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Effects of surface wettability on pool boiling of water using super-polished silicon surfaces

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ABSTRACT

Pool boiling is an efficient cooling technique as a phase change heat transfer mode. Improvement of the boiling performance by postponing the surface dry-out point and increasing the critical heat flux is often necessary for assuring safe performance in many applications involving high heat fluxes. Recently, relevant surface modifications have become an attractive, yet practical approach for enhancing boiling performance. These modifications are implemented either by manipulating the surface wettability characteristics or imposing roughness onto the surface. In most cases, the mentioned modifications are dependent, where variation in one is accompanied by a change to the other. This study aims at the sole impact of surface wettability on the pool boiling performance with super-polished silicon surfaces with different wettability characteristics prepared by chemical vapor deposition and sputtering. Pool boiling experiments are conducted using these surfaces where the heat supply and temperature measurement were performed via an integrated state-of-the-art resistance-temperature detector and heater. The experimental results show a trend in increasing the critical heat flux value of the pool boiling for more wettable surfaces and quantitatively define a low limit for the critical heat flux. Moreover, nucleation and bubble behavior are also studied at incipience.

1. Introduction

Widely encountered in heat transfer applications, such as high-heat-flux cooling of electronic components, quenching processes, and evaporators, pool boiling is a critical heat transport process. It is associated with the heated surface of an immersed body, placed in a pool of liquid [1]. The process is a substantial candidate for high heat removal.

Based on the hydrodynamic and thermal state of a system, the boiling phenomenon is characterized into different regimes. An important one is the nucleate boiling heat transfer regime, in which the surface temperature exceeds saturation temperature, and bubble nucleation and growth happens at the heating surface. A sharp increase in the heat flux as a result of bubble formation makes this regime suitable for high heat removal. Increasing the heat flux further, the nucleate boiling phase is followed by vapor blanketing on the surface. This causes dry-out, significant and immediate increase in the temperature of the heating surface. The peak value of heat flux prior to film boiling is referred to as the Critical Heat Flux (CHF). At CHF, surface rewetting is not possible, efficient nucleate boiling heat transfer is terminated, and consequently, material failure is probable. Therefore, many experimental approaches have been proposed in order to delay the occurrence of CHF and extend the safe thermal performance limit of a heated surface. These activities include, but are not limited to, changing surface characteristics (properties and morphology [2–4]), changing the orientation of the heated surface [5–7], and using conductive operational liquids [8,9].

Changing surface characteristics can be done through changing the surface wettability, surface roughness, or a combination of both. Wetting behavior can be characterized by measuring a static apparent contact angle. Hydrophilic surfaces are believed to delay the occurrence of CHF by assisting bubble generation and improving rewetting of dry spots generated due to severe evaporation at high heat flux [10]. On the other hand, hydrophobicity impedes surface rewetting, resulting in a lower CHF [2].

Surface roughness can be quantified by two different methods; using the surface features' heights [2] or by considering the ratio of an actual area in contact with a fluid to the projected area [11]. Isolating the effects of wettability from those of surface roughness is quite challenging. According to Wenzel's model [12], the

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Nomenclature

a	spreading radius of droplet [m]	β	thermal expansion coefficient [°C^{-1}]
C	constant	β	modified Bond number
CHF	critical heat flux	γ	dynamic receding contact angle [°]
g	gravitational acceleration [m/s^2]	η	dimensionless drop height
h	heat transfer coefficient [W/m^2 K]	ρ	density [kg/m^3]
h_{fg}	latent heat [J/kg]	φ	heater surface angle with horizontal [°]
H	droplet height [m]	σ	surface tension [N/m]
I	Bessel function	θ	static contact angle [°]
k	thermal conductivity [W/m K]	ν	kinematic viscosity [m^2/s]
L	characteristic length [m]	ω	dimensionless volume
Nu	Nusselt number	ξ	dimensionless radial distance
P	pressure [Pa]	c	curvature
q''	heat flux [W/m^2]	l	liquid
R	radius [m]	low	lower boundary
Ra	Rayleigh number	sat	saturation
T	temperature	ss	small slope
V	volume of droplet [m^3]	up	upper boundary
y	vertical distance from the origin [m]	v	vapor
α	thermal diffusivity [m^2/s]		

roughness present on a surface can change the apparent contact angle. Specifically, roughness improves hydrophilicity on hydrophilic surfaces and hydrophobicity on hydrophobic surfaces.

