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Measurement of the bubble nucleation temperature of water on a pulse-heated thin platinum film supported by a membrane using a low-noise bridge circuit

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ABSTRACT

This study describes the performance of stress-minimized platinum (Pt) films supported by thin membranes (200 nm thick) to promote bubble nucleation of water near its theoretical superheat limit. The membrane configurations consist of Pt films deposited on 200 nm thick SiN films over bulk Si, with membranes being formed by etching Si from the back side of the films. Results are compared with more conventional Pt films supported by SiO_2 and Si substrates.

The average metal temperature is monitored by a bridge circuit with capacitive and inductive filtering to reduce noise in the output signal. Voltage pulses with durations ranging between 0.5 and 10 μs are imposed on the bridge to electrically heat the Pt film. The paper includes discussion of fabrication of the films, their treatment prior to using them as temperature sensors, the bridge circuit design for monitoring the change in electrical resistance during the power pulse, the calibration process of the films, and results of the bubble nucleation temperatures for the range of pulse durations examined.

The results show that significantly less power is needed to trigger bubble nucleation on a membrane-supported platinum film compared to a platinum film on a bulk Si substrate. The nucleation temperatures which were closest to the theoretical limit of water were realized at heating rates of nearly 10^9 C/s. The potential for employing back-side etched devices is suggested for fundamental studies of phase transitions of highly superheated liquids and in applications where bubble nucleation is an important process such as for ink-jet printers and microscale bubble pump concepts.

1. Introduction

The nucleation of bubbles on microscale surfaces immersed in subcooled liquids is important to several processes that transport fluids at the microscale, such as bubble pumps [1–5], mixers [2], and actuators [6,7]. Thermal inkjet printing [8–11] is the most prominent application of this concept. The nucleated bubbles exert a piston-like effect that pushes liquid through nozzles to form droplets that are directed to the paper through coordinated motion of the nozzles [12]. Inkjet technologies have also been applied to drug preparation [13] where the solvent consists of a mixture of ethanol, water, and glycerol. Other applications include deposition of polymers [14] proteins and cells [15,16], and 3D printing technologies. A biosensor fabricated by inkjet printing of polymer and enzyme layers has also been reported [17].

In portable bubble pump processes, energy management is an important consideration. Conventional solid-state microheater configurations such as those employed in ink jet applications are fabricated onto a solid substrate (which we term "non back-side etched" NBSE microheaters) such as silicon. The substrate can be an effective thermal path during a power pulse [18] which makes the heating and phase change process inefficient. Solid-state microheater configurations that reduce heat losses will make the phase change process more energy efficient.

In this paper, we present a stress-minimized, suspended microheater for heating liquids. The design consists of a platinum (Pt) film deposited on a SiN membrane etched from the opposite side of the Pt heater, (i.e., a "back-side etched" (BSE) configuration). Results are reported that illustrate the capabilities of the BSE

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Nomenclature

C_2 and C_3	capacitance filters (Fig. 9 and Table 1)	R_p	potentiometer resistance (Fig. 9)
c_p	specific heat	R_{po}	potentiometer resistance (Fig. 9) at balance point
DIP	dual-in-line package (Fig. 8)	R_{so}	internal resistance of DIP socket
k	thermal conductivity	R_{wp}	lead resistance of wires to bridge circuit
$L_{1,2}$	microheater dimensions (Fig. 2)	R_{DIP}	internal DIP resistance
R_h	microheater resistance	t	time
R_{h0}	room temperature microheater resistance	t^*	time during a power pulse at the inflection point (Figs. 1, 13, 14)
R_{jumper}	jumper resistors (Fig. 9)	T	temperature
$R_{PT3,PT4}$	resistances of platinum metallizations (Fig. 12)	T_c	critical temperature
R_{LP}	measured lead resistance for the pulse heating arrangement	T_h	average microheater temperature
R_{LC}	measured lead resistance for the heater calibration arrangement	T_{ho}	average microheater temperature at room temperature
R_{mc}	total measured resistance for calibration process	T_{nuc}	temperature at the starred positions in Figs. 13 and 14
R_{mp}	total measured resistance for pulse heating (Figs. 9 and 12)	θ	temperature coefficient of resistance (TCR)
R_{mpo}	total measured resistance for pulse heating at room temperature	ρ	density
		V_{in}	input voltage to the bridge circuit (Fig. 9)
		V_{out}	measured bridge output voltage (Fig. 9)

designs to nucleate bubbles with considerably less energy compared to more conventional substrate-supported NBSE microheaters. In addition, the microheater configurations provide an effective platform for accurately measuring the bubble nucleation temperature during a power pulse of microsecond duration.

