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ELECTRICAL CONDUCTIVITY OF UO_2 :
PART I. SINGLE CRYSTALS

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by

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TABLE OF CONTENTS

INTRODUCTION	1
SUMMARY	1
EXPERIMENTAL DETAILS	2
Uranium Dioxide Samples	2
Electrical Conductivity Apparatus	2
Atmosphere	4
RESULTS AND DISCUSSION	4
Electrical Conductivity from 290 to 550 °K	7
Electrical Conductivity from 550 to 1250 °K	8
REFERENCES	11
APPENDIXES	12
A. ELECTRICAL CONDUCTIVITY DATA FOR SINGLE CRYSTAL UO ₂	12
B. ELECTRICAL CONDUCTIVITY DATA	13
Specimen MR-1	13
Specimen MR-2	15
Specimen MR-5-a	17
Specimen MR-5-b	17
Specimen EC-S1-A	19
Specimen B-40-A	21
C. Energy of Activation.	23
DISTRIBUTION.	24

LIST OF FIGURES

1	Schematic Description of Four Probe Electrical Conductivity Apparatus	3
2	Change in Electrical Conductivity of Single Crystal UO_2 (MR-5) During Heat Treatment in 8% H_2 -Argon at 1125 °K	4
3	Hysteresis in High Temperature Electrical Conductivity in Single Crystal UO_2 (MR-5) After Prolonged Heating at High Temperatures	5
4	Electrical Conductivity of Single Crystal $\text{UO}_{2.001 \pm 0.0005}$	6
5	Summary of Electrical Conductivity for Single Crystal $\text{UO}_{2.0}$ Between Room Temperature and 3000 °K	7
B.1	Electrical Conductivity of Single Crystal MR-1	14
B.2	Electrical Conductivity of Single Crystal MR-2	16
B.3	Electrical Conductivity of Single Crystal MR-5	18
B.4	Electrical Conductivity of Single Crystal EC-S1-A	20
B.5	Electrical Conductivity of Single Crystal B-40-A	22

ELECTRICAL CONDUCTIVITY OF UO_2

PART I. SINGLE CRYSTALS

INTRODUCTION

The electrical conductivity of uranium dioxide has been studied by a number of investigators. Reviews have been published by Meyer,⁽¹⁾ Willardson and Moody,⁽²⁾ and by the International Atomic Energy Agency.⁽³⁾ Since these reviews, electrical conductivity data for UO_2 have been reported by Meyers et al.,⁽⁴⁾ and Iida.⁽⁵⁾ With the exception of the Iida data, all of the conductivity data concern uranium dioxide containing excess amounts of oxygen. The conduction in the hyperstoichiometric UO_2 below 1100 °K is p-type. Between 1100 and 1300 °K, the oxide exhibits a p-to-n transition,⁽³⁾ with the UO_2 being n-type conductor above 1300 °K. For hypostoichiometric UO_{2-x} , Iida⁽⁵⁾ demonstrated that the conduction was n-type over the entire temperature range from 77 to 1200 °K.

Initially, the low temperature electrical conductivity results were interpreted by assuming that UO_2 was a classical semiconductor and that a band model was valid. However, it has since been shown that band theory may be inadequate in describing the electrical properties of a number of polar semiconductors such as UO_2 .^(3,6,7) Most recently,^(2,3,6,7) the conductivity has been explained by the hopping of charge from one ion to an adjacent ion or by the production and movement of polarons. This mechanism assumes that the mobility of the carriers and not the production of carriers is temperature dependent.^(2,6,7)

With few exceptions, the electrical conductivity of UO_2 has been determined for polycrystalline UO_2 . Single crystal data have been reported by Amelinckx et al.⁽⁸⁾ in the temperature range between 90 and 800 °K and by Iida⁽⁵⁾ for one crystal from 77 to 1200 °K.

This study was made to determine the electrical conductivity of nearly stoichiometric, single crystal UO_2 over a wide temperature range from 298 to 3000 °K, and to evaluate the data in terms of the presently accepted conduction mechanisms for UO_2 and in terms of other electrical and optical properties.

