Compact Lumped Element Model for TSV in 3D-ICs

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Abstract—A wide-band lumped element model for a through silicon via (TSV) is proposed based on electromagnetic simulations. Closed form expressions for the TSV parasitics based on the dimensional analysis method are introduced. The proposed model enables direct extraction of the TSV resistance, self-inductance, oxide capacitance, and parasitic elements due to the finite substrate resistivity. The model's compactness and compatibility with SPICE simulations allows the fast investigation of a TSV impact on a 3-D circuit performance. The parameters' values of the proposed TSV model are fitted to the simulated S-parameters up to 10 GHz with an error less than 5%. It is shown that a TSV capacitance is highly dependent on the positions of ground contacts and has a value of tens of femto farads in a typical current technology. This value is much higher than a minimum device capacitance and requires special design methodologies such as cascaded buffers. Coupling between TSVs will be handled in another paper.

Index Terms— **Three-Dimensional ICs, Through Silicon Via, Modeling , TSV, Dimensional Analysis.**

I. INTRODUCTION

TSV technology is one of the most critical and enabling technologies for 3-D integration. Compared with conventional I/O structures, such as flip-chips and wire-bonding, TSV technologies result in reduction of interconnect length, wire parasitics, propagation delay, and power consumption. TSV technologies provide high interconnect density, small footprint, and heterogeneous integration of the various materials and technologies [1]-[5].

A TSV is a brand new entity to conventional IC structures and its impact on the 3-D circuit performance requires careful characterization and evaluation. Unlike conventional interconnects, a TSV is surrounded by the silicon substrate which has a finite resistivity. This finite resistivity results in nonlinear capacitance, loss modes not present in conventional interconnect, and a large capacitance that is highly dependent on the body contact.

The general structure of a TSV is typically a cylinder with a uniform circular cross-section of a conducting material (copper) surrounded by an insulator (silicon dioxide) which is intended to prevent leakage and resistive coupling through the substrate (silicon) which has its body contacts connected to a DC voltage. This structure is depicted in Fig. 1.

The characteristics of a TSV are dependent on its geometrical parameters such as the TSV diameter, height, oxide layer thickness, and electrical parameters such as the metal conductivity, oxide permittivity, and the silicon substrate resistivity. These characteristics are summarized in Table I .

Recently a number of publications and studies addressed the TSV modeling from different perspectives and different approaches [1]-[12]. Compared to previous publications, this work results in a simple SPICE compatible model that accurately captures all the loss modes of a TSV. The elements of this model are directly calculated in a closed form from the TSV geometry and technology parameters. The nonlinear capacitance, depletion region (MOS Effect), and body contact impact are all captured in the proposed model.

This paper is organized as follows. In Section II, the TSV is physically modeled and characterized. In Section III, the proposed lumped element model for a TSV is introduced. In Section IV, the proposed lumped element model is validated versus electromagnetic simulations. Conclusions are given in Section V.

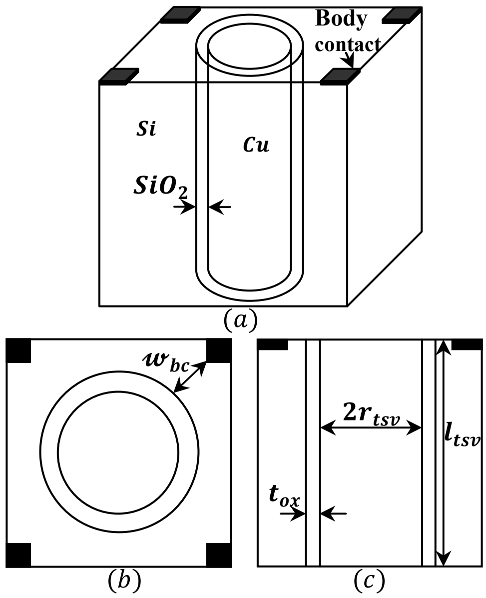

Fig. 1 The through silicon via structure assuming a uniform circular cross-section of cupper surrounded by an oxide inside a silicon substrate (a) 3D view (b) Top view (c) Side view.

TABLE I
TSV PHYSICAL PARAMETERS IN A TYPICAL CURRENT TECHNOLOGY

Geometrical parameters	Symbol	Typical current value μm
TSV radius	r_{tsv}	2.5
TSV height	l_{tsv}	Aspect Ratio*2*r_{tsv} =50
Dielectric thickness	t_{ox}	0.3
Distance to body contact	w_{bc}	5
Electrical parameters	**Symbol**	**Typical current value**
Conductor material	$f(\sigma_c, \mu_c, \varepsilon_c)$	$Cu = (58 * 10^6, 1,1)$
Dielectric material	$f(\sigma_{ox}, \mu_{ox}, \varepsilon_{ox})$	$SiO_2 = (0,1,4)$
Substrate	$f(\sigma_{si}, \mu_{si}, \varepsilon_{si})$	$Si = (10,1,12)$

II. PHYSICAL TSV MODELING

In this section, the physics underlying a TSV behavior is investigated and equivalent circuit elements are derived that capture the TSV behavior. The modeling methodology used in this work is explained in Section II-A. The physical modeling of a TSV using this methodology is presented in Section II-B.

