Effective Cooling of Integrated Circuits Using Liquid Alloy Electrowetting

Kamran Mohseni
Department of Aerospace Engineering Sciences
University of Colorado, Boulder, CO 80309-0429
Email: mohseni@colorado.edu

Abstract

Electrical modulation of surface tension is proposed for actuation and pumping of discrete droplets of liquid metals/alloys for active heat management of Integrated Circuits (ICs) and removal of hot spots on any solid surface. The proposed technique is based on two observations: (i) By using liquid metals or alloys at room temperature (instead of e.g. water or air) heat transfer rate of a cooling system can be enhanced significantly, (ii) Electrowetting is an efficient, low power consumption, and low voltage actuation technique for pumping liquids at micro-scales. These two ideas are employed in this investigation in order to design a novel active heat management technique for high-power-density electronic and integrated micro systems. Preliminary calculations indicate that more than two orders of magnitude increase in heat transfer rate could be achieved by using liquid metals as compared with systems using water as the coolant fluid. Liquid velocities above 10 cm/s is observed with extremely low pumping power consumption and at low actuation voltage ($\sim$2 V). The current technique can be used for active heat management of ICs to detect and properly handle an over-heating event. It is expected that digitized electrowetting to offer a viable cooling strategy to achieve the most important objectives of electronic cooling; i.e. minimization of the maximum substrate temperature and reduction of the substrate temperature gradient and removing substrate hot spots[1].

Keywords

Electrowetting, thermal management, liquid metals, liquid alloys, microsystems

I. Introduction

Heat is an unavoidable byproduct of normal operation of an electronic device. Heat could be generated as a result of electrical energy being converted to thermal energy during circuit activities. Furthermore, Reduction in circuit delay and therefore an increase in speed is often achieved by higher circuit packaging density accompanied by increased power dissipation per circuit. As a result of more demand for increased packaging density and performance, required heat flux removal is increasing at a challenging rate. Excess heat can cause device damage and increase signal noise by increasing the movement of free electrons in a semiconductor device. To this end cooling and thermal management of electronic devices must be improved to maintain the device junction temperature below a safe operating temperature in order to satisfy performance and reliability objectives. Failure in doing so can reduce device performance, reliability and life. It is estimated that every 10°C increase in junction temperature can reduce the device life by a factor of 2. Furthermore, concentrated areas of high heat flux, 2-3 times more than the average chip heat flux can emerge during the operation of an electronic device. These areas, often referred to "hot spots", require special techniques for thermal management.

According to the Semiconductor Industry Association (SIA) roadmap in 2001, the required cooling levels for many microsystems are projected to reach 200 W in near future. Traditionally, heat is removed to the surrounding environment through air-cooled heat sinks. The advantages of the air based system environment is the low cost and ease of implementation. However, significant decrease in thermal resistance and orders of magnitude increase in heat removal could be achieved by using water cooling instead of air. Such liquid heat sinks, often referred to as cold plates, operate very similarly to air cooled heat sinks.

Microchannels are one of the most effective techniques for thermal management of high heat fluxes found in microelectronic devices [1]. The potential for direct integration of microchannels inside the heat generating substrate is particularly attractive as thermal contact resistance could be avoided. The concept of liquid cooling through microchannels was explored more than two decades ago by Tuckerman and Pease [2]. They chemically etched a 50μm $\times 300\mu$m microchannel in a 1 cm $\times$ 1cm silicon chip. They could remove 790 watts heat from the silicon chip by pumping water through the microchannels. At such heat removal rate they observed a 71°C temperature difference in water.

For a complete review of the available techniques for thermal management of electronic circuits, we refer the reader to [3]–[5] an the references in there.

In this manuscript we consider the potential of electrowetting on dielectric and continuous electrowetting for low power thermal management of compact microelectromechanical systems (MEMS) and electronic devices. Surface tension is a dominant force for liquid handling and actuation at micro-scales, and electrowetting is used in this investigation for pumping liquid metals over the hot spots on a chip. Application of electric field at a liquid-solid interface or at the interface of two fluids can cause changes in the surface tension at the interface and can be used for electrowetting actuation and droplet movement. Integration of electrowetting microchannels inside the electronic

[1] A provisional patent on this idea has been filed in 2005.

