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Numerical Thermal Stress Analysis on Semiconductors with Nano-Fluid Coolant

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Numerical Thermal Stress Analysis on Semiconductors with Nano-Fluid Coolant

Luis Medina [α], Kevin Harvey [σ], Cory Davison [ρ], Edgar Rubio [Ѡ], Morteza Mohssenzadeh [¥], Hamidreza Ghasemi Bahraseman [§] & Taha Ghaemi Bahraseman [χ]

Abstract- During the course of normal operation, electrical components made from semiconducting materials undergo significant stress from heating. This causes parts to wear out more quickly or, in the more extreme cases, fail altogether. In order to maintain a stable operating temperature, many different types of cooling systems have been used. Our work investigates the best materials to use in these systems, carefully considering effectiveness, cost, and longevity in our assessment. Ansys simulation software was used to simulate the effects of different coolants on removing heat from a semiconductor. The coolants are air, water, and aluminum oxide. Though we didn't model the results of forced convection across these materials, the natural convection heat transfer results in finding the more efficient coolant. Considering liquid cooling methods for semiconductor-based devices, the kind of fluid plays a vital role in the transfer of energy. The Aluminum Oxide was selected in a 2% solution and 40nm wide particles to simulate for our nanofluid as it is commonly used in the industry and data for it was readily available. The aluminum oxide nanofluid had the best cooling performance of the three tested materials.

Keywords: thermal stress, nano-fluid aluminum oxide coolant, semiconductors.

I. Introduction

Because many of these components can only work properly within a relatively narrow temperature range, an entire industry has materialized that is dedicated to keeping them cool[1]. Consequently, a great deal of time and money has been spent researching the best materials for transferring energy from the delicate components and releasing it into another medium[2]. We entered this project with the goal of finding the most suitable materials for cooling semiconductor-based electrical components like CPUs. The two types of cooling methods examined are the use of heat sinks and pumped liquid cooling.

First, we examine cooling systems using heat sinks. Heat sinks transfer heat from the component via conduction and release that heat in the surrounding air through both convection and radiation. The primary factor in determining the effectiveness of a material for this process is its thermal conductivity, though thermal diffusivity is also a major factor[3]. The former determines the material's ability to transfer heat away from the source while the latter speaks to its ability to move the energy throughout itself, as well as radiate it away. Usually, heat sinks are used in a forced convection system with air being moved across the heat sink fin[4]. We examined several materials for this section and have arranged them within Table_1.

Table 1: Comparison of Suitable Heat Sink Materials [5, 6]

Metals:	Aluminum	Copper	CarbAl
Density	2.7 g/cm^3	8.96 g/cm^3	1.75 g/cm^3
Thermal Conductivity	205 W/mK	401 W/mK	400 W/mK
Thermal Diffusivity	0.84 cm^2/s	1.12 cm^2/s	2.78 cm^2/s
Comments:	Lightweight, decent conductivity, lackluster diffusivity	Excellent Thermal Conductivity, decent thermal diffusivity, relatively heavy	Very lightweight, Excellent Thermal conductivity, Excellent Thermal diffusivity

Though we didn't model the results of forced convection across these materials, from the data present the best material for transferring energy from a component is clearly CarbAl. With a low density reminiscent of aluminum and a thermal conductivity comparable to the much heavier copper, CarbAl provides the best attributes of both materials. Its thermal diffusivity is also significantly higher than the others, allowing for better energy flux throughout itself. This material was designed in 2008 by Applied Nanotech Inc. and remains a superior material for many applications, including heat sinks for high end applications.

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II. NANOFLUID SIMULATION

With regards to liquid cooling systems for semiconductor-based devices, the type of fluid plays a significant role in the transfer of energy. We selected Aluminum Oxide in a 2% solution and 40nm wide particles to simulate for our nanofluid as it is commonly used in the industry and data for it was readily available [7] [8]. The properties of the Materials used (simulated) in this study are provided in tables 2, 3 and 4. Boron-doped silicon and phosphorus-doped silicon, Air, Water, Aluminum oxide nanoparticles for nanofluid.

