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Microscale temperature sensing using novel reliable silicon vertical microprobe array: Computation and experiment

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ABSTRACT

Microscale temperature sensing using a fabricated novel vertical silicon microprobe array was investigated for the first time using a combined simulation and experimental technique. In this context, silicon microprobes were designed with 3 μm in diameter and 30 μm in height. These high-aspect-ratio probes are found to be effective in microscale multisite temperature sensing. The designed microprobes (p-type) were fabricated in <111> out-of-plane orientation using vapor–liquid-solid (VLS) technique on n-type silicon substrate. The temperature dependent shift in the rectifying current–voltage (I–V) curves of the embedded p–n diode was experimentally determined and the temperature sensitivity of diode was found to be −2.3 mV/K at 0.1 μA. A complete 3-D model of the microprobe was created and finite element (FE) method was applied to compute the sensing capability by capturing temperature distribution taking anisotropic and phonon scattering effects on thermal conductivity of silicon into account. The obtained computational result on microscale temperature sensitivity has shown a similar trend of experimental findings. FE simulation thus can serve as a tool to a-priori predict temperature sensing capabilities of microprobes used in many applications such as artificial electronic fingertips of robotic hand/prosthetics, biological soft samples.

Nomenclature

a_r	Radiation cross-sectional area	m^2
c_p	Specific heat	$J\ mole^{-1}\ K^{-1}$
d	Diameter of the probe	m
h_c	Heat conduction coefficient	$W\ m^{-2}\ K^{-1}$
h_g	Heat convection coefficient	$W\ m^{-2}\ K^{-1}$
h_r	Radiative heat transfer coefficient	$W\ m^{-2}\ K^{-1}$
h_j	Contact conductance	$W\ K^{-1}$
r_c	Contact resistance	KW^{-1}
k	Thermal conductivity	$W\ m^{-1}\ K^{-1}$
Kn	Knudsen number	
k_B	Stefan–Boltzmann constant	$J\ K^{-1}$
Δl	Air-gap	m
N_u	Nusselt number	
Pr	Prandtl number	
p	Gas pressure	$N\ m^{-2}$
$\bar{q}_c$	Heat flux vector	$W\ m^{-2}$
r_p	Thermal resistance of probe	$K\ W^{-1}$
T	Temperature	K
ΔT	Temperature increase	K

Greek symbols

λ	The molecular mean free path	(m)
α	Accommodation coefficient	(−)
Ψ	Internal degree of freedom	(−)
ρ	Mass density	$(Kg \cdot m^{-3})$

Subscripts

p	probe
sp	spreading
sub	substrate
ref	reference

1. Introduction

Miniaturized probe sensors with high sensitivity and more functionality suitable for touching and analyzing objects are in great demand in many potential applications such as artificial electronic fingertips of robotic hand/prosthetics for sensing of touch and force/temperature mapping probe arrays to investigate small materials as well as biological soft samples [1–13].

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The piezoresistance effect of silicon can be exploited as one of the principles to probe force [14]. In addition, the shift in the rectifying voltage of a p–n junction has been employed to measure temperature [15].

However, the existing temperature sensing technology is confronted with a big challenge to tantalize vertical microprobes for local temperature sensing with high spatial resolution.

In this context, vertically aligned silicon (Si) microprobes can be used effectively as temperature and force sensors. In this article, we will focus only on temperature sensing using smartly designed vertical Si microprobes. If a p–n junction is incorporated into the microprobe base, the temperature of the probe will vary with the temperature of the measuring object, thereby resulting shift in I–V curves. Compared to planar sensor elements, the advantages of using Si vertical microprobes are manifolds: 1) an object is contacted only in a very small fraction of the microprobe tip, 2) it has the ability for tactile sensing to measure microscale objects such as cells and nerve tissue, 3) it can be extended as nerve potential sensors for spine neural tissue, 4) simultaneous measurement of temperature and force from allocation is possible using same sensor element, 5) the sensor elements can be arranged in several 10 μm spatial intervals thereby allowing to obtain high spatial resolution.