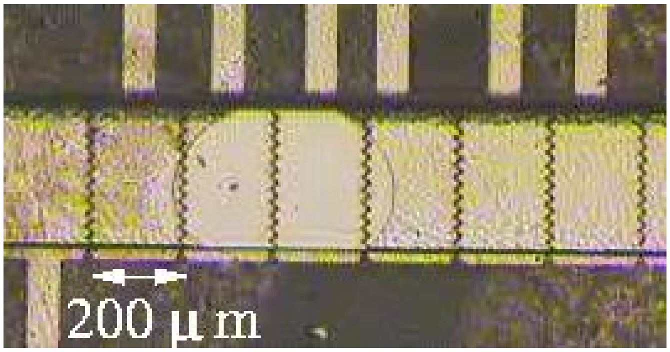

Figure 1. Electrowetting actuation in a microchannel. KCl droplet on a BCB coated microchannel.

devices can significantly enhance the cooling capability of the device by eliminating contact resistance issues.

This manuscript is organized as follows: In the following section the physical concept in electrowetting on dielectric and continuous electrowetting are reviewed. In section III continuous electrowetting of discrete droplets of liquid alloys or metals is proposed for effective heat removal from hot surfaces. Electrowetting of water droplets on dielectric surfaces are also reviewed.

II. Electrowetting

Surface tension is a dominant force for liquid handling and actuation in microscale. Liquid handling and droplet actuation by controlling surface tension has many advantages at microscale. Several mechanisms have been proposed in the literature to control surface tension. These include: using surfactants, thermocapillary [6], electrowetting [7], electrowetting on dielectric [8] (see Fig. 1), continuous electrowetting [9], [10] (see Fig. 2), and light-induced surface tension change [11]. Fast switching response and low power consumption of electric actuation of surface tension has made electrowetting a promising technique in microfluidic devices. In electrowetting, the surface tension between the liquid-solid interface is modified by an external electric field, which reduces the meniscus contact angle and induces motion of a droplet. Droplet velocities of several centimeters per second have been observed [12]–[14]. This study considers the potential of electrowetting on dielectric and continuous electrowetting for low power thermal management of compact microelectromechanical systems (MEMS) and electronic devices. Electrowetting actuation of liquid droplets is a low power consumption technique with minimal liquid heating to achieve high droplet velocities.

a) Electrowetting on Dielectric: Variation of surface tension as voltage changes is governed by the Lippmann equation

$$\frac{d\gamma_{SL}}{dV} = \sigma \tag{1}$$

where γ_{SL} the surface tension energy of the solid-liquid interface, V is the applied voltage, and σ is the charge density. The charge density is related to the stored energy in the capacitor through

$$\sigma = \frac{\epsilon_0\epsilon}{d} A_{SL} V \tag{2}$$

where $\epsilon_0\epsilon$ is the dielectric constant of the isolating layer between the electrode and the droplet, d is the thickness, and A_{SL} is the contact area of solid-liquid interface. Considering the changes in surface energy before and after the application of an electric potential V, one can write

$$\gamma_{SL}(V) = \gamma_{SL\,0} - \frac{1}{2}\frac{\epsilon_0\epsilon}{d}V^2 \tag{3}$$

Using the Young's equation $\gamma_{SG} = \gamma_{SL} + \gamma_{LG} \quad \cos\theta$ we finally obtain the relation between the applied voltage V and any change in the contact angle θ

$$\cos\theta(V) = \cos\theta_0 + \frac{\epsilon_0\epsilon}{\gamma_{LG}2d}V^2 \tag{4}$$

where θ_0 is the contact angle of the liquid in the absence of applied voltage. Sometimes this relation is also called the Lippmann equation.

