

MEMS-BASED THERMAL MANAGEMENT OF HIGH HEAT FLUX DEVICES EDIFICE: EMBEDDED DROPLET IMPINGEMENT FOR INTEGRATED COOLING OF ELECTRONICS

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ABSTRACT

Increases in microprocessor power dissipation coupled with reductions in feature sizes due to manufacturing process improvements have resulted in continuously increasing heat fluxes. The ever increasing chip-level heat flux has necessitated the development of thermal management devices based on spray and evaporative cooling. This lecture presents a comprehensive review of liquid and evaporative cooling research applied to thermal management of electronics. It also outlines the challenges to practical implementation and future research needs.

This presentation also describes the development of EDIFICE: Embded Droplet Impingement For Integrated Cooling of Electronics. The EDIFICE project seeks to develop an integrated droplet impingement cooling device for removing chip heat fluxes over 100 W/cm^2 , employing latent heat of vaporization of dielectric fluids. Micro-manufacturing and MEMS (Micro Electro-Mechanical Systems) will be discussed as enabling technologies for innovative cooling schemes recently proposed. Micro-spray nozzles are fabricated to produce 50-100 micron droplets coupled with surface texturing on the backside of the chip to promote droplet spreading and evaporation. A novel feature to enable adaptive on-demand cooling is MEMS sensing (on-chip temperature, remote IR temperature and ultrasonic dielectric film thickness) and MEMS actuation. EDIFICE is integrated within the electronics package and fabricated using advanced micro-manufacturing technologies (e.g., Deep Reactive Ion Etching (DRIE) and CMOS CMU-MEMS). The development of EDIFICE involves modeling, CFD simulations, and physical experimentation on test beds. This lecture will then examine jet impingement cooling of EDIFICE with a dielectric coolant and the influence of fluid properties, micro spray characteristics, and surface evaporation. The development of micro nozzles, micro-structured surface texturing, and system integration of the evaporator will also be discussed.

1. Introduction

In recent years, there have been enormous increases in chip-level heat fluxes. As the process speed reaches the 1-2 5Hz range and there is an increasing demand for miniaturization, thermal management is becoming a critical bottleneck to system performance. The increase in process speeds has been made possible by greater chip level integration of electronic components and by trends such as single chip segmented processors with integrated cache memory. Due to these enhancements, the chip level heat fluxes have also gone up tremendously, already reaching 50 W/cm^2 for many high and commercial applications and are expected to exceed 100 W/cm^2 before the decade ends. Conventional air cooled designs are no longer adequate to remove these heat fluxes and, for a number of applications, direct air-cooling will have to be replaced or supplemented by other high performance compact cooling techniques.

2. Heat Removal of High Heat Fluxes: Literature Review

Liquid-vapor phase change, direct and indirect liquid cooling, impinging jets, droplets and sprays are attractive cooling options for removing high heat fluxes because of their associated heat transfer coefficients. Two-phase heat transfer, involving evaporation of a liquid in a hot region and condensation of vapor in a cold region, can provide the removal of much higher heat fluxes than can be achieved through conventional forced air-cooling, which is the reason why considerable research has been redirected towards these approaches for thermal management of electronics.

In direct liquid cooling, the electronics are either immersed in a pool or in contact with droplets, jets or sprays of a dielectric liquid. Even though liquid cooling can be employed with or without boiling, boiling can greatly reduce the electronics chip temperature compared with single-phase liquid cooling. This approach of liquid cooling with boiling has been extensively studied in the past, starting with the pioneering work of Bergles and his group [see papers, 1- 10] and continuing with Incropera [10], Bar-Cohen [11] and other researchers. The main issues investigated are the critical heat flux (CHF) levels that can be attained, temperature overshoot and incipient excursion, bubble growth and departure as well as the effect of surface enhancement. Critical heat flux (CHF) is the peak heat flux in the boiling curve of the coolant. Any further increase in the heat flux would cause drastic increase in the electronics temperatures.

Nonn et al. [12] have reported investigations on jet impingement flow boiling with FC-72 and FC-87. They concluded that higher jet velocities give rise to higher CHF. Studies by Nakayama and Copeland [13] and Copeland [14] indicate that when flow rate is kept constant and the number of

nozzles is increased, the CHF increases. CHF values as high as 200 W/cm^2 were attained with FC-72 multiple jet impingement boiling on a chip. Ma et al. [15] present an extensive literature survey of jet impingement cooling with and without boiling. Their studies, as well as other studies in literature, indicate that cooling uniformity improves by using an array of jets. They point out that research is required on understanding the interaction of jets in multiple jet impingement system.

Numerical work, which incorporates two-phase effects in jet impingement, has been reported in the literature. With relevance to electronic cooling, Wang et al. [16] performed a computational study of two-phase jet impingement cooling of a simulated chip by solving the averaged transport equations for the two phases. Some of their important conclusions are that the boiling of an impinging jet produces the best cooling and that an optimized flow rate exists for the impinging jet. Heat pipes and thermosyphons are examples of indirect liquid cooling with two-phase heat transfer which can transport large heat rates with small temperature differences and exploit the benefits of two-phase heat transfer [17]. Palm and Tengbald [18] have presented a review of recent literature.

