HIGHLY EFFICIENT IONIC WIND-BASED COOLING MICROFABRICATED DEVICE FOR MICROCHIP COOLING APPLICATIONS

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ABSTRACT

This work explores an innovative and advanced thermal management solution using a microfabricated air-cooling technology that employs an electrohydrodynamic corona discharge (i.e. ionic wind pump) to stimulate forced convection for efficient heat removal from electronic components and devices. The device provides a high COP (coefficient of performance) of 20.5. In fact, the grid structures used in its design enhance the overall heat transfer coefficient and facilitate a batch and IC compatible process. ANSYSTM was used to computationally simulate the jet impingement phenomenon and resulting cooling effects of the device. COMSOL MultiphysicsTM was additionally employed to computationally explore the effects of collector-emitter configuration. For a larger-scale application, performance can be appreciably enhanced by using an array of these microscale devices.

INTRODUCTION

As microelectronics continue to be miniaturized and their performance improves, power density increases substantially, and currently exceeds 10 W/cm² [1]. Consequently, the need for novel and innovative thermal management solutions is becoming critical. This is largely because the performance of these sensitive electronic components depends on temperature, and even a small increase in temperature can lead to issues relating to device lifetime and performance.

Conventional forced-air cooling technologies (i.e. fans) are largely impractical as next generation solutions due to their large volume and high power consumption. For example, the large volume and weight associated with fin-array heat sinks and high power consumption associated with the attached fans make them impractical. Alternative technologies such as liquid microjet cooling [2] are attractive since they do offer significant heat removal, but concerns regarding their cost, weight, reliability, stability, pumping and refrigeration requirements, in addition to the fact that there is hesitation regarding exposing a microelectronics system to liquid, complicate their use [1]. Alternatively, finding a technologically feasible solution that meets the requirements of large heat removal effectiveness; low weight, volume and cost; zero noise generation; no moving parts; but with the use of comparatively simple technologies would certainly be attractive. This work explores ionic wind devices, which can provide enhanced convection solutions for applications that would have otherwise been cooled by natural convection/radiation or an alternative forced air cooling solution with all of these benefits.

The innovative microfabricated ionic wind pump employs an electrohydrodynamic corona discharge for efficient heat removal due to the convective effects induced by the device. The purpose of the work described herein was to test a single ionic wind pump, which could then be employed in an array for use in larger-scale applications. Conceptually, the cooling device, placed in contact with a hot microelectronics device, functions by applying a sufficiently high voltage between a single high-curvature tip and two parallel electrodes. Consequently, a jet of ambient air impinges on the hot, oppositely charged plates, thereby removing heat and acting as an “active heat sink” device.

THEORY, MATHEMATICAL MODELS, AND IONIC WIND PUMP DEVICE

The ionic wind pump device works by applying a sufficiently high voltage (with corresponding low current, so therefore low power) between a high curvature emitting electrode and a low curvature collecting electrode, which results in a high electric field that ionizes nearby air molecules. The ionized air molecules, through subsequent collisions, transfer their momentum to the nearby neutral air molecules as they are propelled from the emitter and towards the collector electrode due to the presence of the high electric field. In other words, the resulting electric force creates a jet of air with substantial velocity termed an ionic or corona wind that impinges on the collecting electrodes. Figure 1 demonstrates the phenomenon schematically for a single emitter in a specific parallel arrangement of collector electrodes (more commonly, a single point-to-plane configuration is employed [3]). If the collecting electrode is at a relatively higher temperature, then this impinging air stream can be used for forced convective cooling. While the charged molecules effectively stick to the collector plate, there is a net bulk flow of neutral molecules away from the emitters, which behaves more like “plug flow” rather than being fully developed. Consequently, boundary layer effects that may otherwise minimize cooling effectiveness are mitigated, and performance is enhanced.

