A System for Liquid Cooling of Electronic Elements with EHD Pumping Mechanism

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Abstract—In this paper a proposed system is presented for cooling electronic elements where liquid coolant flow is induced using miniature injection Electrohydrodynamic (EHD) pumps. A Semiconductor CSD02060 diode packaged in TO-220 with an integrated heat exchanger was used as the cooled electronic element. We experimentally studied and numerically simulated the thermal characteristics of the diode cooled with EHD flow in the function of coolant flowrate. Results show that EHD micropumps can be successfully applied for cooling electronic elements such as the CSD02060 diode. The transient thermal impedance of the tested diode was 7.8°C/W for coolant flowrate of 1.5 ml/min.

Keywords—Cooling system, electrohydrodynamic flow, EHD, integrated heat-exchanger

I. Introduction

As electronic elements become smaller and more power consuming, more problems with dispersing waste heat arise. Traditional cooling techniques are no longer applicable in many fields of technology because of a large size of traditional cooling systems and their low efficiency. Currently, lack of efficient technique of heat removal from electronic elements is one of major obstructions to further miniaturization of an electronic systems in such applications as computers, biomedicine, automobile and aerospace technology [1]. Therefore, over the past few decades various cooling systems for electronic elements have been proposed, for example: impinging air jets [2], thermoelectric coolers [3], direct immersion cooling [4], miniature heat-pipes [5] and liquid microflow cooling systems. Compared to other cooling techniques, liquid microflow systems seems to be an ideal cooling solution in applications where high efficiency and a small size of the cooling system are indispensable. In this cooling technique, liquid coolant is introduced close to the critical part of the electronic element requiring significant cooling by means of an integrated heat exchanger and of micropumps. Many pumping mechanisms for microflow cooling systems were tested [6]: from traditional mechanical pumps, through phase change pumps [7], magnetokinetic pumps [8], electroosmotic pumps [9] and finally to electrohydrodynamic (EHD) pumps. The advantages of the EHD pumps are: non-mechanical mechanism of pumping, relatively simple design, low vibration and noise emission, low power consumption and simple control of their flow rate.

In EHD pumping mechanism working liquid is set into motion as a consequence of applied high voltage. In general, when voltage is applied to a volume of dielectric liquid its driving force can be expressed as Eq. (1) [10].

$$\vec{F} = q\vec{E} - \frac{1}{2}\vec{E}^2\nabla\varepsilon + \frac{1}{2}\nabla\left[\vec{E}^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\rho\right] \quad (1)$$

where q is the free space charge density, ε is the liquid permittivity and ρ is its mass density. The first term of Eq. (1) represents the Coulomb force which is main driving force in most types of EHD pumps. The second term is dielectrophoretic force caused by the gradient of liquid permittivity. The last term is electrostrictive force. There are three basic mechanisms of EHD pumping in which Coulomb force is the driving force: induction pumping, conduction pumping and ion-drag (injection) pumping [11]. In our system for cooling electronic elements we applied a miniature ion-drag type EHD pumps for coolant pumping.

The mechanism of ion-drag pumping was first described by Stuetzer [12] and Pickard [13] in 1960's and was investigated by many groups since then [14]–[18]. During the ion-drug pumping free charges are injected into the dielectric liquid from the positive electrode (called emitter). Next, injected charges are dragged by the Coulomb force towards another electrode (called collector) due to the high electric field created between the electrodes. Through the friction, a part of kinetic energy of dragged charges is transferred to adjacent liquid setting it into motion.

In this paper we present the design and test results of a system for cooling electronic elements (for tests we used semiconductor CSD02060 diode) in which liquid coolant flows through heat exchanger integrated with the electronic element, forced by miniature, ion-drag type EHD pumps.

II. Cooling system design

The experimental setup of the system for cooling electronic elements is presented in Fig. 1. It consisted of an electronic element (CSD02060 Silicon Carbide (SiC) Schottky Diode from Cree Inc. packaged in TO-220) with an integrated heat exchanger, three EHD pumps (connected in series or parallel) and reservoir of the liquid coolant with a heat-sink. The heat exchanger integrated with the diode was fabricated by

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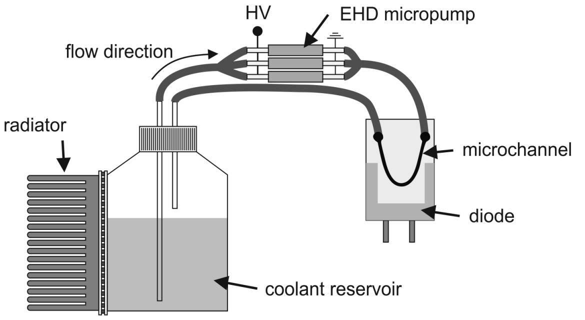

Fig. 1. Cooling system with an EHD-induced coolant flow for CSD02060 diode packaged in TO-220.