Single-phase jet impingement cooling has been investigated experimentally and numerically. Stevens and Webb [19] have reported experimental results with single phase, single jet impingement cooling of a simulated chip with water as the cooling fluid. The important results of their investigation demonstrate that the heat transfer coefficient is highest in the stagnation zone of the impinging jet and that the velocity of the jet is most influential in determining the heat transfer coefficient. A series of papers by Womac et al. [20- 22] have examined jet impingement cooling of a simulated chip with single and multiple jets using FC-77 and water in single phase as coolants.

Maddox and Bar-Cohen [23] conducted a study on the design of a submerged jet impingement cooling system. They conclude that the Martin correlation [24] for submerged jet impingement is the most appropriate for electronic cooling design calculations. Other important results indicate that Nu increases with increasing Re and Pr. Also, with an increase in the number of jets per chip, the pumping power reduces and also the heat transfer improves. There are other papers also in the literature (e.g., [25, 26]) dealing with single-phase jet impingement cooling yielding results similar to those discussed above.

Analytical and numerical work has been performed with single-phase jets for electronic cooling. Lienhard et al. [27, 28] considered a single free surface jet impinging on a constant heat flux surface. The energy equation is solved by integral analysis and various zones in the wall jet region are identified based on the growth of the thermal and hydrodynamic boundary layers and point of transition to turbulence. Nusselt number correlation as a function of the radial coordinate is

presented. Lienhard et al. [29] also examined the influence of the Weber number on the stagnation point heat transfer. When the Weber number is very small, the stagnation point velocity gradient increases, resulting in enhanced heat transfer.

Enhanced surfaces have proven successful in inducing higher heat transfer rates and lower temperature overshoots in pool and jet impingement boiling. Enhanced surfaces have been investigated at length by Bergles (e.g., [8, 33, 34]) and several other researchers, and surveys have been published in the literature (e.g., [35, 36]). In the context of electronics cooling, Nakayama et al. [37, 38] investigated the effect of nucleation sites and designed enhanced surfaces that achieved critical heat fluxes above 100 W/cm^2 with fluorinated dielectric liquids. Pool-boiling research with FC-72, using specially designed surface cavities on silicon substrates, achieved heat flux removal rates of about 10 W/cm^2 with a superheat of 10 C [39] and up to 55 W/cm^2 with a superheat of 42 C [40].

Work has also been reported on surface enhancement of chips to improve heat transfer on jet impingement cooling. Sullivan et al. [41] used smooth and roughened spreader plates to increase heat transfer from the chip surface on which a single jet impinged without any phase change. Smooth spreader plates reduced thermal resistance by 50% and roughened spreader plates reduced thermal resistance by 80%. Saw-cut and dimpled surfaces were used as roughened spreader plates. The authors emphasize the need to select roughness dimensions carefully in order to gain any advantage over smooth surfaces. Teuscher et al. [42] have reported similar work with surface enhancement.

The effect of smooth surfaces and micro-structured surfaces on boiling of FC-72 jets was investigated by Wadsworth and Mudawar [43]. Surfaces with micro-grooves and surfaces with micro-studs were used. Their results indicate that enhanced surfaces augment heat transfer coefficients as well as CHF. The surface with micro-grooves gave the best performance, yielding CHF values in excess of 160 W/cm^2 with a jet velocity of 2 m/s .

Boiling spray cooling of chips has been investigated experimentally by Yao et al. [44], using FC-72 as the coolant. They found that heat transfer from the chip surface is more uniform with sprays than with impinging jets. They also studied the influence of liquid subcooling and mass flux. Their experiments showed that there was no boiling incipience temperature overshoot associated with spray cooling. Amon et al. [45] determined the optimal configuration of micro-structured silicon surfaces

etched with DRIE into islands and studs. They found that the studs enabled the spreading of liquid by surface tension whereas the islands created thin films for effective evaporation.

3. MEMS Fabrication

Micro-manufacturing fabrication and the development of related processes are leveraged by the large investment in Very-Large-Scale Integrated (VLSI) circuit manufacturing. Advantages of this approach include much lower manufacturing costs and greater integration and miniaturization. In addition, it enables the integration of sensors and actuators with better performance than what can be achieved by conventional manufacturing approaches. The research performed in the Carnegie Mellon University MEMS laboratory on fabrication and design of integrated MEMS is driven by the long-term objective of low-cost customized integrated microsystems for manufacturing, sensing and actuation applications.

Different integrated-MEMS process technologies have been proposed and demonstrated. The proper choice for a particular application is based on cost, manufacturability and design flexibility. Over the past six years, a unique process has been developed at Carnegie Mellon that integrates MEMS with conventional CMOS (Complementary Metal-Oxide-Semiconductor) electronics, and which addresses the needs of diverse, robust and low-volume integrated MEMS production [47]. CMOS is the most common integrated circuit technology, which is used for the manufacture of almost all of the digital electronics in computers and consumer appliances. The availability of foundry CMOS ensures both access and affordability since the electronics market place dictates reliable and low-cost production resulting in high-yield manufacturing.

Within the EDIFICE project, described next, we are investigating Deep Reactive Ion Etching (DRIE) silicon structures for micro-fluidic systems, where micro-valves and micro-nozzles are manufactured on a common silicon wafer. This can be combined with single-crystal-silicon (SCS) micro-structures building upon the CMOS CMU-MEMS process. The sequence employs a post-CMOS deep silicon backside etching, which enables fabrication of high aspect ratio and flat MEMS devices with integrated circuitry. This new CMOS-DRIE MEMS process incorporates the benefits of CMOS composite structures with the superior mechanical properties of SCS.