SUMMARY

The electrical conductivity of near-stoichiometric uranium dioxide ($\text{UO}_{2.001}$) was measured from room temperature to 3000 °K. Below ~550 °K, the curve of the $\log \sigma$ versus T^{-1} is linear with calculated activation energies between 0.17-0.20 eV. At temperatures between 550 and 1250 °K, an effect occurs that causes a change in slope which appears as a hump in the curve. With increasing temperature, the electrical conductivity increases rapidly above ~1250 °K where the conduction changes from p-type to n-type. The activation energy increases slightly with temperature from ~1.1 to ~1.6 eV with the best linear fit of ~1.5 eV. The high temperature conduction is assumed to be intrinsic; however a large difference exists between the thermal energy gap (3.0 eV)

and that derived from optical absorption data (5.25 eV).

EXPERIMENTAL DETAILS

Uranium Dioxide Samples

The UO_2 single crystal specimens for electrical conductivity measurements were machined from large crystal boules grown from an arc-fusion melt. A description of the specimens are given in Table I.

Samples MR-1 and MR-2 were obtained from the same crystal. MR-5b was cut from MR-5a after initial conductivity measurements were made on MR-5a. The specimens were of undetermined crystallographic orientation.

Each crystal was heat-treated in the electrical conductivity apparatus for

8 hr at 1125 °K in purified 8% H_2 -argon prior to conductivity measurements. The O:U ratio of the crystals after this heat treatment deviated only slightly from stoichiometric UO_2 (O:U < 2.001).

Electrical Conductivity Apparatus

The electrical conductivity was measured by two techniques in three apparatus. A two-probe method was employed to measure the conductivity between 2200 and 3000 °K. The UO_2 sample (~0.35 cm diam and ~0.65 cm long) was positioned in the heating zone by two tungsten electrodes. Tungsten voltage probes were clamped between the sample ends and the electrodes.

The specimen was preheated to approximately 2000 °K by tungsten heater

TABLE I. *Uranium Dioxide Single Crystals*

Specimen Designation	Size (cm)		O:U ^(a)	Impurity Content ^(b) (ppm)
	Diameter	Length		
MR-1 ^(c)	0.35	0.63	2.001	Al 100, Cu 5, Fe >300, Mg 5, P <50, Pb 2, Si 54, V <50, Zn <50, all others total <1.
MR-2 ^(c)	0.63	2.5	2.001	Same as MR-1
MR-5 ^(d)	0.63	3.0	2.001	Al 2, As <2, Ca 2, Co <10, Cr <5, Fe 41, Mg 1, Na <2, Si 35, Zn <50, all others total <1.
EC-S1-A	0.63	1.9	2.001	Al 10, Cr <5, Mg 1, Mn <1, Ni <5, Pb 5, Cl <10, V <50, Zn <50, all others total <1.
B-40-A	0.63	1.9	2.001	Al 5, Ca 1, Cr <5, Fe 10, Mg 1, Ni <5, Pb 3, Si 21, V <50, Zn <50, all others total <1.

(a) Oxygen to uranium ratios were determined by coulometry after electrical conductivity measurements.

(b) Determined by emission spectroscopy.

(c) Specimens MR-1 and MR-2 were fabricated from the same crystal boule.

(d) MR-5b was machined from MR-5a after initial measurements were obtained from MR-5a.

strips. Higher temperatures (maximum surface temperatures of 3000 °K) were obtained by direct resistance heating of the UO_2 . Temperatures were measured with an optical pyrometer and were calibrated using materials of known melting points. The 60 cycle/sec voltage and current required to heat the sample were measured and resistance calculated using Ohms Law. Because of small temperature gradients within the specimen at the higher temperatures and the large current required to heat the specimen, the data obtained by this apparatus are less accurate than data obtained by following methods. Measurements were not practical below 2000 °K because of poor contacts between sample and voltage probes.

The second method was a four-probe technique using two different apparatus. A large UO_2 specimen (0.63 cm diam and ~3.0 cm long) was positioned inside a 2.5 cm diam tungsten tube between two tungsten electrodes which were also used as current leads. Two tungsten voltage probes were pressed against the UO_2 sample to maintain good contact. The tungsten tube was heated by direct current. Temperatures were measured with an optical pyrometer, and conductivity measurements were obtained between 1050 and 2050 °K.

A second four-probe apparatus was used to make the majority of the conductivity measurements between 298 and 2750 °K* (Figure 1). A tungsten mesh ele-

ment with a hot zone 3.5 cm in diameter and 9 cm long was heated by direct current from motor-driven generators. The oxide specimen (0.63 cm diam and 1.9 cm long) was held in the furnace between two tungsten probes. These probes were also used as current leads during conductivity measurements. Two sharp-pointed, tungsten rods were set into very shallow holes 0.63 cm apart on the specimen surface to measure the voltage drop across the specimen. Good contacts were maintained by applying pressure to these probes.