TABLE I
BASIC PROPERTIES OF ISOPROPYL ALCOHOL ($(CH_3)_2CHOH$)

Boiling point (at 1 atm)	82.3 [°C]
Melting temperature	-88 [°C]
Density	0.7810 [g/ml]
Dielectric constant	19.9
Dipole moment	1.66 [D]
Viscosity	2.073×10^{-3} [Pa·s]

manufacturing a pattern of microchannels in the diode package by means of laser micromachining. The EHD pumps forced the coolant flow, in the closed-loop, from the reservoir to the heat exchanger and back to the reservoir.

Pure isopropyl alcohol $(CH_3)_2CHOH$ was used as a coolant. Its basic properties are presented in Table I.

A. Heat exchanger

In order to make a heat exchanger integrated with the diode we created several patterns of microchannels in the metal part of diode package (Fig. 2) by means of laser micromachining, so that the coolant could be introduced close to a heat-critical areas of the diode. Microchannels were both 500 μm wide and deep. The microchannels were covered with a transparent polydimethylsiloxane (PDMS) resin and a thin glass plate. Transparent resin and glass plates were used in order to verify that no gas bubbles were generated in the coolant during the cooling process that were large enough to result in significant drop in both flow rate and pressure of coolant.

B. Ion-drag EHD micropump

The ion-drag type EHD micropump (Fig. 3) was composed of a ceramic (Al_2O_3) pipe and two stainless-steel electrodes inserted coaxially into the ceramic pipe. Each electrode was a 10 mm pipe of external and internal diameter of 0.8 mm and 0.5 mm, respectively. The distance between electrodes was 3 mm, a positive high DC voltage was applied to one electrode while the other electrode was grounded. A Spellman SL300 power supply was used as high voltage source. The pumping effect was observed in the direction from the HV electrode (emitter) towards the grounded electrode (collector).

The maximum flow rate generated by a single EHD pump was 0.5 ml/min and the maximal pressure was 500 Pa for an applied voltage of 12 kV. For higher voltages we observed

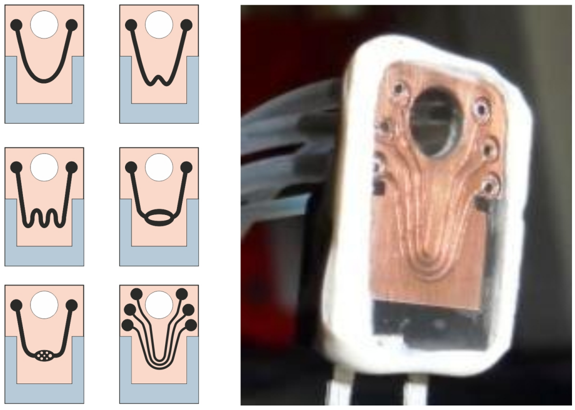

Fig. 2. Schematics of microchannel patterns and a photograph of CSD02060 diode with integrated heat exchanger.

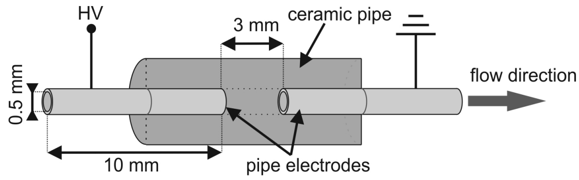

Fig. 3. Schematic of EHD pump construction.

formation of the large gas bubbles in the coolant and a significant drop in both flow rate and pressure. For applied voltage of 12 kV the measured current was 20 μA, thus the EHD pump power consumption was 240 mW.

III. RESULTS

A. Micro-PIV measurements

To measure the EHD flow profile across the microchannel we used the micro-PIV technique. The micro-PIV stand included a dual pulsed Nd:YAG laser (532 nm wavelength, 15 ns pulse duration, 20 mJ pulse energy), a microscope NIKON Eclipse TS100 with a Kodak Megapixel CCD camera and Dantec Flow Manager software on a PC. The working liquid contained fluorescent seed particles (polyamide spheres of diameter of 10 μm filled with Rhodamine B). The seed particles were introduced into the working liquid after it passed the EHD pump. Thus seed particles did not disturb the EHD pumping mechanism. During a single measurement, particles were flashed with the laser twice, making the particle emit the fluorescence light. After each flash an image of fluorescent light was taken by the CCD camera. The resulting pictures were analyzed to determine the movement of seed particles. Since the time between laser pulses was known, a flow velocity map inside a microchannel could be easily determined. A series of such measurements was performed for each observation area along the microchannel and an averaged flow velocity profile and flow rate were calculated.

