Boiling Heat Transfer Enhancement by Coupling Nanoscale Evaporation in Buried Nanochannels

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Principal Investigator(s): Shalabh C. Maroo

User(s): An Zou, Sidharth P. Raut, Manish Gupta

Affiliation(s): Department of Mechanical and Aerospace Engineering, Syracuse University, Syracuse, NY 13244

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Contact: scmaroo@syr.edu, azou@syr.edu, spraut@syr.edu, magupta@syr.edu

Website: http://maroo.syr.edu

Primary CNF Tools Used: Heidelberg mask writer DWL 2000, manual photoresist spinner, GAC auto stepper, YES image reversal oven, ABM contact aligner, SÜSS MA6-BA6 contact aligner, e-beam evaporator, Oxford PECVD, GSI PECVD, Glen 1000 Plasma, Anatech resist strip, Oxford 81/82 etcher, optical microscope, scanning electron microscope, atomic force microscope

Abstract:

We explicitly coupled pool boiling with nanoscale evaporation by using buried nanochannels to enhance boiling critical heat flux (CHF) by ~105%. This enhancement is attributed to the formation of extra menisci and contact line in nanochannels. The work reported here is part of a journal article which is currently under review.

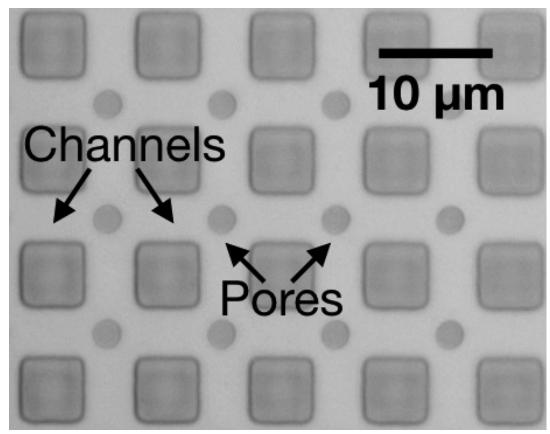

Figure 1: Optical microscope image of the sample with buried nanochannels.

Summary of Research:

Boiling and evaporation are two distinct forms of liquid-to-vapor phase change, which is an efficient mechanism to move heat from a solid surface. Boiling has been used in a multitude of residential and industrial applications such as refrigerators, heat exchangers, boilers, etc. However, pool boiling is limited by occurrence of critical heat flux (CHF), the maximum stable heat flux a system can be operated at. Heat flux higher than CHF can irreversibly damage the surface due to a sudden and dramatic temperature increase. CHF occurs when liquid fails to quickly rewet the surface creating dry regions for extended periods of time, with typical values of ~ 80 W/cm^2 for water on silicon dioxide (SiO_2) surface. On the other hand, nanoscale evaporation has recently [1] been shown the capability to remove transient heat flux ~ 8000 W/cm^2 for the same water-silicon dioxide combination over a very short time span in a single 2D nanochannel.

In this work, we combine these two techniques of pool boiling and nanoscale evaporation to increase CHF of pool boiling. The coupling is attained by creating buried 1D nanochannels underneath the surface where wicking in the channels maintains the surface wet, and creates additional evaporating menisci. Thus, nanoscale evaporation occurs in channels and pores, while boiling happens on the surface above.

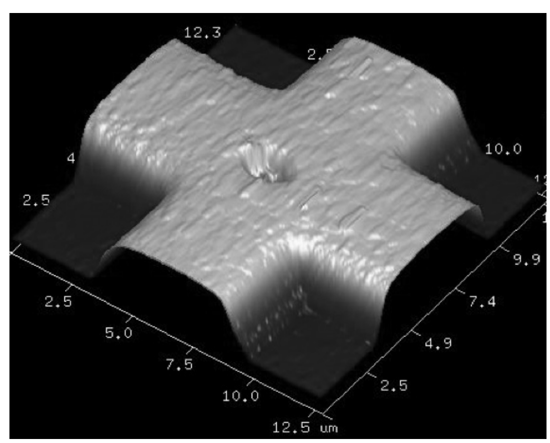

Figure 2: Atomic force microscope (AFM) image of the profile of channels and pores.

The buried cross-connected nanochannels were fabricated on a Si substrate by etching patterned sacrificial metal layers buried under a 300 nm thick SiO_2 film from plasma enhanced chemical vapor deposition (PECVD). The channel geometry was determined by the pattern of sacrificial layers, which was attained by a lift-off process. The cross-connected channels, made from two sets of channels perpendicular to each other, allow for ease of liquid exchange inside the channels. Further, at each intersect of the channels, a 2-µm pore was fabricated allowing liquid present above the surface to flow into the channels. Figure 1 shows an image of these nanochannels (width: 5 µm, spacing: 5 µm, height: 728 nm) from optical microscope. Due to the conformal deposition of PECVD SiO_2, trenches of depth same as channel height formed on the top surface between adjacent channels, Figure 2 shows an atomic force microscope (AFM) image of the surface.

The pool boiling experiments were conducted at atmospheric pressure under saturated conditions using deionized (DI) water. The experiment setup consists of a polycarbonate water bath and a thermal insulated copper block. Five cartridge heaters are embedded in the copper block allowing for a maximum power input of 1250 W (heat flux of 1250 W/cm^2). The heat input to the copper block is controlled with a variable alternating current (AC) to AC transformer. Four equally spaced K-type thermocouples are inserted into the center axis of the copper block to measure the temperature gradient. In water bath, four immersion heaters and a resistance temperature detector (RTD) is used to maintain bulk water at its saturated temperature. In experiments, the sample with buried nanochannels was bonded on the top of the copper block using solder paste to ensure good attachment with minimal thermal contact resistance.

The sample was immersed in a pool of DI water, which was degassed by boiling it for 30 minutes and maintain its temperature at 97-100°C for another 30 minutes. Boiling on sample was achieved by increasing the output voltage of the variable transformer. To obtain the boiling curve, the output of the variable transformer was increased in small increments. The temperature readings were recorded after reaching steady state, which is determined by the criterion that the temperature changes from all thermocouples were less than 0.5°C over one minute. The steady state was reached usually in 10-15 minutes after changing the output power. CHF was obtained when an incremental increase of power supplied resulted in dramatic increase of surface temperature, and its value was taken as the last stable heat flux recorded during experiments. The heat flux was obtained from measured temperature gradient using Fourier's law; while the surface temperature was obtained from the reading from the thermocouple closest to the top surface, also using Fourier's law. ~ 105% CHF enhancement was obtained with an absolute value of 177.40 ± 2.43 W/cm^2.

This enhancement is attributed to nanoscale evaporation from additional menisci inside the nanochannels formed by passive wicking of liquid. This CHF value is in good agreement (within 5% error) to the CHF model, which predicts CHF enhancement when surface force gets augmented due to elongated and/or additional contact line.

In summary, we achieved ~ 105% pool boiling CHF enhancement by explicitly coupling boiling with nanoscale evaporation using nanochannels. This enhancement is mainly contributed by the additional menisci and contact line created by the wicking flow in the nanochannels. The obtained boiling enhancement can be increased by optimizing the nanochannel geometry as well as potentially using 2D nanochannels.

References:

[1] Y. Li, M.A. Alibakhshi, Y. Zhao, and C. Duan, "Exploring ultimate water capillary evaporation in nanoscale conduits," Nano Letters, vol. 17, pp. 4813-4819, 2017.