Temperatures were measured from 298 to 1850 °K with a platinum versus Pt-13% Rh thermocouple positioned adjacent to the sample. An optical pyrometer

FIGURE 1. Schematic Description of Four Probe Electrical Conductivity Apparatus.

* Although the apparatus is capable of conductivity measurements at temperatures in excess of 2750 °K, changes in UO_2 specimen geometry occurred due to vaporization losses at higher temperatures, even in 15 psi inert gas.

measured temperatures about 1050 °K. No temperature gradient across the sample was observed.

The same instrumentation was used for all four-probe measurements. A direct current voltage across the sample was provided from a solid state power supply. The applied potentials were less than 2 V (generally less than 1 V) with currents less than 100 mA. The applied dc potential was reversed as rapidly as possible, and the current-voltage relationship was measured with current flow in both directions. An average of the two values was used to calculate the resistance. Voltages were measured with a millimicrovoltmeter, while currents were measured with a micro-microammeter.

Atmosphere

Measurements were made in purified 8% hydrogen-92% argon at atmospheric pressure. The oxygen and water content of the gas was <1 ppm and <5 ppm, respectively..

Measurements were also made in purified argon. However, the measurements in the low temperature range were not reproducible during thermal cycles apparently because of O:U changes on UO_2 in the nonreducing atmosphere.

RESULTS AND DISCUSSION

The complete electrical conductivity data are given in Appendix A. The appendix includes all data points, plots of log versus T^{-1} , and a summary of activation energies.

The electrical conductivity below 1100 °K was not reproducible during the initial measurements of a nonheat treated specimen or when measurements were made in purified argon atmosphere.

These variations in conductivity are attributed to stoichiometric changes during heating and cooling cycles.

Each single crystal specimen was heat treated in the conductivity apparatus in the purified 8% hydrogen-argon atmosphere for 8 to 10 hr at 1125 °K. Electrical conductivity measurements were obtained during this period. The heat treatment was terminated after the electrical conductivity data did not change with time. The final O:U after heat treatment was 2.001 ± 0.0005 .

For example, crystal MR-5, which had an initial O:U ratio of 2.01, was heated under the above conditions. The electrical conductivity decreased with time (Figure 2). After approximately 4.5 hr, the sample was cooled to room temperature and exposed to air for 16 hr. At the start of the succeeding

FIGURE 2. Change in Electrical Conductivity of Single Crystal UO_2 (MR-5) During Heat Treatment in 8% H_2 -Argon at 1125 °K. (Specimen was Cooled to Room Temperature, Exposed to Air and Heated Again to 1125 °K at Times A and B)

heating cycle (A), the electrical conductivity had increased. However, the conductivity decreased rapidly on subsequent heating. After approximately 6 hr, no significant changes in conductivity were observed. The final conductivity was ~20% of the initial value; the final O:U ratio was 2.001 ± 0.0005 .

Crystals having an as-fabricated O:U ratio less than 2.001 exhibited an increase in conductivity during heat treatment as the O:U ratio increased to 2.001.

The use of a purified, reducing atmosphere of 8% hydrogen in argon eliminated the variations observed during measurements in argon. The small amounts of oxygen in the argon (<1 ppm O_2 and <10 ppm H_2O) were sufficient to alter the stoichiometry of the specimen; consequently, the data were not reproducible during the temperature cycles. The conductivity tended to drift to higher values when the sample was held at temperature, which resulted in a higher conductivity during the cooling cycle.

Similar changes in UO_2 electrical conductivity in this temperature range (300 to 1150 °K) have been observed by other investigators.^(2,6,9-13) This nonreproducibility has been attributed to stoichiometric changes resulting from the high oxygen content of the inert gases. Wolfe⁽⁷⁾ suggested that the variations were probably caused by the oxidation of the specimen surface and not by a homogeneous change in specimen stoichiometry.

To minimize the effects of residual oxygen in the atmosphere, measurements were made in a reducing atmosphere of

8% hydrogen in argon, employing the mass equilibrium of H_2-H_2O to reduce the oxygen pressures. Oxygen pressures at 1125 °K were estimated to be $\sim 10^{-25}$ atmospheres compared to the $\sim 10^{-17}$ atmospheres in the argon atmosphere in the presence of the high temperature tungsten.

