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Abstract. For bulk solid-solid interfaces, the thermal contact resistance TCR) is generally attributed to a mismatch in the acoustic impedances (density x sound velocity) of each medium [1]. Here, we present a novel study of the TCR for a bulk Silicon crystal (111) in contact with superfluid helium, as a function of the acoustic impedance of the superfluid. The cell design and experimental technique are discussed in [2]. The acoustic impedance is varied by monitoring the pressure of the superfluid. Measurements are carried-out at T~1.8 K, from a few torrs (vapor pressure) up to 25 bars, corresponding to approximately an 80% change in the acoustic impedance of the superfluid. The experiments show no change in TCR over the entire pressure range, indicating a negligible contribution due to the acoustic impedances. A comparison to the diffuse mismatch model [1] is discussed.

1. Introduction

Nanotechnology has reignited intense research in the thermal contact resistance (TCR) phenomenon for over the last decade. For small temperature jumps, $R_K = \Delta T / Q$, where R_K is the TCR and Q is the heat flux (in W/cm^2) across the interface. At low temperatures (long wavelengths) and for macroscopic solid–solid interfaces, the TCR is generally due to a mismatch [1] in the bulk acoustical properties (density and speed of 1st sound). This is described by the acoustic model (AM), which is considered to be a reference model. Here, the phonon scattering process at the interface is specular and elastic. The transmission coefficient is determined by the acoustic impedances of each medium, as in the case of transmission of ordinary acoustic waves across a boundary between two materials. At higher temperatures (short wavelengths) and for thin film multi layer [3-4] systems, the measured TCR values are generally much weaker (in some cases by almost two orders of magnitude) than that predicted by the AM theory. For these cases the diffuse mismatch model (DM), which assumes random elastic scattering at the interface, tends to give better qualitative agreement with experimental results. It is important to note that neither the AM nor the DM models explain quantitatively experimental data. Consequently, the prediction of the TCR at solid-solid interfaces remains an important open problem.

In light of the above, we present first measurements of the TCR at the interface between a Silicon single-crystal in contact with superfluid helium as a function of the acoustic impedance of the superfluid. As we monitor the pressure in the superfluid at a fixed temperature, its density and speed of sound (ordinary sound) changes correspondingly. Since the acoustic properties of the Silicon crystal are not modified with pressure in this study range, the measured TCR is a direct function of the superfluid impedance only. Another advantage is that the surface state of the crystal may be fully characterized (surface roughness and chemical purity) and it remains unaltered throughout the experiment. The experiment presented here is conducted at a temperature of 1.8 K for pressures ranging from the saturated vapour pressure (a few torrs) up to 25 bars. The density and the speed of sound of the superfluid as a function of pressure and temperature are well documented [5].

2. Experimental

The cell designed for the experiment is made-up of a Silicon single crystal rod ($\phi = 6.2$ mm) with a highly polished mirror surface at one extremity, perpendicular to the C axis of the crystal along the rod. This surface is in contact with superfluid helium. A heater is placed at the other extremity of the rod. There are three RuO$_2$ thermometers (T_1, T_2 and T_3) anchored onto the crystal and another T_L is placed in the superfluid. The thermometers are 12 mm apart and T_1 is closest to the interface. The distance d between the interface and T_1 is ~2 mm. The experimental cell is fixed to the cold source of the ^{3}He refrigerator as shown in figure 1.

The experimental technique is summarized as follows. A phonon heat flux Q is applied along the C axis of the crystal into the superfluid as the temperature of the latter is controlled to within less than 2 mK. A fraction of the phonon flux which is reflected at the interface, back into the crystal, is detected by all thermometers on the crystal. The effect is preponderant on thermometer T_1 as it shifts to T_1' for a change in heat flux by ΔQ. The TCR is then given by the expression:

$$(T_1 - T_1') = (R_K + d/K) \Delta Q \tag{1}$$

where K is the thermal conductivity of the Si crystal. Further details of the experimental cell and technique are given in ref. [2].

3. Results & Discussions

Figure 2 shows measurements of the TCR as function of the superfluid pressure at T~1.82K. Clearly, no change in the TCR is observed as the pressure is increased from SVP to 25 bars (solidification pressure). The TCR data has a constant value of $R_K = (5.22 \pm 0.2)$ cm^{2}K/W, independent of the pressure at the interface. The correction due to the second term in equation (1) is completely negligible since the mean free path of phonons is much greater than d. The pressure in the cell is monitored using a Bourdon manometer and it is read with a precision of ~0.15 bars.

