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Research paper

Hot-spot cooling using microliter liquid drops

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HIGHLIGHTS

- The electrowetting phenomenon can change the apex and contact radius of a drop.
- Attaching a mercury drop to the surface of a hot-spot can decrease its temperature.
- Increasing the drop contact angle by 31° leads to 82% heat transfer enhancement.
- A TCRI can suppress hot-spots on a surface with non-uniform heat flux.

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ABSTRACT

In this paper, a new concept is developed for cooling integrated circuits (IC) in the electronic and computer industries. Microliter liquid drops are employed in combination with the electrowetting phenomenon to form a thermal conductance regulating interface (TCRI) between the heat-sink and the cooling target. An experimental setup was arranged in which a mercury drop could be attached to/detached from the surface of a hot-spot and, hence, influence its temperature. In addition, an in-house numerical code was developed to further investigate various parameters of the cooling system. The Navier–Stokes and energy equations were solved in a 2D/axisymmetric domain and the volume-of-fluid (VOF) technique was used to track the deformation of the free surface of the drops under the effect of the electrowetting phenomenon. Finally, as a sample case, a 4 × 4 array of mercury drops was considered to form a TCRI between a cooling target with non-uniform heat flux and a heat-sink. It was shown that the TCRI can be used to effectively suppress hot-spots on the surface of the cooling target. Various parameters of the cooling system were also examined.

1. Introduction

In recent years, thermal management has become an important issue in designing and manufacturing high-performance electronic devices including microprocessors. The Moore's law generally predicts that the number of transistors on integrated circuits (IC) nearly doubles every two years [1]. Moreover, based on the International Technology Roadmap for Semiconductors (ITRS), it is expected that the number of transistors in high-performance computers increases from 1 to 150 billion until 2026 with the transistor size decreasing constantly from 40 nm to 6 nm [2]. Since the chip size in these computers remains constant at about 260 mm^2, these changes will lead to a higher concentration of transistor in microprocessors. As a result of this concentration, the heat generated by a set of transistors will be dissipated from a much smaller surface area. This fact poses new cooling challenges with more emphasis on the design of new cooling systems to cope with the ever-increasing requirements of the computer and electronic industries in the future.

Up until now, several cooling technologies have been proposed and examined. Heat pipes, thermosyphons, MEMS-based systems [3,4], thermoelectric and vapor-compression refrigeration systems are among these technologies. However, the most widespread cooling system used in the computers is the fan-cooled heat-sink. Despite its simplicity and acceptable performance for existing computers, this system is not suitable for cooling purposes in the small dimensions, considering the decrease in the size of the transistors. Another drawback of this system stems from the fact that the heat-sink has a constant thermal conductance. As a result, if a heat-sink is used for dissipating the heat from a surface with highly non-uniform heat flux, a non-uniform temperature distribution will appear. Non-uniform temperature distributions, mostly

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known as hot-spots, may result in high thermal stresses which eventually lead to the failure of the electronic device.

Considering the multicore CPUs with each core working independently and the above-mentioned developments in the semiconductor technology, the formation of highly non-uniform heat fluxes on the surface of the ICs is inevitable. Therefore, developing new methods of IC cooling to suppress the undesirable hot-spots has been the focus of many studies in the literature. For instance, Farnam [5] used a numerical method to study the application of microchannels in microprocessor cooling. By passing a fluid through a microchannel, he showed that the fluid flow can spread the dissipated heat on the surface of the microprocessor to bring about a more uniform temperature distribution. In a different method, Wang and Bar-Cohen [6] employed the thermoelectric features of the silicone used in the microprocessor itself to dissipate the generated heat.

An alternative to the new cooling technologies mentioned above is the drop-based/digital microfluidic devices where discrete liquid drops are actuated over an array of electrodes using the electrowetting phenomenon. The electrowetting phenomenon was first introduced by Gabriel Lippmann [7]. After that, Berge [8] suggested using a dielectric to prevent from drop electrolysis and derived the Young–Lippmann relation for the first time using an energy minimization approach. Since then, electrowetting-on-dielectric (EWOD) and digital microfluidics have been widely investigated and applied in various fields by other researchers [9–13].