Heating for prolonged periods in excess of 3 hr above 2500 °K resulted in a hysteresis in the conductivity curves (Figure 3). The conductivity values increased at the high temperatures. On cooling to room temperature, the conductivity returned to their original low temperature values. These changes

FIGURE 3. Hysteresis in High Temperature Electrical Conductivity in Single Crystal UO_2 (MR-5) After Prolonged Heating at High Temperatures

could possibly have resulted from a decrease in stoichiometry. The calculated oxygen pressures at these temperatures were estimated to be $\sim 10^{-11}$ atmospheres (calculated from H_2-H_2O) which is low enough to form hypostoichiometric UO_2 .⁽¹⁸⁾

The electrical conductivity of single crystal $UO_{2.001 \pm 0.0005}$ are given

as $\log \sigma$ versus T^{-1} (Figure 4). The data are in excellent agreement with data reported by Amelinckx et al.⁽⁸⁾ for single crystals with comparable O:U ratios and with data of Wolfe⁽⁷⁾ for 98.6% TD polycrystalline $UO_{2.001}$ (Figure 5). Although the low temperature values for UO_{2-x} reported by Iida⁽⁵⁾ are very much lower, the data

FIGURE 4. Electrical Conductivity of Single Crystal $UO_{2.001 \pm 0.0005}$

FIGURE 5. Summary of Electrical Conductivity for Single Crystal $\text{UO}_{2.0}$ Between Room Temperature and 3000 °K

are in fair agreement near 1250 °K in the apparent intrinsic portions of the electrical conductivity curve.

The electrical conductivity data for single crystal UO_2 can conveniently be separated into three temperature ranges 290 to 550 °K, 550 to 1200 °K, and 1200 °K and above (Figure 4).

Electrical Conductivity from 290 to 550 °K

Below approximately 550 °K, the curve of the $\log \sigma$ versus T^{-1} appears to be linear. From the slope, activation energies for samples MR-5 and EC-SIA were calculated to be 0.17 and 0.20 eV, respectively. However, it may be ques-

tioned whether $\log \sigma$ versus T^{-1} best describes the data in this temperature range. Recent studies of electrical conductivities of UO_2 (2,3,6,8) have suggested that band theory is inadequate in describing the conduction mechanism for UO_2 . These authors have explained the conduction mechanism by the jumping of holes (or electrons) from one ion to a neighboring ion. The holes are localized at the uranium cations (U^{+5}) and are not free to move through the lattice. The mobility rather than the production of carriers is suggested as the thermally activated process as the positive hole jumps from the U^{+5} to the adjacent U^{+4} .

A theoretical basis for this hopping mechanism is provided by small polaron theory. In ionic crystals, the interaction between holes (or electrons) and phonons is so strong that the ion polarizes its surroundings. The polarization reduces the potential energy and the energy levels of the holes are lowered. Small polaron motion is used to describe the current transfer in UO_2 , and leads to a hopping model with thermally activated mobility.

The electrical conductivity data have been plotted in the form $\log \sigma$ versus T^{-1} . However, in the case of the hopping mechanism of polaron concept, the conductivity is expressed in its simplest form as $\log \sigma T$ versus T^{-1} . These two methods for presenting the data give different activation energies. For example, MR-5 and EC-SIA, the activation energies were 0.22 and 0.23 eV using the latter method. These values are approximately 20% higher than the energies obtained from a $\log \sigma$ versus T^{-1} curve. These energies are very similar to the values obtained by Amelinckx et al.⁽⁸⁾ for single crystals with similar O:U ratios using a similar plot. The curve $\log \sigma T$ versus T^{-1} did not improve the linearity of the data in this temperature range.

Electrical Conductivity from 550 to 1250 °K

At temperatures between 550 and 600 °K an effect occurs that causes a change in slope of the $\log \sigma$ versus T^{-1} curve. (The changes were also observed in the $\log \sigma T$ versus T^{-1} curve.) The result appears as a hump in the curve between 550 and 1250 °K. This curve decreases in slope at the higher

temperatures and corresponds to an activation energy of approximately 0.13 eV (see Appendix B). These changes are reversible, occurring both on heating and cooling, but were observed at different temperatures for different samples: ~550 °K for EC-SIA, ~650 °K for MR-5 and ~1100 °K for MR-3.

