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**ELECTRICAL RESISTANCE OF YTTERBIUM
AS A FUNCTION OF TEMPERATURE AND PRESSURE**

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ELECTRICAL RESISTANCE OF YTTERBIUM AS A FUNCTION OF TEMPERATURE AND PRESSURE

Abstract

We have measured the piezoresistance of ytterbium from three sources at pressures up to 40 kbar and at temperatures between 21 and 90°C under hydrostatic and quasi-hydrostatic conditions. From our data, from calculations of Hugoniot state temperatures, and from the geometrical effect of plane strain on resistance, we also calculated the piezoresistance of ytterbium along the Hugoniot. Our computed results agree with the experimental Hugoniot data of Brown for the same samples to within 10%. Considering the approximate calculations we used as well as possible errors in the experimental

measurements, this agreement is good.

Although resistance hysteresis upon unloading from the Hugoniot is observed in shock studies, we saw no measurable hysteresis at constant temperatures below the fcc-to-bcc transition. Only minor resistance hysteresis would be predicted on the basis of the temperature differences between the Hugoniot and the release states. The fcc-to-bcc transition in ytterbium, which occurs between 37 and 39 kbar at room temperature, is predicted to occur between 34 and 35 kbar along the Hugoniot as the transformation pressure decreases with increasing temperature.

Introduction

The electrical properties of ytterbium as a function of pressure have received considerable study, particularly at room temperature and lower.¹⁻⁶ Since we were primarily interested in comparing our measurements with those obtained in shock-wave studies, our measurements covered the expected temperature ranges of the Hugoniot and the isentropic release paths.

We used the four-lead electrical-resistance system described by Stromberg and Jura⁷ in a 40-kbar piston-and-cylinder system. We also used a four-lead electrical-resistance system in a hydrostatic system in conjunction with a resistance bridge and a null detector that was capable of resolving $1 \times 10^{-4} \Omega$.

Experimental Procedure

Stromberg and Stephens¹ obtained electrical-resistance data with a Bridgman

anvil system that used the four-lead electrical-resistance system described

by Stromberg and Jura.⁷ In our experiments with the piston-and-cylinder system, we used a similar setup. Figure 1 shows the details of our equipment. A constant current passed through the sample via the piston and the back-up block, and the voltage drop was measured independently by means of two copper leads. A calibrated strain-gage load cell was used to measure the force on the piston, and a continuous record of resistance versus pressure was obtained with an x-y recorder.

The pressure system was calibrated by means of a calibrated load cell and an S-R-4 box. The internal friction was obtained with the method described by Stephens,⁸ in which displacement is measured by a rectilinear potentiometer and applied force is measured by a load cell. These two signals are displayed on an x-y recorder while the pressure is increased and decreased. After the cell was pressed to the maximum pressure, we obtained a hysteresis loop of piston displacement versus pressure, which established the friction described by Bridgman.⁹

In our experiments with the hydrostatic system, the resistance was measured with a four-lead system that employed a Müller resistance bridge and a null detector. The temperature was monitored with a Chromel-Alumel thermocouple that was 0.6 cm from the ytterbium wire. The pressure was measured with a 7-kbar Heise gage. Figure 2 shows the details

Fig. 1. Piston-and-cylinder system used to measure the electrical resistance of ytterbium as a function of temperature and pressure.

of the setup. The pressure-transmitting medium was a diffusion-pump oil.

In the hydrostatic system, both the pressures and the resistances are known to within 0.5%. In the piston-and-cylinder system, the pressures are known to within 2% and the resistances to within 1%.

Fig. 2. Hydrostatic system used to measure the electrical resistance of ytterbium as a function of temperature and pressure.

Sample Description

Samples were cut from a 0.001-in.-thick foil obtained from Stephen R. Brown (designated "LRL ytterbium") and from a 0.003-in.-thick foil obtained from Harold

D. Stromberg ("Stromberg ytterbium"). Gold tabs were used on the ends of these samples to reduce contact resistance. A third sample consisted of a Stanford

Research Institute ytterbium shock-wave grid ("SRI ytterbium") that was sent to us by Douglas D. Kechugh. The source of all three materials was the Research Chemicals Company, and the stated

purity was 99.9 wt%. Anionic impurities such as oxygen usually are not included in such a statement of purity, and purity probably varies from one batch to another.