Water was selected as the working fluid because of published data with which to compare measured nucleation temperatures [10,19–25], though the metrology developed is applicable to other fluids. The microheaters are immersed in subcooled water and heated with nominally square voltage pulses for durations ranging from 0.5 μs to 10 μs. This range is relevant to several industrial processes. The surface heating rate will be controlled by varying the pulse time and pulse amplitude.

2. Detecting bubble nucleation

When a bubble nucleates on a surface, liquid is displaced as the bubble grows. The microheater surface temperature increases and eventually the (relatively high thermal conductivity) liquid is displaced by the (comparatively low thermal conductivity) vapor and from there on the surface temperature increases in a manner consistent with it being in contact with a gas.

Fig. 1 schematically illustrates how the surface temperature may evolve under the conditions envisioned. The macroscopic manifestation of what is ostensibly a nano-scale process produces a temperature range (ΔT) over which the transition from solid/liquid to solid/gas contact occurs. Without direct visual evidence of the nucleation process [26–28] a mathematical definition of the spatially averaged nucleation temperature (T_{nuc}) is taken to correspond to the inflection point, $\frac{\partial^2 T}{\partial t^2}\Big|_{t=t^*} = 0$ [10].

3. Fabrication of BSE structures

The aspect ratio (L_1/L_2, see Fig. 2) of the BSE and NBSE microheaters used in the present experiments was 15:1 (i.e., 150 μm long, 10 μm wide, 200 nm thick). This ratio was considered to provide a reasonably uniform average temperature over the surface of the microheater. Heat transport to the connecting metallizations could be significant for very small aspect ratios (1:1) which would produce both a nonuniform and lower average temperature. This makes it more difficult to use the microheaters as a tool to measure the nucleation temperature. The microheater material employed was Pt in view of its hardness and strong linear variation of electrical resistance with temperature.

The platinum metallization is structurally supported with either a thin SiN membrane or for comparison a SiO_2 backing layer on bulk Si. For traditional NBSE structures, backside heat losses are reduced by bonding to a low thermal conductivity material such as SiO_2. The thermal resistance scales as δk where δ is thickness and the thermal conductivity k is comparatively small for SiO_2 [29]. As such, NBSE structures incorporated a SiO_2 backing with $\delta_{SiO2} = 2$ μm. BSE structures need a backing for structural support during bubble nucleation, but it is desirable for this backing to be as thin as possible. This support was provided by a SiN layer with $\delta_{SiN} = 0.2$ μm.

Figs. 2a and 2b show side-view schematics of the BSE and NBSE configurations, while Fig. 2c shows a top view optical micrograph of a BSE device. The "microheater" itself is the metallization of length L_1 and width L_2. The membrane consists of a rectangle upon which a 200 nm Pt/10 nm Ti layer is deposited and under which the Si substrate has been removed. In earlier tests, the 200 nm thick membranes were stable up to a size of 5 mm × 5 mm. The configurations employed in the present study incorporated a 200 μm wide membrane. The fabrication sequence of BSE structures is illustrated in Fig. 3 [30]. Starting with a double-side pol-

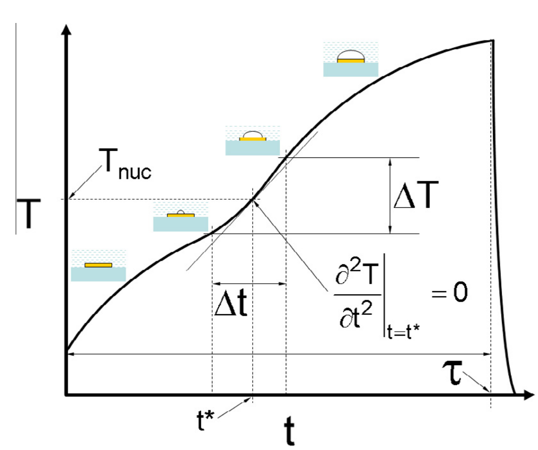

Fig. 1. Schematic of average microheater surface temperature during a power pulse. A bubble nucleation event centered at t^*, defined by the second derivative being zero, occurs over Δt and ΔT for a voltage pulse of duration τ.