Table 2: Properties of Materials Common to Liquid Cooling Systems [9]

Fluids	Air	Water	Al_3O_2 Nanofluid
Density	1.225 kg/m^3	998.2 kg/m^3	3.95 g/cm^3
Thermal Conductivity	0.0242 W/mK	0.6 W/mK	30 W/mK
Specific Heat	1006.43 J/kg-K	4182 J/kg-K	541-955 J/kg-K
Convection Heat Transfer Coefficient	1000 W/(m^2-K)	3001 W/(m^2-K)	9000 W/(m^2-K)

Table 3: Properties of Semiconductor [4]

Density	2.33 g/cm^3
Specific heat	0.168 Cal/g-K
Thermal Conductivity	149 W/m-K
Thermal Expansion	2.6 μm/m-K
Young's Modulus	51-80 GPa
Poisson's Ratio	0.064-0.28

Table 4: Nanoparticles Properties

Aluminum Oxide Al_2O_3 99+% purity, 80 nm radius [9]	
Crystallographic Structure	Rhombohedral
Density	3.97 g/cm^3
Thermal Conductivity	18 W/ mol-K
Specific Heat	880 J/kg-K
Price	$55 / 100 gram
Tin Oxide SnO_2 99.9% purity, 50-70 nm radius [10]	
Crystallographic Structure	Tetragonal
Density	6.95 g/cm^3
Thermal Conductivity	40 W/ mol-K
Specific Heat	44.3 J/mol-K
Price	$110 / 100 gram
Silicon Oxide SiO_2 99.9% purity, 800 nm radius [11]	
Crystallographic Structure	Amorphous
Density	2.65 g/cm^3
Thermal Conductivity	1.1-1.4 W/ mol-K
Specific Heat	1.01 J/g-K
Price	$98 / 100 gram

III. ANSYS ANALYSIS SETUP & METHODOLOGY

Simulation was done using convection to transfer heat from SM to cooling fluid. Convective heat transfer coefficient (h_c) was used the principal property of fluid for simulation.

We found that this coefficient depended type of medium such as gas or liquid, flow properties such as velocity, viscosity and other flow and temperature dependent properties [8].

Many of the research papers we found used other values and coefficients that are the norm in the field of thermodynamics. Nusselt, Rayleigh, and Reynolds numbers were discussed in these papers, however, since these are out of the scope of this class, we decided to use convection [12-14]. The terms stated above do depend on convection so it's not as to completely ignore the experimental results from researchers; convection allowed us to simplify our model.

Main purpose was to compare the cooling capabilities of air, water, and nanofluids by forced convection. Finding comparable values for the heat transfer coefficients (HTC) of each of these values was a problem, mainly because it was difficult to find experimental results that had been performed under the same conditions [12-15]. However, we were able to find papers that contained the information for water and aluminum oxide nanofluids although there were calculations needed as well as estimating values from graphs demonstrating results. These papers contained the needed coefficients for water and Al-Ox under similar conditions such as mass flow (1.5 liters per minute) and temperature (40℃) therefore we could use comparable values for their respective HTCs [7, 8].

A simplified geometry was used in the simulation. The actual geometry of a transistor (our example for semiconductor) was convoluted. In addition, the electronic components had to be omitted from the modeling because the focus was on thermal impact and because it was simpler to declare one region of the geometry as the heat source. Another simplification had to do with energy bands, to understand and model such concept, an understanding of Fermi function, Fermi-Dirac distribution, Boltzmann approximation, and electron concentration under different temperature conditions [12-15].

What we expected to see in the ANSYS Fluent heat maps was the heat dissipated from the source out through the boundaries making contact with the fluid. However, this was not the case the first few times that we ran the simulation. This was due to the geometry of our model; we had placed one geometry meant to represent the fluid above the geometry representing the semiconductor. There was an issue with the boundary where the surfaces met and thus, we decided to change our approach by convection.

Once we read up on how convection worked, we could set up our model an analogous fashion [5]. This resulted in a simpler model where only a single geometry was needed which was meant to represent the semiconductor.

