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Effect of heated zone size on micro and nanoscale convective heat transfer☆

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ABSTRACT

Recent studies on free convective heat transfer from micro and nanoscale structures show that the heat transfer coefficient is size dependent. The heat transfer coefficient is found to increase at smaller scales, which is ascribed to the higher surface area to volume ratio. Also, the mode is changed from advection to conduction due to the decaying influence of the gravitational field. Interestingly, it is tacitly assumed that the size effect is due to the specimen, since not a single study on the effect of the size of heat source on the convective heat transfer exists in the literature. In this study, we provide unambiguous experimental evidence of the predominance of heater size on the heat transfer coefficient. For micro-heaters, the heat transfer coefficient is measured to about 3200 W/m^2 K. This value drops to about 110 W/m^2 K for a millimeter scale heater and to 10 W/m^2 K for a macroscopic heater; all for a nanoscale thin film specimen. This finding is particularly significant in microelectronic applications where localized heating (hot spots) in small areas is very common.

1. Introduction

Heat transfer from hot solids to the surrounding environment is a widely studied subject owing to its significance in various thermal systems. Studies have been undertaken to investigate the effect of the characteristic length scale on the heat transfer mechanism [1,2]. Accurate design of thermal management systems at small length scales is of paramount importance due to the rapid miniaturization of electronic devices (Moore's law) and increasing power dissipation densities. Such structures with micro-heaters are used in integrated circuits, gas sensors [3], micro-thermo-gravimetry [4], data storage [5] and micro-actuators [2]. The heat transfer at such small scales is a topic of growing interest. Kim et al. [6] studied heat transfer from a micro-cantilever heater and reported a heat transfer coefficient on the order of 1000 W/m^2 K due to increased conduction through air. Relatively little work has been published to understand the mechanism of heat transfer and the variation of heat transfer coefficient with different conditions [7,8]. The general consensus is that the micro scale thermal conduction between the solid and the adjacent fluid contributes majorly to the heat flow. This is in contrast to the conventional theory of the advective flow due to buoyancy dominating the natural convection in macro scale objects. This is because the driving buoyant force is very negligible and the heat loss in enhanced by the large surface area to volume ratio at such micro length scales. It is also shown that the widely used 3ω technique is still valid using the heat conduction model [9]. Due to an altogether different mechanism of heat transfer, the heat transfer coefficient is more sensitive to the operating conditions like the temperature of specimen and the ambient pressure [8,10].

In microelectronic, micro-electromechanical systems (MEMS) and any other applications involving current flow through narrow resistors, very large density power dissipation takes place. This raises the local temperature, which is cooled by removal of the heat by either convective heat transfer or thermal interface materials. These systems are designed by heat transfer simulation to determine the limits of safe operating temperatures and to determine the role of heater length [11]. In applications with integrated heaters, the heaters are at micro length scales and they form hot spots upon a continuous operation which lead to their premature failure. Cooling involving atomic super-lattice [12,13] and micro-channels [14] are used for hot spot mitigation in microprocessors.

Whether it is cooling of microprocessors or macroscale objects, the literature considers only the surface to be cooled, and no consideration is given to the active size of the heated zone. Or in other words, the literature tacitly assumes that the cooling dynamics is dominated by the specimen size. This is not categorically true. It is obvious that the Biot number increases as the heater size increases. The relative ratio of the boundary layer thickness to the characteristic length increases as the Biot number decreases [8]. Intuitively, the cooling characteristics of the heater should influence the cooling of the specimen, it being the source of heat to the specimen. For example, a nanoscale specimen connected to a macroscopic heater is exposed to a very thick thermal boundary layer. In addition, even though the specimen has low thermal mass, its cooling rate is dominated by the heaters cooling rate or thermal mass. Interestingly, not a single work has been reported to study this effect, which provides the motivation for the present study. Through experimental design with heater sizes spanning from MEMS to macro scales and keeping the specimen size at the nanoscale, we present unambiguous evidence that the size of the heater dominates

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Nomenclature

h	Heat transfer coefficient
T	Local temperature
T_∞	Room temperature of quiescent fluid
T_w	Surface temperature of the specimen
s	Slope of logarithmic temperature plot of thermal boundary layer
Q	Conductive heat flux at specimen surface
k_{air}	thermal conductivity of air
y	distance perpendicular to specimen length
x	distance along the specimen length

the heat transfer coefficient associated with these microstructures. Heat transfer coefficient for different heater sizes is evaluated and then validated from temperature profile along a specimen of known thermal conductivity and same geometry using these heat sources.

2. Experimental setup

Since the recent studies [6–8] suggest that the heat transfer coefficient increases at the micro or nanoscale, the role of the heaters can be unambiguously quantified if heaters of different sizes can be used to specimens of a certain (micro or nanoscale) size. Keeping this argument in mind, heaters of three different sizes are considered for this study: (a) a MEMS heater with 15 μm wide and 20 μm deep resistor size, (b) a resistance temperature detector (RTD) element of dimensions 2 mm × 2 mm and a (c) Kapton (polyamide film) insulated heater of dimensions 1 cm × 5 cm. Fig. 1 shows these heating element. A direct current is passed through each of these heaters and the temperature profile of the quiescent air surrounding the heater is obtained using Infrascope II thermal microscope (Quantum Focus Instruments Corporation) with the spatial and temperature resolutions of about 2 μm and 0.1 K, respectively.