The maximum flow rate generated by the three EHD micropumps connected in series and in parallel was measured, respectively (Fig. 4). In the case of parallel connection the total flow rate was 1.5 ml/min (flow rate generated by single EHD pump was about 0.5 ml/min). In the case of serial

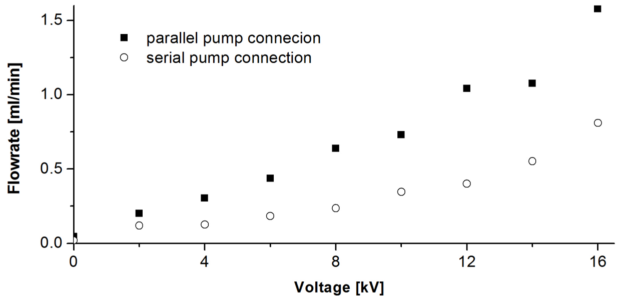

Fig. 4. Coolant flow rate as a function of applied voltage for parallel and serial connection of the three EHD pumps.

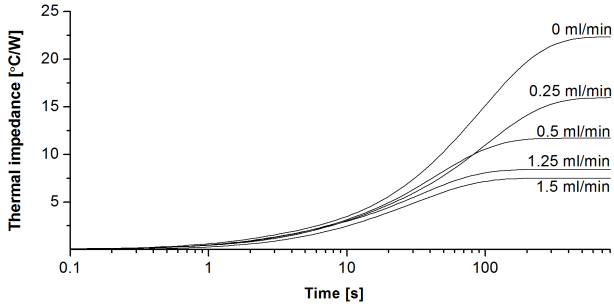

Fig. 5. Measured thermal impedance of the CSD02060 diode for various values of coolant flow rate.

connection of three EHD pumps the resultant flow rate was only 0.8 ml/min. Therefore in the final version of the cooling system EHD pumps were connected in parallel as shown in Fig. 1.

B. Thermal impedance measurements

In order to examine the performance of the cooling system a thermal impedance of the cooled CSD02060 diode with integrated heat exchanger was measured for various coolant flow rates. To obtain the transient thermal impedance first the cooling characteristics was taken. To this end an electric current was applied to the diode, heating it until the electro-thermal steady state was reached. Next, the current was switched off and the diode started to cool down to the ambient temperature of 25°C. During this cooling process, the temperature-sensitive parameter of the diode (voltage drop across p-n junction [19]) was measured. This parameter was used to calculate the temperature surplus of a measured diode over the ambient temperature (the accuracy of temperature surplus measurement was 0.05°C). Finally, transient thermal impedance curves were obtained by inversing the cooling curve and dividing the temperature surplus by the value of power used for heating the diode. It was assumed that all of the power calculated through multiplication of diode voltage drop and current flowing through it was dissipated in form of heat.

The measured transient thermal impedance curves for five values of the coolant flow rate are presented in Fig. 5. As it can be seen in Fig. 5, the most significant differences of temperature surplus are observed for thermal steady state. Because of that, only static parameter - thermal resistance was used for further analyses. The cooling efficiency rises with increasing coolant flow rate. For the highest flow rate of 1.5 ml/min corresponding thermal resistance of the tested diode was 7.8°C/W, almost three times lower than the thermal resistance of this diode with no coolant flow (22.3°C/W).

C. Simulation

We simulated a temperature distribution in CSD02060 diode with integrated heat exchanger for various values of coolant flow rate. The simulations were performed with the use of ANSYS CFX software. Development of geometric model of CSD02060 diode in TO-220 package was difficult due to the

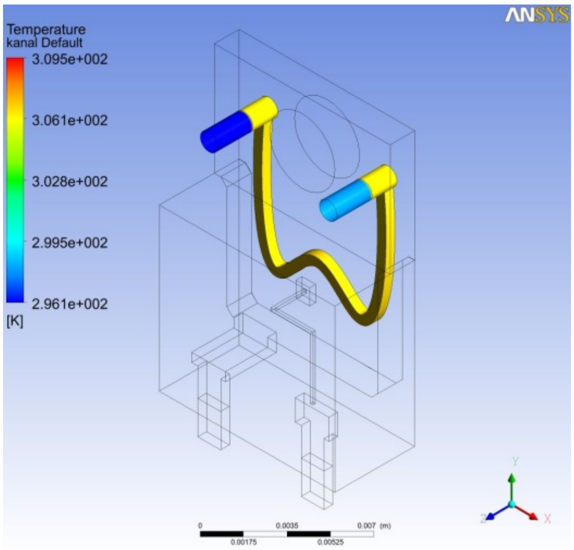

Fig. 6. Geometric model of a CSD02060 diode with microchannel pattern in ANSYS CFX simulation software.