Using ANSYS Fluent, the mesh was imported and given three different boundaries. The bottom edge along with both vertical edges were all labeled “outlet boundary” meaning these edges were to make contact with our test fluids (air, water, nanofluid). The top edge was the heat source; it was meant to be analogous to the conduction band on a transistor although in reality the situation is complex [15]. The surface of the body was the third boundary and this is where the properties of a semiconductor were applied to.

IV. Results

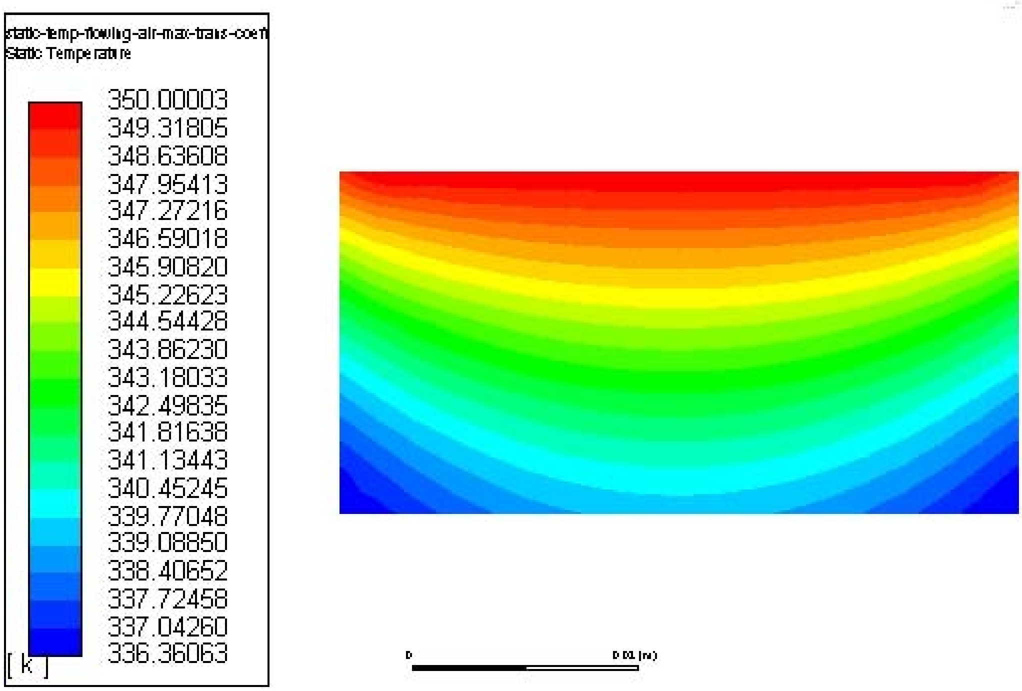

Figure 1: Static Temperature Contour for air with heat transfer coefficient of 1000 W/m^2-K