4. Overall Design of EDIFICE: Embedded Droplet Impingement for Integrated Cooling of Electronics

The objective of this presentation is to describe ongoing work at Carnegie Mellon University to develop a droplet impingement-cooling device, EDIFICE (Embedded Droplet Impingement For Integrated Cooling of Electronics), for removing heat fluxes over 100 W/cm^2 for both portable and desktop electronics [48, 49, 62]. The goal is to integrate the chip cooling solutions with the chip level packaging using MEMS technology, which offers the possibility of miniaturization and inexpensive batch fabrication. The EDIFICE project utilizes latent heat of vaporization of dielectric coolants to obtain high chip heat transfer rates. Cooling is through impingement of micron-sized droplets (50-100 μm) generated through multiple nozzles manufactured with DRIE. The objective is to provide adaptive spatial and temporal cooling. Precise design and control of heat transfer rates would be achieved by using on-chip monitoring of temperature, thermal gradients, and dielectric coolant film thickness. EDIFICE employs MEMS-enabled technologies for manufacturing i) micro-nozzles, swirl nozzles and micro-injectors for jet break-up [50], ii) micro-structured silicon surfaces for the enhancement of thin film evaporation [48], and iii) electrostatic micro-valves for on-demand control of dielectric coolant flow rates [51].

A schematic of the EDIFICE design is shown in Figure 1 along with the overall system. The droplet impingement mechanism, shown in Figure 1, avoids temperature overshoot at boiling incipience and almost eliminates swings in chip temperature and thermal cycling. The system level arrangement transports the removed heat to the periphery of the system, from where it is either dissipated by a condenser/heat sink or stored in a detachable heat storage unit [52]. In this way, the volume near the chip is made available for electronics. In the case of the detachable energy storage unit, it contains an organic phase change material (e.g., eicosene) with a melting temperature of about 50 C along with thermal conductivity enhancers such as aluminum foams [53] or fins [54]. We first developed and implemented this energy storage device for embedded wearable computer applications [55]. For the case of the heat sink/condenser arrangement, the vapor generated at the component level is transported through the system to the combined heat sink and condenser thereby minimizing thermal resistance offered by multi-material interfaces.

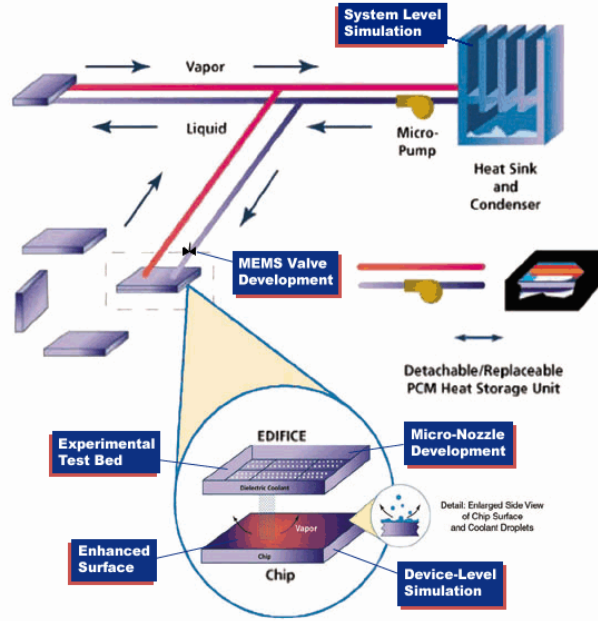


Figure 1: Schematic of EDIFICE and Overall System

The work presented next in this paper describes the development of different components of the EDIFICE project. It reports the experimental test bed and the flow visualization to investigate the role of several parameters in jet/droplet impingement cooling. Numerical results include velocity vector fields and temperature contours in the vicinity of the chip and local heat transfer coefficients at the chip surface. Experimental results include flow visualization of jet break-up, induced by irregular-shaped micro-nozzles and flow swirling, as well as micro-structured silicon impingement surfaces fabricated for enhancing fluid spreading and evaporation.

5. Experimental Test Bed

The test bed for the EDIFICE physical experimentation is depicted in Figure 2 along with a magnification of the vapor chamber. The electronic chip region contains nine, independently controlled, heating zones, which are instrumented for local temperature and heat flux measurement. Nozzles micro-fabricated in silicon are placed on a nozzle holder connected to the liquid reservoir which is air-pressurized. Individual components, such as micro-nozzles, enhanced surfaces, micro-valves and heat sink/condenser, are tested in this system as well as a closed loop for HFE dielectric fluid.

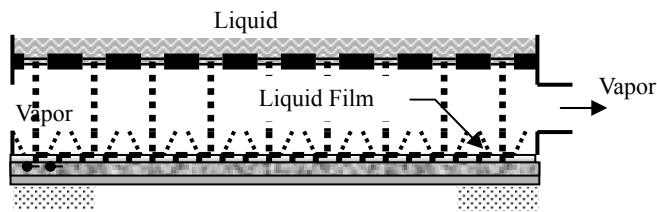
The jets injected from each nozzle are observed using a CCD imaging system. Images are taken and processed for liquid break-up length analysis. The spray impinges on the backside of a silicon-textured chip surface which is thermally controlled based on the readings from heat flux and temperature sensors.

