for by the band model with an effective Fermi temperature of 80 K. Unlike the case of $V_3Si$, the modulus $c_{44}$ is observed to undergo a considerable softening at low temperatures. This softening is not predicted by the theory. The susceptibility displays the predicted maximum near the lattice-transformation temperature. However, the decrease of $\chi$ in the tetragonal state, associated with a drop in the electronic density of states, is not nearly as large as expected. Furthermore, the cubic-state $\chi$ data indicate a much larger Fermi temperature (230 K) than is obtained from the $c_{11}$ and $c_{12}$ data. We review these anomalies in terms of available band-structure calculations. The implications of our experimental results for superconductivity in $Nb_3Sn$ are discussed.

## I. INTRODUCTION

The $\beta$-tungsten compounds $Nb_3Sn$ and $V_3Si$ show a crystallographic transformation[1,2] from a high-temperature-cubic to a low-temperature-tetragonal lattice state which causes a number of physical quantities to behave anomalously. Strong temperature variations have been observed for the magnetic susceptibility[3] and the Knight shift[4] in $V_3Si$ and for the isomer shift in Mössbauer experiments[5] on