International Communications in Heat and Mass Transfer 37 (2010) 792–795

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

# Effects of pulse width and mass flux on microscale flow boiling under pulse heating ☆

Gang Chen, Xiaojun Quan, Ping Cheng *

*Key Laboratory for Power Machinery and Engineering of Ministry of Education, School of Mechanical & Power Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*

ARTICLE INFO

Available online 8 July 2010

*Keywords:*
Microheater
Pulse width
Mass flux
Nucleation temperature and time

ABSTRACT

A Pt microheater ($140\times100\ \mu m^2$) is fabricated on a glass wafer and enclosed in a silicon microchannel of trapezoidal cross section by MEMS technology. With the aid of a high-speed CCD and data acquisition system, subcooled flow boiling phenomena and temperature response on the surface of the microheater under pulse heating are observed and recorded. Experiments are conducted for six pulse widths (50 µs, 100 µs, 200 µs, 600 µs, 1 ms, and 2 ms) under different mass and heat fluxes. With increasing heat flux at a fixed pulse width and different mass fluxes, four flow regimes including single phase, nucleate boiling, film boiling and dry out are identified. Since flow boiling regimes are relatively independent of mass flux, correlation equations based on experimental data for the transitional heat flux of different flow boiling regimes are obtained in terms of pulse width only. It is also found that pulse width and mass flux have little influence on boiling inception time, and the classical analytical solution for the nucleation inception time in terms of heat flux is verified experimentally.

## 1. Introduction

In order to design micro thermal bubble actuators based on MEMS technology, it is important to know boiling characteristics on a microheater under pulse heating conditions. In recent years, much research has been carried out on microscale pool boiling phenomena [1–13]. In particular, Varlamov et al. [1] performed an experiment on boiling of different liquids (including water, toluene, ethanol, and isopropyl alcohol) on microfilm heaters ($100\times100\ \mu m^2$) under pulsed heat fluxes ($q=10^8$–$10^9$ W/m$^2$) with pulse widths of $\tau=2$–$10$ µs, and investigated boiling incipience times versus heat flux and analyzed effects of heat flux and pulse duration on boiling regimes. Li et al. [2] conducted a series of experiment for boiling of water under pulsed heating at various pulse durations ranging from 1 ms to 100 ms on a smooth square platinum microheater ($100\times100\ \mu m^2$), and found three boiling regimes (no bubble, bubble mergence and bubble splash) with increasing pulse power at specific pulse duration. Jung et al. [3] carried out an experiment to study nucleation temperature on micro line heaters (3 and 5 µm wide, 50 µm long and 0.523 µm thick) under steady and fine voltage input (100–200 µs), and a molecular cluster model with the contact angle effect taken into consideration, was used to estimate the nucleation temperature. Hong et al. [5] studied effects of various heating conditions on nucleation temperature and nucleation time on a micro heater ($20\times80\ \mu m^2$) under short electric pulses (1–4 µs). Avedisian et al. [6] performed pulse heating experiments on a microheater ($30\times15\ \mu m^2$) with pulse widths ranging from 0.5 µs to 5 µs at a voltage input of $V_{in}=11.8$ V, and presented the effect of pulse duration on boiling regime.

In our previous work [14], effects of heat flux and mass flux on flow boiling regimes (single phase, nucleation and film boiling) on a microheater ($60\times100\ \mu m^2$) at fixed pulse width of 2 ms were investigated. In this paper, we focus our attention on the experimental study of pulse width and mass flux effects on subcooled flow boiling over a microheater under pulse heating conditions. In particular, the nucleation temperature and boiling inception time under various mass fluxes and heating conditions are investigated. Boiling flow regimes and transition between boiling flow regimes as a function of pulse width based on experimental data are correlated. The measured nucleation times is found to be in good agreement with Hsu's analytical solution [15].

## 2. Experimental setup and procedure

### 2.1. Test section

The microchip composing of three layers, shown in Fig. 1, was used in this experiment to study the flow boiling under pulse heating. First, a trapezoidal microchannel was etched in a <100> Silicon wafer with a thickness of 250 µm through wet etching, and then bonded with a glass wafer (Pyrex7740) having a thickness of 500 µm where the inlet and outlet holes for the working fluid had been drilled. Through wet etching, the chip was then thinned to form a trapezoidal microchannel with the

---

☆ Communicated by W.J. Minkowycz.

* Corresponding author.
*E-mail address:* pingcheng@sjtu.edu.cn (P. Cheng).

0735-1933/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.icheatmasstransfer.2010.03.007

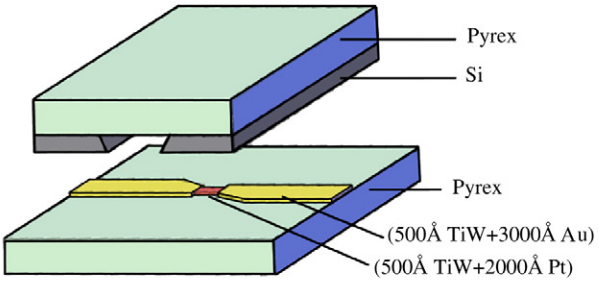

**Fig. 1.** Configuration of microchip.

top width and depth of 600 μm and 150 μm respectively. After that, by lift-off method, a microheater was fabricated on another glass wafer (Pyrex7740) with a thickness of 500 μm, including Pt microheater (500 Å TiW + 2000 Å Pt) and Au pad (500 Å TiW + 3000 Å Au). In order to protect the microheater, a 1 μm layer of SiN was spurted on the surface of the microheater. Finally, the chip with microchannel and the one with the microheater were bonded together. The size of the Pt microheater used in this experiment was $140 \times 100\ \mu m^2$.