Results and Discussion

HYDROSTATIC DATA

The data we obtained from our hydrostatic study are summarized in Fig. 3. The behavior of the SRI ytterbium is somewhat different from that of the LRL ytterbium. Note that the resistance data for the LRL ytterbium upon loading and unloading are quite reproducible and show no pressure hysteresis.

The resistance of the LRL ytterbium can be expressed by

$$\frac{R(P,T) - R_0}{R_0} = 0.0016 (T - 21) + [0.0616 - 3.3 \times 10^{-5} (T - 21)]P + [0.00233 - 5 \times 10^{-6} (T - 21)]P^2, \quad (1)$$

where $R(P,T)$ is the resistance at pressure P (kbar) and temperature T (°C) and R_0 is the resistance at 1 atm and 21°C. This equation should be valid from room temperature to 80°C and at pressures up to 7 kbar. Our experimental data are fitted by the equation to within 1%.

40-kbar DATA

The data on relative resistance versus pressure that we obtained with the piston-and-cylinder system are shown in Figs. 4 and 5 and in Tables 1 and 2. The resistance data in Fig. 4 are corrected to agree with the hydrostatic data at pressures of

5 kbar or less. The data in Fig. 5 show that ytterbium samples from different sources exhibit somewhat different piezoresistances.

At room temperature, the resistance of the ytterbium from all three sources increases rapidly to about 7.5 times the 1-atm resistance at an average pressure of 37 kbar, where a phase transition takes place. The resistance then decreases rapidly to an R/R_0 of 0.8 at 43 kbar.

The transition pressures and the maximum resistances measured by static techniques at room temperature vary from one investigator to another, as is shown in Table 3. The presence of various amounts of impurities in the samples is believed to be one of the reasons for the differences. However, we believe that the pressures in our piston-and-cylinder system are closer to hydrostatic than those in the systems used by other workers, and since ytterbium is a semiconductor at pressures above 10 to 14 kbar, some of the differences may be due to the well known sensitivity of semiconductors to nonhydrostatic stresses.

Hall et al.¹⁰ have shown that the transition in ytterbium is from fcc to bcc. Our data as well as those of many other investigators show that there is considerable hysteresis in the transition at room temperature. Under increasing pressure the

Fig. 3. Resistance of ytterbium as a function of temperature and hydrostatic pressure.

transition begins at 37 kbar and ends at about 43 kbar, while under decreasing pressure the reverse transition begins at 16 kbar and ends at 10 kbar. At higher

temperatures, however, there is somewhat less hysteresis. At 90°C the resistance rises to about 6 times the 1-atm resistance at 34.5 kbar, then decreases

Fig. 4. Resistance of LRL ytterbium as a function of temperature and pressure.

rapidly to 0.8 times the 1-atm resistance at 41 kbar. Under decreasing pressure, the resistance remains nearly constant until about 17 kbar, where the resistance increases. At about 13 kbar, the resistance reaches a maximum, then decreases to the 1-atm value.

Thus, the fcc-to-bcc transition is hysteretic, and hence resistance data at pressures above the transition are also hysteretic. However, we have shown that at constant temperatures there is no resistance hysteresis at pressures within the stability field of the fcc phase.

REDUCTION TO HUGONIOT AND RELEASE-ISENTROPE RESISTANCES

In order to compare the above data to resistances obtained by shock-wave techniques, we must first calculate the temperatures due to shock loading and isentropic release and convert them to $R(P, T)$. Then we must take into account the geometrical effect of plane-strain loading (see Ref. 11).

The temperatures calculated according to the method of Walsh and Christian¹² are shown in Fig. 6, where the temperatures along the Hugoniot and several

Fig. 5. Resistance of ytterbium at 21°C as a function of pressure.

Table 1. Resistance versus pressure of LRL ytterbium at 2°C.

Pressure (kbar)	R/R_0	Pressure (kbar)	R/R_0
0	1.000	42.5	0.780
5	1.366	40	0.80
10	1.94	30	0.87
15	2.75	20	0.98
20	3.74	15.8	1.08
25	4.87	14	1.62
30	6.10	13.5	2.00
35	7.16	10	1.77
36.7	7.38	5	1.27
39.5	3.70	0	1.00

Table 2. Resistance versus pressure of LRL ytterbium at 90°C.

