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BOILING ON MICROCONFIGURED SURFACES IN LIQUID NITROGEN

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ABSTRACT

Measurements are given for pool boiling on 1.27 by 1.27cm vertical silicon surfaces in liquid nitrogen. The microfeatures on the test surfaces were 10μm base length, 7.1μm deep. The center to center spacing of the inverted pyramids was 20, 40, and 60μm for the three different site densities tested. The site density of the 20, 40, and 60μm surfaces was 2.5×10^5, 0.625×10^5, and 0.278×10^5 per cm^2, respectively. The heat transfer performance, at a given wall-superheat, was closely proportional to the site density. No temperature hysteresis or overshoot arose at the onset of nucleation.

Intoduction

Recent experimental demonstrations of high temperature superconductivity were reviewed in [1]. In 1988, superconductivity was demonstrated at 125 K with a thallium-based cuprate material by S. Parkin at IBM. Although low-power applications, such as low-loss microwave devices, with liquid nitrogen cooling,are near realization for cuprate superconductors, high power applications, such as high density electronic devices, are not currently possible at 77K. Recently, organic superconducting materials have shown great potential for high power applications using LN_2 cooling.

The entire boiling curve for LN_2 was explored in [2] with a 5/8" copper heater tube of unknown surface condition. No temperature hysteresis was found in the boiling curve. Critical heat flux occurred at a wall-superheat of about 10°C wall-superheat. The critical heat flux of approximately $5W/cm^2$ was low, in terms of present conventional electronic dissipation rates at room temperature.

Copper and nickel surfaces were used in [3] as active boiling surfaces in LN_2. Artificial nucleation sites improved heat transfer in both the convective vaporization and nucleate boiling regimes. A surface roughened with flint removed more heat at a given wall-superheat than a polished surface prepared with 108μm diameter holes. The random microstructure of the roughened surface may have provided more active nucleation sites than the largely polished one with artificial sites.

Experiments in [4,5], using silicon microconfigured surfaces in water, showed up to a 400% enhancement in the boiling regime over the comparable smooth silicon surface data. The two microconfiguration geometries tested were hexagonal dimples, 3.3μm deep and 11.5μm wide in a square pattern on 22μm centers and trenches; 51μm deep, 12.6μm wide, and 100μm long, with repeat distance of 22μm. The area density of the potential nucleation sites was about 2 x 10^5 per cm^2 for the dimples and 0.41 x 10^5 per cm^2 for the trenches.

Microconfigured silicon surfaces were tested, in [6], in FC-72, a dielectric liquid. The test surface was configured with hexagonal dimples 3.3μm deep and 9.4μm wide. The wall superheat and temperature overshoot at the onset of nucleation were found to be independent of the non boiling immersion time once the potential nucleation sites were degassed. In contrast to earlier measurements using various enhanced surfaces, only a small temperature overshoot arose in the boiling curve.

This communication reports boiling measurements from strictly regular microconfigured surfaces in liquid nitrogen. Three microconfigured surfaces were tested. The obstensibly smooth silicon surfaces had 10μm inverted pyramids etched into the surface with a center to center feature spacing of 20, 40, and 60μm for the three surfaces. Shown in FIG 1a and b are the 20 and 60μm feature spacing surfaces, respectively. The area density of the 20, 40, and 60μm surfaces was 2.5 x 10^5, 0.625 x 10^5, and 0.278 x 10^5 per cm^2, respectively.

Experimental Program

Module design The module was designed to minimize heat losses. The spurious heat losses were calculated to be less than 5% of the input heat flux in all reported measurements. The microconfigured surfaces used for the measurements reported here were 1.27cm by 1.27cm in edge length, by 0.04cm thick p-type (110) oriented silicon chips. The boiling surface of the specimen was polished to the sub micron level. It was then photo etched with inverted square pyramids 10um on a side and 7.1 um deep. These pyramids were repeated on 20, 40, and 60μm centers, recall FIG 1a and b. These spacings correspond to site densities of 2.5 x 10^5, 0.625 x

10^5 and 0.278 x 10^5 per cm^2, respectively. The non boiling back side of the chip was sputter-coated with an 800A^o layer of nichrome. Two 1mm wide parallel gold film contacts were then sputtered along the two vertical opposite edges. See FIG 2. These gold contacts ensured good electrical contact with the power leads. The nichrome layer was a resistance heater. The resistance from one gold contact to the other was 21 ohms at room temperature. Three 40 AWG T-type thermocouples were bonded, with an electrically insulating epoxy along the centerline on the back of the chip. They were in a vertical array. Two 24 AWG insulated copper power leads and two 40 AWG voltage taps were tape soldered to each of the gold contacts. They supplied the required power and measured the voltage drop across the nichrome resistance heater, respectively.