lack of internal dimensioning data, which is not provided in the manufacturer's datasheets. In order to acquire this data a few diodes were disassembled and analyzed providing dimensions and locations of semiconductor structure, wire bonding, soldering thickness, also a third party teardown report of said diode was used thus achieving an approximate accuracy of 0.01 μm for lead plating and semiconductor structure thickness and an accuracy of 0.05 mm for overall diode body measurements [20]. The geometric model of the diode with microchannel pattern of heat exchanger is shown in Fig. 6. Due to the geometrically complicated model of the diode containing relatively large and small parts (especially crucial in the heat exchanger) and a long time required for obtaining of results, transient heating simulations were only conducted for constant value of flow rate of 1 ml/min. Size of the FEM elements varied with smallest elements chosen for heat exchanger in assumed location of possible turbulences and largest FEM elements for the diode frame. Turbulence model chosen for the simulations was SST model.

The goal of the simulations was to benchmark the tested design and subsequently optimize of channel shape and length in order to maximize the cooling capability, and investigation of liquid velocity influence on thermal resistance. During

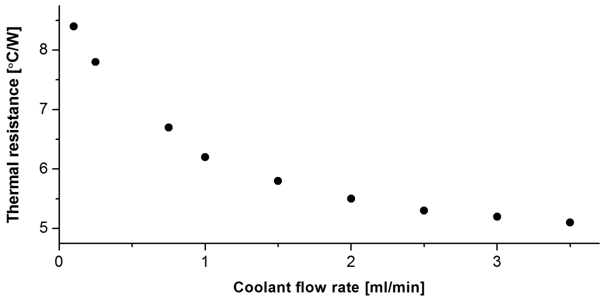

Fig. 7. Dependence of diode thermal resistance from coolant flow rate.

simulations of different channel shapes, a constant flow rate of 1 ml/min was used along with constant power of 2 W dissipated in semiconductor structure in form of heat. The heat generated by the EHD pump was relatively small in comparison with the heat dissipated in the semiconductor structure, and it was neglected in the simulation.

At first, simulation results were compared with data acquired through measurements, in order to ensure validity of the applied model. Simulations of thermal resistance of tested CSD02060 diode achieved very good coherence with measured values. For coolant flow of 1.5 ml/min with power excitation of 2.2 W, measured value of thermal resistance was equal to 7.9°C/W, and value obtained through simulations was 8.1°C/W. In the case without coolant flow, obtained value was 22.5°C/W while measured value was 22.3°C/W.

Proposed channel shapes (Fig. 2) were supposed to increase turbulence in microchannels, especially in the region closest to the heat source. Because of relatively large viscosity of cooling liquid, authors assumed, that proper microchannel shape may reduce the thickness of near-wall layer of liquid in which the liquids speed is largely reduced (as compared with the center of the microchannel). Probably due to the low velocity of the flow, none of the channel shapes could cause turbulent flow at simulated flow of 1 ml/min, and hence there was no large enough difference in thermal resistance of the whole setup to justify use of the more complicated channel shapes. The lowest value of thermal resistance was achieved for longest heat exchangers channel, what can be explained by its large heat exchange surface.

As it can be seen in Fig. 7 simulation shows that the increase in flow rate above 1.5 ml/min does not result in significant change in thermal resistance. Therefore the use of EHD pumps generating flow rate higher than 1.5 ml/min is not crucial for the cooling efficiency.

IV. Conclusion

It was demonstrated that ion-drag type EHD pumps can be successfully applied for cooling electronic elements such as diodes. We have also studied the thermal characteristics of the CSD02060 diode with an integrated heat exchangers cooled by an EHD induced flow. Thermal resistance of the CSD02060 diode cooled with 1.5 ml/min EHD flow was found to be 7.8°C/W. Similar value of thermal resistance (6°C/W) can be obtained for this diode by applying a large RAD-A6405A/150 heat sink to the diode [21]. From the simulation we have found that further increase in flow rate generated by the EHD pump would not significantly increase the cooling efficiency.

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