As the pressure is increased the superfluid density ρ_L increases from 0.145 g/cm^3 at SVP to 0.173 g/cm^3 at 25 bars. The speed of sound c_L changes correspondingly from 239 m/s to 365 m/s. The acoustic impedance of the superfluid $Z_L = \rho_L c_L$ varies by ~80%. This change impacts directly the AM model prediction of TCR as shown by the dashed line in figure 2. For the AM model of the TCR we use the formula [6] $R_K^{-1} = \left[2\pi^3 k_B^4 Z_L T^3 F \right] / \left[15\hbar^3 \rho_S \upsilon_{S,t}^3 \right]$, where ρ_S is the density of the solid. F is a function of the longitudinal and transverse speeds of sound $\upsilon_{S,t}$ in the Silicon crystal and F is set to the typical value of 1.6. This value of F includes Rayleigh wave energy transfer along the crystal surface. In computing R_K as a function of pressure, we used the tables given in ref. [5]. From ref. [1], the DM model prediction of the TCR for solid/superfluid interfaces can be written as

$R_{K,DM}^{-1} = \left[\pi^2 k_B^4 c_L^{-2} \left(\sum_j \upsilon_{S,j}^{-2} \right) \right] / \left[30\hbar^3 \left(c_L^{-2} + \sum_j \upsilon_{S,j}^{-2} \right) \right]$, where j corresponds to longitudinal and transverse

modes in the solid. Since the term $\sum_j \upsilon_{S,j}^{-2} << c_L^{-2}$, we have that $R_{K,DM}^{-1} \propto 1/\sum_j \upsilon_{S,j}^{-2}$. The sound velocities in the solid $\upsilon_{S,j}$ are constants. $R_{K,DM}$ is therefore independent of pressure (dotted lines in figure 2) and has a constant value of $R_{K,DM} = 2.03$ cm^{2}K/W. This value is a factor of ~2.5 smaller than the measured values.

More experiments are presently being carried-out at lower temperatures. Detailed analysis shall be presented in ref. [6].

Finally, we note that previous investigations at Cu-^{3}He interfaces suggest that the Kapitza resistance "is nearly pressure independent" for temperatures greater than 1 K (see fig.2 in ref. [1]). Experiments at Cu-^{4}He interfaces led to similar conclusions as well [7].
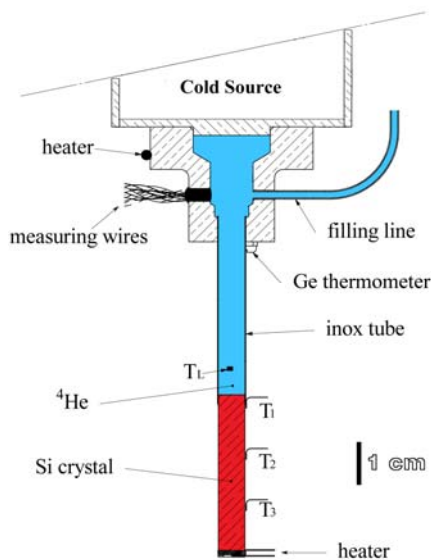

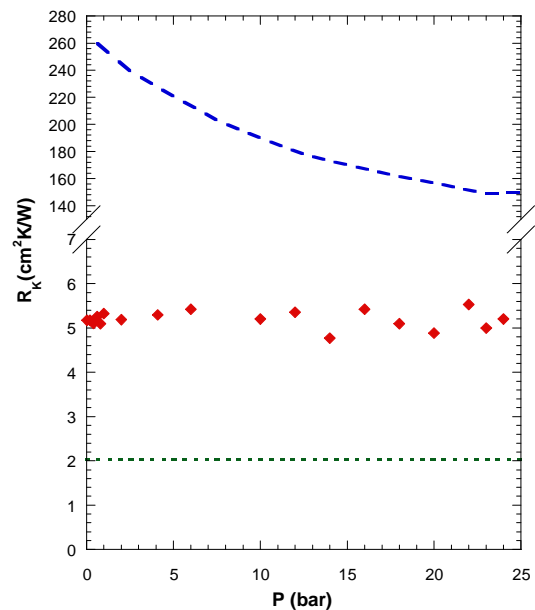**Figure** 1. Schematic representation of experimental set-up

Figure 2. Thermal contact resistance between Si and superfluid helium as a function of pressure at a constant temperature of ~1.82K The dashed and dotted curves represent the acoustic mismatch and the diffuse mismatch models respectively with pressure.

4. Conclusion

The experiment demonstrates no detectable change in the exchange mechanism(s) at the interface as the pressure is raised to 25 bars, just before solidification of the superfluid. To our knowledge, the present study can only be conducted with superfluid helium since its thermal properties allows temperature control, contrary to ordinary liquids. The absence of correlation to acoustic properties in our experimental results gives a direct proof for the first time that heat transfer may be fully governed by a local mechanism at the interface which needs to be identified.

5. References

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