Pressure (kbar)	R/R_0^a	Pressure (kbar)	R/R_0^a
0	1.22	42.5	0.880
5	1.457	40	0.90
10	1.93	30	0.98
15	2.63	20	1.13
20	3.49	16.5	1.24
25	4.39	13.5	2.16
30	5.31	10	1.83
34.6	6.05	5	1.39
36.5	4.76	0	1.22
37	3.20		

^aNormalized to room temperature.

Table 3. Transition pressures and maximum resistances of ytterbium at room temperature as measured by various investigators.

Investigator	Transition pressure (kbar)	Maximum resistance (R/R_0)
Stromberg and Stephens ¹	39	23
Bridgman ²	41 ^a	13
Stager and Drickamer ³	38	~6
Souers and Jura ⁴	40	11
McWhan et al. ⁵	40	~11
King and Harris ⁶	33	8.5
This work	37	7.4

^aCorrected.

release states (which are assumed to be isentropic) are shown. The pressure-versus-volume data were taken from Stephens,⁸ as was the initial compressibility. The heat capacity and the thermal expansion were taken from Gschneidner.¹³ The Grüneisen parameter, $\gamma = (V\alpha)/(\beta C_V)$, was then 1.10, where V is the volume, α is the volume coefficient of thermal expansion, β is the compressibility at a constant temperature, and C_V is the specific heat at a constant volume. Table 4 shows piezoresistances along the Hugoniot and release states as computed from our $R(P,T)$ data and the calculated temperatures.

Fig. 6. Temperature rise as a function of pressure along the Hugoniot and release paths of ytterbium.

Table 4. Static $R(P,T)/R_0$ for Hugoniot and release states (R_0 based at 21°C and 1 atm).

Pressure (kbar)	Hugoniot		Release from 10 kbar		Release from 20 kbar		Release from 30 kbar	
	ΔT (°C)	R/R_0	ΔT (°C)	R/R_0	ΔT (°C)	R/R_0	ΔT (°C)	R/R_0
0	0	1.000	1	1.002	3	1.005	8	1.013
5	10	1.379	11	1.381	13	1.383	19	1.391
10	20	1.93	20	1.93	23	1.93	29	1.93
15	30	2.70	—	—	32	2.69	38	2.68
20	41	3.59	—	—	41	3.59	47	3.57
25	51	4.54	—	—	—	—	55	4.49
30	62	5.39	—	—	—	—	62	5.39
34.5 ^a	74	5.97	—	—	—	—	—	—

^aMaximum resistance, transition begins.

The final expected $R(P,T)$ for plane-strain Hugoniot and release states that incorporates the expected geometrical effect must be calculated next. In hydrostatic studies all dimensions change equally for an isotropic solid, whereas in plane strain only the cross-sectional area is reduced. Consider a rectangular wire having a length L , one side (b) normal to the direction of the shock propagation, and another side (c) parallel to the direction of propagation. For an isotropic solid and plane strain,

$$R_{ps} = \rho(P,T) \frac{L}{A} = \rho \frac{L}{bc} = \rho \frac{L_0}{b_0 c_0 (V/V_0)} \quad (2)$$

since all of the strain is one dimensional. In this equation, R_{ps} is the resistance in plane strain, ρ is the resistivity of the wire, A is the cross-sectional area of the wire, and V/V_0 is the relative volume at P,T . For hydrostatic loading of an isotropic solid, all of the dimensions change equally and

$$R_{hy} = \rho \frac{L}{bc} = \rho \frac{L_0 (V/V_0)^{1/3}}{b_0 c_0 (V/V_0)^{2/3}} = \rho \frac{L_0}{b_0 c_0} (V/V_0)^{-1/3}, \quad (3)$$

where R_{hy} is the hydrostatic resistance. Then, $R_{ps}/R_{hy} = (V/V_0)^{-2/3}$ at the same pressure and temperature.

