Electrical and Joule heating relationship investigation using Finite Element Method

S K Thangaraju, K M Munisamy

Universiti TenagaNasional, Jalan IKRAM-UNITEN, 43009, Kajang, Selangor.

Email: savithry@uniten.edu.my, kannan@uniten.edu.my

Abstract: The finite element method is vastly used in material strength analysis. The nature of the finite element solver, which solves the Fourier equation of stress and strain analysis, made it possible to apply for conduction heat transfer Fourier Equation. Similarly the Current and voltage equation is also liner Fourier equation. The nature of the governing equation makes it possible to numerical investigate the electrical joule heating phenomena in electronic component. This paper highlights the Finite Element Method (FEM) application onto semiconductor interconnects to determine the specific contact resistance (SCR). Metal and semiconductor interconnects is used as model. The result confirms the possibility and validity of FEM utilization to investigate the Joule heating due electrical resistance.

1. Introduction

The current challenge in on-chip interconnects is high temperature due to self-heating or resistive heating or it is also called Joule heating. The quote from Texas Instrument personnel, Mr. Siva (Gurrum, et. al. 2008) supports the motion. Thus, in this research the thermal distribution in semiconductor interconnects due to electrical current will be investigated in Finite Element Method (FEM) and experimental analysis.

There are several literatures reported on Joule heating recently. Read, 2009 has done a research work on Joule heating which was applied onto copper interconnects and the von-Misses strain level was investigated (Read et.al. 2009). When the liner material gets thinner the higher temperature is reached atthe interconnect. And the liner material property influence the temperature profile in the interconnects. But he has not looked at the specific contact resistance effects on the thermal distribution. Pedro in 2011 has reported a study on Joule heating in nanotube (Pedro et. al., 2011). He has made actual-imaging on joule heating but only restricted on the edge and outer surfaces. High current density in interconnects rises the temperatures. Tiedmann uses Scanning Joule Expansion Microscopy (SJEM) and FEM to investigate thermal distribution on aluminum interconnects (Tiedmann et. al., 2009). The expansion in the interconnect is used to validate the FEM model and ANSYS is used for thermal analysis. However, the specific contact resistance and temperature distribution at depletion region is not covered. It is also important to look at Broe’s work, who has studied specifically on the ohmic contact resistance but between metal-metal contact temperatures (Broe et. al., 2010). He has the simple geometry of Ruthenium and Gold, and he has experimentally measured temperature of the material and contact resistance. He has highlighted that as the current density increases the temperature and changes the specific contact resistance value. The softening
temperature is made as failure criteria for the test at each current density. This model is a good candidate for the current FEM model validation.

From the literature reviewed, the paper investigate the thermal effect due to Joule heating in 3-Dimensional interconnect via using Finite Element Method (FEM) to improve the thermal distribution through the specific Contact Resistance (SCR) between different material.

A simple geometry is chosen to investigate the effect of SCR in simple semiconductor and metal interface. The geometry of the simple semiconductor to metal structure built in Finite element Abaqus. Different electrical resistivity value applied on the semiconductor and metal. The conductivity value is calculated for the semiconductors and metal for both electrical and thermal. The FEM is used to carry out the electrical analysis using the Fourier Equation then the heat analysis to investigate the thermal distribution at the SCR region or the hot spots.

2. Background Theory

The electrical Fourier equation is given below in Eq. 1. The equation is solved using Finite element method. The property of current conductivity, \( \sigma \) is defined and Voltage at one surface is given as well.

The current flux distributions from the element are used to calculate the heat flux or joule heat value at each elements using Eq. 2. The calculated heat flux value is then used as input file for heat analysis to obtain temperature distribution by solving Eq. 3. Table 1 shows the similarity of the Fourier Equation for electrical and thermal analysis in FEA.

| Equation 1 | Equation 2 |
|------------|------------|
| **Electrical analysis**<br>\( J_x = \frac{\sigma V}{\Delta x} \) Where,<br>\( J_x \), Current flux, Amp/\( \mu m^2 \)<br>\( \sigma \), Conductivity<br>\( \rho \), resistivity, \( \Omega \mu m \)<br>\( \Delta x \), spatial coordinate in the direction of current flow, (\( \mu m \))<br>\( V \), volt | **Joule heating calculation**<br>\( G = J^2 \rho \) where<br>\( G \), Joule heat power, (W/\( \mu m^3 \))<br>\( J \), Current density (mA/\( \mu m^2 \))<br>\( \rho \), electrical resistivity, (\( \Omega \mu m \)) |

| Equation 3 |  |
|------------|  |
| **Heat Analysis**<br>\( H = k \frac{\partial T}{\partial n} \) where<br>\( H \), Heat Flux, (W/\( \mu m^2 \))<br>\( T \), Temperature (K)<br>\( n \), spatial coordinate in the direction of current flow, (\( \mu m \))<br>\( k \), material thermal conductivity (W/(\( \mu m.K \))) |

