

## High-Pressure Electrical Behavior and Equation of State of Magnesium Oxide from Shock Wave Measurements

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A decrease in resistivity of MgO from  $>10^6$  to  $\sim 10^3 \Omega \cdot \text{cm}$  is observed when thin single crystals are shocked in the [001] direction to  $920 \pm 70$  kbar. This effect may be produced by several electronic processes, or by ionic transport in which the effective  $\text{O}^-$  or  $\text{Mg}^{++}$  diffusion constants are increased by perhaps a factor of  $10^{10}$  from those calculated at high pressure (according to Zener strain-energy model). Voltages are observed during passage of various-strength (70 to 936 kbar) shock fronts through the specimen. These voltages approximately scale as the inverse of the specimen thickness and may arise from net volume polarization ( $\sim 0.2$  to  $\sim 9$  V/cm). Some Hugoniot data to 660 kbar (including measurement of elastic-shock amplitude varying from 35 to 89 kbar) are presented.

### INTRODUCTION

EXPERIMENTS were performed on MgO to explore electrical resistivity, voltage generation under shock compression, and high-pressure equation of state. MgO was studied because it is simply structured (NaCl-type lattice), of technological importance, and a probable constituent of the earth's interior. (The study of electrical conductivity and equation of state of MgO at high pressure may possibly be related to studies of the earth's interior since both resistivity and elastic constants as a function of depth have been inferred from geomagnetic<sup>1</sup> and seismological<sup>2</sup> studies, respectively.)

Measurements of diffusion<sup>3,4</sup> of various species and electrical resistivity<sup>5,6</sup> in single and polycrystalline MgO at atmospheric or reduced pressures and at high temperature have been performed in differing gaseous environments. Controversy exists<sup>5,6</sup> as to whether the conductivity at normal pressures above 1500°K in the pure material results from primarily ionic or electronic carriers. (It has been suggested<sup>5</sup> that electronic conductivity is not of the extrinsic or intrinsic type usually described in semiconductors.) At sufficiently high pressure (and temperature), electronic contributions to conductivity are expected when the valence-to-conduc-

tion band gap ( $\sim 9$  eV at ambient pressure) is decreased. Of interest here is a calculation performed by Wada<sup>7</sup> which predicts metallic conductivity in MgO when the specific volume is decreased by a factor of  $\sim 0.71$ . Of interest to studies of shock compression is the  $10^{14}/\text{cm}^3$  concentration of  $F$  centers in MgO which has been reported<sup>8</sup> to occur in single-crystal MgO after passage of a strong shock-wave disturbance. This result suggests that as in the case of slow deformation,<sup>9</sup> the shock produces copious numbers of charged defects which may give rise to a substantial (and perhaps temporary) resistivity decrease.

### ELECTRICAL MEASUREMENTS

The resistivity experiments summarized in Table I were performed using the longitudinal arrangement (current flow parallel to shock propagation direction) shown in Fig. 1, in which the MgO single crystals were mounted between a metal driver plate and a brass backing electrode. This arrangement is similar to that employed in measuring resistivity of shocked NaCl and NaCl, CsI, and KI by Al'tshuler *et al.*<sup>10</sup> and Doran and Ahrens,<sup>11</sup> respectively. A flat-topped (or nearly flat-

<sup>1</sup> D. C. Tozer, *Physics and Chemistry of the Earth*, edited by L. H. Ahrens, F. Press, K. Rankama, and S. K. Runcorn (Pergamon Press, New York, 1959), Vol. 3, p. 414.

<sup>2</sup> S. P. Clark, Jr., and A. E. Ringwood, *Rev. Geophys.* **2**, 35 (1964).

<sup>3</sup> R. Lindner and G. D. Parfitt, *J. Chem. Phys.* **26**, 182 (1957).

<sup>4</sup> Y. Oishi and W. D. Kingery, *J. Chem. Phys.* **33**, 905 (1960).

<sup>5</sup> S. P. Mitoff, *J. Chem. Phys.* **36**, 1383 (1962).

<sup>6</sup> M. O. Davies, *J. Chem. Phys.* **38**, 2047 (1963).

<sup>7</sup> T. Wada, *Disaster Prevent. Res. Inst., Kyoto Univ. Bull.* **31**, 1 (1960).

<sup>8</sup> W. B. Gager, M. J. Klein, and W. H. Jones, *Appl. Phys. Letters* **5**, 131 (1964).

