An Electrothermal Lumped Modeling Approach for Thin Bond Wires in Microelectronic Chip Packages

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In this proposal, we suggest a method for the numerical simulation of problems containing multi-scale structures. The necessity of very fine meshes is mitigated by modeling the resulting singularities with a lumped element approach. In particular, the embedding of a 1D structure in a 3D setting is addressed here. The 1D-3D interface is established by using de Rham currents in the continuous and nodal Whitney functions in the discrete setting. For an application example, thin bond wires in a microelectronic chip package are considered for electrothermal co-simulation. First results for the linear electrokinetic case are given.

***Index Terms*—bond wires, de Rham currents, electrothermal coupling, modeling, multi-scale, singularities**

I. Introduction

NOWADAYS, with the continuous shrinking of feature sizes in electronics, current densities increase and thus thermal issues arise. In this proposal, we consider the electrothermal simulation of microelectronic chip packages that contain very thin bond wires as shown in Fig. 1a. This setting is numerically challenging due to the 1D-like geometry of the wires. Such a multi-scale problem can be addressed, e.g., with a 1D-3D coupling.

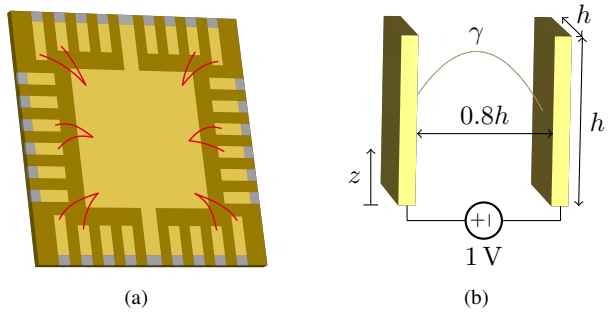
In this work, following [1], we use a 1D network representation for the wires, which we interpret as an electric circuit. Other approaches to incorporate thin wires into the simulation have been proposed for high-frequency applications [2]. The aim of this work is to embed the microelectronics application into the general and rigorous mathematical framework given in [1]. As a result, new discretization strategies become evident and important properties of the numerical scheme, in particular error convergence rates, can be obtained. Specifically, we consider an electrothermal coupling, allowing for the verification of thermal designs.

II. Continuous Formulation

In this work, we neglect magnetic and capacitive effects and consider the coupling of the electrokinetic problem with the static heat equation. For the time being, we additionally neglect the bond wire contribution and consider

$$\nabla \cdot \vec{J}_\sigma(\varphi) = 0, \quad \nabla \cdot \vec{J}_\lambda(T) = Q(\vec{J}_\sigma, T), \tag{1}$$

with suitable boundary conditions. The variables introduced in (1) are the electric potential φ, the electric and thermal current densities $\vec{J}_\sigma$ and $\vec{J}_\lambda$, respectively, the temperature T and the Joule losses Q. The electric and thermal conductivities σ and λ are modeled to be temperature dependent. Due to the comparably small diameter of the bond wires, we treat them using an external 1D model connected to the computational domain D. To represent arising singularities appropriately, de Rham currents [3] are used. They allow to express a current density $\vec{J}$ and a line current I by the 1-currents



(a) (b)

Fig. 1. (a) Microelectronic chip package with applied bond wires and (b) test structure of a bended wire that connects two electrodes.

