Electrowetting with Liquid Alloys

for Electronics Cooling

In an earlier issue of Qpedia, we addressed the technology behind the electrowetting process [1]. Here, we further discuss this interesting technology. Because heat fluxes in electronics are increasing very rapidly, there is an imminent need for cooling devices that can reliably extract heat from components. One important technology with potential in this area is the electrowetting of liquid alloys to generate motion. The liquid can be either water or a liquid metal. Liquid metals have much higher thermal conductivities compared to water, and thus a higher heat transfer.

The concept of moving liquid droplets is shown in Figure 1. In this figure, sequential energizing of the electrodes causes the droplet to move due to electrostatic forces.

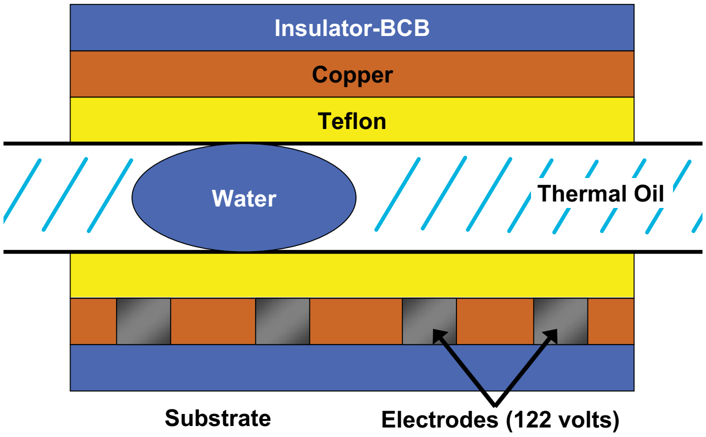

Figure 1. Schematic Showing a Liquid Droplet Actuated by Applying Voltage [1].

The flow of the droplet in the above configuration was analyzed by solving the Maxwell stress equation. This equation relates the body force to an electric filed intensity in a dielectric fluid. By using Green's, theorem one can take the volumetric integral of the divergence of the Maxwell equation to obtain the surface forces. The mechanism in Figure 1 was placed on top of a chip with a size of 15 x 15 mm. The other dimensions of the channel are:

Channel height = 1 mm
Channel length = 15 mm

The average speed of the droplet was estimated to be 10 cm/s. To simulate the problem, Surface Evolver software was used to find the shapes of the droplets. The finite element program MSC-Mark calculates the electrical field distribution. By measuring the droplet angles experimentally, and by previously calculating the values of force as a function of position, the equation of motion can be solved numerically with respect to time starting from zero position.

Figure 2 shows the droplet **position** as a function of time and Figure 3 shows the average droplet **velocity** as a function of time.

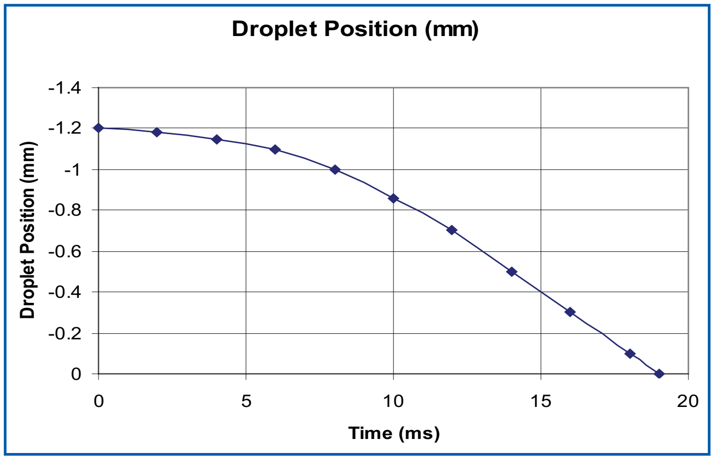

Figure 2. Droplet Position as a Function of Time.

The authors claim the above arrangement can remove up to

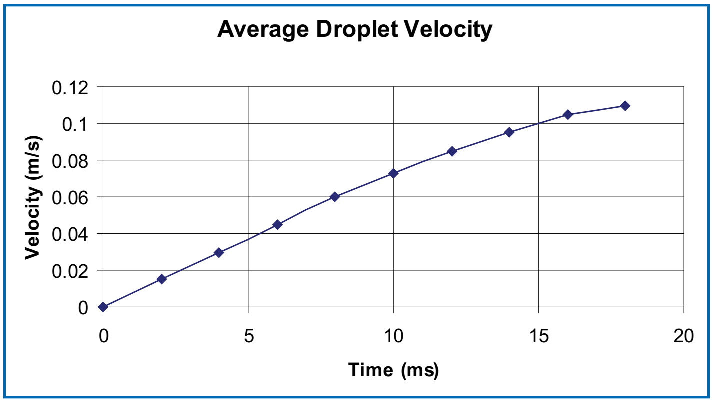

Figure 3. Droplet Velocity as a Function of Time.