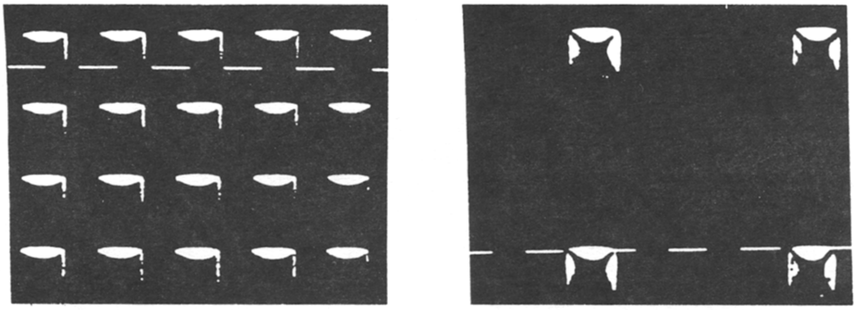

FIG 1a, b: Electron micrographs of microconfigured surfaces. White dashed lines are 10μm in length. a) 10μm inverted pyramid, 7.1μm deep on 20μm centers. b) 10μm inverted pyramid, 7.1 μm deep on 60μm centers.

The instrumented silicon specimen was center-mounted in the test module, see FIG 2, on a stack of five 5.08cm diameter felt wafers. These five wafers were bonded together with Crest Corp. cryogenic adhesive. This layer is called the felt insert. Holes were drilled in the felt insert, in the proper locations, for the instrumentation wires. The felt insert was then mounted inside the short stainless steel tube, with cryogenic adhesive, to create a liquid proof barrier. This horizontal stainless steel tube was 5.08cm ID, 5.40cm OD and 5.08cm long. The instrumentation wires were fed upwards through a thin-walled, 0.95cm OD and 0.051cm thick, stainless steel tube. The tube was welded perpendicular to the side wall of he 5.08cm diameter short tube, 3.81cm from the front face. Fiberglass insulation was packed loosely in the remaining volume of the stainless steel short tube module. Another felt insert was epoxied with cryogenic adhesive, similar to the first felt insert, into the back face of the module. All instrumentation wires were thereby completely sealed from the liquid. The inside volume of the module was vented to ambient pressure via the vertical thin-walled tube. The size of the short module tube, the diameter of the power leads, and the resistance of the nichrome layer were chosen, based on an analysis, to minimize the spurious heat losses.

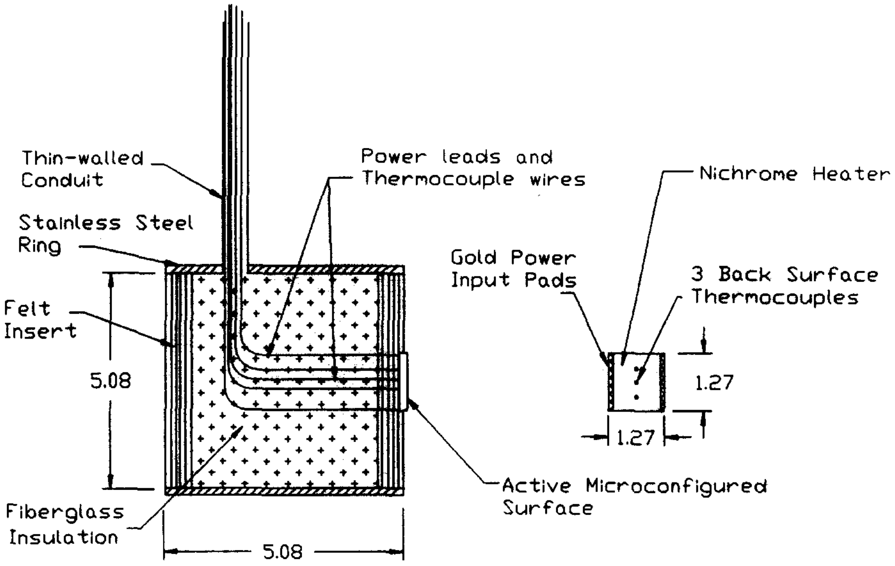

FIG 2: Instrumented backside of silicon specimen and specimen mounted on the test module