In the current investigation, silicon wafers are polished to the smoothest level commercially available. A thin film deposition technique is applied to the wafers yielding a set of different test surfaces made of metals, metal oxides, or metal nitrides. The surfaces have a range of surface wettability but a consistently smooth surface (surface roughness less than 0.35 nm *Ra* for all the samples).

Surface characterization is assessed analytically and experimentally. Pool boiling tests are conducted and their results are analyzed in conjunction with the reliably reported literature data of the impact of surface wetness on the pool boiling performance. An accurate system of capturing the heater's temperature is employed in a novel algorithm for this pool boiling application. Specifically, Resistance Temperature Detecting (RTD) is used. RTD is reliable in simultaneously providing heat and capturing temperature data [13]. By using an RTD as the heating element and the test surface, the sole impact of surface wettability is studied on the pool boiling performance of a surface, as well as the nucleated bubble size and generation cycle.

The objective of the current investigation is to study the effects of wettability independently from surface roughness. Uncoupling and studying the effect of surface wettability independently results in a fundamental understanding of the effects of wettability on the critical heat flux. The wettability of the surfaces considered is changed using different surface chemistry while keeping the surface consistently smooth. A quantitative CHF versus contact angle dataset for smooth surfaces is obtained experimentally and is used as a lower limit for CHF. An upper limit is also defined based on data sets available in the literature for surfaces of different roughness values. Experimental data sets associated with pool boiling of water on a surface of known wettability are expected to lie between the upper and lower limits defined in this paper.

2. RTD/heater design and fabrication

There are challenges associated with pool boiling test assemblies and procedures. These include unknown commercial heater structure and temperature limit, need for external connections to attach a thermocouple to the test surface, long response time and inaccuracy associated with typical thermocouples, among other challenges.

The Resistive Temperature Detecting (RTD) designed, fabricated, and used for this work eliminates these challenges. Specifically, semiconductor fabrication techniques are employed to design and manufacture a thin film heater that also serves as a temperature sensor. The material desired for temperature detection must express a repeatable relation between resistance and temperature. Among the well-known RTD materials, Nickel is considered a suitable option, as it shows a stable and linear behavior in the operation range of −100 °C to 300 °C.

A double-sided polished silicon wafer with a thickness of 500 μm is used as the original substrate to build up thin film layers. Cleaning the silicon substrate is performed in Piranha solution (a 3:1 mixture of concentrated sulfuric acid (H_2SO_4) with hydrogen peroxide (H_2O_2)); it is followed by insulating sides of the wafer with a 2 μm layer of silicon nitride, using Low-Pressure Chemical Vapor Deposition (LPCVD).

The heating element is designed to provide uniform heat over the heater's exposed area. It is also designed to provide a resistance value complying with the capacity of the power supply system in supplying voltage and current. For this reason, a serpentine geometry is used (Fig. 1a). The heater is a 10 mm by 10 mm piece and the serpentine heating element occupies about 91% of its area. Using lithography, sputtering, and lift-off techniques, the desired thin film pattern of nickel is imprinted on one side of a silicon substrate. The other side is reserved for test surface preparation. Attachment of the thin nickel film to the substrate is facilitated by use of chromium as an adhesive layer. Schematic of the thin film components of the RTD/heater combination is illustrated in Fig. 1b. Material, thickness, and deposition method of layers are summarized in Table 1. Employing thin film layers for bonding the heating element to the substrate assures functionality of the heater in high temperatures and eliminates the need for external attachment of the test surface to the heater. Nickel also provides a solderable substrate; therefore, there is no need to deposit an extra layer for power connections. Using a solder mask to consistently control the connection area, electrical wires are soldered to the ends of the serpentine geometry, limited to an area of 1.3 mm by 3 mm.

3. RTD/heater annealing and calibration

The RTD/heater is thermally treated (annealed) in a vacuum oven to stabilize the thin film material, reduce the thermal stresses