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Measurement of the Thermal Conductivity of Molten InSb Under Microgravity

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Thermal conductivity of molten InSb was measured on board the TEXUS-24 sounding rocket by the transient hot-wire method using the originally designed thermal conductivity measurement facility (TCMF). Measurements made through this facility were affected by natural convection on the ground. This natural convection was confirmed to be sufficiently suppressed during a microgravity environment. The thermal conductivity of molten InSb was 15.8 and 18.2 $W \cdot m^{-1} \cdot K^{-1}$ at 830 and 890 K, respectively.

KEY WORDS: InSb; microgravity; molten InSb; thermal conductivity; transient hot-wire method; space experiment.

1. INTRODUCTION

Thermal conductivity data of molten semiconductors are required for computer simulations of crystal growth processes. These data are collected by measuring the thermal response which is detected when heat is imparted to a specimen. When the temperature of the specimen is increased, heat is transferred by convection as well as conduction. This buoyancy convection increases thermal conductivity, thus having a strong effect on thermal conductivity measurements of liquids with low viscosity, such as molten semiconductors.

Buoyancy convection can be suppressed under microgravity (μG) environments, since gravity, the driving force of convection, is already suppressed. Therefore, microgravity environments have been considered

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to be ideal for thermal conductivity measurements [1–3]. However, so far, only one measurement on ethanol was carried out under microgravity in the MASER 1, the Swedish sounding rocket [4].

In this work, the thermal conductivity of molten InSb was measured on board the TEXUS-24 sounding rocket. The measurement facility, TCMF (Thermal Conductivity Measurement Facility), has been specially developed for the TEXUS rocket [5]. The major objectives of the experiments were to confirm the effect of microgravity on the suppression of buoyancy convection and to compare the thermal conductivity value obtained under microgravity with that on the ground [6].

2. EXPERIMENTS

Measurements were performed with ceramic probes using the transient hot-wire method [6]. A printed wire on a thick ceramic substrate is used as a sensor to measure temperature increase that occurs when a constant electric power is applied to the wire. Takegoshi et al. [7] have given a working equation for this kind of probe, based on the assumption that the wire is an ideal line heat source on a flat interface between two media. Thermal conductivity sum $\lambda_L + \lambda_S$ was expressed as follows:

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

where ΔT is the temperature increase of the wire, t is time, and λ_L and λ_S are thermal conductivities of the two media (molten InSb and ceramic substrate), respectively. Q is the constant input power to the wire per unit length.

We have developed ceramic probes for electrically conducting liquids, such as liquid metals and molten semiconductors [8, 9]. Figure 1 shows the ceramic probe used in this experiment. The rod-shaped ceramic probe was made in a cofiring process similar to one which we have previously reported [9]. A platinum sensor wire (A) and electrodes for feeding current (B) were formed on a flat surface of 94% pure alumina substrate. The radial distance from the wire to the outside of the alumina substrate was 14 mm. Potential electrodes (C) were connected at a 90° angle to the wire in order to eliminate effect of the ends of the wire. Platinum lead wires (D) of 0.8-mm diameter were connected to the printed electrodes at the end of the probe.

Length of the printed wire between the potential electrodes was 70 mm. The cross section was 15 μm high and 100 μm wide. In order to avoid the leakage of current through molten InSb and to preserve the

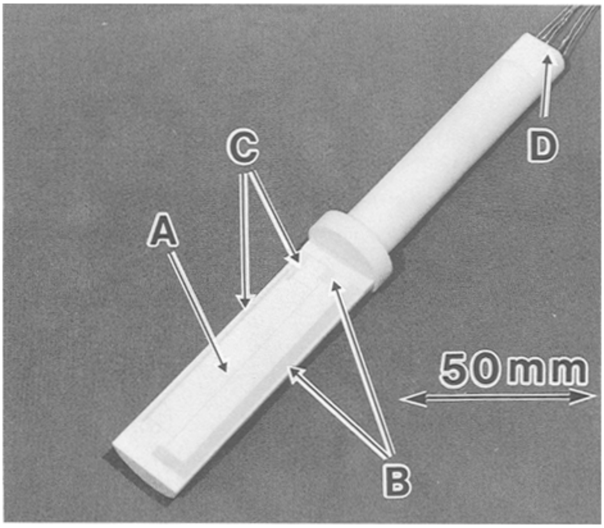

Fig. 1. Ceramic probe for TCMF. (A) Sensor wire; (B) electrodes for applying current to the wire; (C) electrodes for detecting voltage drop in the sensor wire; (D) platinum lead wire.

printed wire and electrodes from corrosion, the wire and electrodes were coated with a thin alumina layer: 60 μm on the wire and 150 μm on the electrodes, respectively. Resistivity of the coating layer was about $1.6 \times 10^9 \, \Omega \cdot \text{cm}$ at 800 K.