Methods and procedure All measurements were made at atmospheric pressure. Data acquisistion and specimen electrical input were automated via a computer interface loop. One of the three thermocouples on the back surface of the specimen, see FIG 2, was continuously monitored as a safety control to avoid boiling crisis. When the surface temperature exceeded a preset limit, power to the test surface was automatically terminated. Complete details of the data acquisition and management system was given in [5].

After a change in input power, the surface temperature reached a steady state very rapidly. Data was taken five minutes after the change in power. Bulk fluid stratification, in the 34 liter dewar, was less than 0.05^{o}C/cm. The three back surface temperature measurements agreed to within 0.3^{o}C. During an experimental run, the boiling curve was ascended and descended. Each experiment was repeated to verify the data.

The front surface temperature was determined from the thermocouple measurements on the back. The thermal conductivity of silicon, for this calculation, was taken at the saturation temperature of nitrogen at 77K to be 9.50 W/cm^{o}C. The calculated temperature difference across the silicon layer, at the highest heat flux imposed during the experiments was 0.07^{o}C.

Measurements in liquid nitrogen were conducted in a 34 liter cryogenic dewar. The static holding time of this dewar is 18 weeks. This small heat leak did not cause appreciable natural convection circulations during the experiment. The 20cm long styrofoam cap of the dewar was drilled to accept the stainless steel module support. Three 40 AWG T-type thermocouples were oriented in a vertical array in the tank to determine any appreciable fluid stratification.

Measured Heat Transfer Performance

Heat flux versus wall-superheat data are shown in FIG 3 for the 10um inverted pyramid microconfigured surfaces, with 20, 40, and 60µm center spacings, respectively. Also included are the boiling data of [2]. That surface was a horizontal copper tube, of 1.59cm OD, without any particular preparation of the boiling surface. These data are also typical of information and trends given in [7].

These new results were repeatable over time. No temperature hysteresis or overshoot arose in the boiling curve. All three spacings indicate substantial enhancement over the data of [2]. The surface with the minimum feature spacing of 20µm, and the largest potential site density of 2.5 x 10^5, showed the largest enhancement, of 30 times, compared to [2]. The surface with the largest feature spacing of 60µm, and the smallest potential site density of 0.278 x 10^5, provided the smallest enhancement of only 40% above the data of [2]], at low flux. The shapes of the boiling curve, for all three feature spacings, are seen to be very similar. These are also qualitatively similar in shape to the boiling curve of [2]. Stable nucleation was maintained on the 20um spacing surface at 10W/cm^2, at a wall-superheat of only 4.5^{o}C. Since it was not possible to make visualizations during these tests, the wall-superheat at the onset of boiling may only be approximately inferred from the boiling curves.

