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# Direct Probing of Nanoscale Heat Transport Phenomena via Scanning Thermal and Shear Force Microscopies

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## Extended Abstract

Heat transfer in thermal junctions is ultimately governed by the nanoscale physical phenomena that occur at the interfaces between the contacting bodies, with capillary meniscus and continuous interfacial liquid layers playing key role in such heat transfer. Nanoscale dimensions of these contacts make these phenomena hard to model and to investigate experimentally. Nevertheless, we were able to overcome this, by using two physical phenomena of different physical nature – a) a heat transport and b) a contact shear strength, that both rely on the ultimate contact between bodies, but depend in a different way on the dimensions, strength and number of nanoscale contacts.

In our experiments, we used scanning thermal microscopy (SThM) – a tool for mapping and measuring local heat transport properties between nanoscale tip and sample (Shi and Majumdar, 2002). We have modified SThM with lateral piezo-stage dithered at few kHz frequency and lateral displacements in the range from few to several tens of nm thus creating a lateral sliding forces measured by the cantilever torsion (Carpick and Salmeron, 1997) measuring and recording both the normal forces and shear forces simultaneously with the SThM signal. Our combined SThM-shear force microscope operated in both ambient and high vacuum (HV) $1\text{x}10^{-7}$ Torr (Pumarol et al., 2012) environments.

While dependence of the heat transport in nanoscale junctions on the normal force has been reported before (Gotsmann and Lantz, 2013), the shear force provides additional vital measurements in our experiments. Namely, the maximum shear force $F_s$ in the single contact between two solid bodies is proportional to the contact area $A$ and the interfacial shear strength $\tau - F_s = \tau A$. At the same time, thermal resistance $R_T$ for the heat transport between the two bodies for the same contact is scaled as inversely of the linear dimension of the contact $R_T \propto 1/a = \sqrt{\pi / A}$ for the diffusive, and inverse of the area $R_T \propto 1/A$ in the ballistic heat transfer regimes. In the approach-retract experiments, the normal force $F_n$ applied to the contact is modified, therefore modifying the contact area. By comparison of the dependence of the $1/R_T$ and $F_s$ on the normal force is therefore possible to investigate the nature of the heat transfer on the nanoscale heat junction. Our experimental data show that the nanoscale contacts we observed scale more as the $1/R_c \sim A$ suggesting that the ballistic heat transfer at the nanoscale tip-surface interface is dominated by ballistic mechanism. Furthermore, comparison of SThM data both for ambient and HV environment suggest that it is the solid-solid contact that is the dominant heat transfer channel of the thermal contact. If liquid bridge would be dominant, we should be able to observed significant decrease of the shear force, with the heat conduction relatively constant. That was clearly not the case in our experiments suggesting that liquid bridge may be less essential for nanoscale heat transport in SThM that originally thought.

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