100 W of power from the chip.

Other authors analyzed the concept of electrowetting in a microchannel and performed analytical studies on the heat transfer [2], the fluid in a micrometer scale may not quite attach to all surfaces unless a voltage is applied to it. The contact angle between a liquid and a solid substrate can be changed according to Lippmann's equation:

$$\cos\theta = \cos\theta_Y + \left(\frac{V}{V_L}\right)^2$$

Where,

θ = Contact angle [rad]

θ_Y = Young's constant [rad]

V = Voltage [volts]

V_L = $\left(\frac{2D\gamma_{LV}}{\varepsilon_0\varepsilon_r}\right)^{1/2}$

D = Silicon layer thickness [m]

ε_0 = Dielectric permittivity of vacuum [F/m]

ε_r = Dielectric constant

γ_{LV} = Liquid-vapor surface tension [N/m]

By applying voltage to droplets the contact angle changes, and consequently a motion of the liquid can be achieved. By using a CCD camera and placing 5 μl drops of water-salt-glycerol mixtures, the authors could detect a transition voltage of 51 V when the drops completely wetted the channels [3].

The liquid droplets are not in continuous motion, and move in packets, thus the authors developed a heat transfer analytical procedure for a periodic motion of the liquid. To look at their procedure, consider the silicon block in Figure 4 with the dimensions l_b x w_b x d_b. The fluid enters the microchannel on the left hand side with temperature T_c. The block is assumed to be heated with a temperature of T_h. For simplicity assume conduction of the block is negligible. This can be corrected later on by calculating the efficiency of the fins. Using the Lagrangian technique of following fluid particles, let's assume the fluid that comes into the channel has a length that is a function of time L(t). The filling function is assumed to have a period of τ and symmetric of about τ/2.

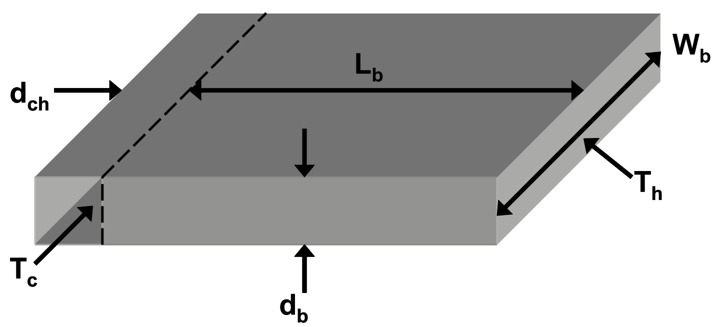

Figure 4. Schematic of a Silicon Block and Microchannel Flow on Left Hand Side [3].

By writing the energy equation for the heated fluid in the microchannel:

$$dm = \rho dV = \rho A_f dx$$

$$dm.C_f \frac{dT_f}{dt} = h_f(T_s - T_f)P_f dx$$

$$T_s = T_h$$

Integrating the above equation

$$\int_{T_c}^{T_f} \frac{dT_f}{T_s - T_f} = \int_{t}^{\tau-t} \frac{h_f P_f}{\rho C_f A_f} dt$$

$$\frac{T_h - T_f}{T_h - T_c} = e^{\frac{h_f P_f (\tau - 2t)}{\rho C_f A_f}}$$

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Where,

dm = Differential mass [kg]

C_f = Heat capacitance of the fluid [J/KgK]

T_f = Fluid temperature [ºC]

T_s = Silicon temperature [°C]

Pf = Microchannel perimeter [m]

h_f = Heat transfer coefficient of the fluid [W/m^2.K]

t = Time [s]

The total heat that is extracted during one period can be calculated as:

$$Q = \int_0^M C_f (T_f - T_c) dm$$

$$Q = \rho L_{max} A_f C_f (T_h - T_c) \left[1 - \frac{1}{L_{max}} \int_0^{\tau/2} V_f(t)\, e^{\frac{h_f P_f (\tau - 2t)}{\rho C_f A_f}} dt \right]$$

$$V_f(t) = dL(t)/dt$$

Where,

$V_f(t)$ is the velocity of the droplet as a function of time in [m/s]

They considered the two cases in square waves and sine waves, filling as shown in Figure 5.

M = mass of the liquid in the half period time

By integrating the last equation for these two cases for a single channel and for multiple channels, they plotted the cooling rate as a function of frequency. It was demonstrated that for a 100 µm square microchannel, a frequency above 0.25 Hz would enhance the heat transfer rate. In fact, their graph shows that at about 10 Hz, a significant improvement in heat transfer can be achieved.

Electrowetting can have significant impact in the area of electronics cooling and is being studied by some major institutions. More research will be needed to bring this concept to a practical perspective. This technology has the capability to transfer heat without mechanical parts with a high degree of reliability.

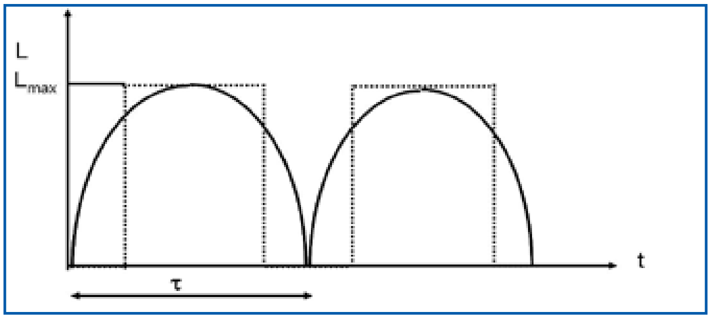

Figure 5. Length of the Droplet as a Function of Time [3].

References:

1. Advanced Thermal Solutions, Inc., Qpedia eMagazine, April 2007. 3, "Chip-level cooling with electrowetting and microchannels."
2. Oprins, H., Nicole, S., Baret, C., Van der Veken, G., Lassance, C., and Baelmans, M., On-Chip Liquid Cooling with Integrated Pump Technology, IEEE SEMI-THERM 2005