$$\mathcal{J}(\vec{v}) := \int_D \vec{J} \cdot \vec{v} \ \mathrm{d}\mathbf{x} \quad \text{and} \quad \mathcal{I}(\vec{v}) := \int_\gamma I\vec{t} \cdot \vec{v} \ \mathrm{d}\mathbf{x},$$

with $\vec{v} \in (C_0^\infty(D))^3$, the unit tangent vector $\vec{t}$ and an arbitrary curve γ. To model a bond wire, we identify γ as the wire's curve and I as its current. Adding the bond wire contribution to (1), we obtain

$$\boldsymbol{div}(\mathcal{J}_\sigma + \mathcal{I}_\sigma)(v) = 0, \tag{2a}$$
$$\boldsymbol{div}(\mathcal{J}_\lambda + \mathcal{I}_\lambda)(v) = \left(\mathcal{Q} + \mathcal{Q}^{\mathrm{bw}}\right)(v), \tag{2b}$$

for all $v \in C_0^\infty(D)$, where $\boldsymbol{div}$ refers to the divergence in the sense of distributions. Here, $\mathcal{Q}$ and $\mathcal{Q}^{\mathrm{bw}}$ are de Rham 0-currents representing the Joule losses Q from the distributed (3D) and from the bond wire (1D) part, respectively.

III. Discretization

To solve the problem presented in Section II, a discretization scheme is required. We first describe the 1D discretization of the wire before explaining the interface to the 3D part. Note that the 3D discretization can be carried out by any applicable scheme, as, e.g., finite differences, finite integration, finite elements and others.

A. 1D Wire

If a spatial discretization is used, a bond wire either needs to be resolved by the 3D mesh or both meshes must be interconnected. Here, we follow the latter approach and model the wire as a series connection of N^{lum} lumped resistors with a 1D discretization of its current, see Fig. 2. This scheme can be understood as a 1D finite element discretization of the wire and we connect it to the 3D discretization by using $(N^{\text{lum}}+1)$ coupling points along its path. The herewith introduced 1D discretization error can be controlled by the choice of N^{lum} and the number of 3D mesh cells.

B. 1D-3D Interface

In the following, we exploit the analogy of the electric and thermal case and use a notation that represents both cases. After the 1D discretization of a single wire was introduced, it needs to be embedded into the 3D discretization of the full model. Using the same symbols for continuous and discrete de Rham currents, the discrete representation of (2) is given by

$$\boldsymbol{div}\,(\mathcal{J}+\mathcal{I})\,(\mathcal{W}_k)=0,\quad k=1\ldots N^{\text{N}},$$

with N^{N} primary grid nodes and $\mathcal{W}_k$ being the nodal Whitney function. For node P_k, the discrete divergence of the wire current reads

$$\begin{aligned}\boldsymbol{div}\,\mathcal{I}(\mathcal{W}_k) &= -\sum_{j=1}^{N^{\text{lum}}} \overline{I}_j\left((\mathbf{R}_{\text{P}}^{\text{bw}})_{j+1,k}-(\mathbf{R}_{\text{P}}^{\text{bw}})_{j,k}\right)\\ &= -((\overline{\mathbf{G}}\mathbf{R}_{\text{P}}^{\text{bw}})^{\top}\overline{\mathbf{I}})_k,\end{aligned}$$

where $\overline{\mathbf{G}}$ is the gradient matrix and $\overline{\mathbf{I}}$ the current vector of the wire. $\mathbf{R}_{\text{P}}^{\text{bw}}$ denotes the operator that connects the 1D wire model to the 3D grid. If the 1D-3D coupling point does not coincide with a grid node, the connection is established by an interpolation scheme using, e.g., the evaluation of nodal Whitney functions. With the potential and temperature vectors $\boldsymbol{\varphi}$ and $\mathbf{T}$, respectively, and $\mathbf{X}^{\text{bw}} := \overline{\mathbf{G}}\mathbf{R}_{\text{P}}^{\text{bw}}$ and $\overline{\mathbf{I}} = \overline{\mathbf{M}}\mathbf{X}^{\text{bw}}\boldsymbol{\varphi}$, the discrete system with bond wire contribution is given by

