DESIGN OF AN IMPROVED HEATER ARRAY TO MEASURE MICROSCALE WALL HEAT TRANSFER

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ABSTRACT

An improved array of microscale heaters is being developed to measure the heat transfer coefficient at many points underneath individual bubbles during boiling as a function of space and time. This heater array enables the local heat transfer from a surface during the bubble growth and departure process to be measured with very high temporal and spatial resolution, and should allow better understanding of the boiling heat transfer mechanisms by pinpointing when and where in the bubble departure cycle large amounts of wall heat transfer occur. Such information can provide much needed data regarding the important heat transfer mechanisms during the bubble departure cycle, and can serve as benchmarks to validate many of the analytical and numerical models used to simulate boiling. The improvements to the heater array include using a silicon-on-quartz substrate to reduce thermal cross-talk between the heaters, decreased space between the heaters, increased pad sizes on the heaters, and progressive heater sizes. Some results using the present heater array are discussed.

INTRODUCTION

Boiling is an attractive heat transfer mechanism because large amounts of heat can be removed with relatively small temperature differences. Due to the difficulty of making measurements underneath bubbles, however, there is still much controversy regarding the relative contribution of the above mechanisms to the overall heat transfer. For example, estimates for the contribution of the microlayer heat flux to the overall heat transfer range from less than 20 percent to almost 100 percent depending on the boiling conditions. The great majority of the experimental data to date have been obtained using heater surfaces that were comparable to, or much larger than, the bubbles, enabling only average heat transfer rates over the entire heated surface to be obtained. Little experimental data is available regarding the *local* heat transfer rates from the wall under and around the bubbles as they grow and depart from the surface. Local heat flux measurements can provide much needed information regarding the relevant wall heat transfer mechanisms during the bubble departure cycle by pinpointing when and where in the cycle large amounts of heat are removed. Cooper and Lloyd (1) used a microthermocouple to obtain temperature fluctuations beneath a growing bubble, and demonstrated the existence of the microlayer. Some more recent work measured the local heat flux from a surface using laser interferometry to obtain contours of the microlayer thickness vs. time (refs 2-6). The rate of change of the microlayer thickness was related to the wall heat transfer through a simple energy balance.

The objective of the present work is to obtain direct measurements of the local heat transfer underneath single bubbles as they grow and depart from the surface so that the contribution of the various heat transfer mechanisms to the overall heat flux can be measured. This study should also provide benchmark data against which numerical codes can be compared. A novel heater surface consisting of an array of microscale heaters will be used to accomplish this. Each individual heater in the array is much smaller than a single bubble, although the heater array is of the same order, or larger than, a single bubble. Each heater represents one resistance in a bridge, and is kept at constant temperature by an electronic feedback loop. By measuring the power required to keep each individual heater at a constant temperature, two dimensional maps of the heat transfer coefficient from the heater surface to the bulk liquid can be obtained. This heater array enables the heat transfer to a surface during the bubble growth and departure process to be measured with high temporal and spatial resolution. Data can also be obtained in the critical heat flux and transition boiling regions without the danger of heater burnout because the heaters are operated in constant temperature mode.

HEATER CONSTRUCTION

The improved heater array is to be constructed on a highly doped silicon layer deposited on a quartz substrate using VLSI techniques. A schematic of the heater construction is shown on Figure 1. The quartz substrate prevents thermal cross-talk between the heaters. The thin Si layer electrically grounds one side of the heaters. A layer of SiO_2 is grown on the Si layer so that the heaters can be electrically insulated. Vias cut into this layer allow electrical connections from the heaters to the wafer. The vias are filled with metal, and an array of platinum resistance heaters in a serpentine pattern is then deposited onto the SiO_2. Another layer of SiO_2 is deposited on top of the platinum resistance heaters as insulation. Vias cut into the top SiO_2 layer allow connections between the power leads and the heaters. The vias are filled with metal and the aluminum power leads are deposited. Below the Si wafer is a guard heater at the same temperature as the heaters, thereby eliminating heat conduction within the substrate--all power flowing into the heaters is transferred to the fluid. A photo of a single heater is shown on Figure 2. The new heater array will have about 240 of these heaters withina 4 mm diameter circle. The resistance heater, the power lead, and the vias are all clearly visible. Although the size of the heaters precludes measurement of the local heat transfer during bubble initiation (which occurs on submicron length scales), wall heat transfer during bubble growth and departure can be measured easily. The heater lines are 5 μm wide and about 6000 μm in total length, with spacing between heater lines of 5 μm. The heaters have a nominal resistance of about 1000 Ω. This is large enough to prevent parasitic resistances due to the leads, contacts, etc. from significantly affecting the measurement, but small enough that the required output voltage of the op-amps do not exceed their rail voltage.