The MEMS heater is fabricated using standard nanofabrication techniques. For validation, either the heater is integrated with the specimen in the device design or the specimen can be fabricated separately and then integrated with the heater. In either case, freestanding micro-fin type specimens are obtained. The nanofabrication process of the device begins with patterning the photoresist on a SOI wafer, 20 μm thick highly doped single crystal device layer silicon, 2 μm buried oxide and 400 μm thick handle layer. The device layer is etched anisotropically by Deep Reactive Ion Etch (DRIE) process. Lithographic patterning on the back side and the similar etch process is done to remove the entire handle layer lying underneath the specimen. Then the device is exposed to vapors of hydrofluoric acid to etch the layer of buried oxide which makes the specimen with no floor. All these steps are schematically shown in our previous study [8]. A separate batch of devices is made using thermally grown oxide as the specimen. The fabrication process for these devices also begins with patterning photoresist on a single side polished (SSP) silicon wafer with 300 nm thermally grown oxide. An anisotropic etch of the oxide layer using CF_4 chemistry followed by an isotropic etch of the silicon beneath the specimen makes the sample free standing.

3. Experimental procedure

3.1. Heat transfer coefficient from thermal boundary layer

Heat transfer coefficient is measured by a steady state technique where a direct current is passed through heaters of each size. This develops a thermal boundary layer that can be captured graphically from infrared (IR) microscopy. The temperature distribution in the boundary layer contains the information on the heat transfer coefficient as described in a mathematical model below. Fig. 2 shows the images from the Infrared microscope of the MEMS, RTD and Kapton heaters respectively. In a typical experiment, these heaters are activated in ambient environment to setup a thermal boundary layer. The thermal boundary layer is then visualized and quantified with the IR microscope. A model described in Section 4.1 is then used to extract the heat transfer coefficient associated with three different heater sizes.

3.2. Procedure for validation of experimental results

To validate the heat transfer coefficient measurements described above, a second set of experiments is carried out. Here, micro-fin shaped rectangular cross-section specimens of material with known thermal conductivity and dimensions are heated with the above mentioned heaters. The IR microscope is again used to measure the temperature profile, this time on the solid specimen and not the thermal boundary layer. An approximation of one-dimensional conduction along the length of the micro-fin specimen together with convection boundary condition allows it to be modeled by the Fourier equation. This model is described in the next section, where it is shown to involve two parameters: the thermal conductivity of specimen 'k_s' and the heat transfer coefficient 'h'. Usage of known materials (silicon and silicon dioxide) as the specimen allows us to obtain the heat transfer coefficient, so that these values can be compared with that measured from the thermal boundary layer technique. Fig. 3 shows two examples of this experimental configuration. In the first example, a MEMS type line heater (not an array as shown in Fig. 2a) is shown to heat a microscale silicon beam (2 μm thick). The second example shows a freestanding thermally grown silicon oxide beam (300 nm thick) heated by a RTD heater. Since these materials are well characterized for their thermal conductivity (140 and 1.2 W/m K respectively), an energy balance model given in Section 4.2 can be used to calculate the effective heat transfer coefficient values that can be cross-checked against the results obtained from Section 3.1.

4. Mathematical model

4.1. Heat transfer coefficient from thermal boundary layer

The heat transfer coefficient is evaluated using two techniques. The first technique is employed for the cases with MEMS heater and RTD elements. This requires measurement of the temperature profile of the

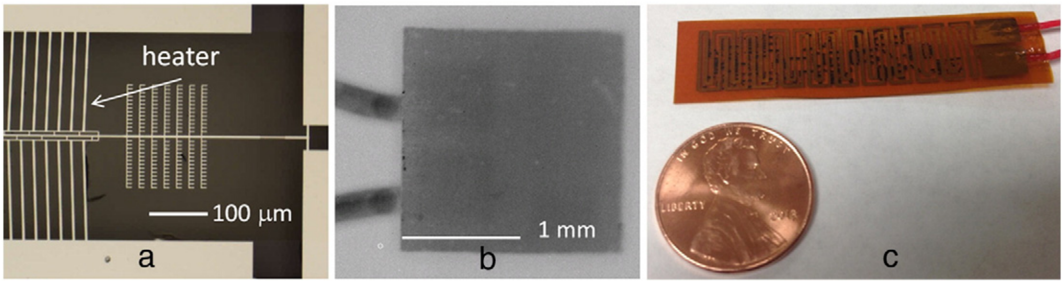

Fig. 1. Optical micrographs of the three different heater sizes: (a) a MEMS heater, (b) a RTD heater and (c) a Kapton foil heater.