Natural and Forced Convective Heat Transfer Analysis of Nanostructured Surface

A. Khabari, M. Zenouzi, T. O'Connor and A. Rodas

***Abstract*—As the number of transistors increases for desperately needed faster processing in integrated circuits, the need to remove heat effectively in small devices is crucial as the physical sizes of electronic devices shrink. This work uses nanoparticle depositions on heat sinks and investigates the heat transfer and device temperature for both natural and forced convections. The results show that there is a detectable variance in heat transfer (about 6%) causing device temperature drop between conventional heat sink and nanostructured surface heat sink with the same physical size using natural convection. As the free air velocity (forced convection) increases, the difference becomes negligible.**

***Index Terms* — Convective Heat Transfer, Heat Sink, Nanoparticles, Nanostructured Surface.**

I. INTRODUCTION

EXTENSIVE research has been done on convective heat transfer in nanofluids in last few years [1-4]. However, little work has been done to improve heat transfer of passive heat exchangers (heat sinks) without increasing their physical sizes using nanoparticles. The conventional method of improving the heat transfer is to increase the surface area or by improving the heat transfer coefficient. However, in this work, instead of increasing the physical size, the surface area was increased at molecular levels by depositing copper nanoparticles on the heat sink surface. Nanoparticles are known to have a very high surface area. Research on nanoscale heat and for energy conversion has also shown promising results [5-6]. In this work Nanoparticles are generated in a differential pressure vacuum system. As shown in Figure 1, the nanoparticles are generated in a nucleation chamber by means of aggregation using a three-inch sputtering source at one-Torr of pressure. The nucleation chamber is cooled by applying Liquid Nitrogen into a jacket around the chamber. The nanoparticles are ejected from a converging-diverging nozzle to form a beam of nanoparticles. The beam enters the gas-separation chamber with a pressure of 1 mTorr. Due to their enormous kinetic energy, nanoparticles follow a straight line and enter the deposition chamber through a 0.5cm orifice as other gas molecules and atoms such as Argon used for sputtering are pumped out by a cryopump. This nanoparticle beam is used to target a heat sink in the deposition chamber with a pressure of 10^{-6} Torr. This process is explained in detail in other publications [7-8].

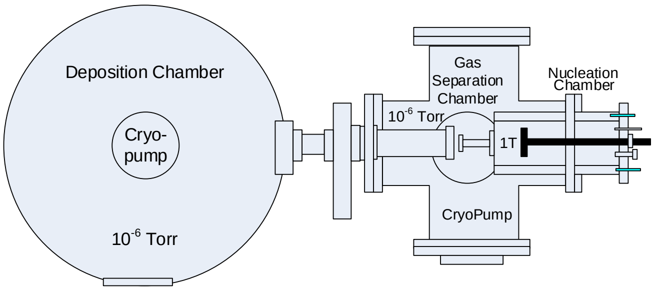

Fig 1: Nanoparticle Deposition System

II. EXPERIMENTAL

The black anodized (aluminum oxide) top surface of the heat sink was removed and polished below nanometer roughness range. To confirm the surface roughness of polished heat sink, the surface of the heat sink was analyzed using an Atomic Force Microscope -AFM (Figure 2). The surface roughness of the polished heat sink is well below nanometer range. Different spots of the polished heat sink were scanned and all confirmed that the surface roughness is below a nanometer range. Copper nanoparticles were deposited on the polished surface. After deposition, the surface of the heat sink was analyzed by an AFM again to find how the heat sink surface was altered after nanoparticle deposition. Figure 3 shows the mean roughness range is about 50 nanometer with a considerable increase in the surface area.

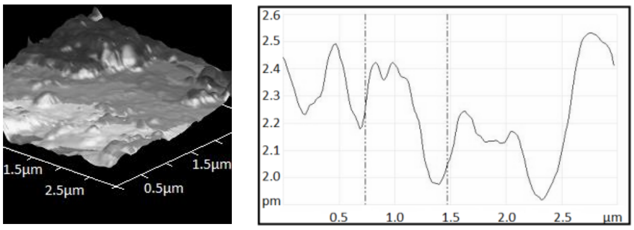

Fig 2: AFM Image of Polished Heat Sink

Figure 4 shows the photo of the heat sink. All dimensions are given in millimeters. The nanoparticles were deposited onto the top surface of the heat sink, and a transistor was mounted on it.