A printed Pt–PtRh thermocouple, calibrated with a standard Pt–Pt 13%Rh thermocouple, was formed 3 mm deep beneath the center of the printed wire. The purpose of the thermocouple was to measure molten InSb temperature more accurately than the thermocouples attached to the surfaces of cartridges (see below).

The ceramic probe was set with InSb in a carbon crucible enveloped by a nickel cartridge. The cartridge structure and vibration test results have been described in detail in a previous report [5].

Two nickel cartridges were set vertical to the ground inside each of two platinum heater-equipped gradient furnaces (furnaces A and B) of the TCMF. Solid InSb was melted before the launch, since a 6-min microgravity period was believed to be too short to homogenize the temperature distribution. Furnace A had temperatures of 843 K on the upper cartridge surface and 838 K on the lower surface, while furnace B recorded temperatures of 903 K on the upper surface and 898 K on the lower surface. Actual temperature differences of molten InSb between the upper and the lower surfaces were thought to be less than 5 K. In both cases, the temperature of the upper surface is higher. As a result convection, which may occur before a launch, can be suppressed.

The measurement system in the TCMF on board the TEXUS-24 rocket consisted of two main parts: a constant-current supply and an A/D (analog/digital) converter [5]. When a constant current is supplied to the printed wire, the voltage drop between potential electrodes is measured and converted into digital data by the A/D converter. The current supply can generate a constant current of up to 2.55 A for a 10-s duration. The A/D converter can measure voltage drops 10 times/s with a resolution of 3.8×10^{-6}. Digital data of measured voltage drops were saved in the DRAM (Dynamic Random Access Memory) cassette in the TCMF [5].

3. RESULTS AND DISCUSSION

Figure 2 shows temperature measured between -900 and $+790$ s by the thermocouple buried in the ceramic probes; 0 s corresponds to the launching of the rocket. 1G reference measurements were carried out every 30 s from -500 s. These measurements were shown as heat pulses indicated in Fig. 2 by A_1 to A_7 and B_1 to B_7. Temperature increased by 6 K for furnace A and by 4 K for furnace B during the 1G measurements. However, as Fig. 2 reveals, these temperatures returned to prereference measurement levels before the rocket was launched. Therefore, it is plausible that the temperature increase in the 1G reference measurements does not influence the μG measurements.

As shown in Fig. 2, measurements from A_9 to A_{13} and from B_9 to B_{13} were performed at an interval of 60 s in a μG environment which was

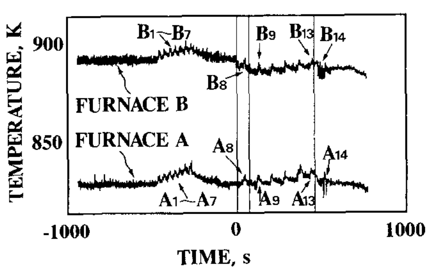

Fig. 2. Temperature of molten InSb measured by printed thermocouple in ceramic probe. A_1 to A_7 and B_1 to B_7, reference measurements on the ground; A_8 and B_8, during launch; A_9 to A_{13} and B_9 to B_{13}, in microgravity; A_{14} and B_{14}, reentry phase.

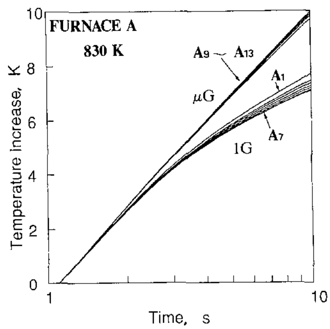

Fig. 3. Temperature increase in the wire as a funtion of time (logarithmic scale) for furnace A.

about 10^{-4} G. In the μG environment, temperatures slightly increased in furnaces A and B. The rate of this temperature increase was about $0.01\ \mathrm{K \cdot s^{-1}}$, which is negligibly smaller than the rate of temperature increases in the μG measurements. Temperatures of the molten InSb samples were determined from Fig. 2 to be 830 K for furnace A and 890 K for furnace B in the μG duration. The temperatures were about 13 K lower than those of the cartridge surfaces. This temperature difference may be due mainly to thermal resistance between the cartridge and the carbon crucible.