Changes in the new heater array are numerous. First the via size has been increased greatly so that the contact resistance between the Pt and the silicon wafer that plagued earlier heaters has essentially been eliminated. Second, the space between the heaters has been decreased to reduce the heat leakage from the heater to the unheated portions of the substrate. Third, the heater sizes will become progressively larger with radial distance in the next generation heater and the number of heaters will be increased, enabling increased resolution at the center of the array where the bubble will be smallest. The fourth improvement is the use of a low thermal conductivity quartz substrate. This will greatly reduce the thermal cross-talk between the heaters that would result if the heaters were made directly on a high thermal conductivity silicon wafer, and greatly increase the frequency response of the heaters.

FEEDBACK LOOP

A schematic of a feedback control circuit used to keep a heater at a constant temperature (constant resistance) is shown in Figure 3. The circuit is similar to the feedback loops used for constant temperature hot-wire anemometers. Each circuit provides a driver voltage to its respective heater that corresponds to the power being dissipated by the heating element, and uses an input signal to select the desired temperature of the heating element. Because the heater is so thin (~2.0 μm), the frequency response of the heaters (10^6-10^7 Hz) is much higher than the bubble departure frequency (10^2-10^3 Hz). No frequency compensation circuitry is therefore needed. The resistance of the heater is controlled using a voltage controlled resistor (VCR) from Siliconix. A VCR was chosen instead of a manual potentiometer so the heaters resistance could be computer controlled. VCRs with resistance ranges from 250 to 650 Ω were chosen for this circuit.

The frequency response of the circuit was measured to be in excess of 20,000 Hz by removing the heater, inputting a square wave, and measuring the circuit output. This is much faster than the frequencies expected during the bubble growth and departure cycle. The next generation feedback control circuit will include provision for calibration of the heater array on the same PCB used for control, and the VCRs may be replaced by IC chips that act as VCR's.

COMPUTER CONTROL CIRCUIT

A microprocessor circuit is used to set the temperatures of the individual heaters in the array using computer control. The microprocessor controls the temperature of each heating element by controlling the voltage applied to the VCRs. The use of a separate system for heater control maximizes the data acquisition capabilities of the main computer since it will not need to share processing time for the heater control process. The microcontroller communicates with the main computer through a standard RS-232 serial data port at 9600 baud.

DATA ACQUISITION SYSTEM

The data acquisition system consists of low-pass filters at the output of each bridge, a high speed multiplexer, and a 16 bit A/D converter sampled by a personal computer. Separate channels are used to measure the time, and the bulk liquid temperature and pressure. The Daqbook 216 from IO Tech was chosen due to its low cost, high resolution (16 bits), high data acquisition rate (100 kHz), portability, and expandability (256 channels maximum).

RESULTS

Heater calibration.--Shown on Figure 4 are some resistance vs. temperature calibrations for sixteen heaters. The data were taken over a period of three days and a temperature range of 28 to 60 °C. It is seen that the curves are very linear, and that all the heaters have approximately the same slope. No drift in the heater resistances were seen over the three day calibration period. The observed resistivity of approximately 2×10^{-3} K^{-1} differs from the published value for bulk platinum of 3.9×10^{-3} K^{-1}. The difference in the two values is not surprising however, since thin film properties are often different from bulk properties.

Heater performance with feedback loop.--The case where only one of the heaters was powered was investigated. The heater resistance (heater temperature) was set so that the bridge output was nominally 1.4 V in air. When acetone was dropped onto the heater, the bridge output was observed to rise with time. As the acetone evaporates, it's temperature decreases and the energy required to keep the heater at constant temperature increases, resulting in an increase in the output of the bridge. The response was relatively slow, since the heater is supplying energy to the high-conductivity silicon substrate which acts as a heat sink. Much faster response is expected if the array is constructed on a quartz substrate and all the heaters are powered.

The case where two adjacent heaters are powered is shown in Figure 5. The resistance of heater 14 was varied, and the response of heater 15 was observed. As expected, the responses are negatively correlated, i.e., an increase in the power supplied to heater 14 results in a decrease in the power supplied to heater 15, and vice versa. This thermal cross-talk between heaters can be greatly reduced by decreasing the thermal conductivity of the substrate, again by constructing the heater array on a quartz substrate.

