Microelectronics Journal 64 (2017) 19–28

Contents lists available at ScienceDirect

Microelectronics Journal

journal homepage: www.elsevier.com/locate/mejo

Effect of cooling fluids on high frequency electric and magnetic fields in microelectronic systems with integrated TSVs

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ARTICLE INFO

Keywords:
Electronics cooling
Integrated TSV
Electromagnetic field
Electro-magneto fluid dynamics

ABSTRACT

A fully 3D conjugate numerical analysis was performed to reveal the effects of air, R134a refrigerant and water on electromagnetic fields of electronic cooling designs made of arrays of micro pin-fins with integrated Through-Silicon-Vias (TSVs). The integrated TSV cooling configuration included 8 cylindrical TSVs with 150 μm diameter each and 200 μm height. The external dimensions of the silicon substrate were 900 × 700 × 280 μm. Each TSV encapsulated four equally spaced copper vias each having a diameter of 40 μm. The impacts of the presence of the stationary cooling fluids without heat transfer on TSVs electric and magnetic fields were examined for five different frequencies; 100 MHz, 500 MHz, 1 GHz, 5 GHz and 10 GHz. Then, separately, the effects of moving cooling water with temperature-dependent physical properties were studied while exposing the cooled micro pin-fin array to a uniform heat flux of 500 W cm^{-2}. For the case of stagnant and moving cooling fluids it was found that water influences the electric field twice as much as either R134a or air and that this influence decreases only negligibly with the increase in frequency of the electric current passing through the TSVs. The influence of the presence of the stagnant and moving cooling fluids on the magnetic field is orders of magnitude smaller and reduces rapidly with the increased frequency.

1. Introduction

Thermal management challenges facing electronic cooling developers [1,2] are currently at the confluence of chip power dissipation well above 100 W cm^{-2} as background heat flux, and localized hot spots with more than 1000 W cm^{-2} fluxes. Several approaches were proposed for cooling such high power chips with multiple hot spots, which has opened a door for new hyper integrated smart systems [3]. In this paper, we will focus on the micro-electronic forced convection cooling concept that uses arrays of micro pin-fins representing Through Silicon Vias (TSVs) [4]. Three-dimensional TSV-based integration has shown very promising results in terms of performance, functionality and power consumption in electronic packaging. In a recent study, Abdoli et al. [5] performed 3D thermo-fluid-stress analyses using different shapes for TSV cross sections to improve the heat transfer and reduce required pumping power. Later, Reddy et al. [6] applied multi-objective optimization techniques to find the optimal micro pin-fin cooling configurations for high heat flux chips with a hot spot.

One of the interesting phenomena occurring in this type of cooling systems, and yet to be studied, is the interaction between the electric, magnetic, thermal and pressure fields involved. Savidis et al. [7], He and Lu [8], Xie and Swaminathan [9], He et al. [10] and Xie et al. [11] investigated voltage drops in power delivery network for TSV-based 3D integration packages. It is well understood that electric fields and magnetic fields can influence the flow-field and consequently the heat transfer [12]. This area has been well researched and is known as electro-magneto-fluid dynamics [13].

An even more intriguing issue is the answer to a potentially important question: is it possible for the cooling fluid and its flow-field and temperature field to influence the imposed high frequency electric and magnetic fields in the TSVs? This possible "reverse" interaction is especially intriguing for very small systems such as micro-electronics cooling where the electric and magnetic signals transmitted through TSVs should not be altered by any possible electric and magnetic fields induced by the either stationary or moving and temperature-dependent cooling fluid. Xei et al. [11] performed an electrical-thermal modeling of TSV arrays in case of pure conduction with no cooling fluid involved. They reported that the temperature dependency of material properties such as the silicon conductivity cannot be neglected for TSV array design. At least in the case of 2D magnetohydrodynamic flows, it was shown analytically that such "reverse" interaction is possible when electric conductivity of the cooling fluid is temperature-dependent [14,15].

The aim of this paper is to address the question of sensitivity and magnitude of such "reverse" influence of the various common stagnant

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http://dx.doi.org/10.1016/j.mejo.2017.03.015
Received 28 November 2015; Received in revised form 13 February 2017; Accepted 30 March 2017

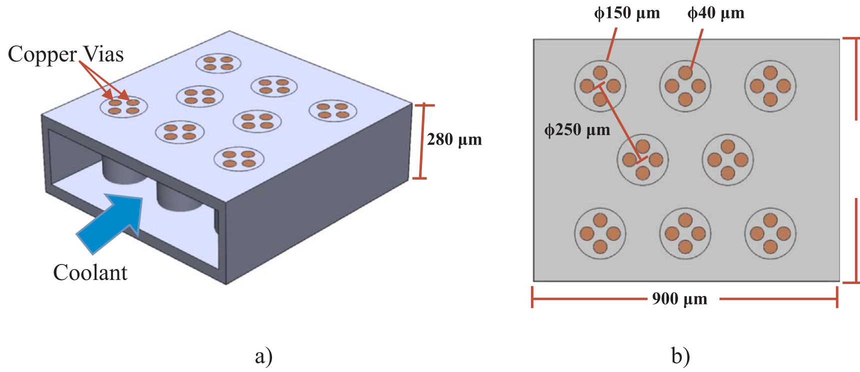

Fig. 1. Single stack cooling design with integrated TSVs, a) 3D view, b) top view with dimensions.

