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Dynamic characteristics of transient boiling on a square platinum microheater under millisecond pulsed heating

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Abstract

A series of experimental investigations of boiling incipience and bubble dynamics of water under pulsed heating conditions for various pulse durations ranging from 1 ms to 100 ms were conducted. Using a very smooth square platinum microheater, 100 μm on a side, and a high-speed digital camera, the boiling incipience was observed and investigated as a function of the bulk temperature of the microheater, pulse power level, and pulse duration. Given a specific pulse duration, for low pulse power levels, there would be no bubble nucleation or bubble mergence, for moderate pulse power levels, individual bubbles generated on the heater merged to form a single large bubble, while for high pulse power levels, the rapid growth of the individual bubbles and subsequent bubble interaction, resulted in a reduction in bubble coalescence into a single larger bubble, referred to as *bubble splash*. The transient heat flux range at which bubble coalescence occurs was identified experimentally, along with the temporal variations of bubble size, bubble interface velocity and interface acceleration.

Keywords: Kinetics of boiling; Boiling incipience; Bubble dynamics; Explosive boiling; Pulsed heating; Microheater

1. Introduction

Pulsed heating and the associated nucleate bubble generation have been successfully used in a number of applications including thermal ink jet printers [1], bubble actuated pumps [2,3], microarray fabrication [4], bubble actuated micro-mixers [5], bio-actuators [6], medical imaging [7], DNA hybrid enhancement techniques [8], fuel injection [9] and numerous other applications at micro-length scales [10]. The fundamental mechanism used in these applications is the rapid bubble formation and growth on a small microheater, which results in a driving force that can induce the flow of the liquid. In principle, classical nucleation theory can be used to predict the boiling incipience on these microheaters and classical bubble dynamics can be used to predict the bubble behavior after the initial formation.

Asai [1], who was one of the first to study bubble dynamics on microheaters under microsecond pulsed heating conditions, developed a detailed dynamic model to predict bubble growth and collapse. Iida et al. [11] experimentally determined bubble formation and bubble nucleation rates, utilizing fast transient visualization techniques, while Avedisian et al. [12] and Thomas et al. [13] measured the nucleation threshold as a function of variations in the measured temperature for microsecond pulses. Zhao et al. [14] investigated the pressure and power generated from explosive boiling in printer heads. Yin et al. [15] studied the boiling phenomena and bubble dynamics on a serpentine, 260 μm square microheater under millisecond pulsed heating. Deng et al. [16] investigated the boiling

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Nomenclature

C_g	solubility of dissolved gas
C_P	specific heat of platinum
e_R	electrical resistivity
h	Prantle constant
h_{fg}	heat of evaporation
J	bubble nuclei density
k	Boltzmann constant
K_h	Henry's constant
N_0	molecule number per unit volume
q	heat flux
$\dot{Q}$	power
R	resistance; radius of bubble
$\dot{R}$	interface velocity of bubble
$\ddot{R}$	interface acceleration of bubble
t	time
T	temperature

Greek symbols

θ	contact angle; thermal coefficient of resistivity
σ	surface tension
λ	thermal conductivity of platinum
μ	dynamic viscosity
υ	kinetic viscosity
ρ	density of platinum
τ_P	pulse duration

Subscripts

l	liquid
v	vapor

phenomena and bubble dynamics on a very small line microheater, 0.5 μm in width, under millisecond pulsed heating. More recently, Li and Peterson [17] conducted an experimental analysis on the bubble nucleation and bubble dynamics on a smooth square microheater for pulsed heating in the millisecond range. The process of bubble growth and collapse during millisecond pulsed heating has indicated that bubble collapse can be significantly influenced by the pulse duration and power level and that there exists a sudden bubble shrinkage immediately following the pulsed heating [16,17].

As a result of the growing number of potential applications, the boiling phenomena resulting from microheaters subjected to either micro or millisecond pulse heating are of increasing interest. The previous review of recent research indicates that there is currently insufficient understanding of these phenomena to direct the design of MEMS-based devices. A better understanding of both boiling nucleation and the associated bubble dynamics occurring on microheaters, is critical to the design and operation of these devices. This will require information on how the pulse power level and duration are related to the maximum bubble radius, bubble life, and bubble behavior. An investigation of the bubble nucleation and bubble dynamics on a 100 μm square platinum heater with a very smooth surface (average roughness of 50 Å) fabricated on a Pyrex wafer was conducted. After the initial calibration of the microheater, a series of experiments was conducted to explore the boiling incipience and the bubble dynamics for millisecond pulse heating, using a high-speed CCD digital camera. The principal objectives of this investigation are to provide detailed information on bubble growth and collapse under various heating scenarios; to examine the maximum bubble radius as a function of the pulse duration and power level; and to determine the power levels and duration range at which bubble actuation in MEMS applications are feasible.

2. Experimental system

The microheater used in the current investigation was 100 μm square and 1700 Å thick, as illustrated in Fig. 1 and the detailed fabrication information can be found in Ref. [17]. Table 1 illustrates the properties of all of the materials utilized in the experimental investigation. The average roughness of the microheater surface was approximately 50 Å (5 nm) measured by using a surface scanning profilometer. This roughness is in the range of the critical bubble size for homogeneous bubble nucleation and, as such, helps to minimize the influence of cavity size on bubble nucleation.

The temperature of the microheater can be obtained from the relationship between the resistance and the temperature. The detailed calibration process of the relationship between the resistance and temperature of the microheater was also described in Ref. [17]. With the calibration and the curve fit, the resistance of the microheater, R_{heater}, was linearly related to the temperature as

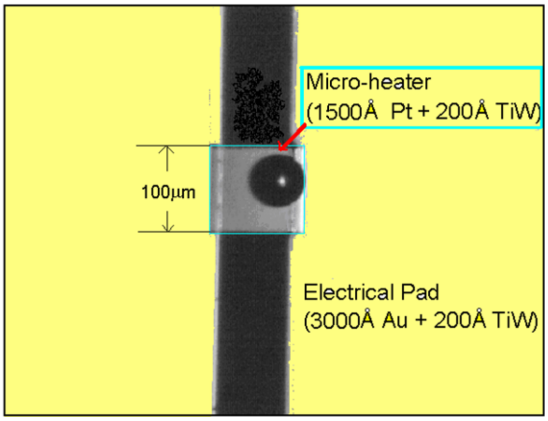

Fig. 1. The fabricated microheater.