The temperature at which this change occurs also appears to vary with changes in the oxygen content of the atmosphere. Although the data are not reproducible quantitatively, the temperature of this change appears to increase with increases in oxygen content of the atmosphere.

Similar changes in the slope of the conductivity curve have also been observed by other investigators. Wolfe⁽⁷⁾ observed two activation energies of 0.20 eV (using $\log \sigma$ versus T^{-1}) at temperature below 675 °K and of 0.13 eV above 675 °K. He attributes the high temperature energy to the jump process and the low temperature energy to the removal of holes plus the jump process. These values are very close to those observed in this study.

Iida⁽⁵⁾ detected a rapid change in conductivity near 175 °K, which he attributes to a high impurity concentration.

Amelinckx et al.⁽⁸⁾ observed this increase in slope at ~475 °K, and it was more pronounced in those specimen that had been quenched. He attributes this change to the phase transition in the specimen from UO_{2+x} plus U_4O_9 .

Other possible causes could involve changes in the thermally activated process (e.g. in addition to the mobility, the carrier density might also become

thermally activated). The effect may be even more complex, if the difference between the polarized ion and the lattice ion were greater than unity, i.e., U^{+6} and U^{+4} . Further measurements of the conductivity in this temperature range as a function of oxygen pressure are required to clarify the exact cause of this change.

The slope of the $\log \sigma$ versus T^{-1} curve increases slightly above 1250 °C. E_g increases with increasing temperature from ~ 1.1 eV at the lower temperatures to ~ 1.6 eV at the higher temperatures (see Appendixes B and C). Best linear fit of all data indicate an activation energy of ~ 1.5 eV. (An E_g of ~ 3.0 eV was calculated from a $\log \sigma T$ versus T^{-1} curve.)

The nonlinearity of the curve above 1250 °K suggests either that the σ_0 is temperature dependent and that the slope does not give a true value for the energy or that E_g itself depends upon the temperature.

The large change in activation energy between 1150 and 1400 °K corresponds to the p-to-n transition observed in thermoelectric property measurements.⁽¹²⁾ This may be interpreted as a transition to intrinsic conduction. Evidence for the existence of intrinsic conduction has been found by Willardson et al.⁽⁹⁾ and by Wolfe.⁽⁷⁾

Assuming that the conductivity above 1250 °K is intrinsic, the conductivity can be expressed as

$$\sigma = \sigma_0 \exp -E_g/2kT$$

where E_g is the energy gap between the conduction and the valence band and σ_0

is a temperature dependent coefficient. However, the temperature dependence of σ_0 is generally small compared to the exponential term, especially over a small temperature range. The activation energy is one-half E_g .

A significant difference exists between the energy gap derived from conductivity data (3.0 eV) and that derived from optical absorption data.⁽³⁾ Of the values for the optical energy gap (2.0 to 5.25 eV), the highest is probably the most valid. The lower energy values were determined by using thin sections where absorption densities are very large and a measurement of the absorption edge is very difficult. In addition, in very thin sections, single crystals appear yellow in transmitted light.⁽³⁾ This suggests a larger optical energy gap than 2.0 eV.

As suggested by Wolfe,⁽⁷⁾ the absorption spectrum for UO_2 between 2000 and 7000 Å most probably consists of a strong absorption edge at 2400 Å (5.25 eV), two intense bands between 2500 Å (5.0 eV) and 5000 Å (2.5 eV) with an absorption edge near 6600 Å (2.00 eV).

A direct numerical agreement between the thermal energy gap and the optical energy gap should not be expected in polar solids.^(15,16) The optical energy transition occurs without relaxation obeying selection rules requiring no change of momentum. The thermal energy transition occurs with an energy change in equilibrium configuration. The selection rules may be relaxed if the electron (or hole) interacts with the lattice, and the transition is accompanied by the emis-

sion or absorption of a phonon. This latter energy is measured from electrical conductivity data. Thus, the optical energy gap should always be larger than the thermal energy gap, making it difficult to compare directly the absorption energy spectra and electrical conductivity data.

