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The Thermal Diffusivity of Gold

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The thermal diffusivities of four gold samples have been measured from 325 to 1225°K. The sample purities varied from about 95 to 99.999% and the resistivity ratios from 3 to 600. The thermal diffusivity of gold was found to be sensitive to the impurity concentration. The thermal diffusivity data were combined with published specific heat data to obtain thermal conductivity values. Electrical resistivity and Seebeck coefficient measurements were also made on the samples.

Key Words: Gold, Lorenz number, Seebeck coefficient, thermal conductivity, thermal diffusivity.

1. Introduction

Recently there has been increasing interest in understanding the high temperature thermal conductivity of metals. In order to do so, much additional accurate data is needed on the simpler metals such as Cu, Ag, and Au. Thermal diffusivity data on a series of gold samples of different purities is reported here. Gold was chosen because of the availability of reasonably pure samples and the almost total lack of published thermal conductivity data above 300°K.

2. Measurements

The thermal diffusivity measurements were made by a modified Angstrom method. The techniques and equipment which were used for these measurements have been described previously [1, 2]¹. The three sample thermocouples consisted of 0.025 cm diam Pt and Pt/10% Rh wires spot welded to the gold sample. Current for electrical resistivity measurements was applied to the sample through 0.061 cm diam Pt wires spot welded to the sample ends. The apparent electrical resistivity was measured after each measurement of thermal diffusivity by a standard 4-wire technique. Two of the Pt thermocouple wires were used as voltage probes. The thermal diffusivity measurements were made with the samples in one atmosphere of helium and with a 2.5°K amplitude 30 sec period temperature sine wave.

The absolute Seebeck coefficients of the samples were measured by a method described by Heller and Danielson [3]. Two of the thermocouples welded to the sample for thermal diffusivity measurements were used for the Seebeck coefficient measurements. The wires were reconnected externally so that the instantaneous voltage developed across the Pt - Au - Pt junctions could be plotted as a function of the voltage across the Pt/10% Rh - Au - Pt/10% Rh junctions on a x-y recorder.

The 30 sec period sine wave used for thermal diffusivity measurements was also used to supply the varying temperature gradient for the Seebeck coefficient measurements. The absolute Seebeck coefficient of gold could then be calculated from the absolute Seebeck coefficient of platinum reported by Cusack and Kendall [4] and the Pt - Pt/10% Rh thermocouple tables published by Adams and Davisson [5].

3. Samples

Four gold samples of different purity were obtained from four different sources in the form of rods 0.35 cm in diam and 30 cm long. Table 1 lists the samples, the manufacturer, the purity stated by the manufacturer and our measured values for the ratio of the electrical resistivity at 300°K to the electrical resistivity at 4.2°K after the samples had been annealed at 1225°K for 1 hr.

¹Figures in brackets indicate the literature references at the end of this paper.

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Table 1. Sample Characterization.

Sample	Manufacturer	Purity	$R_{300}/R_{4.2}$
Au 1	Johnson, Matthey and Co.	99.999%	600
Au 2	Sigmund Cohn	99.99%	310
Au 3	Aremco	99.9999%	110
Au 4	Mint Gold	-	3

4. Results

The thermal diffusivity results for the four samples are shown in fig. 1. Each point represents the average of two diffusivity values obtained from the two thermocouple combinations at a given temperature. The deviation of the points for each sample from a smooth curve drawn through them was less than 1.5%. The thermal diffusivity was dependent on the purity of the sample and decreased with increasing impurity concentration. For the most impure sample, Mint gold, the thermal diffusivity was found to go through a maximum value at about 725°K.

The electrical resistivities of the four samples are shown in fig. 2. The electrical resistivities of the two samples of highest purity were the same, and were lower than the values for the other two samples. The electrical resistivity versus temperature curve for Au 4 is higher than, and not parallel to, the curves for the other three samples. This difference between the curves implies a high impurity concentration and also a violation of Matthiessen's rule.

The Seebeck coefficients for the four gold samples are shown in fig. 3. The data for the gold samples are based on the absolute Seebeck coefficient of platinum reported by Cusack and Kendall [4]. They report an accuracy of $\pm 5\%$ for their platinum data. The absolute Seebeck coefficients for samples Au 1, Au 2, and Au 3 agreed within $\pm 2\%$ over the entire temperature range; and since the differences in the data for the three samples were less than the total errors for the measurements, the values were averaged to give one curve of Seebeck coefficient versus temperature. As expected the results for Mint gold were considerably lower and approached the values observed for the other three samples only at the highest temperatures.