5.1 Development and Characterization of Micro-Nozzles

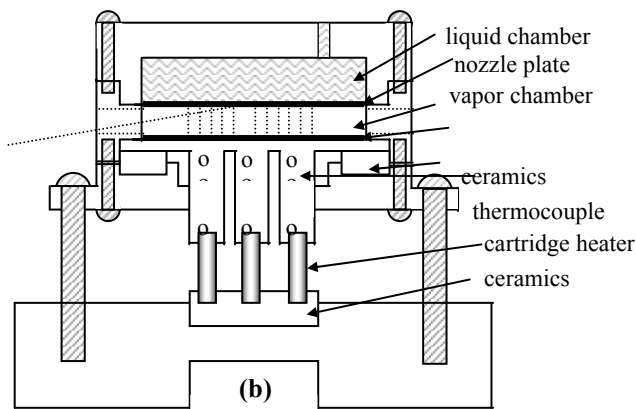
The focus of micro-nozzle development is to gain an understanding of the breakup of jets emerging from irregularly shaped orifices at pressures of less than 15 psig. The micro nozzle orifice geometries are designed to activate three primary destabilization mechanisms (i) surface tension-related breakup, (ii) breakup due to generation of turbulent disturbances, or (iii) swirl-induced breakup. A detailed description can be found in Wu and Yao (2001), and Yao, Amon et al. (2001).

The orifice shapes investigated in the project are designed to excite these destabilization mechanisms, and are shown in Figure 3. The circular jet is considered the reference. The square, triangle, medal, cross and star may be considered axisymmetric distortions of the circle. The rectangle, dumbbell, V, I and H may be considered asymmetrical distortions. Sharp edges and cantilever intrusions are designed to promote disturbances.

Long rectangular openings are more likely to produce a square fan spray. The two balls for the dumbbell are likely to pull the liquid sheet apart by surface tension. Axisymmetric geometries are expected to show more cylindrical-jet-like behavior during disintegration and asymmetrical geometries would tend to exhibit sheet-like behaviors. Swirl is also used as a breakup mechanism, as shown in Figure 3. Here the swirler is created by combining an inlet chip (Fig. 3(b)) with a swirl chip (Fig. 3(c)) to create tangential slots through which the fluid can flow. Performance comparisons between differently shaped nozzles are done either on an area-equivalent basis or on the basis of equal hydraulic diameter. All the nozzles of 100 μ m area-equivalent diameter have the same opening area as a circle of 100 μ m diameter. In this study, only two nozzle sizes are tested: the 100 μ m area-equivalent diameter and the 150 μ m hydraulic diameter.



(a)



(b)

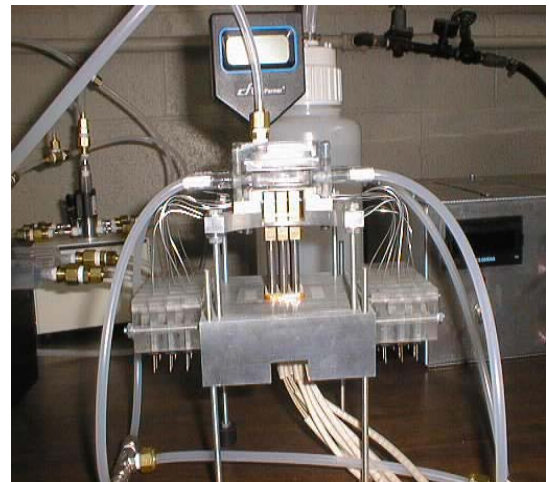


Figure 2: Schematics of (a) vapor chamber, (b) test bed, and (c) picture of EDIFICE test bed

The nozzle is made of silicon and is micromachined using deep reactive ion etching (DRIE). DRIE allows anisotropic etches and can create deep cavities with nearly vertical walls. DRIE is preferable to conventional machining methods such as electric discharge machining (EDM) and laser cutting because it allows greater precision and geometric complexity. The silicon chips used here have a thickness of 500 μm , and are processed in a single-turn helical ICP etching system developed by Surface Technology Systems Ltd. (STS). At 500 μm thickness, this system allows the smallest dimension machinable to be 16.6 μm . All nozzles micro-fabricated in this project have minimum dimensions greater than this limit.