The $R(P,T)$ predicted from the results in Table 4 and from the geometrical effect employing the pressure-versus-volume data of Stephens⁸ are shown in Table 5 and are compared in Fig. 7 to the experimental Hugoniot data of Brown¹⁴ and Keough.¹⁵ The calculated release states in Table 5 and Fig. 7 are also assumed to be in plane strain. The calculated release states at pressures of 20 kbar and below are close to coinciding with the Hugoniot. Certainly, the pressure hysteresis that has been observed in shock-wave studies^{14,15} is not due to any great extent to temperature

Table 5. Predicted R/R_0 values for Hugoniot and release states after corrections for temperature and geometrical effects.

Pressure (kbar)	Hugoniot	Release from 10 kbar	Release from 20 kbar	Release from 30 kbar
0	1.000	1.002	1.005	1.013
5	1.409	1.411	1.413	1.421
10	2.01	2.01	2.01	2.01
15	2.87	—	2.86	2.85
20	3.88	—	3.88	3.86
25	4.98	—	—	4.98
30	5.99	—	—	5.99
34.5	6.71	—	—	—

Fig. 7. Hugoniot piezoresistance of ytterbium.

effects. The fact that ytterbium's temperature coefficient of resistance is posi-

tive to 10 to 14 kbar and is negative at high pressures leads to little difference

in the resistances upon shock loading and isentropic release.

Note that the resistance curve in Fig. 7 terminates at 34.5 kbar. At this point, we calculate that the P,T trajectory of the Hugoniot intersects the fcc-to-bcc transition, and thus the maximum resistance occurs at 34.5 kbar. Note also that our predicted piezoresistance along the Hugoniot agrees with most of Brown's data to within 10%. In this case, however, we are comparing the same ytterbium. Keough's data for ytterbium from a different batch but from the same company indicate lower resistances at the same pressure than either our prediction or Brown's data.

The agreement of our prediction to within 10% of the experimental data is perhaps all that can be expected. There are

errors in the Hugoniot measurements and in our $R(P,T)/R_0$ measurements. Certainly, there are errors in the calculation of the Hugoniot temperatures, and there could be as much as a 20% error in ΔT .

In addition, errors in the pressure-versus-volume data are reflected in the $(V/V_0)^{-2/3}$ term in the calculated geometry effect.

Finally, and perhaps most importantly, we have not considered the well known fact that the resistance of semiconductors (and ytterbium is a semiconductor above 10 to 14 kbar) is sensitive to deviatoric stresses as well as to pressure and temperature.

We conclude that the experimental Hugoniot measurements¹⁴ agree reasonably well with the calculated Hugoniot based on our static $R(P,T)$ data and the plane-strain factor.

References

1. H. D. Stromberg and D. R. Stephens, J. Phys. Chem. Solids **25**, 1015 (1964).
2. P. W. Bridgman, Proc. Am. Acad. Arts Sci. **83**, 1 (1954).
3. R. A. Stager and H. G. Drickamer, Science **139**, 1284 (1963).
4. P. C. Souers and G. Jura, Science **140**, 481 (1963).
5. D. B. McWhan, T. M. Rice, and P. H. Schmidt, Phys. Rev. **177**, 1063 (1969).
6. E. King and I. R. Harris, J. Less-Common Metals **20**, 237 (1970).
7. H. Stromberg and G. Jura, Science **138**, 1344 (1962).
8. D. R. Stephens, J. Phys. Chem. Solids **25**, 423 (1964).
9. P. W. Bridgman, Proc. Am. Acad. Arts Sci. **74**, 21 (1940).
10. H. T. Hall, J. D. Barnett, and L. Merrill, Science **139**, 111 (1963).
11. D. D. Keough, R. F. Williams, and R. A. Pasternak, Piezoresistive Shock Transducer Study Using Lithium, Stanford Research Institute, Rept. PGD-6403 (1968).
12. J. M. Walsh and R. H. Christian, Phys. Rev. **97**, 1544 (1955).
13. K. A. Gschneidner Jr., "Physical Properties and Interrelationships of Metallic and Semimetallic Elements," in Solid State Physics: Advances in Research and Applications, F. Seitz and D. Turnbull, Eds. (Academic Press, New York, 1964), vol. 16.
14. S. R. Brown, Development of Piezoresistive Stress-History Gages, Lawrence Radiation Laboratory, Livermore, Memo DET 70-48 (1970).
15. D. D. Keough, Development of a High-Sensitivity Piezoresistive Shock Transducer for the Low Kilobar Range, Stanford Research Institute, Rept. DASA-2508 (1970).

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