$$\begin{aligned}-\mathbf{G}^{\top}\mathbf{j}_{\sigma}(\boldsymbol{\varphi})+(\mathbf{X}^{\text{bw}})^{\top}\overline{\mathbf{M}}_{\sigma}\mathbf{X}^{\text{bw}}\boldsymbol{\varphi}&=\mathbf{0},\\ -\mathbf{G}^{\top}\mathbf{j}_{\lambda}(\mathbf{T})+(\mathbf{X}^{\text{bw}})^{\top}\overline{\mathbf{M}}_{\lambda}\mathbf{X}^{\text{bw}}\mathbf{T}&=\mathbf{Q}+\mathbf{Q}^{\text{bw}},\end{aligned}$$

where $\mathbf{G}$ is the 3D gradient matrix and $\mathbf{j}_{\{\sigma,\lambda\}}$ are the discrete currents in the 3D part. $\overline{\mathbf{M}}_{\{\sigma,\lambda\}}$ contains the conductance values of the 1D circuit elements and $\mathbf{Q}$ and $\mathbf{Q}^{\text{bw}}$ are the discrete Joule losses from the 3D and the 1D model, respectively. This problem is closely related to the one presented in [1].

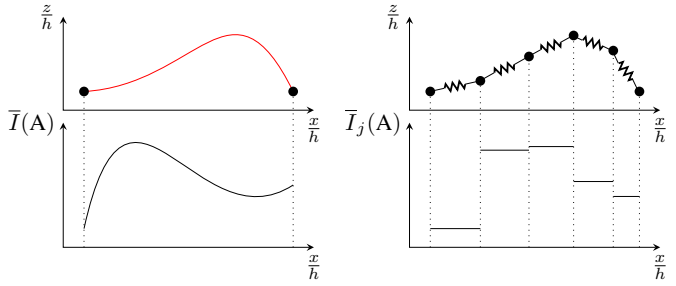


Fig. 2. Bond wire model of N^{lum} lumped elements and its discretized current.

TABLE I
JOULE POWER $\widehat{Q}$ WITH THE WIRE FRACTION α.

		in-house	CST
α	$3\cdot10^{-3}$	3.79 W	3.80 W
	$5\cdot10^{-3}$	10.51 W	10.56 W

IV. Numerical Validation

For a first validation, the proposed method was applied to the linear electrokinetic problem. As a test structure, a thin bended copper wire of thickness d that connects two copper electrodes of height $h = 1\,\text{cm}$ was used and a voltage of $1\,\text{V}$ was applied (c.f. Fig. 1b). The remaining space is filled by an epoxy mold with $\sigma = 10^{-6}\,\text{S/m}$. Since the validity of the singular 1D wire model is given by the relative dimension of the wire thickness compared to the size of the full model, the fraction $\alpha = d/h$ instead of the absolute wire thickness is used.

For the spatial discretization, a regular orthogonal Cartesian hexahedral mesh is applied. Using an equidistant distribution of the mesh nodes in each coordinate direction and with the 1D-3D connections points giving additional nodes, an almost homogeneous mesh with $2.86\cdot10^6$ cells is obtained. As a reference, the CST EM STUDIO® was used to compute a solution with a resolved wire using a fine mesh with local and adaptive refinement.

The quantity of interest is given by the Joule loss power of the 1D and 3D part and has been calculated by

$$\widehat{Q} = -\boldsymbol{\varphi}^{\top}\mathbf{G}^{\top}\mathbf{j}_{\sigma}(\boldsymbol{\varphi}) + \boldsymbol{\varphi}^{\top}(\mathbf{X}^{\text{bw}})^{\top}\overline{\mathbf{M}}_{\sigma}\mathbf{X}^{\text{bw}}\boldsymbol{\varphi}.$$

This power was computed using $N^{\text{lum}} = 4$ for different wire fractions α, see Table I. Reference values computed by CST EM STUDIO® are shown as well. Since the 1D model becomes more accurate for thinner wires, the modeling error is expected to decrease with decreasing α. On the other hand, the discretization error can be controlled by N^{lum} for the 1D model and by the choice of the 3D grid.

V. Acknowledgment

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