In order to obtain large contact angle changes for a given applied voltage one needs to increase the capacitance of the capacitor at the the solid-liquid interface (see *e.g.* [15]). This can be achieved by coating the electrodes with a thin dielectric coating with high dielectric constant (see *e.g.* [16], [17]), which is often referred to as electrowetting-on-dielectric (EWOD). It should be noted that one could expect to transport liquid droplets of most materials at low temperature by electrowetting actuation. As a result a potential application is cryogenic cooling where liquid droplets of cryogenic liquids at low temperatures are transported by electrowetting actuation. Some of the common cryogenic liquids are Helium-3, Helium-4, Hydrogen, Neon, Nitrogen, air, Argon, Oxygen, and Methane which are all in liquid forms at temperatures lower than at least 201 °C.

b) Continuous Electrowetting: The average velocity of a mercury droplet in a micro channel was estimated by Jackel *et al.* [18] to be

$$V = -\frac{D}{6\mu L} q\Delta\phi \tag{5}$$

where D is the equivalent diameter of the microchannel, L is the length of the mercury slug, $\Delta\phi = \phi(0) - \phi(L)$ is the voltage difference between the two ends of the mercury slug, and $q \sim 0.05$ C/m^2 is the typical initial charge density in the Electric Double Layer (EDL) for mercury in most aqueous electrolytes. Velocities of order of 10 cm/s is expected for a Mercury droplet with $D/L = 0.2$. Reynold number around 4000 is expected in a microchannel with a channel hight of 500 μm.

III. Liquid Metals/Alloys Electrowetting for Thermal Management

Proposed Cooling Technique: Heat management of a high performing electronic device requires high heat flux to maintain its optimal operation. The surface might have hot spots that could cause system failure. To remedy this situation we propose

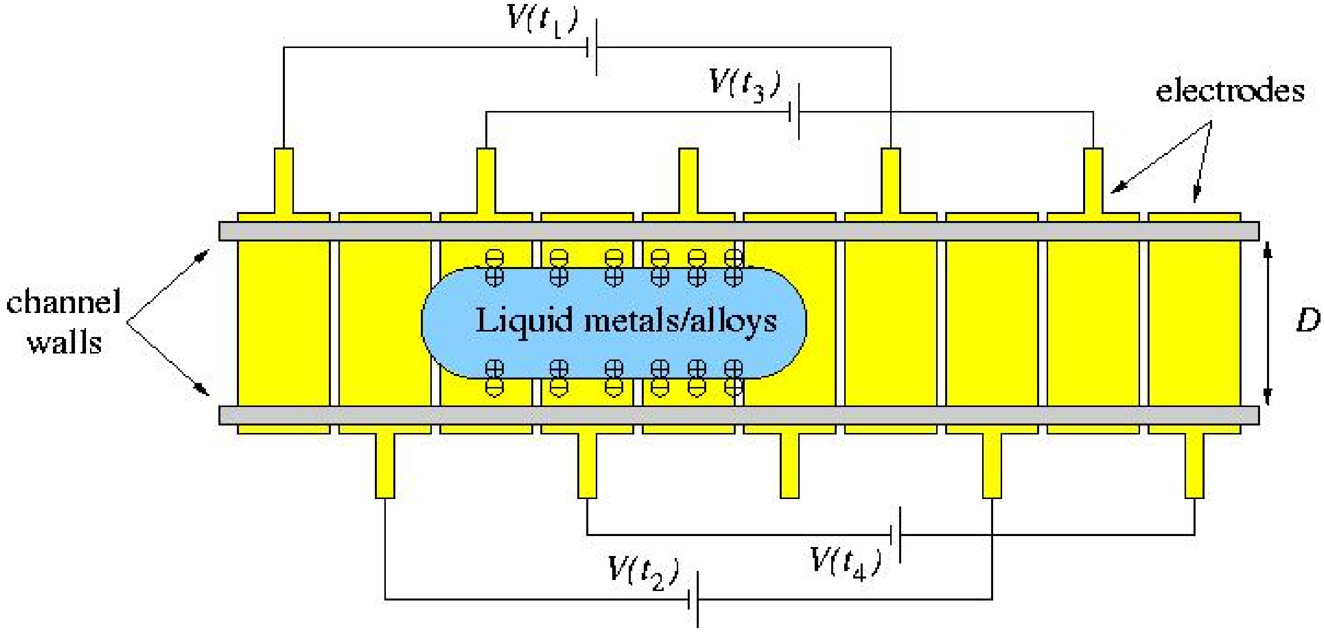

Figure 2. Continuous electrowetting. By sequenced activation of voltages on electrodes at times $t_1, t_2, t_3, \cdots$ one can transport a liquid metal droplet to any location in a microchannel.

