Second, because of uncertainties in the equation of state of molecular hydrogen at high densities, estimates of the pressure required to obtain metallic hydrogen are varied.[13] However, pressures somewhat less than a megabar are typical of these estimates and we remark that pressures in the 600-kbar range are presently available in the laboratory. The range will no doubt be increased and this presents the possibility of developing a high-temperature superconductor stable in the practical sense[14] near atmospheric pressure. An estimate of the possible upper bound on T_C will hinge, of course, on a more detailed estimate of the umklapp contributions to N_0V.

It is a pleasure to thank Professor J. Krumhansl for many helpful discussions, Professor R. Bowers for his critical remarks, and Professor D. Langreth for his valued comments.

---

*Work supported in part by the Advanced Research Projects Agency through the Materials Science Center at Cornell University, Report No. 928, and in part by the National Science Foundation.

[1]J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 108, 1175 (1957).

[2]When applied to metallic hydrogen, whose ions are point charges, this approximation becomes exact.

[3]D. Pines, Phys. Rev. 109, 280 (1958).

[4]E. Wigner and H. B. Huntington, J. Chem. Phys. 3, 764 (1935); R. Kronig, J. deBoer, and J. Korringa, Physica 12, 245 (1946); W. C. De Marcus, Astron. J. 63, 2 (1958); A. A. Abrikosov, Astron. Zh. 31, 112 (1954).

[5]This is strictly a metastable phase. Calculation of the barrier between metallic and molecular phases shows it to be about 0.2 eV/electron.

[6]N. W. Ashcroft and D. C. Langreth, Phys. Rev. 155, 682 (1967).

[7]Notice that for Al, $\alpha^2=1$ predicts $N_0V<0$.

[8]If we take $\alpha^2=0.3$, then $N_0V=0.25$. Note that $\alpha^2=0.2$ in metallic hydrogen.

[9]As r_s decreases, Θ_D increases roughly as r_s^{-1}. This partly compensates the accompanying decrease in N_0V.

[10]This assumes that the screening of the conduction electrons does not alter the bonding on the H_2^+ by the σ orbital.

[11]Notice that the r_s value of 1.6 is not far outside the value 2.07 (corresponding to metallic Al) for which the BCS theory is successful. Corrections arising from possible strong-coupling effects should not seriously alter the conclusions.

[12]For a summary of the data, see G. M. Michaux, Handbook of the Physical Properties of the Planet Jupiter, National Aeronautics and Space Administration Publication No. SP-3031 (U. S. Government Printing Office, Washington, D. C., 1967). The inner core of Jupiter is thought to be composed of helium. This may also be metallic under high pressure, first with He^+ ions and subsequently with He^{++}. At corresponding r_s values the latter has a lower Debye temperature than H^+, but being polyvalent, its N_0V value is higher and superconductivity in high-density He^{++} is also a possibility.

[13]The transition pressure is found from the common tangent to the energy-density curves for metallic and molecular hydrogen. The curve for the metal has a minimum (at a density lower than that of the contact point on the tangent) and the metal is metastable here at zero pressure.

[14]See Ref. 5. The question of long-term stability at zero pressure is open at the moment.

STRESS-INDUCED ORDERING OF POINT DEFECTS IN COPPER NEAR 10°K*

R. Nielsen† and J. R. Townsend
Department of Physics, University of Pittsburgh, Pittsburgh, Pennsylvania
(Received 20 November 1968)

An anelastic process near 10°K has been found in proton-irradiated copper. It is tentatively identified as the result of stress-induced ordering of the interstitial member of a close pair. The reorientation occurs without annealing being observed. The thermal activation energy for reorientation is 0.015 eV; the strain symmetry axis is in the ⟨111⟩ direction.

The low-temperature behavior of point defects produced in copper by irradiating with energetic particles has been extensively studied in recent years.[1-5] These investigations have yielded much information concerning the annealing of these defects but have left clouded the issue of the atomic configuration of certain defects. By studying the mechical response of a sample to an alternating stress, one can in principle observe the stress-induced ordering of those defects with a strain field whose symmetry is lower than that of the lattice. By observing the effect of applying the stress along different crystallographic directions in single-crystal samples, any preferred orientation of the defect strain field may be investigated.