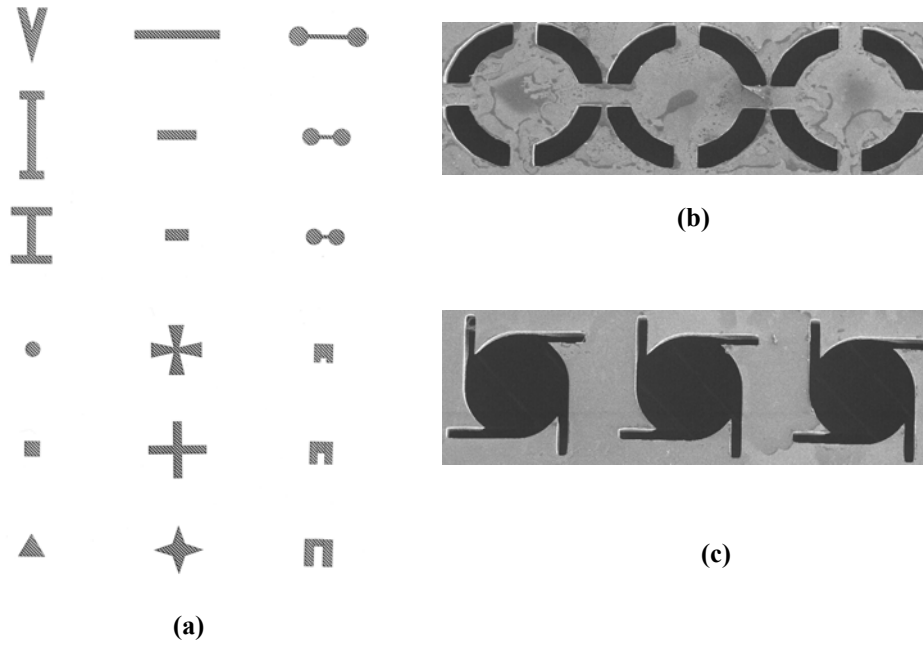


Figure 3: (a) Nozzle orifice shapes, (b) inlet chip, and (c) swirl chip

The working fluid for most tests is HFE-7200, one of 3M special dielectric fluids. Compared with water, the lower viscosity and surface tension of HFE are expected to result in better atomization performance. The smaller latent heat of HFE compared to water requires a higher flow rate to remove the same amount of heat. While this is a disadvantage, the higher HFE flow rates allow the use of turbulence to break up jets. Indeed, the corresponding flow rate for water would be so small as to cause difficulties for nozzle design and pump selection. HFE is more environmentally friendly than FC-72 in terms of zero ozone depletion potential, low global warming potential and short atmospheric life time (0.8 years). Some testing and characterization with water have also been done. Details are available in Wu and Yao (2001).

Effect of Nozzle Shape

Figure 4 shows the breakup length L/d for axisymmetric and sheet-like orifices for HFE. The Rayleigh breakup region (laminar region), the first wind-induced breakup region (transition region) and the second wind-induced breakup region (turbulent region) are identifiable in the experimental data. The laminar portions of all the curves overlap, with the exception of the cantilever-long nozzle. The laminar zone is extended and the transition to turbulence is delayed when the orifice geometry changes from circle to square, triangle, medal and cross. This is because the surface tension

suppresses the laminar disturbances introduced by the irregular shape of nozzles. This suppression by surface tension causes the delay of Rayleigh jet breakup and delays transition to turbulence. After shape-induced disturbances are damped, the irregularly-shaped liquid jet returns to a circular cross-section due to surface tension, and the process of Rayleigh jet breakup commences. The curve for the star-shaped orifice is very close to that for the circular jet. The curve for the cantilever-long nozzle deviates from the standard stability curve.

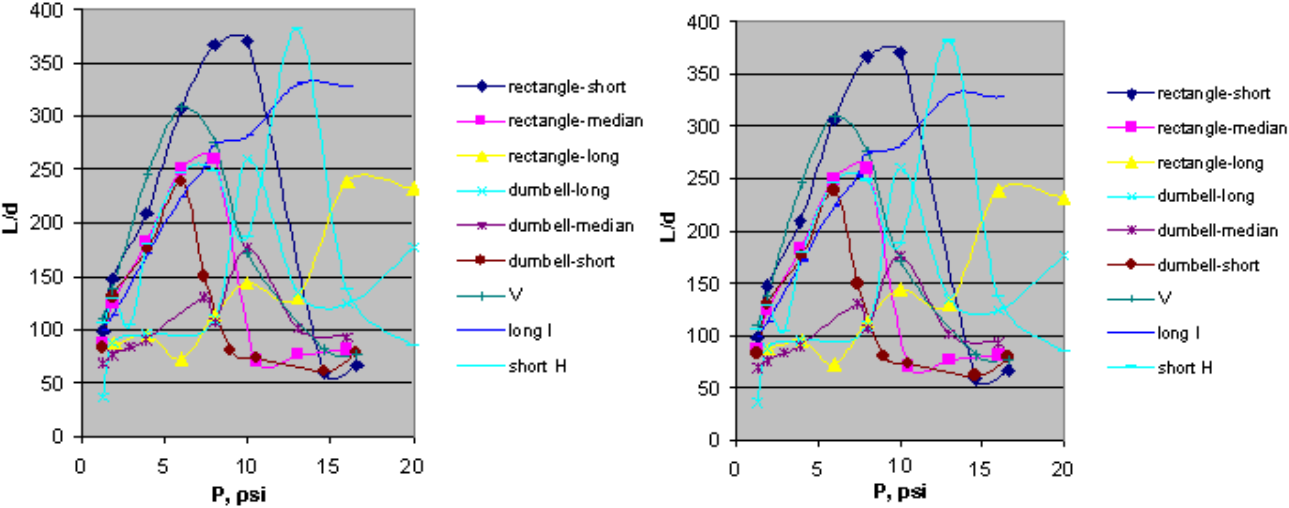


Figure 4: Breakup length L/d of area-equivalent diameter $100\mu\text{m}$ nozzles (a) axisymmetric geometries and (b) sheet-like geometries

Sheet-like geometries generally induce stronger disturbances and the transition point occurs at injection pressures beyond 5 psig. Except rectangle-long, dumbbell-median and dumbbell-long nozzles, the stability curves of sheet-like geometries resemble that for the circular jet since they eventually are returned to circular cross sections. Their laminar portions are parallel and have similar slopes. However, liquid sheets issued from rectangle-long dumbbell=median and dumbbell-long nozzles maintain their shapes and their curves of jet breakup length rise at a much slower slope than that of axisymmetric geometries when the injection pressure increases. This is due to their relatively larger ratios of geometric feature size to the area equivalent diameter. A large ratio indicates larger disturbances to be suppressed by surface tension; their shapes more effectively resist surface tension.