### 2.2. Experimental procedure

Before performing the experiment, the Pt microheater was calibrated to give its resistance–temperature characteristic. For this purpose, the microchip was placed in a thermal bath whose temperature could be controlled. A thermocouple was attached to the microheater. During calibration, the temperature of the thermal bath was increased gradually and recorded synchronously with the corresponding resistance of the circuit. After fitting the experimental data, the expression of resistance as a function of temperature is given as follows:

$$R_c = 3.5358 + 0.01008T \tag{1}$$

which shows a linear relationship between the resistance with respect of temperature. Here, $R_c$ is the resistance of microheater circuit, which included the resistances of Pt microheater, connecting wire and contact.

The experimental system is similar to those in our previous work [14]. Distilled water at a subcooled degree of 80 °C was driven by a syringe pump to flow through a filter and entered the test section. A microscope and a high-speed CCD were used to observe and record boiling phenomenon through the glass plate. A pulse generator was used to control the pulse input through the control circuit. The pulse signal from pulse generator was also used to trigger CCD. A standard resistance was connected in series with the microheater. During the experiment, the voltages of the microheater circuit and the precision resistance were recorded by a high-speed data acquisition system.

### 2.3. Data reduction

The heat supplied to the microheater is given by

$$q = P_{pt} / A \tag{2}$$

where $A$ is surface area of Pt microheater, and $P_{pt}$ is power supplied to microheater which can be determined from

$$P_{pt} = P_c\left(R_{pt} / R_c\right) \tag{3}$$

The power supplied to circuit $P_c$ and resistance of circuit $R_c$ can be calculated through measured data. To determine $R_{pt}$, it is noted that $R_c$ has three main components: Pt microheater $R_{pt}$, connecting wire $R_w$ and contact $R_{cont}$, i.e.,

$$R_c = R_{pt} + R_{cont} + R_w \tag{4}$$

Assuming that the resistance of contact $R_{cont}$ and connecting wire $R_w$ are constant (i.e., independent of temperature), then $R_{cont} + R_w$ can be obtained from above equation at 20 °C to give,

$$R_{cont} + R_w = R_c\left(20^\circ C\right) - R_{pt}\left(20^\circ C\right) \tag{5}$$

where $R_c$ (20 °C) can be measured and $R_{pt}$ (20 °C) can be calculated approximately as,

$$R_{pt}\left(20^\circ C\right) = \rho_{20^\circ C}\, l / s \tag{6}$$

where $l$ and $s$ are length and cross-sectional area of Pt microheater in the direction of current respectively, with $s = w\delta$, where $w$ and $\delta$ are the width and thickness of Pt microheater, and $\rho_{20\ ^\circ C}$ is the resistivity of Pt at 20 °C. It follows from Eqs. (3)–(5) that

$$P_{pt} = P_c\left(R_{pt} / R_c\right) = \left\{R_c - \left[R_c\left(20^\circ C\right) - R_{pt}\left(20^\circ C\right)\right]\right\} P_c / R_c \tag{7}$$

where $P_c$ and $R_c$ are computed from

$$P_c = V_c I_c = V_c V_s / R_s \tag{8}$$

$$R_c = V_c / I_c = V_c R_s / V_s \tag{9}$$

with $V_c$ and $V_s$ being the voltages across the circuit and across the standard resistance $R_s$. Thus, heat flux supplied to the microheater can be computed from Eqs. (2), (7)–(9).

## 3. Results and discussions

### 3.1. Flow boiling regimes

For a given mass flux and pulse width, it is found that boiling mode on the microheater will transform from nucleate boiling at low heat flux to film boiling at high heat flux. With further increase in heat flux, the surface of microheater was covered totally by vapor film and there appeared a growing light spot at the center of microheater, where dry out occurred. In order not to damage the microheater, heat flux will not be increased further when dry out appeared.

It can be concluded from vitualization study that with increasing heat flux, microscale boiling over the microheater can be classified into four different regimes: single phase, nucleate boiling, film boiling and dry out. Fig. 2 shows the effect of pulse width on microscale boiling regimes at a mass flux of 45 kg/m$^2$s. With increasing pulse width, it is shown that less heat flux is required to induce boiling regime transition, which is similar to the results obtained by Li et al. [2]. The sizes of regimes of single phase, nucleate and film boiling are reduced with increasing pulse width, which is similar to the results obtained by Lim et al. [9]. Since it is shown that the mass flux has little effect on boiling regimes [14], we therefore obtained an expression for heat flux $q$ required for regime transitions based on a mass flux of 45 kg/m$^2$ s as:

$$q = a + b^{*} \exp\left(-\tau / c\right) \tag{10}$$

where $q$ is heat flux supplied to microheater, $\tau$ is pulse width, $a$, $b$, and $c$ are constants, whose values for three transitions are listed in Table 1. It is shown from Table 1 that the value of $c$ is relatively unchanged for the