These measurements have been performed dur-

ing and after exposure to 9-MeV protons produced by the Van de Graaff accelerator at the Nuclear Physics Laboratory of the University of Pittsburgh. The samples were mounted on a piezoelectric bender bimorph and electrostatically driven as a cantilevered bar in transverse flexure at their resonant frequencies ranging from 600 Hz to 8 kHz. In this method the alternating stress is produced longitudinally along the sample; so the resonant frequency is directly proportional to the square root of the effective Young's modulus of the material.[6] The internal friction was determined during the free decay of the sample using the electronic method described by Swartz.[7] The temperature of the samples during the irradiations was maintained below 15°K at all times.

The polycrystalline copper samples were cut approximately 1 cm long from wire, 0.005 in. in diameter. The wire was obtained from the Sigmund Cohn Co., Mt. Vernon, New York and was stated to be 99.999% pure. The wire was first rolled to an oval cross section with a small axis of approximately 0.004 in. and then annealed in a vacuum furnace at 600°C or above. Following this anneal, the resistivity ratio [R(300°K)/R(4.2°K)] was measured; it varied from 800 to 1000. The single-crystal samples were spark cut from a pure copper single crystal grown by Fiore and Bauer at the Carnegie Institute of Technology. The samples were etched and chemically polished to their final size by an acid solution. The crystallographic orientation of the longitudinal axis of the samples was either ⟨100⟩ to within 1° or ⟨111⟩ to within 3°, as determined from full-rotation x-ray photographs.

After irradiation, a typical anelastic internal-friction peak was observed at about 9.5°K in five polycrystalline and in two ⟨111⟩-oriented single-crystal samples (see Fig. 1). The peak did not appear in two ⟨100⟩-oriented single-crystal samples. Associated with the peak was a relaxation modulus defect approximately equal to the height of the internal-friction peak. The width at half-maximum of the peak was about 2°K, which is about 30% wider than would be expected theoretically, assuming a standard linear solid with a single activation energy and a single relaxation time. From the temperature shift of the peak maximum for different resonant frequencies, the energy of activation for the contributing process was determined to be 0.015 ± 0.002 eV and the attempt frequency was $8 \times 10^{11 \pm 1}$ sec^{-1}.

The internal-friction peak was not affected by temperature annealing to about 25°K. Ten-minute isochronal anneals at 2°K intervals show the peak decreasing in height from 26 to 38°K (see Fig. 2). Since the peak was thermally stable, it was possible to observe the peak height as a function of integrated beam flux. The height of the

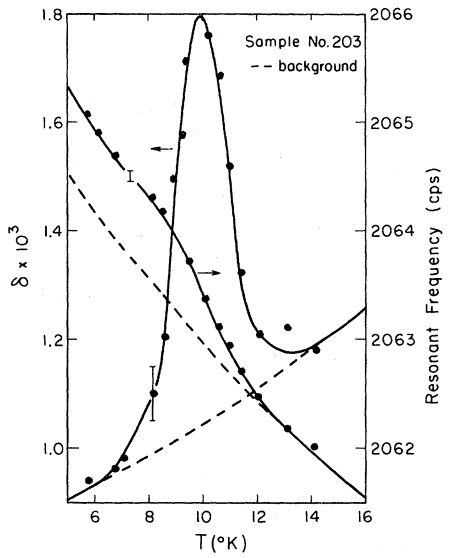

FIG. 1. Temperature dependence of internal friction δ and fundamental frequency of a cantilevered Cu single crystal. Longitudinal stress is parallel to ⟨111⟩ crystallographic axis. Background frequency curve based on post-anneal results.

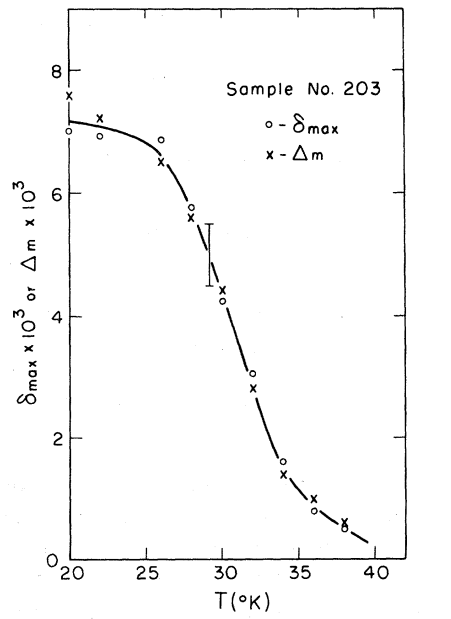

FIG. 2. Effect of 10-min isochronal anneals at indicated temperatures on data of Fig. 1. Δ_m is $2[f\text{-}f(\text{background})]/2063$.

