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Investigation of heat transfer around microwire in air environment using 3ω method

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ABSTRACT

The 3ω principle is presented for the measurement of the heat transfer coefficient (h) based on natural convection model and heat conduction model. The 3ω technique is used at room temperature to measure h over the surfaces of microwires of the diameters 10–100 μm at horizontal and vertical orientations. The fitted results show that the heat loss from the microscale platinum wire to the air is dominated by heat conduction and the natural convection contribution is negligible. The comparison of the measured third harmonics for horizontal and vertical wires justifies that the orientation effect is negligible at microscales. The measured value of h is nearly two orders larger than that at macro scale and of the similar order to those from other literatures. Based on the 3ω principle, an explicit expression with a heat conduction shape factor is introduced and can predict the heat transfer coefficient reasonably in the validated range of frequency. Both the experimental results and the theoretical analysis conclude that the scale effect of heat transfer may be contributed to two factors: the effect of buoyancy, the driving force at microscales may be negligible; the heat loss is enhanced mainly by high ratio of surface to volume at microscales. It also shows the validation of the 3ω principle for thin wire if the heat loss to surrounding gas is dominated by heat conduction at microscale.

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1. Introduction

With the fast development of microstructures and integrated circuits, heat loss to air through natural convection brings an important effect on microstructures. The effect of scaling below 1 mm on the natural convective coefficient is still a topic of debate. The complexity lies in the interplay of the very thin boundary layers and the relative change of importance of driving forces at microscale.

Several promising theoretical studies argue that natural convection may be less important than thermal conduction for microscale devices [1–4]. Peirs et al. [1] have proposed a scaling law for natural convective coefficient and suggested $h \sim 100$ W m^{-2} K^{-1} for air when the scale is less than 100 μm, which is 5–10 times larger than that at macro scales, and compared shape memory actuators with electrostatic, magnetic and piezoelectric actuators based on thermal aspects and scaling effects on both convective and conductive heat transfer, which is a quite novel approach. Jafarpur and Yovanovich [2] presented a simple but accurate approximate analytical method based on a linearization of the energy equation for the area mean Nusselt number (Nu) for free convection heat transfer from isothermal spheres for the range of Rayleigh number (Ra) $0 < Ra < 10^8$ and all Prandtl numbers. Guo and Li [3] argued that natural convection should be less significant at the microscale because buoyancy, the driving force for natural convection becomes very small. Kim and King [4] investigate transient heat conduction between a heated microcantilever and its air environment with continuum finite element simulations, and the simulated effective heat transfer coefficients around the heater and around the leg are considerably large and on the order of 1 kW m^{-2} K^{-1}.

Up to now, only a little published experimental work has investigated heat flow from the microscale heater to its nearby air environment. Hu et al. [5] fabricated a microheater on a silicon nitride membrane and characterized the natural convection on the microheater precisely using the 3ω method, with the heater oriented at different angles to the gravitational field and h reaches 30.4 W m^{-2} K^{-1}; the temperature oscillation of the thin film at different angle has little difference; the heat loss to the surrounding air is dominated by heat conduction and the natural convection

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Nomenclature

A	heat transfer area around the microwire, m^2
c_p	specific heat capacity, J/K
d	wire diameter, m
h	heat transfer coefficient, W/m^2 K
I	amplitude of oscillating current, A
k	thermal conductivity, W/m K
K_n	Knudsen number, Λ/d
l	length of wire, m
P	heating power, W/m
q_V	power intensity, W/m^3
r	radial direction, m
r_0	radius of wire, m
R	electric resistance at temperature T, Ω
R_0	electric resistance at initial temperature, Ω
R_{th}	thermal resistance of the platinum wire, l/kS, K/W
S	cross section area, m^2
t	time, s
T	temperature, K
$V_{3\omega}$	voltage component at 3ω, V
x	axial direction, m
Greek letters	
ϕ	phase angle, °
α	thermal diffusivity, m^2/s
β	coefficient of volume expansion, K^{-1}
θ	temperature difference, K
Λ	mean free path, m
ν	kinematics viscosity, m^2/s
ρ	density, kg/m^3
τ	thermal diffusion characterization time, $\tau = l^2/\alpha$, s
ω	angular frequency, s^{-1}
Subscript	
1	properties for platinum wire
2	properties for air
a	air