<sup>9</sup> G. K. Walters and T. L. Estle, *J. Appl. Phys.* **32**, 1854 (1961).

<sup>10</sup> L. V. Al'tshuler, L. V. Kuleshova, and M. N. Pavlovskii, *Soviet Phys.—JETP* **12**, 10 (1961).

<sup>11</sup> D. G. Doran and T. J. Ahrens, Stanford Research Institute, Project 4100, Contract DA-04-200-ORD 1279, Final Rept., 31 Aug. 1963.

TABLE I. Resistivity and shock-induced voltage, MgO.

| Shot No. | Explosive system <sup>a</sup> (Code) | Initial specimen thickness <sup>b</sup> (mm) | Shock pressure (kbar)         | Particle velocity <sup>c</sup> (mm/ $\mu$ sec) | Shock-induced voltage (scaled) (V/cm) | Resistivity ( $\Omega$ -cm)                   |
|----------|--------------------------------------|----------------------------------------------|-------------------------------|------------------------------------------------|---------------------------------------|-----------------------------------------------|
| 11 542   | A                                    | 5.0                                          | 70 $\pm$ 5                    | 0.744                                          | 0.212 $\pm$ 0.009                     | Passive <sup>d</sup>                          |
| 10 562   | C                                    | 3.4                                          | 182 $\pm$ 6 <sup>e</sup>      | 0.59 <sup>e</sup>                              | 0.96<br>(0.48–0.96)                   | >4.2 $\times$ 10 <sup>4</sup>                 |
| 10 561   | D                                    | 2.5                                          | 424 $\pm$ 20 <sup>f</sup>     | 1.31 <sup>f</sup>                              | 6.56 $\pm$ 0.09                       | >8.3 $\times$ 10 <sup>4</sup>                 |
| 10 563   | D                                    | 4.7                                          | 444 $\pm$ 12 <sup>e</sup>     | 1.36 <sup>e</sup>                              | 6.68 $\pm$ 0.50                       | Passive <sup>d</sup>                          |
| 10 887   | E                                    | 3.4                                          | 660 $\pm$ 33 <sup>f</sup>     | 1.92 <sup>f</sup>                              | 6.25<br>(6.25–6.61)                   | $\infty$ <sup>g</sup>                         |
| 10 888   | F                                    | 2.6                                          | 798 $\pm$ 24 <sup>h</sup>     | 2.23 <sup>h</sup>                              | 9.09 <sup>i</sup><br>(8.18–9.30)      | $\infty$ <sup>i</sup>                         |
| 10 464   | G                                    | 1.9                                          | 882 <sup>f</sup><br>(845–926) | 2.32 <sup>f</sup>                              |                                       | 1.2 $\times$ 10 <sup>3</sup><br>(0.9–1.8)     |
| 10 889   | H                                    | 1.1                                          | 962 $\pm$ 29 <sup>h</sup>     | 2.60 <sup>h</sup>                              | 8.48 $\pm$ 0.09 <sup>i,j</sup>        | 7.3 $\times$ 10 <sup>3i,j</sup><br>(6.6–12.8) |
| 10 890   | H                                    | 1.1                                          | 910 $\pm$ 27 <sup>h</sup>     | 2.44 <sup>h</sup>                              | 8.76 $\pm$ 0.17 <sup>i,j</sup>        | 9.3 $\times$ 10 <sup>3i,j</sup><br>(8.0–13.2) |
| 10 891   | H                                    | 1.2                                          | 936 <sup>f</sup><br>(883–991) | 2.49 <sup>f</sup>                              | 10.21 $\pm$ 0.29 <sup>i,j</sup>       | 1.4 $\times$ 10 <sup>3i,j</sup><br>(1.1–2.6)  |
| 10 891   | H                                    | 1.5                                          | 936 <sup>f</sup><br>(883–991) | 2.49 <sup>f</sup>                              | 8.04 <sup>i,j</sup><br>(8.04–8.30)    | Passive <sup>d</sup>                          |

