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Measurement of the Thermal Conductivity of Molten Semiconductors[1]

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The thermal conductivity of molten InSb in the temperature range between 800 and 870 K was measured by the transient hot-wire method using a ceramic probe. The probe was fabricated from a tungsten wire printed on an alumina substrate and coated with a thin alumina layer. The thermal conductivity was found to be about $18\,W \cdot m^{-1} \cdot K^{-1}$ at the melting point and increased moderately with increasing temperature. The thermal conductivity of alumina used as the substrate for the probe was also measured in the same temperature range.

KEY WORDS: alumina; high temperature; InSb; thermal conductivity; transient hot-wire method.

1. INTRODUCTION

Several numerical simulations of convection during semiconductor crystal growth have recently been undertaken using a high-speed computer [1, 2]. These simulations are a very powerful method to understand mass and heat transfer processes in crystal growth. They are also important when studying crystal growth in microgravity environments to save time and avoid unnecessary space experiments. However, few thermophysical data for molten semiconductors are available for the simulation. The thermal conductivity of molten semiconductors is largely unknown. Convection in molten semiconductors makes it difficult to measure the thermal conductivity accurately.

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We are planning to measure the thermal conductivity of molten semiconductors in microgravity. Since buoyancy convection does not take place in space, precise measurements for the thermal conductivity can be performed, separating heat transfer by conduction from that by convection. We have developed a ceramic probe for use in electrically conductive liquid [3, 4]. In the present work, the thermal conductivity of molten InSb was measured using the probe as a feasibility study for thermal conductivity measurements in space.

2. EXPERIMENTAL APPARATUS

Details of the ceramic probe and measuring apparatus for the probe were reported in previous papers [3, 4]. A metallized wire was printed on an alumina substrate. An alumina layer for insulation was formed over the surface and metallization. When the surface of the probe is in contact with liquid, the temperature rise ΔT of the wire by input power q is related to the thermal conductivities of the liquid and the substrate as follows [5]:

$$\lambda_L + \lambda_S = \frac{q}{2\pi} \Big/ \frac{d(\Delta T)}{d[\ln(t)]} \tag{1}$$

where the thermal conductivities λ_L and λ_S are those of the liquid and the alumina substrate, respectively, and q is the power input per unit length of the wire. The principle for a measurement using the probe is the same as that for a conventional hot-wire probe. The temperature rise ΔT is measured when a constant input power q is provided to the wire. The sum of the two thermal conductivities is calculated from ΔT using Eq. (1). λ_L is determined by subtracting a known λ_S from $\lambda_L + \lambda_S$. A wheatstone bridge was used to detect slight changes in the temperature rise; this technique is often used in the conventional hot-wire method [6].

Figure 1 shows a specimen container in a horizontal furnace. The

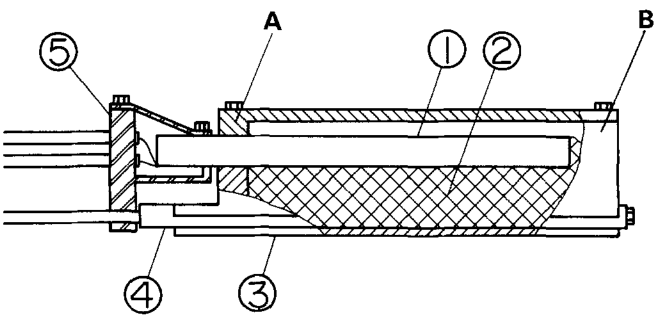

Fig. 1. Specimen container assembly. (1) ceramic probe; (2) molten InSb; (3) carbon specimen container; (4) container holder; (5) probe holder.

isothermal zone of the furnace was 15 cm long to cover the specimen container. After the thermal environment around the specimen had stabilized, the wire-printed surface of the probe was brought into contact with the surface of molten InSb by inserting the probe horizontally. On inserting the probe, the oxide layer formed on the specimen surface was removed by the head of the probe; the wire-printed surface thus contacts a clean specimen surface. In addition, the probe was not damaged by the volume change upon solidification of the molten InSb, since the probe was removed before solidification.

3. RESULTS

The thermal conductivity of an alumina substrate was measured in a low-pressure nitrogen atmosphere (10^{-2} Torr), at temperatures in the range 790–890 K. Each measurement was repeated three times at the same temperature. Since the thermal conductivity of nitrogen is two orders of magnitude smaller than that of alumina [7], the effect of nitrogen conduction on the measured thermal conductivity was considered to be negligible.