Possessing exceptional benefits, the electrowetting phenomenon has made its way in several novel applications such as lab-on-a-chip devices [14], variable focus lenses [15,16], electronic displays [17], medical diagnostics and biosensors [18]. In addition, the electrowetting phenomenon can be used for IC cooling purposes. This idea was first put into action by Paik [19] using printed circuit boards (PCB). Using an experimental setup, a 6 μL water liquid drop was moved through an array of 9 electrodes to dissipate the heat from a hot-spot with 30 W/cm^2 heat flux. To cool a hot-spot with a heat flux of 7.6 W/cm^2 on a 2D array of electrodes, Cheng and Chen [20] manipulated a 39 μL water drop in a similar manner. It was found that the drop is capable of dissipating 86% of the generated heat by the hot-spot. Oprins et al. [21] used the FLUENT software to simulate the movement of a drop between two parallel plates and its effects on cooling the top plate. Using a simple 2D model, they found that the generated circulations inside the drop improve the heat transfer from the top plate. In other studies performed in this area, the potential capability of using liquid drops in cooling ICs has been examined [22].

In this paper, a new concept of hot-spot cooling is proposed in the form of a thermal conductance regulating interface (TCRI). The structure of the TCRI is such that it can be used to transform a fan-cooled heat-sink into a system with the capability of hot-spot cooling. The proposed TCRI includes a 2D array of liquid drops which can be actuated using the electrowetting phenomenon to change the thermal conductance between the cooling target and the heat-sink. Therefore, a PCB-based experimental setup is designed to study the effects of the electrowetting phenomenon on various geometrical parameters of the drops in combination with Image-processing techniques. In the next step, an experimental setup is arranged in the form of a hot-spot cooling system to investigate the influence of mercury drops on the temperature of a hot-spot. Numerical simulations are also employed to support the proposed hot-spot cooling concept. The Navier–Stokes and energy equations are solved in a 2D/axisymmetric domain and the volume-of-fluid (VOF) technique is used to track the deformations of the drop free surface under the effect of electrowetting phenomenon. In addition, the FLUENT software is used to test the capabilities of a sample TCRI in suppressing hot-spots on the surface of a cooling target with non-uniform heat flux. Detailed descriptions of the experimental and numerical studies are discussed in the paper.

2. Hot-spot cooling technique

The electrowetting is a phenomenon in which the apparent contact angle of a polarizable/conductive liquid drop and, hence, the wetting behavior of the drop on the surface can be changed by employing an electric field. The change of the apparent contact angle in this phenomenon is generally governed by the Young–Lippmann relation:

$$\cos(\theta_V) = \cos(\theta_0) + \frac{\varepsilon_0 \varepsilon_d}{2d\gamma_{lg}} V^2 \qquad (1)$$

where ε_0 is the vacuum permittivity, ε_d the dielectric constant, d the dielectric thickness, and γ_{lg} is the liquid/gas surface tension. Since electrowetting is an electromechanical phenomenon [23], it has no effect on the local contact angle of the drop θ_0 (i.e. the actual contact angle very close to the surface) [24]. Equation (1), however, shows that the apparent contact angle will change to a lower value θ_V. Therefore, the new shape of the drop is the result of the equilibrium between the surface tension forces and the electrical forces generated upon applying the voltage V [25]. This fact can be seen in Fig. 1.

As seen in Fig. 1, when the voltage is applied, the drop further spreads on the surface resulting in a reduction of the height of the drop apex. Possessing this feature, the electrowetting phenomenon is a great candidate for manipulating liquid drops to design a cooling system with variable thermal conductance. Based on this feature in this paper, a new system is designed which manipulates

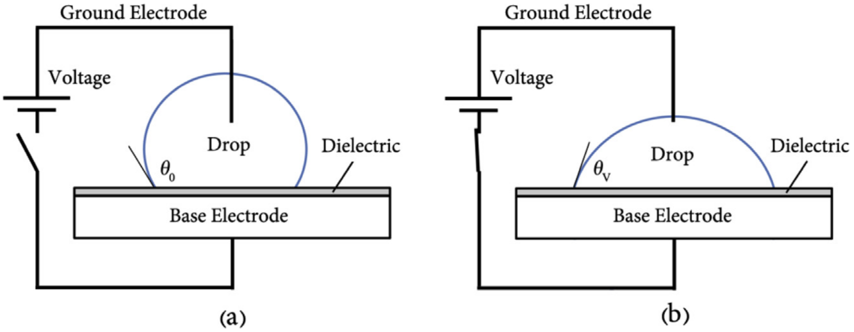

Fig. 1. The schematic of the electrowetting phenomenon. (a) Before applying a voltage, the apparent contact angle of the drop is higher. (b) After applying the voltage, the apparent contact angle decreases and the drop spreads on the surface.