Heater burnout.--To determine the heater burnout point, the current through the heater was measured as the voltage across the heater was increased while the heater was in still air. From these two measurements, the heater resistance/temperature and the power supplied to the heater were calculated. The heater temperature as deduced from the resistance measurements was observed to increase from 28 to 51 °C at the maximum voltage of 20 V. The temperature was not higher since the the substrate served as a heat sink for the heaters. The heat flux from the heaters at 20 V was calculated to be in excess of 600 W/m^2.

The heaters should easily be able to handle the maximum expected local heat transfer coefficient (~200 W/m^2).

CONCLUSIONS

An improved heater array for wall heat transfer measurements during nucleate boiling has been designed and will be constructed this fiscal year. The improvements include increased via size, decreased spacing between heaters, a progressive heater size, and the use of a low thermal conductivity substrate. Upgrades to the feedback loops are also planned.

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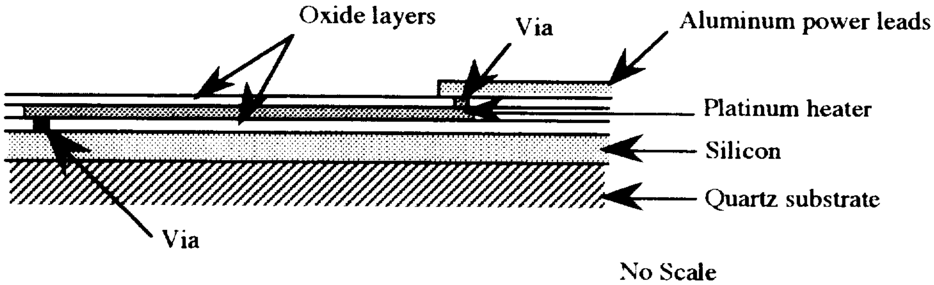

Figure 1--Schematic of heater construction.

Figure 2--Photograph of single element showing the resistance heater, the power lead, and the vias.

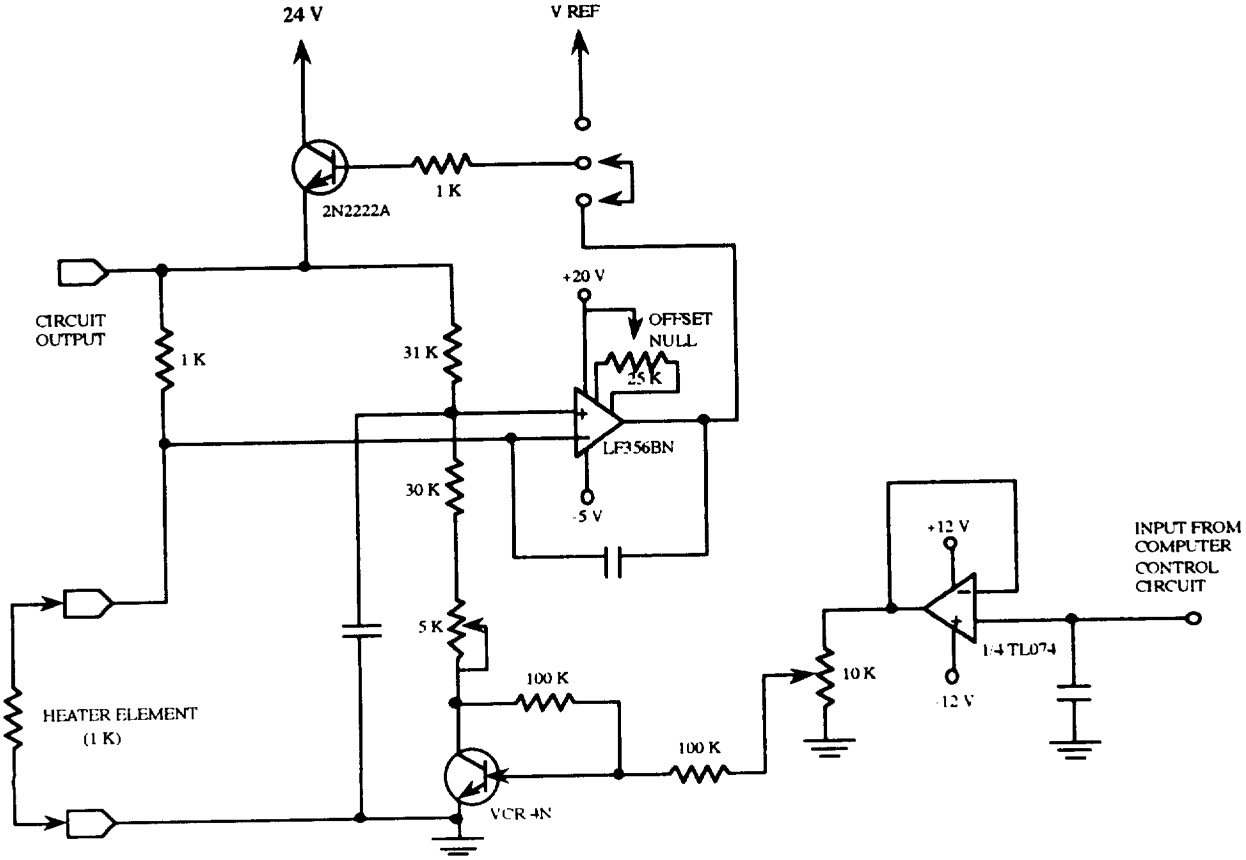

Figure 3--Schematic of feedback loop.