Figure 1: Schematic of the corona discharge/ionic wind pump. A perspective of a simple arrangement of a single emitter electrode (positive charges) located at the midpoint between two parallel collector electrodes (negative charges) with a subsequent flow pattern. The emitter electrode ionizes surrounding air molecules, which are forced towards the collector electrodes. The collected charged molecules may stick to these electrodes, but the neutral molecules with which they collide and exchange momentum are propelled, thereby creating an “ionic wind”.

Since the average flow velocity critically influences the achievable cooling rate of the device, the key parameters affect its magnitude. Electrohydrodynamic theory reveals that the induced air velocity due to the ionic wind is a function of the corona discharge current (I_{corona}), the gap between the emitting electrode and the collecting electrode (d), and the effective surface area of the collecting electrode (A). This average velocity due to the ionic wind ($\bar{v}$) is given by [4]:

$$\bar{v} = \left(\frac{2}{f} \right)^{1/2} \left[\frac{I_{corona} d}{\rho_{air} \mu A} \right]^{1/2} \quad (1)$$

where f is the aerodynamic loss factor of the device, μ is ion mobility in air, and ρ_{air} is air density at ambient temperature. Therefore to enhance velocity, the collecting surface area must be small, the gap size large, and the corona current high. However, if the current is too high, power consumption and corresponding Joule heating/ resistive heating will be too large. If the gap size is too large, the very high voltage and power consumption are also required. Therefore, these parameters must be optimized accordingly.

The Townsend expression to analyze the voltage and current requirements is given by:

$$I_{corona} = BV(V - V_0) \quad (2)$$

where B is a coefficient (related to the emitting electrode radius, ion mobility, electrode gap, and other geometrical factors such as tip shape, tip surface, etc.), V is the applied voltage, and V_0 is the corona onset voltage (inception voltage) at which the corona discharge is initiated. So obviously to increase B , the design parameters of the emitter tip and other geometrical factors are accordingly adjusted. Additionally, the applied voltage must be sufficiently high, and certainly greater than the inception voltage, which can be analyzed using Peek's breakdown criterion, which is also employed to calculate the electrical field as expressed by equation (3).

$$E_{critical} = af_0 \delta (1 + b \sqrt{\frac{\delta}{r}}) \quad (3)$$

where $a = 30 \text{ kV/cm}$, $b = 0.3 \text{ cm}^{1/2}$, $f_0 = 1$ (for smooth surfaces), δ is relative air density, and r is the tip curvature radius; and which relates to voltage by Paschen's law as represented by:

$$E(x) = \frac{2V}{\left(\frac{2x}{r} + 1 \right) r \ln \left(\frac{2d}{r} + 1 \right)} \quad (4)$$

where x is the position of the electric field from an emitter surface. Thus, reducing the size of the sharp electrode will produce higher electric field strengths than a larger one for the same applied voltages. This is one of the reasons that an effective ionic wind pump device must be microfabricated such that its components are of microscale dimensions.

As described previously, the ionic wind pump device acts as an "active heat sink"; and the planar collector electrodes act as conventional cooling fins, but in addition the presence of the emitter tip enables forced convection without the use of a fan. The total amount of power dissipated, Q_{total} , from this "active heat sink" is then given by Newton's law of cooling:

$$Q_{total} = \eta_0 h_{avg} A \Delta T \quad (5)$$

where η_0 is the overall efficiency of the cooling device, h_{avg} is the average heat transfer coefficient, A is the total surface area available for heat transfer, and ΔT is the temperature drop between the cooled surface and surrounding air (ambient temperature).

MICROFABRICATION PROCESS

The manufacturing process developed for the device uses glass wafers, a single photolithographic mask and a low cost copper-based electroplating process as previously reported [3]. Various design configurations were tested experimentally and modeled computationally to maximize the cooling effect, and a prototype device with an effective surface area of 0.77 mm^2 , a thickness of $\sim 17 \text{ }\mu\text{m}$, and an emitter tip-to-collector plate gap of $\sim 1 \text{ mm}$ was studied. In fact, the grid structures used in its design (Figure 2) enhance the overall heat transfer coefficient and facilitate

a batch and IC compatible process.