An additional distinction exists between the thermal and optical energy gap in polar crystals. The redistribution of ionic charge can change the relative configuration of the bands. This change is a relatively slow, thermally activated process. During the faster, optical excitation process, this charge redistribution does not occur. The differences in the thermal and optical excitation processes can be described in terms of the low frequency (ϵ_s) and the high frequency (ϵ_o) dielectric constants.

This difference is proportional to $(\epsilon_s - \epsilon_o)/\epsilon_s \epsilon_o$.⁽¹⁰⁾ If ϵ_s is larger than ϵ_o , as is probable in ionic crystals, the optical energy gap would be larger than the thermal energy gap.

The ratio of the optical-to-thermal energy transitions is approximately equal to ϵ_s/ϵ_o .⁽³⁾ This value for UO_2 has been reported as 24/5.8.⁽³⁾ Assuming the optical energy gap is 5.25 eV, the corresponding thermal energy gap would be 1.27 eV, substantially less than the measured value.

However, a simple band model is assumed in this analysis, and it has been pointed out previously that simple band theory may not be valid for UO_2 . Thus, a correlation of electrical and optical properties is complicated and does not appear feasible using present theory.

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APPENDIX A
ELECTRICAL CONDUCTIVITY DATA
FOR SINGLE CRYSTAL UO_2

DESCRIPTION OF MEASUREMENT CONDITIONS

<u>Specimen</u>	<u>Specimen Size, cm</u>		<u>Apparatus</u>
	<u>Diam.</u>	<u>Length</u>	
MR-1	0.320	0.635	Two probe
MR-2	0.695	3.0	Four probe-Tungsten tube furnace
MR-5-a	0.635	1.91	Four probe-Tungsten tube furnace
MR-5-b	0.635	1.91	Four probe-Tungsten mesh furnace
EC-SI-A	0.635	1.91	Four probe-Tungsten mesh furnace
B-40-A	0.635	1.91	Four probe-Tungsten mesh furnace

APPENDIX B
ELECTRICAL CONDUCTIVITY DATA

SPECIMEN MR-1

Run Number 1		Run Number 2	
Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹	Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹
2483	55.50	2453	59.5
2543	80.0	2633	82.6
2703	118.0	2753	97.1
2553	90.9	2513	72.5
2473	57.1	2443	50.3
2573	83.3	2303	29.2
2658	109	2183	25.9
2223	15.4	2053	14.4
1898	5.7	1938	8.61
		2463	78.1
		2573	115.1
		2883	186.

FIGURE B.1. Electrical Conductivity of Single Crystal MR-1.

SPECIMEN MR-2

Run Number 1	
Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹
1046	0.077
1058	0.069
1083	0.086
1087	0.072
1088	0.096
1107	0.087
1170	0.100
1225	0.108
1276	0.138
1287	0.107
1838	0.500

Run Number 2	
Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹
1053	0.046
1087	0.065
1247	0.107
1163	0.138
1332	0.140
1431	0.194
1538	0.470
1658	0.960
1654	0.770
1828	1.93
1908	3.90
2041	7.80

Run Number 3	
Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹
1214	0.107
1282	0.114
1395	0.255
1401	0.225
1412	0.241
1550	0.440
1550	0.460
1631	1.06
1653	0.860
1832	2.55
1845	2.58

Run Number 4	
Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹
1048	0.059
1086	0.063
1239	0.110
1297	0.106
1316	0.130
1333	0.142
1429	0.245
1538	0.425
1650	0.850
1664	0.880

Run Number 5	
Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹
1212	0.105
1395	0.265
1401	0.184
1418	0.215
1629	0.940
1653	0.725
1825	1.98

FIGURE B.2. Electrical Conductivity of Single Crystal MR-2.

SPECIMEN MR-5-a

Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹	Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹
293	0.00128	1513	0.730
1128	0.187	1543	0.807
1218	0.215	1585	0.980
1253	0.230	1651	1.461
1277	0.253	1715	2.011
1308	0.276	1784	2.921
1346	0.316	1594	1.111
1380	0.364	1318	0.275
1432	0.461	1123	0.175
1466	0.526		

SPECIMEN MR-5-b

Cycle Number 1

Run Number 1

Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹	Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹
830	0.0935	895	0.0909
860	0.102	867	0.0877
873	0.0948	870	0.0885
1083	0.123	613	0.0347
1107	0.123	583	0.0286
1110	0.123	573	0.0258
1251	0.135	360	0.00374
1255	0.140	340	0.00222
1113	0.106	305	0.00129
1100	0.104	297	0.00118