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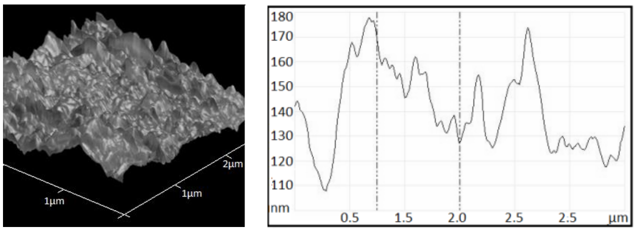

Fig 3: A Three-Micron AFM Image of Deposited Nanoparticles onto the Polished Heat Sink

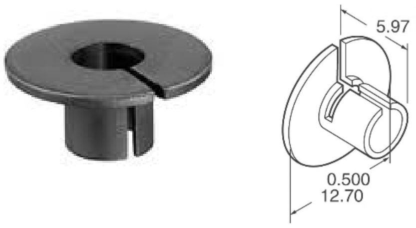

Fig 4: The Heat Sink's Photo and Dimensions in Millimeter
Courtesy of Mouser Electronics

III. RESULTS AND DISCUSSIONS

To find how the heat transfer in the heat sink was affected before and after nanoparticle deposition, a silicon Planar Epitaxial NPN Transistor (2N2222A) is used as a heat source. Figure 5 shows a transistor fixed-bias circuit.

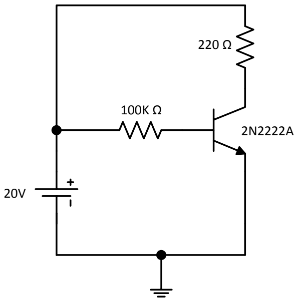

Fig 5: A Transistor Biasing

The power dissipated in the transistor is calculated by subtracting the total power dissipated in the base and collector resistors from the total power delivered by the power source (Eq. 1).

$$P_{diss} = P_{del} - P_{Rb} - P_{Rc} = 0.57 \text{ W} \qquad (1)$$

The transistor temperature was monitored using a conventional heat sink and a nanoparticle deposited heat sink by natural and forced convections. Figure 6 shows the difference in temperature by the means of natural convection. Each experiment was run three times at the same ambient temperature of 25°C. As shown in Figure 6, the device temperature was monitored for 180 seconds. The device temperature with a conventional heat sink approached the steady-state temperature of 73°C, and the device with the deposited copper nanoparticles reached 69°C, a drop and improvement of 4°C.

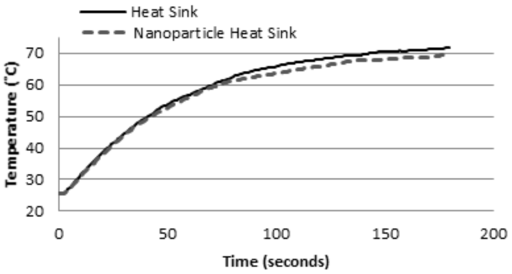

Fig 6: Natural Convection Heat Transfer

Next, a fan was used in a small wind tunnel to investigate the effect of forced convection on both conventional and nanostructured heat sinks. The experiment was conducted at two low and high air velocities, 2.9 m/s and 3.7 m/s.

Figure 7 shows the device temperature at low fan speed for three minutes. The device temperature with a conventional heat sink approached the steady-state temperature of 34.5°C, and the device temperature with the deposited copper nanoparticles onto the heat sink reached close to 33°C, a drop and improvement of 1.5°C.

And finally, Figure 8 shows the device temperature at high fan speed for three minutes. The device temperature with a conventional heat sink approached the steady-state temperature of 34°C from the ambient temperature and the device temperature with deposited copper nanoparticles onto the heat sink approached the steady-state temperature of 33.5°C, a drop and improvement of only 0.5°C.

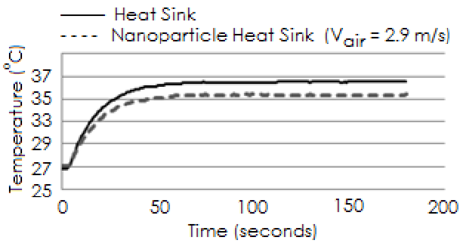

Fig 7: Forced Convection Heat Transfer (Low Fan Speed)

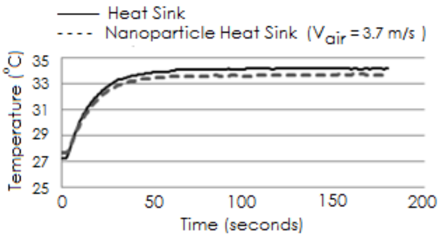

Fig 8: Forced Convection Heat Transfer (High Fan Speed)

Table I summarizes all three experiments (natural convection, low airflow and high airflow forced convections) with the temperature drop when the copper nanoparticle deposited heat sink was used.