5. Discussion

The thermal diffusivities (fig. 1) of the two highest purity samples, Au 1 and Au 2, which have resistivity ratios of 600 and 310, respectively, differ by only 0.7% at 350°K and by 3% at 1225°K. Since the errors in the measurement are about 2%, it is difficult to report any real difference in the thermal diffusivities of the two samples, although the higher purity sample appears to have a higher thermal diffusivity.

Au 3, with a resistivity ratio of 110, has a thermal diffusivity 7% lower than Au 1 at 350°K. This difference represents a real change in thermal diffusivity with purity. For the most impure sample, Au 4, the thermal diffusivity at 350°K is 36% below the value observed for Au 1, the most pure sample. The shape of the thermal diffusivity versus temperature curve for Au 4 is different from the shape of the other sample curves and represents the effect of large amount of impurities on the thermal diffusivity.

The thermal conductivities of the four samples were obtained from the product of the measured values of thermal diffusivity and the published values of density and specific heat. A constant density [6] of 19.30 gm/cm³ was used. The specific heat results of Jaeger, Rosenbohm, and Bottema [7] were used in the calculation since their data is the most recent published and, if extrapolated to low temperatures, connects smoothly to the data of Geballe and Giauque [8]. Figure 4 shows the thermal conductivities calculated for each of the four samples and also shows data reported by Mikryukov [9]. The data reported by Mikryukov [9] is on a polycrystalline sample of gold with a reported purity of 99.99%.

The thermal conductivity curves reflect the same differences in purity observed in the thermal diffusivity data because the same specific heat values were used for all samples. This is probably justified for the three samples of highest purity since the specific heat is usually rather insensitive to small amounts of impurities. It may not be valid to use the specific heat for pure gold to calculate the thermal conductivity of Au 4 which has a high impurity concentration. The smoothed thermal diffusivity, the thermal conductivity, the electrical resistivity and Seebeck coefficient for Au 1 are given in table 2. These results represent our best values for the properties of pure gold.

Table 2. Transport properties of pure gold

Temperature °K	Thermal Diffusivity cm ² /sec	Thermal Conductivity watts/cm-deg	Electrical Resistivity ohm-cm	Seebeck Coefficient μV/deg
325	1.140	2.97	2.43	1.93
400	1.121	2.96	3.05	2.37
500	1.093	2.94	3.93	2.83
600	1.062	2.92	4.84	3.15
700	1.028	2.90	5.76	3.35
800	0.994	2.86	6.75	3.51
900	0.954	2.82	7.76	3.67
1000	0.920	2.78	8.89	3.85
1100	0.874	2.73	10.06	4.03
1200	0.826	2.66	11.35	4.29

The apparent Lorenz numbers were calculated from the thermal conductivity and electrical resistivity data. The resulting curves are shown in fig. 5. The curves for all four samples are in good agreement and, at high temperatures, are all within $\pm 7\%$ of the theoretical value of $2.45 \times 10^{-8} \text{ V}^2/\text{°K}^2$.

6. Conclusions

The thermal diffusivities of four gold samples with resistivity ratios ranging from 600 down to 3 have been measured from 325 to 1225°K. The thermal diffusivity values and published specific heat values were used to calculate the thermal conductivities. The thermal conductivities for the samples of higher purity are in good agreement with data on gold reported by Mikryukov [9]. The calculated Lorenz numbers agree well with theory.

7. References

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Figure captions

- Figure 1. The thermal diffusivity of gold as a function of temperature. The data show the effect of different amounts of impurities with Au 1 the most pure sample and Au 4 the most impure sample.
- Figure 2. The electrical resistivity of gold as a function of temperature above 300°K.
- Figure 3. The Seebeck coefficient of gold as a function of temperature. The effect of large amounts of impurities on the Seebeck coefficient can be seen in the data for Au 4.
- Figure 4. The thermal conductivity of gold as a function of temperature.
- Figure 5. The apparent Lorenz number as a function of temperature for gold. The Wiedemann-Franz law predicts a constant Lorenz number of $2.45 \times 10^{-8} \text{ V}^2/\text{K}^2$.