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Electrospray cooling for microelectronics

Weiwei Deng [a], Alessandro Gomez [b,*]

[a] Department of Mechanical, Material and Aerospace Engineering, University of Central Florida, 4000 Central Florida Blvd, Orlando, FL 32816, USA
[b] Department of Mechanical Engineering and Material Science, Yale University, 9 Hillhouse Ave., New Haven, CT 06520, USA

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ABSTRACT

The challenge of effectively removing high heat flux from microelectronic chips may hinder future advancements in the semiconductor industry. Spray cooling is a promising solution to dissipate high heat flux, but traditional sprays suffer from low cooling efficiency partly because of droplet rebound. Here we show that electrosprays provide highly efficient cooling by completely avoiding the droplet rebound, when the electrically charged droplets are pinned on the heated conducting surface by the electric image force. We demonstrate a cooling system consisting of microfabricated multiplexed electrosprays in the cone-jet mode generating electrically charged microdroplets that remove a heat flux of 96 W/cm^2 with a cooling efficiency reaching 97%. Scale-up considerations suggest that the electrospray approach is well suited for practical applications by increasing the level of multiplexing and by preserving the system compactness using microfabrication.

1. Introduction

Advancements of integrated circuits (IC) have recently been hampered by the severe challenge of the removal of high heat flux. Effective chip cooling may become the bottleneck of further progress in the microelectronic industry. Compared to conventional fan cooling that often relies on a thermal spreader, cooling by direct liquid impingement on the chip back side is promising for high heat flux removal, because it eliminates contact thermal resistance, promotes high velocity gradients that favor heat dissipation, and exploits the liquid latent heat when phase change occurs [1]. The coolant can take the form of impinging jets [1–3] or sprays [4,5]. Microjet arrays generated by silicon microfabricated nozzles with open [2] or closed drainage [3,4] are examples of jet cooling. Spray cooling, currently used in some supercomputers such as the CRAY X1, in principle is more effective than jet impingement cooling [6], mainly because the liquid film formed by sprays is typically much thinner (by a factor of 10) than that of liquid jets [7].

The physical process of spray cooling results from the impact of droplets on a heated surface, which, in turn, may lead to splash, spread, or rebound [8]. Especially when the surface temperature is higher than the Leidenfrost point of the liquid, the droplet tends to rebound because the pressure of the vapor below the liquid partially lifts the droplet [9]. As a result, in conventional sprays only a fraction of the liquid cooling capacity is exploited because of this rebound loss.

A possible approach to reduce or even entirely eliminate this loss is to electrically charge the droplets with respect to the hot conducting surface and rely on Coulombic attraction, if charge leakage on contact is sufficiently slow [10]. In this context, the electrospray (ES) is potentially well-suited for cooling purposes because of its unique properties. Although there are numerous functioning modes of this device [11,12], the most appealing one from the point of view of achieving fine liquid dispersion with ensuing enhanced evaporation in a relatively short time is the so-called cone-jet mode [13]. In that mode an electrohydrodynamic process is established in which a spray of monodisperse droplets is formed by passing a liquid with sufficient electrical conductivity through a capillary charged to a high potential with respect to a ground electrode a short distance away. Under the effect of a high electric field, the liquid meniscus takes the shape of a cone from the tip of which a thin liquid thread emerges, leading to the cone-jet mode [13]. This microjet breaks into a stream of charged droplets that eventually spread to form a spray. Among the key features distinguishing the electrospray from other atomization techniques are: the quasi-monodispersity of the droplets; the Coulombic repulsion of the charged droplets, which induces spray self-dispersion, prevents droplet coalescence and enhances mixing; and the capability of producing droplets of uniform size even at the nanoscale. In addition, the number density is reasonably uniform throughout the spray. The inner diameter of the ES nozzle is typically 10–100× larger than the droplet, which reduces the risk of clogging and dramatically decreases the liquid pressure drop, from $\sim 10^5$ Pa of a conventional atomizer [14] to $\sim 10^3$ Pa of ES systems.

ES has been widely used in ionization mass spectroscopy [15]. In virtually all other applications, it has been plagued by one

* Corresponding author. Tel.: +1 203 432 4384; fax: +1 203 432 7654.
E-mail address: Alessandro.Gomez@yale.edu (A. Gomez).

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critical drawback: the low flow rate of a single ES source, which would make it inadequate even for spray cooling. This drawback has been recently overcome by microfabricated multiplexed ES (MES) systems [16,17], which allow for the dispersion of large total flow rates through multiple, densely packed ES sources operating in parallel. Applications of MES in combustion [18], material synthesis [19] and electric propulsion [20] have recently been reported. In the context of spray cooling, the "digital" version [21] of the MES devices, in which each individual spray can be turned on/off selectively via electronic control, has also the potential for local thermal management of hot spots on microelectronic chips.

ES cooling has been attempted in [22] but the authors operated a single ES in a broad range of flow rates and voltage with relatively coarse dispersion of the liquid, that is outside the desirable cone-jet mode. In fact, optimal behavior is reported in the "ramified" regime, that, on physical ground should be far less promising than the fine atomization of the cone-jet mode. A 4× modest level of multiplexing by conventional fabrication was reported in the non-peer reviewed literature with a promising cooling enhancement [23], but few details are available in the abstract to assess those claims. Here we report on an application to microelectronic chip cooling of a compact, microfabricated MES device operating in the cone-jet mode. We will demonstrate a miniaturized MES cooling device that removes a heat flux of 96 W/cm^2, with the potential of additional scale up, and with an unprecedented cooling efficiency reaching up to 97%.