Table I: Comparison Summary of Temperature Differences

	Difference in Temperature	Percentage improvement in Temperature (%)
Natural convection	4.0ºC	5.8
Low airflow (V_{AIR}= 2.9 m/s) forced convection	1.5ºC	4.5
High airflow (V_{AIR}=3.7 m/s) forced convection	0.5ºC	1.5

The heat transfer rate can be expressed by Eq. (2) where Q is the rate of heat transfer, A is the heat transfer surface area, h_c is the convective heat transfer coefficient and ΔT is the temperature difference between the surface and the surrounding air.

$$Q=h_c \, . \, A. \, \Delta T \qquad (2)$$

The convective heat transfer coefficient of air is expressed by the following imperial equation, Eq. (3), where V (m/s) is the air flow velocity [9] which graphically presented in Figure 9.

$$h_c = 10.45\text{-}V + 10\, V^{1/2} \qquad (3)$$

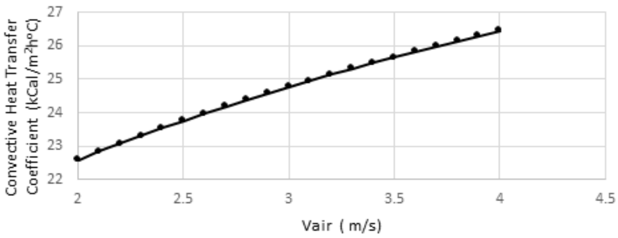

Fig 9: Convective Heat Transfer Coefficient as a Function of Air Velocity

The experimental results shown in Table I verify that the effect of the nanoparticle deposited surface in lowering the device temperature is more pronounced at the lower heat transfer coefficient. Since the total power dissipated is kept constant, it can be seen from Eq. 2 for all three cases for a given surface area, ΔT is inversely proportional to the heat transfer coefficient.

IV. CONCLUSION

Copper nanoparticles were deposited on a heat sink to investigate the rate of heat transfer by means of natural and forced convections as the surface area, at the molecular level, increased while the physical size of the heat sink remains the same. The device operating temperature was lowered about 6% by the means of natural convection. By the means of forced convection, 1.5% improvement in the device temperature was observed for higher air velocity and 4.5% for lower air velocity. As a result, the heat transfer rate improvement using nanoparticle deposition is more effective in natural convection than in forced convections.

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REFERENCES

[1] Wen, Dongsheng, and Yulong Ding. "Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions." International Journal of Heat and Mass Transfer 47.24 (2004): 5181-5188.

[2] Daungthongsuk, Weerapun, and Somchai Wongwises. "A critical review of convective heat transfer of nanofluids." Renewable and Sustainable Energy Reviews 11.5 (2007): 797-817.

[3] Manca, Oronzio, Yogesh Jaluria, and Dimos Poulikakos. "Heat transfer in nanofluids." Advances in Mechanical Engineering 2010 (2010).

[4] Chein, Reiyu, and Jason Chuang. "Experimental microchannel heat sink performance studies using nanofluids." *International Journal of Thermal Sciences* 46.1 (2007): 57-66.

[5] Chen, G., and Ali Shakouri. "Heat transfer in nanostructures for solid-state energy conversion." Transactions-American Society of Mechanical Engineers Journal of Heat Transfer 124.2 (2002): 242-252.

[6] Vashaee, Daryoosh, and Ali Shakouri. "Improved thermoelectric power factor in metal-based superlattices." *physical review letters* 92.10 (2004): 106103.

[7] Urban, F. K., A Hosseini-Tehrani, P. Griffiths, A. Khabari, Y.-W. Kim, and I. Petrov. "Nanophase films deposited from a high-rate, nanoparticle beam." *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures* 20.3 (2002): 995-999.

[8] Khabari, A., F. K. Urban III, P. Griffiths, I. Petrov, Y.-W. Kim and C. Bungay. "Nanoparticle beam formation and investigation of gold nanostructured films." *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures* 21.6 (2003): 2313-2318.

[9] Osczevski, Randall J. "The basis of wind chill." *Arctic* 48.4 (1995): 372-382