to use low melting point alloys that are in liquid form at room temperature. The schematics of our heat management device is shown in figure 3. One approach is to make a small gap between the hot surface and a patterned electrode. The liquid metals/alloys are located in the gap where the sequential activation of the electrodes can create necessary forces for rapid transport of the droplets along the channel. Electrowetting could be used to transport liquid metals/alloys from a pool to hot spots on a chip. The electrowetting pumping process is low power and efficient, and requires low voltages [14]. Alloys liquid at room temperatures are easily available in the market now; e.g., Indium Corporation of America[2]. High vapor pressure and high thermal conductivity have made liquid metals attractive for high intensity cooling applications. The main advantages of using liquid alloy systems over other liquids (such as water or oils; see [19]) are: higher thermal conductivity far superior than ordinary non-metallic liquids which makes them ideal for heat removal, and much higher surface tension (in excess of one order of magnitude) than most non-metallic liquids which make them suitable for electrowetting transport. These characteristics, suggest that liquid alloy electrowetting can achieve heat flux removal capabilities far beyond many other alternative techniques. In particular, in the following section we compare the heat removal capability of water droplets with typical liquid metals and alloys. Furthermore, the system has no moving mechanical parts to leak, wear out, or stick. Therefore, no lubricants are required. By using discrete droplets, in contrast to continuous liquid flow, any need for valves and pumps are eliminated and all the basic fluidic operations can be achieved via digitized electrowetting. The current technique can be used for *active* heat management of ICs and compact microsystems to detect and properly handle an over-heating event. This is in contrast to passive heat dissipation mechanisms, such as heat sinks and fans that requires continuous coolant flow.

Many of the heat transfer advantages of using liquid metals have been known and investigated for decades [20]. A major advantage of using liquid droplets is the ability to transport them by electrowetting. Lee and Kim [10] demonstrated electrowetting transport of mercury droplets in sulfuric acid at 4 cm/s speed using 1-3 V driving voltage. The power consumption was 10-30 μW at an average current of only 10 μA. This suggest that continuous electrowetting can potentially operated at very low power. Other advantages of this technology are the low power consumption and ease of fabrication.

Another advantage of digitized liquid alloy electrowetting is in the the suppression capability for temperature overshoots during the dissipation of transient power spikes. In many applications, thermal transients last for only a short period. Consequently, no continuous operation is needed. In such cases digitized droplets can be mobilized, if needed, to address local thermal management demands. Furthermore, the latent heat of phase change of such alloys can be exploited as a phase change thermal energy storage [1]. Since the temperature of the alloy remains more or less constant during the melting, droplets of such alloys can be used for thermal management of transient power spikes.

It should be noted that Mercury is also an option. Mercury has very high surface tension and could be easily and effectively mobilized by electrowetting. However, Mercury is toxic and it is not recommended for general use in cooling systems. On the other hand, liquid alloys have the same advantages as Mercury, but the metals in these alloys are not toxin and the

[2] See < http://www.indium.com/products/fusiblealloys.php >

vapor pressures of these alloys are substantially lower than Mercury. Physical properties of some liquid metals and alloys are listed in Table 1.

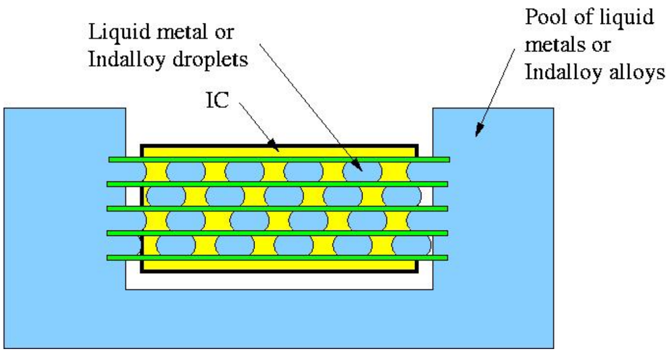

Figure 3. Liquid alloy electrowetting for cooling of electronic devices.