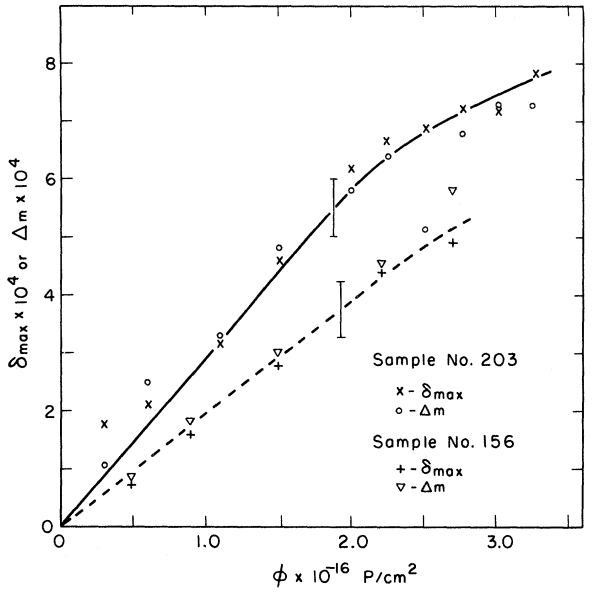

FIG. 3. Growth of an anelastic process near 10°K with integrated proton flux. Sample 203 is a single crystal with stress parallel to ⟨111⟩ axis; sample 156 is a polycrystalline wire.

peak grew linearly with increasing irradiation dose with a slope of $(0.19 \pm 0.02) \times 10^{-3}/(10^{16} p/\mathrm{cm}^2)$ for a polycrystalline sample and $(0.29 \pm 0.03) \times 10^{-3}/(10^{16} p/\mathrm{cm}^2)$ for a ⟨111⟩-oriented single-crystal sample (see Fig. 3).

The absence of this internal-friction peak in the ⟨100⟩-oriented single-crystal samples indicates that the ⟨100⟩ axis is a neutral axis for the strain field of the defect. This indicates that the symmetry axes for the defect strain field lie along the ⟨111⟩ crystallographic axes. The defect which contributes to the internal-friction peak anneals in a temperature range around 32°K, which is the same temperature range in which resistivity recovery is found. The resistivity recovery in this temperature range is usually designated as stage I_b or I_c and is attributed to the mutual annihilation of interstitial-vacancy close pairs. The energy of activation for the interstitial migration thought to occur in stage I_b or I_c is about 0.09 eV.[2]

The linear dependence of the peak height on integrated flux, the large attempt frequency of 8×10^{11} Hz, and the pronounced dependence on crystal orientation all point toward stress-induced reorientation of a point defect as the source of this anelastic process. That annealing occurs in the stage-I_b or -I_c region suggests that a close pair is the defect responsible. It would seem likely that the interstitial member of the close pair has several reorientations available which produce a strain with symmetry about the ⟨111⟩ direction. These reorientations are separated by activation-energy barriers of 0.015 eV compared with an activation energy for annealing of 0.09 eV.

The contributions of Dr. Donald Stabell in the form of assistance and helpful discussions are gratefully acknowledged as is the cooperation of the Van de Graaff personnel.

---

*Research supported by the U. S. Atomic Energy Commission.

†Present address: Autonetics Division, North American-Rockwell Co., Anaheim, Calif.

[1]A. C. Damask and G. J. Dienes, Point Defects in Metals (Gordon and Breach Publishers, Inc., New York, 1963), pp. 261-294.

[2]J. W. Corbett, R. B. Smith, and R. M. Walker, Phys. Rev. 114, 1452 (1959).

[3]A. Sosin and H. N. Neeley, Phys. Rev. 127, 1465 (1962).

[4]C. J. Meechin, A. Sosin, and J. A. Brinkman, Phys. Rev. 120, 411 (1960).

[5]G. D. Magnuson, W. Palmer, and J. S. Koehler, Phys. Rev. 109, 1990 (1958).

[6]P. M. Morse, Vibration and Sound (McGraw-Hill Book Company, Inc., New York, 1948), pp. 157-161.

[7]J. C. Swartz, Rev. Sci. Instr. 35, 1573 (1964).