Effect of Nozzle Size

Nozzles with 150 μm hydraulic diameter were fabricated for the same shapes discussed previously. A nozzle with 150 μm hydraulic diameter gives an area-equivalent diameter which is of 150 up to 1700 μm . Figure 5 shows the jet break up behavior of various nozzles at 13.1 psig for HFE. The shape-induced disturbances are surprisingly significant for these large nozzles. Surface tension does not damp the surface disturbances very much. The jets preserve the shape of the initial disturbance. For example, the central ‘beam’ of the dumbbell nozzle, the rectangles and each ‘leg’ of star, cross and medal all develop liquid sheets rather like fan sprays.

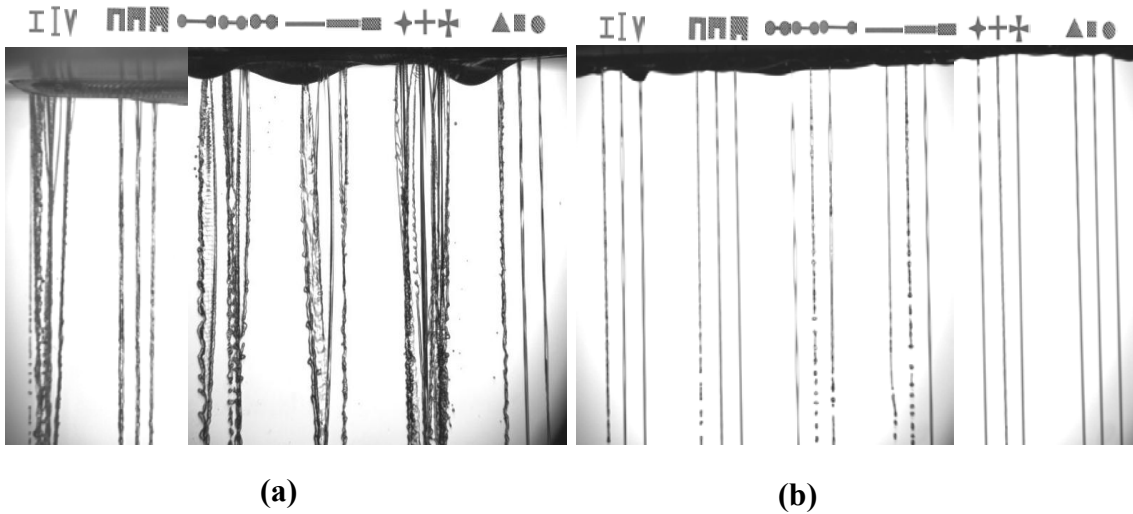


Figure 5: Effect of nozzle sizes (a) same hydraulic diameter 150 μm , 13.1 psig injection pressure and (b) same hydraulic diameter 100 μm , 16.0 psig injection pressure

On the other hand, the jets from nozzles of 100 micron area-equivalent diameter are shown in Figure 5. For these smaller jets, the odd shaped nozzles create jets of various shapes. However, these jets did not disperse further quickly. Instead, many of them restored back to almost circular jets afterwards due to the strong effects of surface tension. As expected, the effect of surface tension goes inversely with the jet diameter. For HFE at 100 micron jet diameter, the surface tension suppresses the surface disturbance of the odd shapes in many cases.

Effect of Swirling

With swirl chips, jet breakup lengths are greatly reduced for all the nozzles geometries, as shown in Figure 6. For HFE, hollow cone sprays are seen to develop. Swirl is more favorable for axisymmetric geometries of nozzles. Swirl-induced instabilities cause the formation of droplets with

sizes much smaller than the jet diameter. Due to the radial component of the movement, jets disperse significantly and result in a wider distribution of liquids over the target.