Run Number 2

Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹	Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹
295	0.000909	688	0.0565
723	0.0680	630	0.0405
748	0.0748	625	0.0409
761	0.0771	578	0.0306
760	0.0790	573	0.0286
767	0.0790	533	0.0216
778	0.0832	533	0.0205
783	0.0836	491	0.0151
1251	0.152	464	0.0118
1256	0.149	453	0.0111
1261	0.148	433	0.00883
1265	0.149	430	0.00808
1112	0.129	413	0.00684
1101	0.125	413	0.00653
1111	0.129	375	0.0405
930	0.108	370	0.00374
911	0.106	371	0.00318
909	0.109	369	0.00306
861	0.0974	338	0.00230
858	0.0969	306	0.00191
821	0.0880	306	0.00186
815	0.0843	300	0.00142
787	0.0812	298	0.00136
776	0.0771	298	0.00135
741	0.0694		
733	0.0682		
688	0.0571

FIGURE B.3. Electrical Conductivity of Single Crystal MR-5.

SPECIMEN EC-S1-A

Run Number 1		Run Number 2	
Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹	Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹
813	0.171	2060	8.53
830	0.174	2368	17.00
1073	0.250	2563	20.06
1093	0.254	2418	21.11
1101	0.252	2250	15.92
1163	0.273	2068	11.40
1175	0.279	1870	8.46
1178	0.287	1863	8.02
1239	0.304	1635	5.10
1246	0.321	1513	1.63
1250	0.323	1450	0.983
1255	0.323	1383	0.729
1093	0.257	1266	0.627
1003	0.231		
943	0.207		
809	0.155		
746	0.143		
685	0.118		
633	0.0955		
583	0.0687		
551	0.0538		
530	0.0451		
480	0.0263		
441	0.0174		
423	0.0137		
400	0.0100		
358	0.00566		
318	0.00156

FIGURE B.4. Electrical Conductivity
of Single Crystal EC-S1-A

SPECIMEN B-40-A

Run Number 1			
Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹	Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹
654	0.0401	1121	0.158
658	0.0374	1128	0.159
788	0.0710	1111	0.154
825	0.0811	1112	0.154
852	0.0887	1130	0.158
878	0.0903	1127	0.159
883	0.0942	1126	0.158
989	0.125	1137	0.162
1011	0.129	1138	0.162
1031	0.131	1128	0.160
1031	0.136	1144	0.163

Run Number 2			
Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹	Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹
1114	0.154	688	0.0436
1120	0.147	613	0.0339
1116	0.156	570	0.0300
1114	0.155	538	0.0226
1114	0.153	523	0.0210
1068	0.142	453	0.0127
1068	0.143	444	0.0113
1002	0.132	410	0.0080
1000	0.133	399	0.0070
972	0.120	363	0.0042
968	0.122	358	0.0037
897	0.0985	342	0.0027
885	0.0966	332	0.0024
771	0.0643	318	0.0017
778	0.0657	312	0.0016
702	0.0477		

Run Number 3			
Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹	Temperature, °K	Conductivity, ohm ⁻¹ cm ⁻¹
1143	0.1464	1773	1.823
1136	0.1450	1573	0.721
1130	0.1461	1573	0.721
1273	0.1871	1575	0.719
1268	0.1880	1373	0.274
1273	0.1876	1373	0.276
1480	0.4477	1373	0.279
1473	0.4249	1173	0.165
1473	0.4267	1173	0.163
1673	1.223	1173	0.164
1673	1.201	1173	0.168
1673	1.223	973	0.120
1873	3.114	973	0.117
1880	3.095	973	0.119
1876	3.095	773	0.0686
1923	3.756	777	0.0683
1929	3.721	773	0.0674
1773	1.866		
1773	1.832

FIGURE B.5. Electrical Conductivity
of Single Crystal B-40-A

APPENDIX C
ENERGY OF ACTIVATION

<u>Specimen</u>	<u>Temperature, °K</u>	<u>Activation Energy</u>	
		<u>Low Temperature, eV</u>	<u>High Temperature, eV</u>
MR-1	1898-2983	--	1.64
MR-2	1048-2041	--	~1.3
MR-5-a	293-1784	0.17	1.39
MR-5-b	293-2600	0.17	1.56
EC-S1-A	318-2563	0.20	~1.1
B-40-A	312-1929	0.17	1.25

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