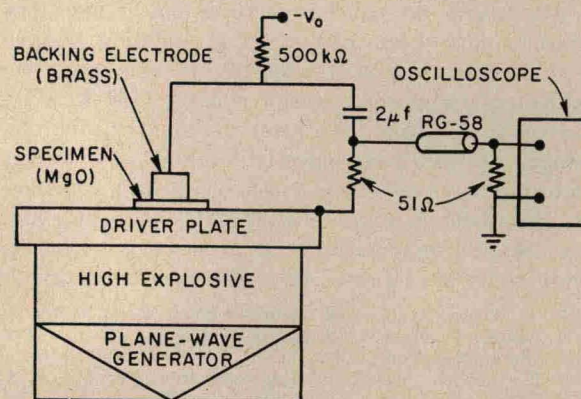
<sup>a</sup> See Table II.<sup>b</sup> Specimen shocked in [001] direction.<sup>c</sup> Inferred from Hugoniot data generated in shots 10 520, 10 724, and 11 461.<sup>d</sup> Passive experiment (zero applied voltage).<sup>e</sup> State in driver plate and specimen from Manganin-wire shock-pressure gauge.<sup>f</sup> State in driver plate and specimen from previous determination with same explosive system.<sup>g</sup> Fired in #200 Dow-Corning silicone oil.<sup>h</sup> State in driver plate and specimen from driver free-surface velocity (electrical pin-contact measurement).<sup>i</sup> Guardring electrode arrangement.<sup>j</sup> Fired in "liquid carbonic" Grade "A" helium (99.998% He).

topped) shock wave, whose duration is at least as great as the shock travel time through the specimen, is produced in the driver plate by the impact of an explosively launched planar flyer plate or by a plane-wave-initiated thick pad of high explosive in contact with the driver plate (Table II). The resulting shock wave in the driver plate propagates into the specimen and then into the brass backing electrode. Because the latter approximately matches the specimen shock impedance, a

portion of the specimen will remain in the high-pressure compressed state for a time interval which depends on both the duration of the shock pulse and the lateral specimen dimensions. The specimen is thin compared to the backing electrode or driver plate. The specimen resistivity is measured during the time that a substantial portion of the specimen is in the high-pressure state (usually before 0.5  $\mu$ sec has elapsed after the shock front has left the specimen and is propagating into the backing electrode). The voltage  $v_x$  observed on the oscilloscope during this time is related to the specimen

TABLE II. Explosive and plate accelerating systems.

| Code | System composition                                                                                                                                              |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| A    | $\frac{1}{4}$ in. thick aluminum projectile (speed: 0.64 mm/ $\mu$ sec, accelerated by gas gun) + $\frac{1}{4}$ in. aluminum                                    |
| B    | P-80 <sup>a,b</sup> + 2 in. Baratol <sup>b</sup> + $\frac{3}{4}$ in. 2024 aluminum                                                                              |
| C    | P-60 <sup>a,b</sup> + 2 in. Baratol + $\frac{3}{8}$ in. 2024 aluminum                                                                                           |
| D    | P-60 + 2 in. 9404 <sup>b</sup> + $\frac{3}{8}$ in. 2024 aluminum                                                                                                |
| E    | P-80 + 4 in. 9404 + $\frac{1}{16}$ in. Lucite + $\frac{1}{4}$ in. tool steel + $1\frac{1}{2}$ in. air (Free-Run) + $\frac{3}{8}$ in. brass (Anaconda #238)      |
| F    | P-80 + 4 in. 9404 + $\frac{1}{16}$ in. Lucite + $\frac{3}{16}$ in. tool steel + $1\frac{1}{2}$ in. air (Free-Run) + $\frac{3}{8}$ in. brass (Anaconda #238)     |
| G    | P-80 + 4 in. 9404 + $\frac{1}{16}$ in. Lucite + $\frac{1}{8}$ in. stainless steel + $1\frac{1}{2}$ in. air (Free-Run) + $\frac{3}{8}$ in. 2024 aluminum         |
| H    | P-80 + 4 in. 9404 + $\frac{1}{16}$ in. Lucite + $\frac{1}{8}$ in. stainless steel + $1\frac{1}{2}$ in. air (Free-Run) + $\frac{3}{8}$ in. brass (Anaconda #238) |

<sup>a</sup> P-60 and P-80 denote 6- and 8-in.-diam explosive plane-wave generators.<sup>b</sup> Manufactured by Mason and Hanger, Inc., Amarillo, Texas.FIG. 1. Mechanical configuration and circuitry, shock resistivity experiments. ( $v_0$  and 0 are recorded at oscilloscope when specimen resistivity approaches zero and infinity, respectively.)