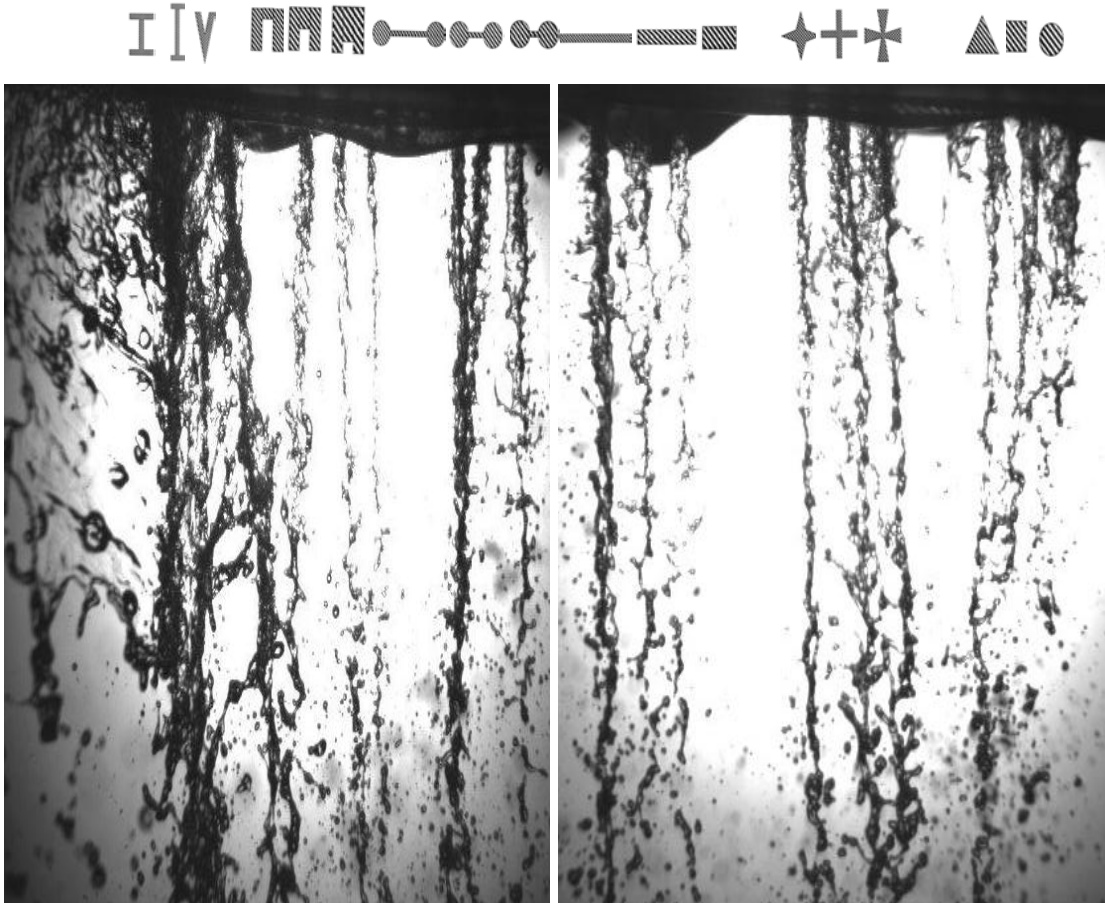


Figure 6: Effect of swirling for same hydraulic diameter 150µm

Effect of Vapor Flow

All jet breakup results shown previously were tested in open space. When multiple nozzles are applied in a confined chamber for the purpose of cooling a target surface, a significant amount of vapor is generated on the heated surface due to the evaporation of the impinging liquid. A typical situation taken from the glass window of the test chamber is shown in Figure 7. Multiple arrays of circular jets coming from the ceiling of the chamber a strong rising vapor layer at the bottom. The droplets of the disintegrated jets encounter the opposing vapor flow and decelerate. Some of the droplets even form clusters. These droplets eventually arrive at the surface but droplet dynamics are affected by the vapor flow at the surface.

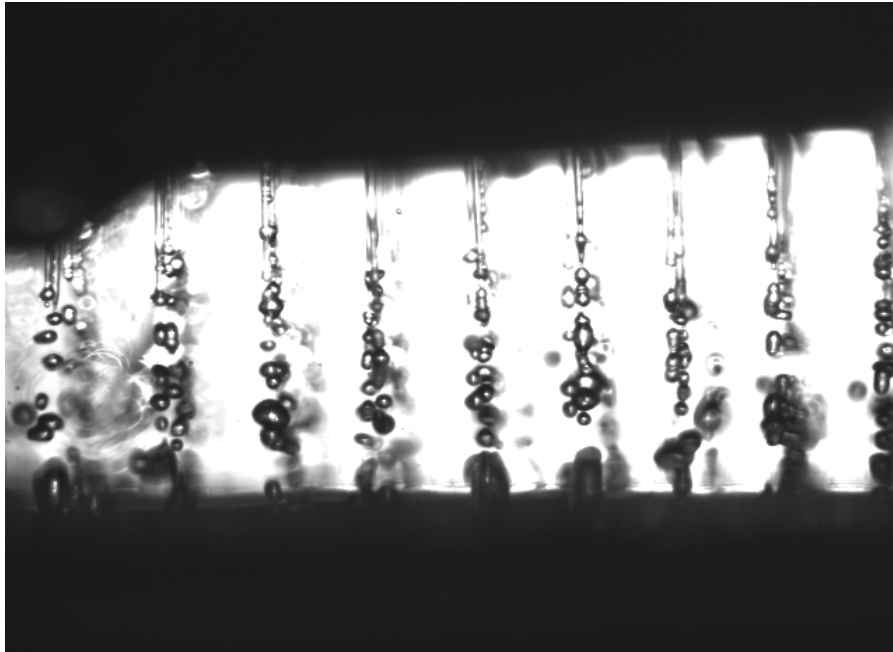


Figure 7: Effect of vapor flow on multiple jets and droplets in the vapor chamber

5.2 Silicon Micro-Surface Texturing

The back side of the chip is textured using Deep Reactive Ion Etching (DRIE). This is done (i) to increase spreading in order to decrease the film thickness, and (ii) to provide nucleation sites to promote boiling. Figure 8 shows the different surface textures that have been investigated. Figure 8(a) shows the standard geometric arrangement of studs, including stud width, height and spacing in μm . Arrangement (b) (referred to as 50% spacing) is derived from arrangement (a) by decreasing the stud width to a third. Arrangement (c) (referred to as partial stud) is derived from (a) by removing a stud to create a nucleation site.