A. Modeling Methodology

The methodology adopted in the modeling of a TSV is to fit a proposed lumped element model to the complete frequency dependent TSV numerical data. This data is obtained from an electromagnetic field solver over a wide range of TSV physical parameters using the dimensional analysis method.

Two different methods of simulation have been performed in order to investigate the electrical characteristics of a TSV. The first method is based on a 3D full-wave field solver, HFSS [13] and the second one is based on a 3D Quasi-static field solver, Q3D [14]. The difference between the full-wave and the quasi-static results for the S_{21} parameter of a TSV in a frequency sweep from few Hz to 100 GHz is due to Q3D limitations [14], where AC inductances are assumed frequency independent while AC resistances are approximately scaled by square root the frequency. The error due to these limitations is is less than 5% which is acceptable. Hence, the quasi-static simulator is used in the rest of this work.

B. Nonlinearities (MOS Effect) of a TSV

TSVs have a MOS-like capacitor structure, where the TSV metal behaves similar to a gate and the silicon substrate behaves similar to the bulk of a MOS transistor [10]-[12]. This structure is described by the following set of equations:

$$r_T = r_{tsv} + t_{ox} + w_{dep} \quad (1)$$

$$r_1 = r_{tsv} + t_{ox} \quad (2)$$

$$r_0 = r_{tsv} \quad (3)$$

where, r_{tsv} is the TSV radius, t_{ox} is the oxide thickness, and w_{dep} is the substrate depletion width.

By solving Poisson's equation in a cylindrical co-ordinate system, the following equations result [10]:

$$\frac{qN_a}{2\varepsilon_s}\left(r_T^2 ln\frac{r_T}{r_1} - \frac{r_T^2 - r_1^2}{2}\right) = 2V_T ln\frac{N_a}{n_i} \quad (4)$$

$$V_{th} = \phi_M - \chi - \frac{E_g}{2q} + V_t ln\frac{N_a}{n_i} + \frac{qN_a(r_T^2 - r_1^2)}{2\varepsilon_{ox}} ln\frac{r_1}{r_0} , \quad (5)$$

where,
V_{th} is the threshold voltage,
ϕ_M is the metal work function,
χ is electron affinity of Si (in V),
E_g is band gap energy of Si (in eV),
q is the electronic charge = 1.6022×10^{-19}coulombs,
V_t = 0.026 V (at 300K),
N_a is the doping concentration of the acceptors ions, and
n_i is the intrinsic carrier concentration of Si (assuming p-type).

The full depletion approximation was used in deriving the above equations. This approximation assumes that there are no mobile charge carriers in the depletion region and the charge in this region is entirely due to the ionized atoms.

By solving (4) and (5), a closed form expression for the depletion width can be derived, which is given by:

$$w_{dep} = -0.5r_1 + e^{0.5W\left(\frac{-0.367qN_a r_1^2 - 0.8*10^7 * V_t \varepsilon_{si} ln\frac{N_a}{n_i}}{qN_a r_1^2}\right)} \quad (6)$$

where W is the Lambert function and is calculated as follows:

$$W(z) = \sum_{n\geq 1} \frac{(-n)^{n-1}}{n!} z^n \quad (7)$$

The planar MOS capacitance is given by the well known formula [15],

$$C_{mos} = \frac{C_0}{\sqrt{1 - \frac{V_g}{V_{th}}}} , \quad (8)$$

where C_0 is the reference capacitance at $V_g = 0V$. By analogy to a MOS device, the TSV depletion capacitance can be derived from (8) (using dimensional analysis method which will be discussed in the next section) and is given by:

$$C_{dep} = \frac{2\pi\varepsilon_{si} l_{tsv}}{\ln\left(1 + \frac{t_{ox} + w_{dep}}{r_{tsv}}\right)\sqrt{1 + \frac{V_{tsv}}{V_{th}}}} , \quad (9)$$

where, V_{tsv} is the voltage on the TSV. The depletion width w_{dep} from (6) was used.

The duality concept between the resistance and the capacitance was introduced in the microwave area [16] and results in the following relation:

$$R = \frac{\varepsilon\rho}{C} , \quad (10)$$

by using this duality relation, the voltage dependent depletion resistance is given by:

$$R_{dep} = \frac{\ln\left(1 + \frac{t_{ox} + w_{dep}}{r_{tsv}}\right)\sqrt{1 + \frac{V_{tsv}}{V_{th}}}}{2\pi\sigma_{si} l_{tsv}} . \quad (11)$$

The depletion resistance and capacitance are highly nonlinear and change by more than 100% in the range between 0 to 1 volts. None of previous related publications have obtained a formula for the depletion resistance.