IV. Heat Transfer Analysis

In most cases it is expected that electrowetting flow in microchannels to be in laminar flow regime. This is mainly due to low Reynolds number flow associated with flow in microchannels. Correlations for the average Nusselt number in continuous flow in microchannels in terms of Prandtl and Reynolds numbers have been reported in the literature [1], [21], [22]. In general, significant variations has been observed in these correlations. Many possible explanations for such deviations from classical theory has been suggested. These include relative surface roughness of the microchannels and the entrance effect. While for high Prandtl number fluids extensive theoretical and experimental data are available, low Prandtl number data are scarce. Accurate numerical simulation of low Prandtl number flow with applications to electrowetting cooling of electronic devices is the topic of a future investigation.

In this section, a simplified comparison of laminar heat transfer in micro pipes is offered in order to highlight significant heat transfer enhancement by using liquid alloys or metals as compared with water. In the case of electrowetting of liquid alloys, the flow could reach turbulent flow regimes. Turbulent heat transfer is not reviewed here. However, one could expect a higher heat removal capacity in turbulent regime. Similar analysis for continuous pumping of liquid metals at macro-scale channels was presented in [20], where they used correlations from classical heat transfer theory.

We will consider steady laminar flow in a two dimensional flow between two parallel plates. One of the walls represent the hot surface of an electronic device. We assume that the flow is hydrodynamically developed while the flow can still be developed thermally. We also assume that the range of variations in the coolant temperature is small enough that constant fluid properties can be assumed. Such a flow is the plane version of the thermally developing flow, often known as the Graetz problem [23].

We assume that the flow is fully developed when it enters the region of thermally developing flow at $0 < x < L$, see Figure 4. We consider two cases of constant wall temperature T_w and constant wall flux q_w. The coolant enters the heated region at a uniform temperature of T_{in}.

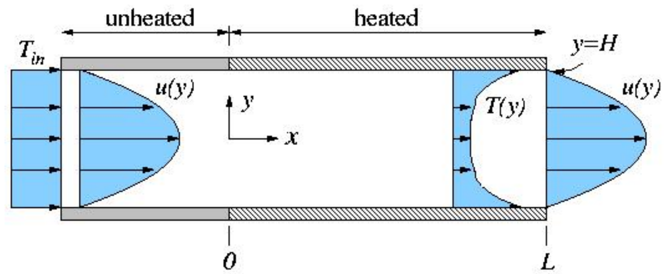

Figure 4. Thermally developing flow between two parallel plates.

The droplet velocity is assumed to follow the well-know parabolic profile

$$\frac{u}{U_{\mathrm{m}}} = \frac{3}{2}\left(1 - \left(\frac{y}{H}\right)^2\right) \quad (6)$$

The energy equation, represented in terms of temperature T, can be written as

$$u\frac{\partial T}{\partial x} = \frac{\nu}{Pr}\Delta T \sim \frac{\nu}{Pr}\frac{\partial^2 T}{\partial y^2} \quad (7)$$

where ν is the kinematic viscosity and Pr is the Prandtl number. In dimensionless form, this equation is reduced to

$$\frac{\partial \theta}{\partial X} = \frac{1}{U}\frac{\partial^2 \theta}{\partial Y^2} \quad (8)$$

with the following notation

$$\begin{aligned} \theta &= \frac{T - T_{\mathrm{w}}}{T_{\mathrm{in}} - T_{\mathrm{w}}}, \\ Y &= \frac{y}{2H}, \\ X &= \frac{x/(2H)}{RePr} \end{aligned}$$

where $2H$ is the gap between the plates and $Re = U\,2H/\nu$. Since the velocity field is assumed fully developed, no radial velocity component appears in this equation. This equation can be solved numerically using the appropriate boundary and entrance conditions. Finite difference method is employed to solve these equations. The results are shown in Fig. 5. We note that in the low Prandtl number flows the term $\partial^2 T/\partial x^2$ in the energy equation could be significant and a more complicated analysis is required. However, in the first approximation these results are used to compare the heat transfer coefficients in both high and low Prandtl number flows.