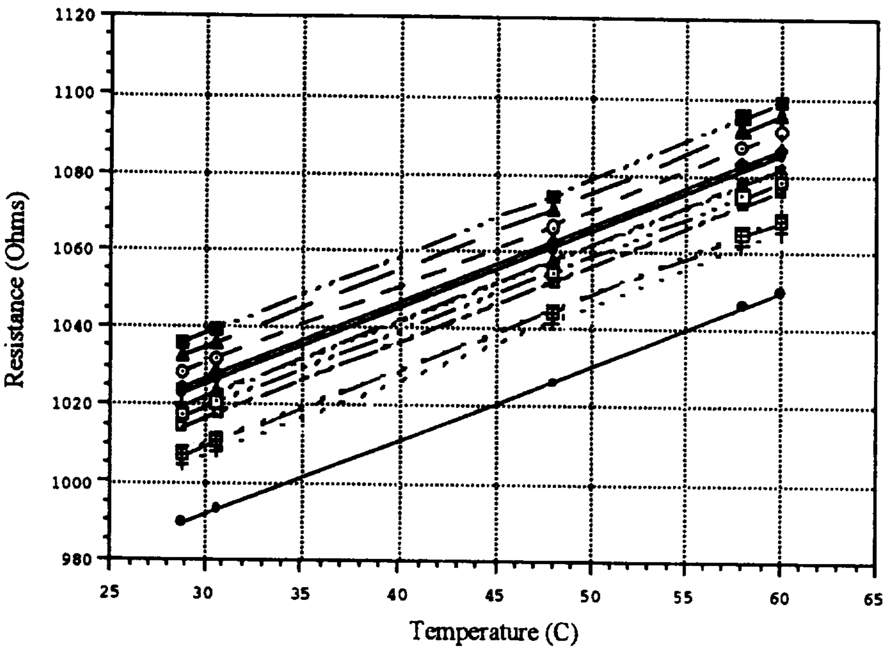

Figure 4--Typical calibration curves for heaters.

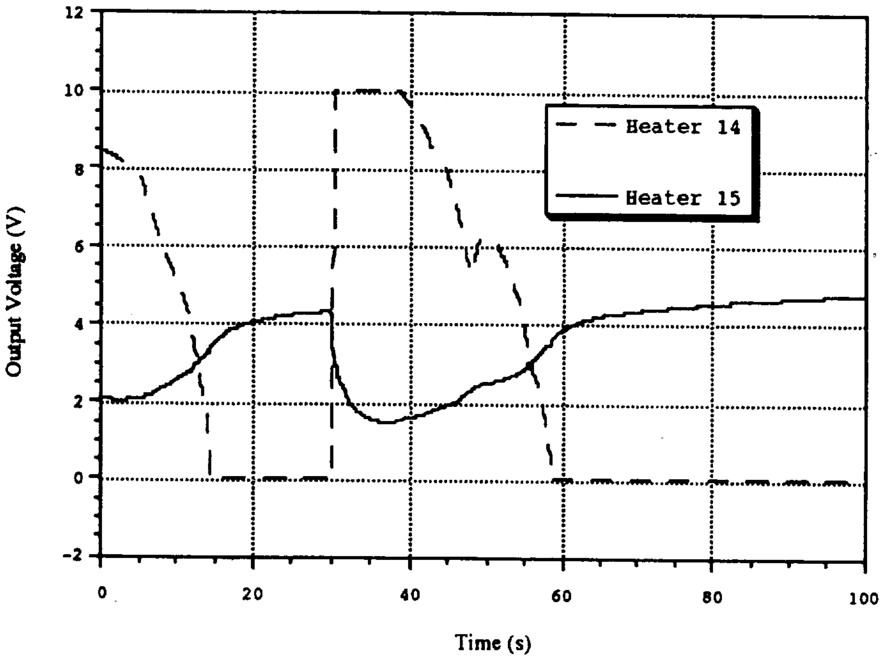

Figure 5--Output for two side by side heaters.