Figure 2 shows a typical example of ΔT plotted against $\ln(t)$ for the substrate. Figure 3 shows the apparent thermal conductivity and the correlation coefficient calculated from the line in Fig. 2. Both were calculated by using 20 measured values of ΔT for each value of $\ln(t)$. The sampling rate was 40 data points/s. As shown in Fig. 3, the apparent ther-

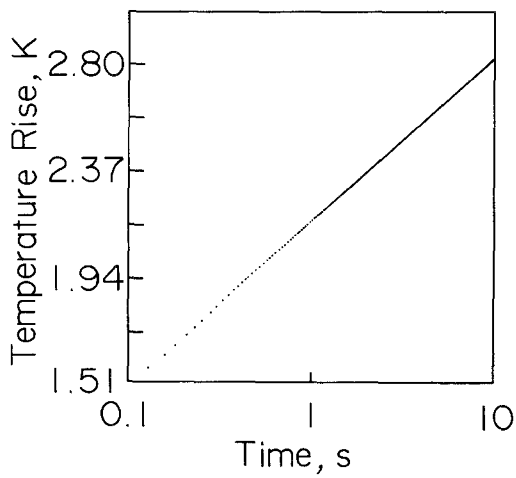

Fig. 2. Temperature rise vs $\ln(t)$ for alumina substrate at 840.5 K.

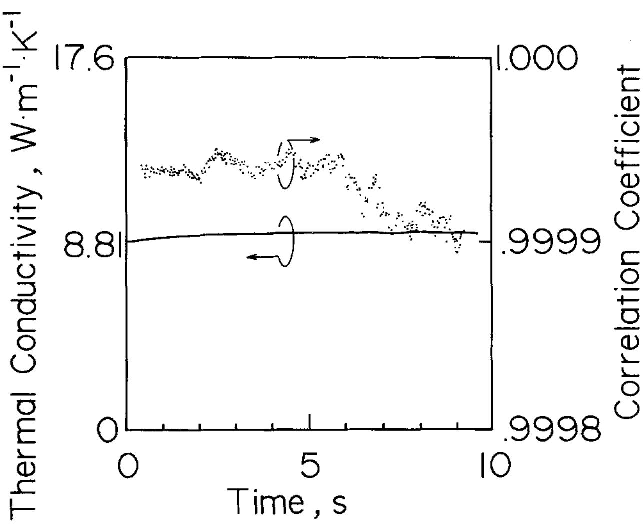

Fig. 3. Apparent thermal conductivity and correlation coefficient.

mal conductivity was constant after 3 s, and the correlation coefficient was about 0.99993. Lower apparent conductivities before 3 s are considered to be due mainly to the heat capacitance of the alumina insulation layer [4]. The thermal conductivity was determined from the apparent conductivity by compensating for errors due to resistances of electrodes [4]. Figure 4

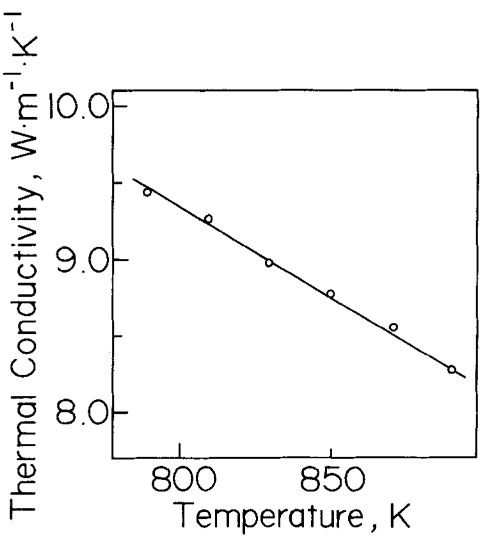

Fig. 4. Thermal conductivity of alumina substrate as a function of temperature.

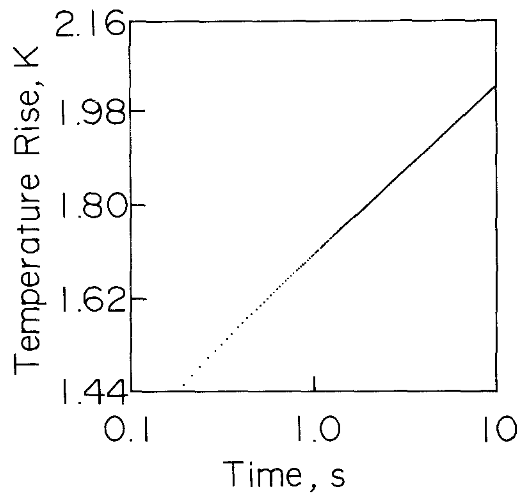

Fig. 5. Temperature rise vs $\ln(t)$ for molten InSb at 843.0 K.