When there is an air-gap between the microprobe and object, the temperature sensing capability of probes is controlled by three modes of heat transfer namely conduction, convection and radiation. The dominant mode of heat transfer depends on sensing temperatures, size of device, and air-gap. If the air gap between the probe tip and W-needle is small (several microns), heat conduction in air has a dominant effect. Therefore, air-gap thermal contact resistance would play a significant role in heat conduction to probe. To conduct sensing capability of microprobe, a Tungsten (W) needle) with a constant temperature was employed in this research to mimic the object. Even when, The usefulness of the analogy between the flow of electric current and the flow of heat becomes apparent when a satisfactory description of the heat transfer at the interface of two conducting media is needed. Due to machining limitations, no two solid surfaces will ever form a perfect contact when they are pressed together. Tiny air gaps will always exist between the two contacting surfaces due to their roughness. Thus, heat flux near the interface is constricted in the microcontact regions manifesting contact resistance (see in Fig. 2). The contact resistance, r_c can be represented by the following equation

$$r_c = \frac{\Delta T}{q A_a} \tag{1}$$

where q is the heat flux (in W/m^2) and A_a is the apparent cross-sectional area (in m^2). Due to asperities, contacting interfaces are never perfectly flat, thus microscopic contact area (actual) is usually much less than macroscopic contact area (apparent, A_a). Due to deformation, contact area varies with the applied normal force between the two contacting interfaces.

However, in terms of contact conductance, contact resistance is defined as

$$r_c = \frac{1}{h_j A_a} \tag{2}$$

$$= \frac{1}{(h_c + h_r + h_g) A_a} \tag{3}$$

where contact conductance h_j is the sum of three series heat conductances namely: 1) the conduction between contacting points between two surfaces of W-needle and microprobe (h_c), 2) the radiation through the air-gap between the surfaces (h_r), and 3) the gas conduction through the air-gap (h_g). When thickness of air-gap is small, heat conduction through air-gap maybe approximated to be controlled only by heat conduction coefficient, h_g through air [16]

$$h_g = \frac{\kappa_a}{\Delta \ell} \tag{4}$$

where $\Delta\ell$ is the thickness of air-gap and κ_a is the thermal conductivity (of air).

In similar fashion, heat transfer coefficient for conduction (h_c) in material is defined as

$$h_c = \frac{\kappa}{\Delta x} \tag{5}$$

where Δx is material thickness and κ is the thermal conductivity of material.

In words, h represents the heat flow per unit area per unit temperature difference. The larger h_c is, the larger the heat transfer q.

Now, 1-D Fourier's law of continuum heat conduction reads [17]

$$q = -\kappa \frac{\partial T}{\partial x} \tag{6}$$

where q is the heat flux as mentioned before and κ is thermal conductivity.

Using conservation of energy, one may readily obtain a 1-D heat equation in simpler form without any heat source or sink

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial^2 x} \tag{7}$$

where α is the thermal diffusivity ($\alpha = \frac{\kappa}{\rho c}$), ρ is mass density and c is specific heat and ρc denotes volumetric heat capacity (ability to store heat).

However, if the characteristic length of gas layer, $\Delta\ell$ has the same order of magnitude as the molecular mean free path of gas molecules (air), (λ), the Fourier heat conduction equation breaks down and the gas begins to exhibit noncontinuum effects. The onset of noncontinuum gas rarefaction effect is typically indicated by the Knudsen number, Kn defined as the ratio of λ to $\Delta\ell$. Based on the magnitude of the Kn number, heat conduction in air can be divided into four different regimes: continuum ($Kn < 0.01$), slip i.e. temperature-jump ($0.1 > Kn > 0.01$), transition ($10 > Kn > 0.1$), and free-molecular ($Kn > 10$).

In continuum regime, the conductive heat flux, q_c in W/mm^2 is defined as [18]

$$q_c = -\frac{k_r \left(T_t^{\xi+1} - T_p^{\xi+1}\right)}{(\xi+1) T_r^{\xi} L} \tag{8}$$

where, T_t (373 K) is the source temperature (hot body) and T_r (293 K) is the reference temperature in Kelvin, T_p is the temperature of probe tip, ξ (0.770) is the temperature exponent, k_r is thermal conductivity at reference state (293 K), and L is the characteristic length of gas layer (in the first case it is 5 μm).

The conductive heat flux, q_{fm} in free-molecular regime is represented by [19]

$$q_{\mathrm{fm}} = -\left(\frac{8 k_B}{\pi m}\right)^{\frac{1}{2}} \frac{\alpha}{2-\alpha} \left(1 + \frac{d_f}{4}\right) \left(T_t^{1/2} - T_p^{1/2}\right) p \tag{9}$$

where, k_B (1.38066×10^{-23} J/K) is the Stefan–Boltzmann constant, m (4.27×10^{-26} kg) is gas mass, d_f (=2, considering rotation and vibration) is the internal degree of freedom, α is the accommodation coefficient (0.8 to 0.98) where a lower bound value is considered, and p (1.01325×10^5 Pa) is atmospheric gas pressure.