Figure 2: Image of a single microfabricated ionic wind pump device. Two parallel grid-structured collector plates and a single emitter tip are shown. When a certain high voltage is applied between the emitter tip and the collector electrodes, the corona discharge (ionization of air molecules) results in a visible purple haze around the emitter (inset).

MODELING AND EXPERIMENTAL RESULTS

The performance of the microfabricated ionic wind pump device was experimentally investigated by building the experimental setup as demonstrated in Figure 3. Additionally, characterization experiments such as I - V (current-voltage) characteristics of the corona discharge-based device were conducted as shown in Figure 4. To measure corona current, the collecting electrode was placed in series with a small resistor to the ground. The corona current was observed from the measurement of the voltage drop across the resistor by the multimeter. A large resistance was also placed in series between the emitter and high voltage terminal to avoid damage to the device.

Figure 3: Picture of the experimental setup for the temperature testing. (1) Microfabricated ionic wind pump device; (2) two thermocouple sensors with high thermal conducting paste and Kapton tape covering the ends of the sensors; (3) National Instruments data acquisition (DAQ) board with a cold-junction compensation temperature sensor; (4) thermal spreader; (5) hot plate; (6) high voltage power supply; (7) multimeter; and (8) infrared thermography.

To test the cooling effects due to the ionic wind, the thermocouple was positioned in thermal contact with the backside of the vertical collector plate, the entire device was placed on a hot plate, and temperature was measured as a function of applied voltage and corona discharge current. Temperature was recorded by

using a National Instruments data acquisition (DAQ) board with a cold-junction compensation temperature sensor. The total size of thermocouple including the Kapton tape (required for electrical insulation from the high voltage) and thermal paste is approximately half of the height of the collector plate. In this setup, the heat transfer between the hot collector plate and the cooler air environment was also measured. As shown in Figure 5, the single device achieves a maximum temperature drop of 4.1°C with an applied voltage of -1.35 kV . The electrically induced thermal effects (Joule heating) starts occurring at a corona current larger than $\sim 7\text{ }\mu\text{A}$ or an applied voltage greater than 1.35 kV . Using the experimental results for a single device, a 2-D array of the microfabricated ionic wind pumps covering approximately $2''$ square should be able to dissipate greater than 2 W of heat using about $1/5$ the power input as a conventional fan.

Figure 4: Experiments-based I-V curve for the microfabricated ionic wind pump device.

Figure 5: Average temperatures on the collector vs. applied voltage due to the ionic wind.

Infrared thermography (TVS-200EX) was also employed to record the temperature distribution around and on the surface of the device both before and after a voltage was applied to the electrodes. An infrared thermography image (Figure 6) exhibits a drop in temperature of approximately $\sim 4^{\circ}\text{C}$ at the edge of the collector plate, similar to that observed by direct temperature measurement. The resulting current density for this device was 8.9 A/m^2 , and its electrical power consumption was less than 9.3 mW , which is significantly lower than previously reported studies [5], [6].

FLOTTRAN CFD ANSYSTM was used to computationally simulate the jet impingement phenomenon of air from emitter to collector and resulting cooling effects of the device. First to verify the finite element model, a single element device using input

parameters and a design configuration as reported in [5] was simulated. For this structure, an emitting tip was located above one collecting electrode. Their experiments revealed an average heat transfer coefficient of $63.7\text{ W/m}^2\text{K}$ (considering a natural convection coefficient of $\sim 10\text{ W/m}^2\text{K}$), and an experimentally derived total heat removal rate of $\sim 1.54\text{ W}$ (Q is low since only a single element was tested). Using the same design parameters, the simulation presented herein revealed a heat transfer coefficient of $63.5\text{ W/m}^2\text{K}$ and a calculated heat removal rate using equation (5) of 1.57 W . Clearly, the simulation results match the published data closely, providing confidence in the modeling efforts.