shows the thermal conductivity of the substrate as a function of temperature; the thermal conductivity decreased with increasing temperature. The following expression was obtained for the thermal conductivity λ_s (in $W \cdot m^{-1} \cdot K^{-1}$) as a function of the temperature T (in K) between 800 and 890 K

$$\lambda_s = 18.66 - 0.01162T \quad (2)$$

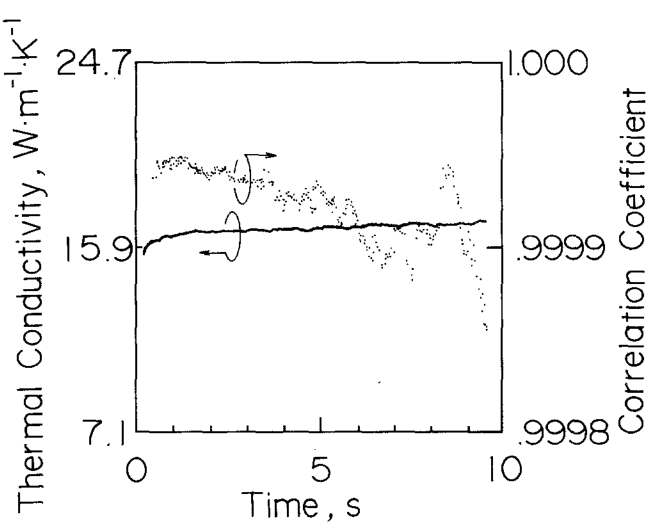

Fig. 6. Apparent thermal conductivity and correlation coefficient.

The thermal conductivity at 800 K is 9.36 $W \cdot m^{-1} \cdot K^{-1}$ from the above equation. This is 11 % smaller than the value for 98 % dense polycrystalline alumina, 10.4 $W \cdot m^{-1} \cdot K^{-1}$ [8].

The thermal conductivity of molten InSb was measured in the range 800–870 K. InSb was synthesized by melting 5 *N* Sb and 6 *N* In in 1.4-atm N_2. Figure 5 shows the results for this system. Figure 6 shows the apparent thermal conductivity and the correlation coefficient derived from the data in Fig. 5. A linear relationship was found, like that for the alumina substrate. Although the apparent thermal conductivity increased with elapsed time, the sum of the thermal conductivities for the molten InSb and the substrate was calculated by averaging the apparent conductivity between 3 and 5 s. Figure 7 shows the thermal conductivity of molten InSb versus temperature. The measured thermal conductivity increased slightly with increasing temperature.

In order to check for leakage of the current from the wire into the molten InSb, the resistances of the wires were checked during measurements for the alumina substrate and the molten InSb. The difference in resistances was less than 1 % for two cases. This means that no significant leakage took place during the measurement of molten InSb.

The temperature difference between the front and the back of the specimen container was measured at 830 and 900 K. Two calibrated

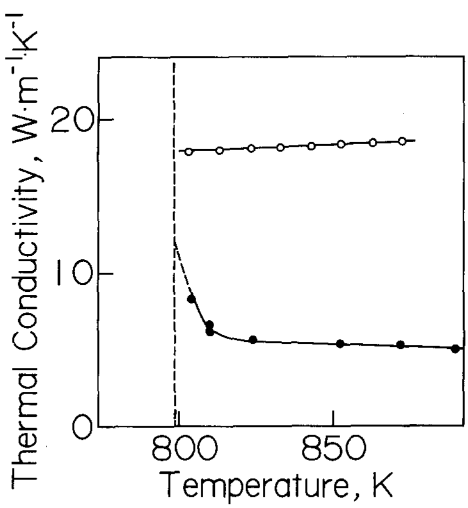

Fig. 7. Thermal conductivity of molten InSb as a function of temperature. (○) Present work; (●) Amirkhanov and Magomedov [9].

thermocouples were buried at locations A and B in the container with molten InSb as shown in Fig. 1. The temperature differences were less than 1 K at both 830 and 900 K.

4. DISCUSSION

Regarding the present measurements, we must consider the following two points. The first is leakage of current from the wire into the molten InSb through the coating layer, and the second is natural convection in the molten InSb. Those two factors might raise the measured thermal conductivities. The leakage was found to be small according to this study. It is difficult to know if the convection exists or not; the measurements of temperature rise vs $\ln(t)$ give no basis on which to decide whether convection exists or not. Measurements indicated that the temperature uniformity is rather good along the direction parallel to the probe. Since heat is received from the inside wall of the furnace and it is conducted away through a probe holder, the temperature of the probe is thought to be lower than the temperature at the bottom of the specimen container. If this is the case, convection could occur in the molten InSb during measurements of the thermal conductivity. The measured value would then be higher than the true value for molten InSb. However, if the thermal conductivity changes abruptly near the melting point as reported by Amirkhanov and Magomedov [9], this change should be observable.

Thermal conductivity was calculated from the Wiedemann–Franz law using the electrical conductivity of molten InSb [10]. The calculated values were $19.6\ W \cdot m^{-1} \cdot K^{-1}$ at 848 K and $20.6\ W \cdot m^{-1} \cdot K^{-1}$ at 893 K. The calculated thermal conductivities increase with increasing temperature. Compared with the present result, the calculated thermal conductivity values and their temperature dependence may indicate that InSb is rather metallic in the molten state [11].

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