The preceding analysis was for relatively high Prandtl number fluids, such as water. While the Prandtl number for most liquid metals and alloys are outside this region, the result in Fig. 5 can still be used as a general guide and an order of magnitude estimate to compare heat removal capacity of liquid metals as compared with water. Using the values of thermal conductivity of water and various liquid alloys and metals (see Table 1) one can observe that the heat transfer rate can be

Liquid metal or alloy	Density ρ kg/m^3	Melting point °C	Boiling point °C	Thermal cond. k W/mK	Specific heat C J/kg/°C	viscosity μ kg/ms = N s/m^2	surface tension σ N/m
Hg	13546	-39	356	8.4	140	0.15×10^{-3}	0.47
Ga	6093	29.98	1983	33.49	343.32	1.89×10^{-3}	0.735
water	1000	0	100	0.6	4184	0.86×10^{-3}	0.0717
NaK	860	-12.6	785	0.232 at °C	949	0.522×10^{-3}	0.12
Bi-alloys	$\sim$ 9500	47-271	8.4	15	197	–	–
Indalloy 46L	6499	7.6	–	–	–	–	–
Indalloy 51	6499	10.7	–	–	–	–	–
Indalloy 60	6350	15.7	–	–	–	–	–
Indalloy 77	6145	25.0	–	–	–	–	–

Table 1: Physical properties of some liquid metals and alloys.

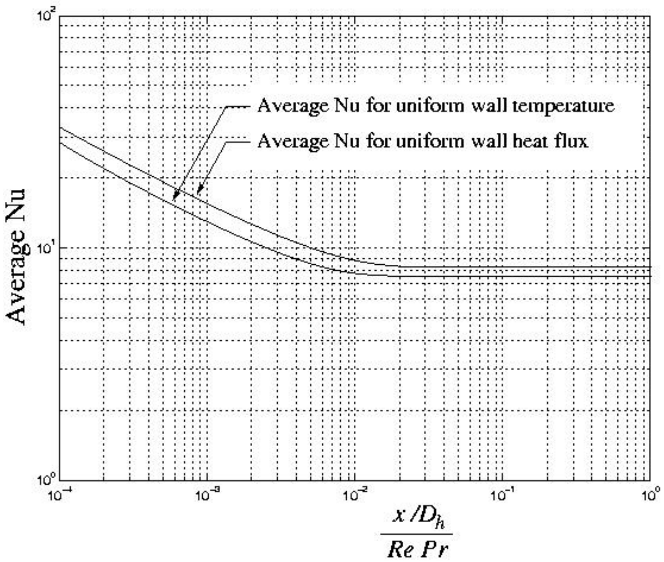

Figure 5. Average Nusselt number in the thermal entrance region of a hydrodynamically developed flow between parallel plates.

enhanced by up to two orders of magnitude if water is replaced by liquid alloys or metals. We point out that in the case of droplet movement (as contrasted with the continuous flow) the heat transfer rate needs to be adjusted based on how the droplet length and distance between droplets in the channel. Here, if the droplets are separated by a distance equal to their length, one can assume that the heat transfer rate is reduced by a factor of two.

V. Conclusions

Increase in circuit density, clock speed, and packaging densities in modern integrated circuits (ICs) have brought thermal issues into the spotlight of high-speed IC designs. Local overheating in one spot of an IC can cause a system failure due to resulting clock synchronization problems and parameter mismatches. Digitized electrowetting of liquid alloys and metals are suggested for active thermal management of high power microsystems. Our initial analysis, while simplified and rough, suggest that significant enhancement in heat transfer rate can be achieved by using liquid metals or alloys as compared with water. Electrowetting is a low power, cost effective, and simple approach for active control of hot spots or thermal management of transient overshoots in electronic devices.

References

[1] C. Sobhan and S. Garimella, “A comparative analysis of studies on heat transfer and fluid flow in microchannels,” *Microscale thermophysical Engineering*, vol. 5, pp. 293–311, 2001.

[2] D. Tuckerman and R. Pease, “High performance heat sinking for VLSI,” *IEEE Electron Device Letters*, vol. 2, no. 5, pp. 126–129, 1981.

[3] R. Remsburg, Ed., *Advanced Thermal Design of Electronic Equipment*. New York, NY: Chapman & Hall, 1998.