contribution can be negligible. Kim et al. [6] showed that the orientation effect is negligible at microscales by investigating experimentally the natural convection around microfin arrays on vertical and horizontal surfaces. Hou et al. [7] investigated the natural convection between air and microwires ranging from 39.9 μm to 350.1 μm placed horizontally and vertically, the experimental results show that the deviation between the experimental Nusselt number and the values of the classical correlations increases with decrease of the wire diameter. Lee et al. [8] performed measurement and modeling of heat flow between the cantilever and a partial vacuum environment, showing remarkably high thermal conductance between the cantilever and its partial vacuum environment, with an effective heat transfer coefficient near 2000 W m^{-2} K^{-1}. Frequency-dependent thermal responses of the microcantilevers were studied and the reported effective heat transfer coefficients around the microcantilever were in the range 1000–3000 W m^{-2} K^{-1} [9]. From the limited measurements, it is not clear that these effective convection coefficients are the best possible estimates or what the underlying physical mechanism is that results in their values. These experimentally determined values for heat transfer coefficient are well in excess of what would be expected for natural convection, and it is likely that natural convection is not the dominant heat transfer mode. Therefore, it is desirable that more work be needed to understand natural convection at small scales, microscale thermal conduction between a solid and a quiescent fluid, and the relative magnitudes of these heat transfer mechanisms under various conditions.

Besides the wide application in thermal characterization of thin films and thin wires [10–12], the 3ω method based on Fourier law has been applied to determination of the thermal conductivity or heat capacity of liquids [13,14] and gases [15–17] with an ultra thin wire both as a heater and sensor based on different thermal conduction models. Through the use of a high vacuum and a different theoretical formulation, the 3ω technique is also available to measure the properties of the heating element itself; in order to ensure a stable third harmonic signal and to eliminate the heat loss due to radiation and convection, the measured samples are usually placed in a vacuum chamber [12]. For an individual single-wall carbon nanotube on a substrate in vacuum, neglecting convection and radiation losses, introducing a thermal contact resistance term into the one-dimensional heat conduction equation, a linear relationship between the third harmonics and current still validates [18]. Wang et al. [13] and Chen et al. [14] applied the 3ω method to measure thermal conductivities of liquids using a several micrometer platinum wire. Recently, Yusibani et al. [15–17] derived a two-dimensional analytical solution for the 3ω method for measurement of thermal conductivity of materials with a fine wire; the analytical solution includes the wire heat capacity and the effect of heat losses from the ends of the wire. Although many studies have been done on the characterization of the thermal conductivity and diffusivity of the wire specimen itself under different thermal boundary conditions, application of the 3ω method to the measurement of heat transfer coefficient is still difficult especially when the wire specimen is immersed in gas medium. One important reason for this is that we do not obtain a straight line when we plot the in-phase 3ω voltage component against the logarithm of the frequency; the other is that we do not obtain an analytical solution including the natural convection. Successful characterization of natural convection heat transfer on the microheater in air [5] and thermal conductivities of gases [15–17] and liquid [13,14] in frequency-domain makes it promising to precisely measure the heat transfer coefficient around microwire in air using the 3ω method if the heat transfer process is dominated by thermal conduction.

The major hypothesis of the 3ω method is the description of the heat transport using the Fourier equation to obtain the value of the thermal conductance. At small dimensions non Fourier effects may come into play. Heron et al. [19] demonstrated that the 3ω cannot work anymore when the mean free path is increasing up to the size of the nanosystems; great care has to be taken when using the 3ω method at very low temperature; the better situation is when the sample to be measured is also the thermometer. Shenoy et al. [20] presented the 3-omega method for thermal conductivity measurement using the hyperbolic heat conduction equation (HHCE) and mathematical expressions representing the conditions when non-Fourier effects cannot be neglected are formulated; non-Fourier effects need to be taken into consideration when measuring low temperature thermal conductivity for sub micron thick dielectric films with high thermal diffusivity at short timescales or at higher frequency than ~MHz. Fortunately, even if the non-Fourier effects need to be taken into consideration, the 3ω method can still characterize the thermal properties by introducing a correction term [19] or using the HHCE [20]. But for most cases especially at high temperature and at relatively low frequency, the 3ω method neglecting non-Fourier effects holds well [10–18,20].

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