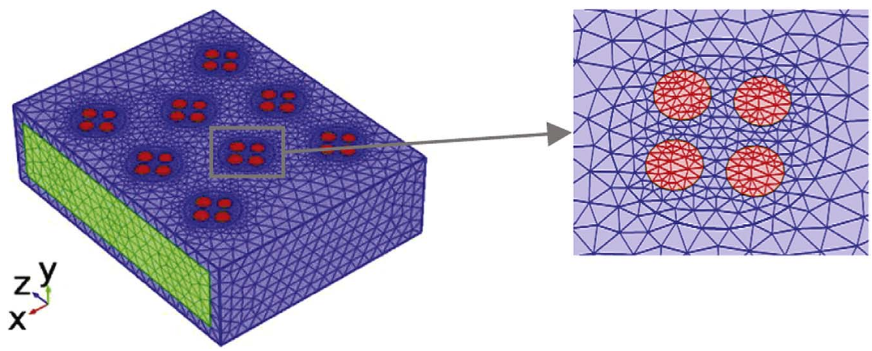

Fig. 2. Hybrid computational grid with an enlarged view of a single TSV and the four imbedded vias.

and moving cooling fluids on the applied electric and magnetic fields passing through the TSVs. The answers will be found by performing fully conjugate three-dimensional numerical simulations using an elementary electro-magneto-hydro-dynamics model based on the Navier-Stokes equations and Maxwell equations. Impacts of three different fluids (air, R134a liquid refrigerant and water) on electric and magnetic fields of TSV-based electronic integration packages were investigated for five different frequencies of the electric and magnetic fields in the range between 100 MHz and 10 GHz.

2. Design and methodology

A single stack cooling system with 8 integrated micro pin-fins (Fig. 1) was virtually designed for numerical simulations. Silicon was used for the substrate material and the micro pin-fins.

Fig. 1a illustrates all micro pin-fins and copper vias arrangements on the array with dimension of 900 µm × 700 µm (Fig. 1b). As this figure depicts, total height of silicon substrates was 280 µm. Fig. 1b shows the spacing between the micro pin-fins, and diameters of micro pin-fins and copper vias.

Maxwell's equations were the governing equations for multi-domain electromagnetic simulations

$$\nabla . D = \rho \tag{1}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{2}$$

$$\nabla . B = 0 \tag{3}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \tag{4}$$

Here, ρ is the electric charge density, E is the electric field, D is the electric displacement field, J is the electric current, B is the magnetic field and H is the magnetic flux density. To solve these equations, material constitutive relations are required which relate electric field (E) to electric displacement field (D), current (J) to electric field (E), and magnetic field (B) to magnetic flux density (H).

The applied electric field and magnetic field frequencies in the range of 100 MHz and 10 GHz correspond to wavelengths between 3 cm and 3 µm in vacuum. Therefore, the AC/DC analysis module in COMSOL Multiphysics software [16] was the proper module to use for simulations. This module integrates the frequency domain form of the magnetic fields interface, as follow

$$\nabla \times \mu^{-1}(\nabla \times A) + (j\omega\sigma - \omega^2\varepsilon)A = J_s \tag{5}$$

Here, μ is magnetic permeability, ε is electric permittivity, ω is frequency, σ is electric conductivity, A is magnetic vector potential, J_s is the source current. The following equations are solved for the electric field and induced current

$$E = j\omega A \tag{6}$$

$$J_i = \sigma E \tag{7}$$

Here, J_i is the induced current. In order to integrate the Eqs. (1) through (5) using finite element technique, all solution domains have to be discretized spatially and temporally. Fig. 2 illustrates the hybrid computational grid generated by the COMSOL Multiphysics software. Fig. 2 (left) shows the grid in the entire solution domains. Fig. 2 (right) shows an enlarged view of the grid inside and around one of the silicon pin-fins with four imbedded copper vias. Total number of degrees of freedom for each of the analysis computations was 4233637.

He and Lu [8] studied the voltage drop for different number of TSVs. They reported around 2.5 mV voltage drop for 4 TSVs and 1 mV voltage drop for 8 TSVs. They showed that voltage drop decreases by increasing the number of TSVs up to 16 TSVs. They did not take into account the effects of the cooling fluid.

In this paper, voltage drop of 1 mV was assumed for copper vias. The direction of voltage drop was set in the opposite of y-axis. The rest of boundary surfaces were assumed to be electric insulators. In the following sections, results of fully 3D conjugate numerical simulations for each of the three fluids are presented separately.