Measurements of A_8 and B_8 were carried out during the rocket acceleration. Measurements A_{14} and B_{14} were performed during the rocket's reentry phase. However, the data for these measurements were too noisy to be analyzed.

Figures 3 and 4 show the temperature increase ΔT in the wire as a

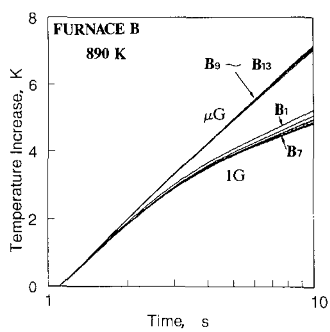

Fig. 4. Temperature increase in the wire as a function of time (logarithmic scale) for furnace B.

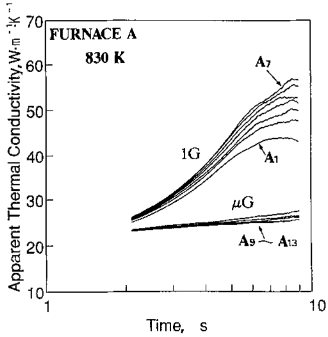

Fig. 5. Apparent thermal conductivity as a function of time (logarithmic scale) for furnace A.

function of ln(t) for furnaces A and B. The applied current was 1.5 A, which corresponds to 87.6 W $\cdot$ m^{-1}. Figures 5 and 6 show apparent conductivities $\lambda_L + \lambda_S$ calculated according to Eq. (1). ΔT curves in the 1G reference measurements were deviated from linear relationships as shown in Figs. 3 and 4. As a result, Figs. 5 and 6 demonstrate that the apparent conductivities for the 1G measurements abruptly increase with elapsed time. This is due primarily to convection caused by wire heating. In addition, the apparent conductivities for the 1G references reached higher values in later measurements, suggesting that the convection may be accelerated by successive heating of the wire.

However, closer inspection of Figs. 3 and 4 further reveals that ΔT attained a linear relationship in the μG measurements. It is clearly seen in Figs. 5 and 6 that the apparent conductivities are mostly constant with

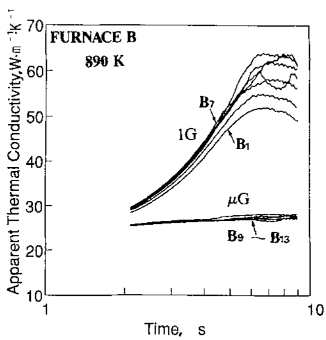

Fig. 6. Apparent thermal conductivity as a function of time (logarithmic scale) for furnace B.

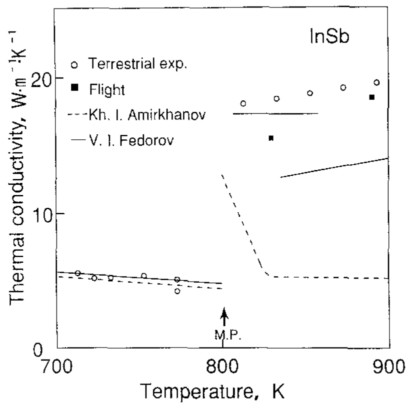

Fig. 7. Thermal conductivity of molten InSb. (■) Flight experiment in TEXUS 24; (○) terrestrial experiment [6, 12]; (-----) Ref. 10; (——) Ref. 11.

elapsing time for each measurement. This suggests that the contributions of convection to the apparent thermal conductivities were, to a great extent, reduced.

Figure 7 shows thermal conductivity of InSb near the melting point. The thermal conductivities obtained from the measurements A_9 and B_9 were 15.8 and 18.2 $W \cdot m^{-1} \cdot K^{-1}$ at 830 and 890 K, respectively. Thermal conductivities measured in terrestrial experiments are shown for the solid and liquid states [6, 12]. The thermal conductivities measured by two other groups of researchers [10, 11] were different from each other and from our results obtained in terrestrial experiments, which demonstrated a higher measured thermal conductivity. We could not clearly estimate the contribution of convection contained in our previous measurement [6, 12]. The difference in Fig. 7 between the data of the TEXUS flight and the terrestrial experiment may be due to convection in the crucible during terrestrial experiments.

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