2. Experimental setup

MES fabrication and testing details are documented elsewhere [16,17]. Here we summarize briefly its main features. The device has a 3-layer structure (Fig. 1a): a liquid distributor layer microfabricated in silicon with multiple nozzles (Fig. 1b) as ES sources held at high voltage V_1, an extractor electrode layer held at an intermediate voltage V_2, and a glass insulator/spacer layer sandwiched between the distributor and the extractor. The value $(V_1 - V_2)$ is fixed at 1.5 kV, while V_2 is varied from 1 to 3 kV. Fig. 1c and d provides a glimpse of the progress made in multiplexing and compacting these devices, with the visualization of sprays generated by two MES devices: a 91-nozzle chip with packing density of 253 sources/cm^2, and a 19-nozzle chip with a packing density of 11,000 sources/cm^2. In the present work, we use 19 or 37 nozzles with a packing density of 253 sources/cm^2 and with a footprint of 7.6 mm^2 and 14.8 mm^2, respectively. The sprays diverge with a semi-angle of $\sim 10°$ and can cover the entire 16 mm^2 of the thermal test element.

A liquid coolant such as ethanol with a boiling point of 78.3 °C is supplied at flow rates ranging between 25 cc/h and 100 cc/h through the entire MES device to deliver charged droplets with typical mean diameter (d_{10}) of 25 μm and a relative standard deviation (RSD) of 10%, as measured by Phase Doppler Anemometry (PDA). All diameter values used in this work refer to d_{10}. The accuracy of the PDA is also confirmed by the video frames recorded using a high speed camera, as will be explained shortly. The flow rate is set by a syringe pump with an uncertainty ±1%. The droplet size is fine-tuned by adjusting K, the electrical conductivity of the liquid, for example by doping the liquid with PPM level of 1-ethyl-3-methylimidazolium ethylsulfate, an ionic liquid (IL). To measure K, we first measured the resistance R_L of a liquid column confined in a Teflon tubing with known cross section area A_L and length L, and then used the equation $K = L/R_L A_L$. Additional physical properties of ethanol are listed in Table 1.

Fig. 2 depicts the setup for the heat transfer experiments, with the components in Fig. 1a and b, clearly identified. We use four Resistance Temperature Detector (RTD) elements (Omega, Model F2020, Class B) as both temperature sensor and heater to mimic the Joule heating of a microelectronic chip. Each RTD measures $2 \times 2 \times 0.38$ mm^3, has a thin, narrow, and meandering platinum resistance path sandwiched between the glass coating and the 380 μm-thick Alumina ceramic base with a high thermal conduc-

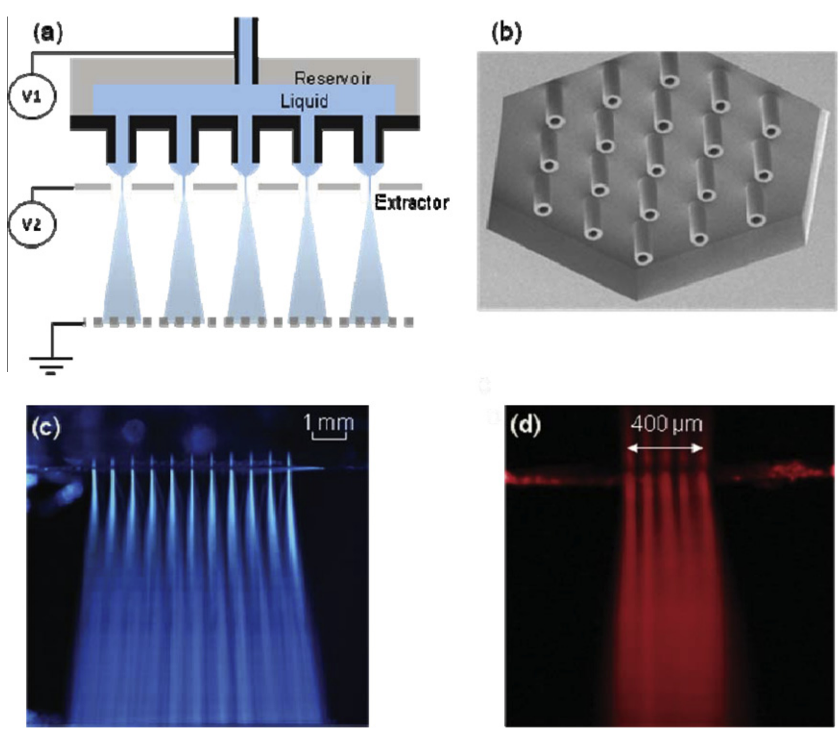

Fig. 1. MES device. (a) A device schematic showing the key components including liquid reservoir, silicon nozzle chip, and the extractor. (b) Scanning electron micrographs (SEM) of a 19-nozzle array. (c) Spray visualization of a 91-nozzle MES system with packing density of 253 sources/cm^2. (d) Spray visualization of a 19-nozzle system with packing density of 11,000 sources/cm^2.