3. Model Development

A simple geometry is chosen to investigate the effect of SCR in simple semiconductor and metal interface. The Figure 1, Figure 2, and Figure 3 shows the geometry of the simple semiconductor to metal structure built in FEM platform. The Table 1 illustrates the electrical resistivity used for semiconductor and metal. Table 2 shows semiconductor and metal calculated conductivity value for both electrical and thermal. Next Table 3 shows the SCR value used and Table 4 summarize the electrical and conductivity value applied at the SCR region in FEM (Abaqus).
**Figure 1.** Simple semiconductor to metal contact geometry – view in Z-X and X-Y plane

| Table 1: The electrical resistivity used for semiconductor and metal |
|---------------------------------------------------------------|
| **Material** | $\rho_s$ $(\Omega \cdot cm)$ | $\rho_s$ $(\Omega \cdot \mu m)$ |
| Silicon   | $4.5 \times 10^{-6}$ | $4.5 \times 10^{-2}$ |
| Aluminum | $4 \times 10^{-6}$ | $4 \times 10^{-2}$ |

| Table 2: The electrical and thermal conductivity used for semiconductor and metal |
|-----------------------------------------------------------------------------|
| **Material** | Electrical conductivity, $\sigma$ | Thermal conductivity, $k$ |
| -------------------------- |-----------------|-----------------|
| Silicon        | $222.22 \times 10^3$ | 148 | $1.48 \times 10^{-4}$ |
| Aluminum       | $250 \times 10^3$ | 25 | $2.50 \times 10^{-4}$ |

| Table 3: The Specific Contact Resistance (SCR) value used for Semiconductor to metal interface |
|------------------------------------------------------------------------------------------------|
| **Interface** | $\rho_s$ $(\Omega \cdot cm^2)$ | $\rho_s$ $(\Omega \cdot \mu m^2)$ |
| Silicon-Aluminum | $1 \times 10^{-6}$ | $1 \times 10^{-2}$ |

| Table 4: The electrical and thermal conductivity value applied for SCR - baseline |
|-----------------------------------------------------------------------------|
| $\rho_s$ $(\Omega \cdot \mu m^2)$ | $1 \times 10^{-2}$ |
| $R_c = \rho_s \times \text{area (}\Omega\)$ | $1 \times 10^{-2}$ |
| $R_c \times \text{thickness (}\Omega \cdot \mu m)$ | 2 |
| SCR electrical Conductivity $(\Omega \cdot \mu m)^{-1}$ | 0.5 |
| SCR Thermal Conductivity (W/(\mu m.K)) | $2.00 \times 10^{-4}$ |
Table 5: Varying SCR values configuration used

| SCR Rho-c (Ω.cm²) | SCR-1 | SCR-2 | SCR-3 | SCR-4 |
|------------------|-------|-------|-------|-------|
| SCR Rho-c (Ω.µm²) | 1.00E-06 | 1.00E-07 | 1.00E-08 | 5.00E-08 |
| Area of interface(µm²) | 1 | 1 | 1 | 1 |
| Resistor | 100 | 10 | 5 | 5 |
| Thickness (µm) | 0.02 | 0.02 | 0.02 | 0.02 |
| Resistor X thickness (Ω.µm) | 2 | 0.2 | 0.02 | 0.1 |
| SCR electrical conductivity (Ω.µm)⁻¹ | 0.5 | 5 | 50 | 10 |

Figure 3 shows the computational model of the simple semiconductor to metal geometry with fully meshed and boundary conditions and loads imposed. In Abaqus for electrical analysis the current density at the surface is given as 1 Amp/ (µm)². That makes the total current at the surface is 1Amp for 1µm X µm area. And for the heat analysis the Joule heating will be the heat flux at all the nodes and the boundary temperature is set to be 308 K at both end side of the geometry.

Figure 2. Computational model developed with mesh boundary conditions and Load setting in Abaqus.

Result and Discussion

SCR = 1 X 10⁻⁶ (Ω.cm²)

The Figure 5 shows the electrical potential distribution output from electrical analysis. The blue color indicates the zero electrical potential which was set in the boundary condition. The opposite side has the highest voltage of 0.465 Volt. Figure 6 below is the final heat flux distribution due to heat sink application. The input for the calculation would be the Joule heating as in the Eq. 2. The highest heat flux value is at the bottom part of silicon (semiconductor) with values of 0.254 W/( µm.K). The interface has the lowest heat flux value of 0.00119 W/( µm.K).
Voltage Distribution

Heat flux distribution

Figure 3: Output of electrical analysis – Electrical potential in Volts

Figure 4: Heat flux distribution in W/(µm.K)

Temperature distribution from Heat Analysis

The temperature distribution in Figure 6 shows the temperature output from heat analysis, from Eq. 3. The boundary temperature is 308K as set initially. The interface region has recorded highest temperature of 628K, temperature difference of 320K.

Figure 5. Temperature distribution – from heat analysis in (K).

Table 6: Summary highest Temperature recorded in the model with varying SCR.

| SCR value | 1 X 10^{-6}(Ω.cm^{2}) | 1 X 10^{-7}(Ω.cm^{2}) | 1 X 10^{-8}(Ω.cm^{2}) | 5 X 10^{-8}(Ω.cm^{2}) |
|-----------|------------------------|------------------------|------------------------|------------------------|
| Temperature Difference (K) | 320                    | 279.9                  | 276                    | 277.7                  |
Conclusion

It can be concluded that the electrical analysis and heat analysis can be done using FEM software. However, a subroutine is needed to input the output value of heat flux from electrical analysis into heat analysis. The Fourier equation for electrical and heat conduction is solved separately to obtain the temperature output.

The varying SCR value has confirmed that the temperature distribution is changing with SCR value. And the Figure 6 and Table 6 show that the relationship between the Rho-c value of SCR and temperature difference is linear.

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Figure 6. Rho-c of SCR against temperature difference
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