The results of spreading and dryout tests done to determine the efficacy of these texturing arrangements are shown in Figure 9. A single drop of HFE impinges on the cold textured surface, and spreading and dryout times are measured. The surface with 50% spacing (Fig. 8(b)) is seen to perform the best, indicating that surface tension is active in creating a thin film suitable for quick evaporation.

Figure 10 shows the measured surface heat flux versus imposed surface superheat for the textures in Figs. 8(a) and (b). In this test, a stream of HFE impinges on the surface which has imposed on it a

fixed surface superheat. We see that in the absence of boiling the surface with 50% spacing exhibits a substantially higher heat flux, indicating a far thinner film, and more effective spreading. However, once boiling commences, both surfaces are equally effective, and more effective spreading does not offer any particular advantage. Tests with other surface textures designed to promote nucleation are currently underway.

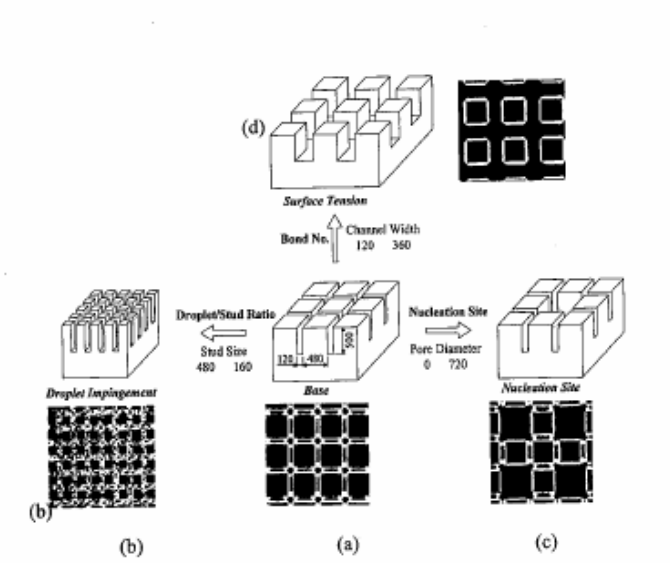


Figure 8: Surface texturing arrangements

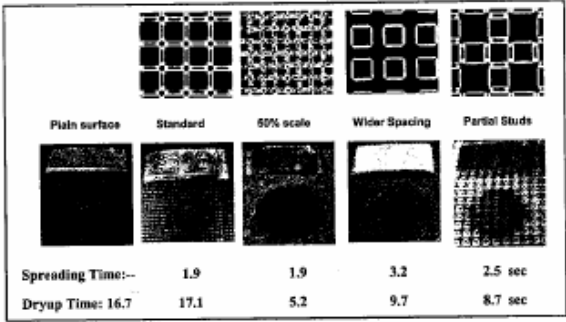


Figure 9: Spreading and dryout time for cold surface with different surface texturing.

Concluding Remarks

Microprocessor power density has been steadily increasing over the past decade due to increases in microprocessor power dissipation and reduction in feature size of the processing (CPU) core, where most of the power on a die is generated. This trend is expected to continue into the future, leading to next generation electronics with a power dense core covering a fraction of the total die surface area bounded by regions of reduced power density cache, with localized power densities exceeding 100 W/cm^2 . Conventional cooling technologies in the electronic industry have limitations on removing these non-uniform, high heat fluxes from the surface of microprocessors. The combination of high heat fluxes with the non-uniformity of heat dissipation requires technologies able to remove large amounts of heat in a spatially and temporally variable manner. This paper has presented a comprehensive overview of state-of-the-art heat removal technologies that can meet the challenging cooling requirements of next generation electronics, including direct liquid cooling, liquid-vapor phase change, non-refrigeration phase change techniques, pool boiling, jet impingement cooling and evaporative spray cooling.

Experimental and numerical work reported on evaporative spray cooling has generally involved uniform and constant spray patterns on heated surfaces. For electronics cooling applications, with non-uniform heat fluxes concentrated in the CPU core, several challenges need to be addressed when considering evaporative spray cooling, such as avoiding fluid accumulation in areas of low power dissipation. This may cause pool boiling and result in thermal performance degradation which can lead to critical heat flux limitations.

This paper has also described the development of EDIFICE, an integrated evaporative spray cooling device micro-fabricated in silicon for package-level cooling of high-heat flux electronics. It combines efficient phase-change heat transfer utilizing latent heat of vaporization of dielectric coolants and on-chip control to provide localized, adaptive, on-demand cooling. To satisfy temporal and spatial heat removal requirements, it contains built-in software to provide on-demand cooling achieved through the control of droplet sizes, impingement frequencies and impingement locations based on the on-chip sensing of temperature, thermal gradients and dielectric film thickness. Basic experiments to develop and characterize micro-nozzles are reported, as well as experiments with chip surface texturing to improve spreading and boiling behavior. Current work on the project involves the fabrication of an actual miniature EDIFICE device and its testing and characterization in real electronics.

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