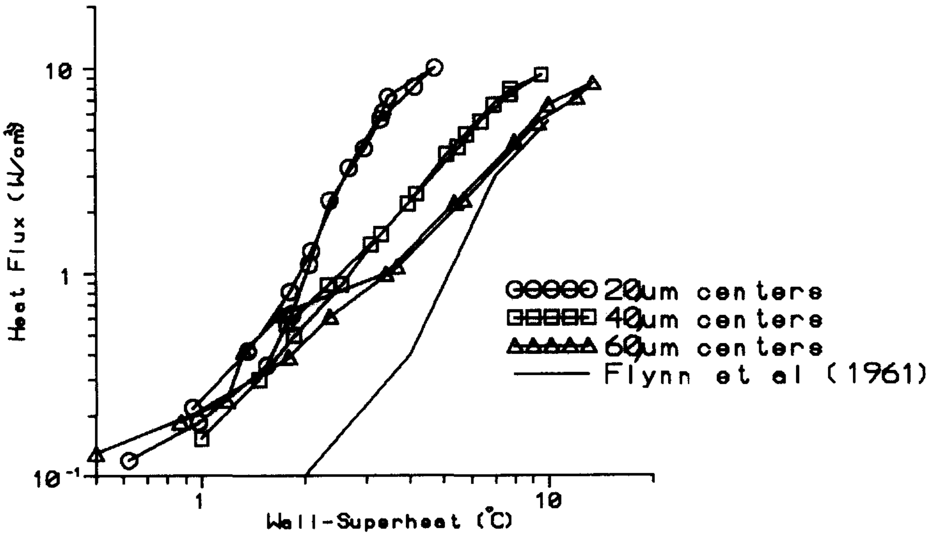

FIG 3: Comparison of the boiling heat flux versus wall-superheat, for the 10µm inverted pyramid with 20, 40, and 60µm spacing, in liquid nitrogen. Also included are the data trends of [2].

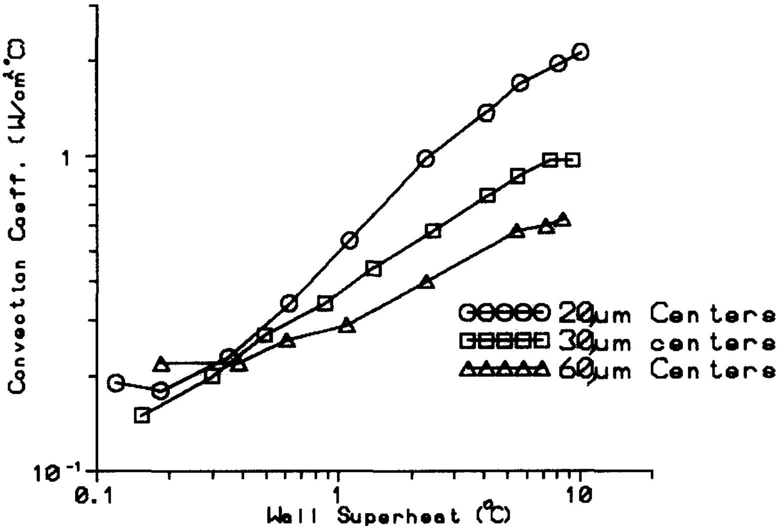

FIG 4: Comparison of the boiling heat transfer coefficient versus wall-superheat, for the 10µm inverted pyramid with 20, 40, and 60µm spacing, in liquid nitrogen.

At low wall-superheat, the data for the three spacings are in close agreement. After the apparent onset of nucleation the three curves diverge rapidly with increasing wall-superheat. The wall-superheat required to dissipate 8W/cm^2 was 3.5, 7.7, and 11.4^{o}C for the 20, 40 and 60μm feature spacings. These values amount to an increase in wall-superheat of 325%, from the smallest to the largest center-spacing surfaces. It is difficult to estimate the onset of nucleation. However, the required wall-superheat for nucleation appears to be about 2^{o}C for all three spacings. It appears to occur at about 4^{o}C for the measurements of [2]. FIG 4 compares the heat transfer coefficient for the 10um inverted pyramid surfaces, at center spacings of 20, 40, and 60μ m. The maximum heat transfer coefficient arises for the 20μm center spacing, at a heat flux of 10.1W/cm^2. It is 2.13W/cm^{2o}C or 3750BTU/hrft^{2o}F.

Microconfiguration site spacing, or density, has been found to strongly affect the overall boiling heat transfer in liquid nitrogen. A very important quantitative conclusion has arisen as discussed in [8]. It arises from the foregoing measurements of boiling performance at different microfeature spacings, or feature surface density. The dissipation heat flux, at a given wall-superheat, was found to be very closely proportional to microfeature surface density, as sites per unit area. This simple result may be expected considering the uniformity and large density of the potential nucleation sites.

Conclusions

Boiling heat transfer results in liquid nitrogen are presented for regular microconfigured surfaces. The smooth silicon surfaces were microconfigured with 10μm inverted pyramids etched into the surface with a center to center feature spacing of 20, 40, and 60μm for the three test surfaces, respectively. The area density of the 20, 40, and 60μm surfaces was 2.5 x 10^5, 0.625 x 10^5, and 0.278 x 10^5 per cm^2, respectively. The heat transfer performance showed very large enhancement over the copper tube data in [2]. No temperature hysteresis or overshoot was measured in the determination of the nucleate boiling curve. The heat flux, at a given wall-superheat was closely proportional to the number of inverted pyramids per unit area.

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