[4] I. Mudawar, “Assessment of high-heat-flux thermal management schemes,” in *Proceeding of the IEEE Inter Society Conference on Thermal Phenomena*, 2000.

[5] R. Chu, R. Simons, M. Ellsworth, R. Schmidt, and V. Cozzolino, “The use of a contraction to improve the isotropy of grid-generated turbulence,” *IEEE Transactions on Device and Materials Reliability*, 2005, to appear.

[6] T. Sammarco and M. Burns, “Thermocapillary pumping of discrete drops in microfabricated devices,” *AIChE J.*, vol. 45, no. 2, pp. 350–366, 1999.

[7] H. Matsumoto and J. Colgate, “Preliminary investigation of micropumping based on electrical control of interfacial tension,” in *Proceedings of the IEEE MEMS*, Napa Valley, CA, 1990, pp. 105–110.

[8] H. Verheijen and M. Prins, “Reversible electrowetting and trapping of charge: Model and experiments,” *Langmuir*, vol. 15, no. 20, pp. 6616–6620, 1999.

[9] G. Beni, S. Hackwood, and J. Jackel, “Continuous electrowetting effect,” *Appl. Phys. Lett.*, vol. 40, no. 10, pp. 912–914, 1982.

[10] J. Lee and C. Kim, “Surface tension driven microacuation based on continuous electrowetting,” *J. MEMS*, vol. 9, no. 2, pp. 171–180, 2002.

[11] K. Ichimura, S. Oh, and M. Nakagawa, “Light-driven motion of liquids on a photoresponsive surface,” *Science*, vol. 288, no. June 2, pp. 1624–1626, 2000.
[12] M. Prins, W. Welters, and J. Weekamp, “Fluid control in multichannel structures by electrocapillary pressure,” *Science*, vol. 291, no. January 12, pp. 277–280, 2001.
[13] M. Pollack, R. Fair, and A. Shenderov, “Electrowetting-based actuation of liquid droplets for microfluidic applications,” *Appl. Phys. Lett.*, vol. 77, no. 11, pp. 1725–1726, 2000.
[14] K. Yun, I. Cho, J. Bu, C. Kim, and E. Yoon, “A surface tension driven micropump for low-voltage and low-power operations,” *IEEE J. of MEMS*, vol. 11, no. 5, pp. 454–461, 2002.
[15] K. Mohseni and A. Dolatabadi, “Electrowetting droplet actuation in micro scale devices,” American Institute of Aeronautics and Astronautics, *43rd AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, AIAA paper 2005-0677, January 10-13 2004.
[16] E. Seyrat and R. Hayes, “Amorphous fluoropolymers as insulators for reversible low-voltage electrowetting,” *J. Appl. Phys.*, vol. 90, no. 3, pp. 1383–1386, 2001.
[17] H. Moon, S. Cho, R. Garrell, and C. Kim, “Low voltage electrowetting-on-dielectric,” *J. Appl. Phys.*, vol. 92, no. 7, pp. 4080–4087, 2002.
[18] J. Jackel, S. Hackwood, and G. Beni, “Electrowetting switch for multimode optical fibers,” *Appl. Opt.*, vol. 22, no. 11, pp. 1765–1770, 1983.
[19] V. Pamula and K. Chakrabarty, “Cooling of integrated circuits using droplet-based microfluidics,” in *Proc. ACM Great Lakes Symposium on VLSI*, 2003, pp. 84–87.
[20] A. Miner and U. Ghosal, “Cooling of high-power-density microdevices using liquid metal coolants,” *Appl. Phys. Lett.*, vol. 85, no. 3, pp. 506–508, 2004.
[21] G. Duncan and G. Peterson, “Review of microscale heat transfer,” *Appl. Mech. Rev.*, vol. 47, no. 9, pp. 397–428, 1994.
[22] N. Obot, “Toward a better understanding of friction and heat/mass transfer in microchannels – a literature review,” *Microscale Thermophysical Engineering*, vol. 6, pp. 155–173, 2002.
[23] A. Bejan, *Convection Heat Transfer*, 2nd ed. United States: Wiley-Interscience, 1994.