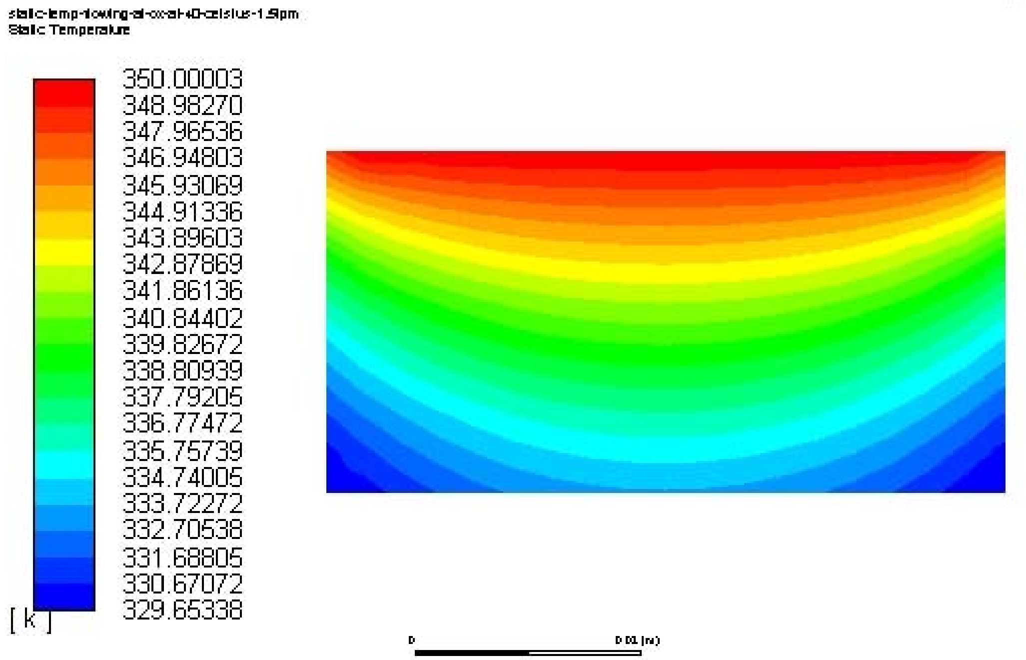

Figure 2: Static Temperature Contour for Water with heat transfer coefficient of 3000 W/m^2-K

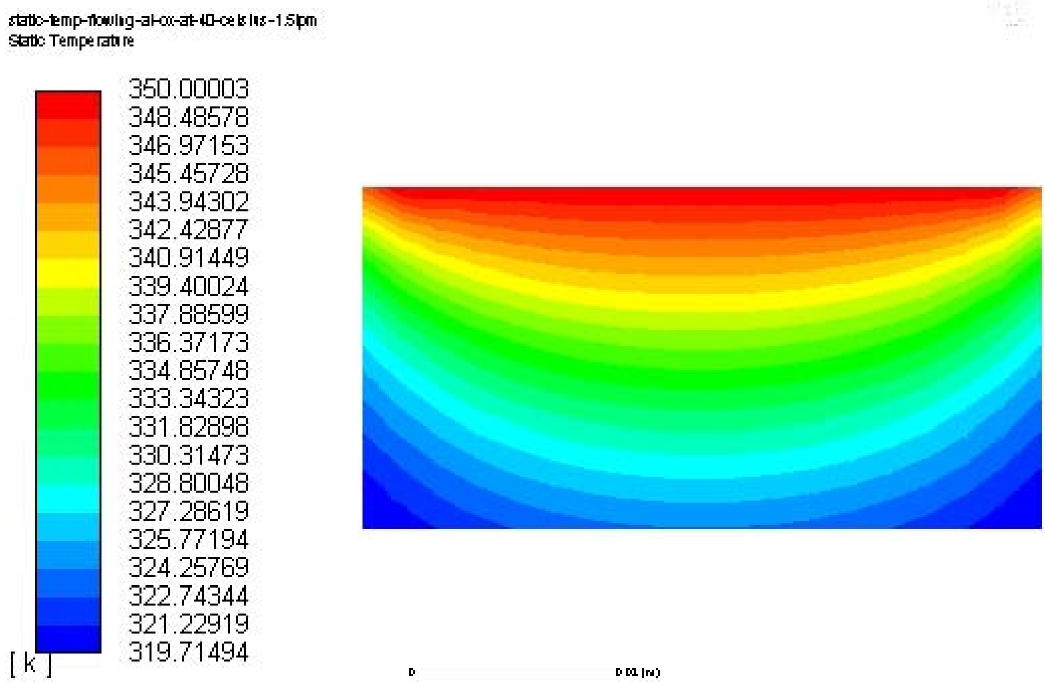

Figure 3: Static Temperature for Al-Ox Nanofluid with heat transfer coefficient of 9000 W/m^2-K

A nanofluid composed of 98% water and 2% aluminum oxide (of particle size 40nm) showed significant improvement (Figure 3) in the rate of heat transfer over water (Figure 2) and air (Figure 1). Faiza Nazir's results showed a 200% improvement over water's rate of heat transfer [7].

V. Discussion

According to a handful of the research papers and experimental reports, the principal variables that accounted for the nanofluid's superior performance included: intensification of turbulence or eddy, suppression or interruption of the boundary layer as well as dispersion or back mixing of the suspended nanoparticles, in addition to the nanoparticles' thermal conductivity and heat capacity [12].

VI. Conclusion

The Al_3O_2 (40nm @ 2% volume) nanofluid had the best cooling performance of the three tested materials.

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