Figure 6: Microscope and corresponding infrared images (inset) of a single element ionic wind pump device. The purple hue suggests the surrounding area is approximately 50°C while the edge of the collector plate is cooled by approximately $4 - 5$ degrees during operation of the device.

Figure 5 shows the simulation results for the device described herein and characterized experimentally. The simulated average collector plate temperature compares favorably to the temperature obtained from the thermocouple measurement. As an example, the temperature distribution on a single collector determined from these simulations is shown in Figure 7. Using the average heat transfer coefficient on this collector as outputted by the simulation software ($3.1075 \times 10^3\text{ W/m}^2\text{K}$), the total heat removal was calculated to be $\sim 190\text{ mW}$ by applying Newton's law of cooling, corresponding to a COP of 20.5. For a comparable simulation in which a solid collector plate was modeled (i.e. no grid structure), the total heat removal was only 134 mW , demonstrating the enhancement obtained using a grid configuration.

Figure 7: Temperature profile (in $^{\circ}\text{C}$) of a single collector plate on which a jet of air is impinging (corresponding to an applied voltage

of 1.35 kV) using a 3-D ANSYSTM thermal/fluids simulation. The bottom boundary of the collector plate is set at the measured temperature, and ambient air impinges on all sides, leading to a cooling effect.

COMSOL MultiphysicsTM was additionally employed to computationally explore the effects of a two-dimensional collector-emitter configuration on the electrohydrodynamic phenomenon, the flow field and resulting cooling effects. Note that the effect of the grid structure was not investigated. Figure 8 illustrates the velocity vectors in the flow field (shown as arrows); and the temperature field for four cases: a) no ionic wind; b) emitter located along the midline of the collector; c) emitter located one-quarter of the distance between boundaries; and d) emitter located one-eighth of the distance between boundaries. Jet impingement from emitter to collector is clearly demonstrated.

Figure 8: COMSOL MultiphysicsTM-based 2-dimensional (2D) electrohydrodynamic simulations (top view) demonstrating different temperature distributions and velocity flow fields. (a) Ionic wind is turned off. (b) Emitter location is in the middle of the left boundary. (c) Emitter location is located at one-quarter of the length of the left boundary. (d) Emitter location is located at one-eighth of the length of the left boundary.

Moreover, the flow field and resulting heat transfer are significantly influenced by the location of the emitter tip. The temperature reduction due to ionic cooling demonstrated in Figures 8.b, 8.c and 8.d are relatively equal (approximately 3°C maximum). However, there is an increasing average y -velocity for the arrangements depicted in Figures 8.b (zero y -velocity), 8.c and 8.d. Thus, the un-symmetric emitter position will generate higher velocities in y -direction, which is particularly important once an array structure is employed to avoid recirculation of warmed air. The discrepancy between the temperature drops exhibited by the simulation (less than 3°C) and experimental (greater than 4°C) results is likely due to the fact cooling is enhanced by the presence of the collector grid structure studied experimentally but which was not modeled for this particular computational investigation.

CONCLUSIONS AND FUTURE WORK

This work demonstrates an innovative and advanced microfabricated air-cooling technology that employs an electrohydrodynamic corona discharge (i.e. ionic wind pump) for efficient heat removal from electronic components and for thermal management applications. The microfabricated ionic wind pump-based cooling device also generates zero noise; contains no moving parts; boasts a low weight, volume and cost; and uses comparatively simple technologies. Moreover, this “active heat sink” can be scaled for either highly localized hot-spot cooling or integrated onto a larger thermal-exchange surface to enhance heat transfer. Using optimized designs with different configurations, a microfabricated ionic wind pump device could then be employed in a three-dimensional array for use in larger-scale microchip cooling applications and enhanced thermal spreaders, which are typically found in mobile cell phones and ultrathin laptops. Experimental and computational work is ongoing to further optimize designs.

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