III. Proposed Lumped Element Model for a TSV

In this section, the proposed equivalent circuit model is presented. The structure of the model is explained in Section III-A as well as the relation between the equivalent circuit and the physical TSV structure. Closed-form expressions for the circuit elements as functions of the TSV geometry, body contacts, and technology parameters are presented in Section III-B.

A. Physics-Based Proposed Model

An equivalent circuit model of a TSV using lumped *RLC* elements is required to efficiently represent their electrical performance for circuit simulation with other design components in standard simulators. Compared with an electromagnetic field solver, a lumped equivalent-circuit model dramatically reduces computation time and supports transient analysis. However, nearly no simulators accept a frequency-dependent description for a lumped component at the entry level. Hence, models are needed that capture the frequency dependence of the TSV using a set of lumped *RLC* elements. The proposed lumped element model for a TSV presented here has been derived from the well-known single π structure, and it is shown in Fig. 2. The equivalent model captures the frequency dependence by its $R, C,$ and L elements. The critical and unique circuit components in the proposed lumped element model are (R_0, L_0, R_1, L_1, C_{ox}, C_{si}, C_{dep}, R_{si}, R_{dep}) which account for the TSV resistance, inductance and capacitance characteristics at high frequencies.

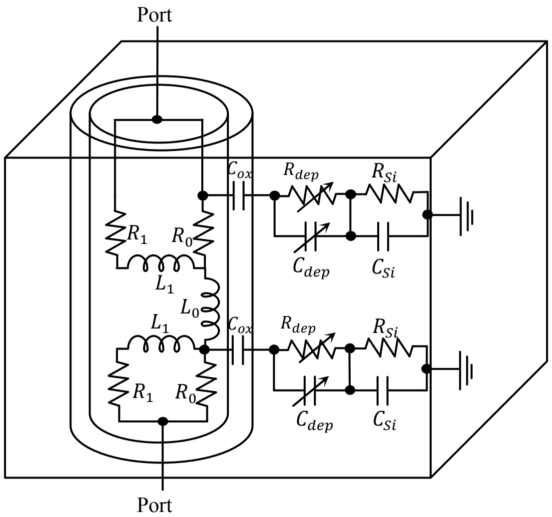

Fig. 2 The proposed lumped model for a TSV based on a single π structure. The model is composed of R_0,L_0, R_1, L_1, C_{ox}, C_{si},C_{dep}, R_{si}, and R_{dep} .

B. Closed Form Expressions for the Model Elements

Dimensional Analysis is a powerful technique used to reduce the number of physical variables through the identification of the variables' dimensions and combining the original variables to deduce a canonical number of dimensionless variables [17]. Modeling the capacitance of the TSV using the dimensional analysis approach Results in:

$$\frac{C}{\varepsilon_{ox} r_{tsv}} = f\left(\frac{l_{tsv}}{r_{tsv}}, \frac{t_{ox}}{r_{tsv}}\right) \quad (12)$$

The capacitance depends on only two dimensionless variables instead of four physical variables. Similarly, we can obtain R and L as :

$$R\sigma r_{tsv} = f\left(\frac{l_{tsv}}{r_{tsv}}\right) \quad (13)$$

$$\frac{L}{\mu r_{tsv}} = f\left(\frac{l_{tsv}}{r_{tsv}}\right) \quad (14)$$

The closed form equations for the TSV are extracted in two steps; the first one is by fitting the field solver based S-parameters up to 10 GHz to the proposed equivalent lumped element model using curve fitting techniques [18]. The second step is using forms suggested by the physical laws to guide the curve fitting software to produce the closed form equations. The closed form formulas for the TSV parameters are given by:

$$L_0 = \frac{155\mu_0 r_{tsv}}{2\pi} ln\left(1 + 0.01\frac{l_{tsv}}{r_{tsv}}\right) \quad (15)$$

$$L_1 = \frac{55\mu_0 r_{tsv}}{2\pi} ln\left(1 + 0.01\frac{l_{tsv}}{r_{tsv}}\right) \quad (16)$$

$$R_0 = \frac{330\ln\left(1+0.01\frac{l_{tsv}}{r_{tsv}}\right)}{2\pi\sigma_c r_{tsv}} \quad (17)$$

$$R_1 = \frac{200\ln\left(1+0.01\frac{l_{tsv}}{r_{tsv}}\right)}{2\pi\sigma_c r_{tsv}} \quad (18)$$

$$C_{ox} = \frac{2\pi\varepsilon_0\varepsilon_{0x} l_{tsv}}{\ln\left(1+\frac{t_{ox}}{r_{tsv}}\right)} \quad (19)$$

$$C_{si} = \frac{0.5\pi(8n_{bc}+1)\varepsilon_0\varepsilon_{si} l_{tsv}}{\ln\left(1+\frac{w_{bc}}{r_{tsv}}\right)} \quad (20)$$

$$R_{si} = \frac{\ln\left(1+\frac{w_{bc}}{r_{tsv}}\right)}{0.5\pi(8n_{bc}+1)\sigma_{si} l_{tsv}} \quad (21)$$

where, n_{bc} is number of body contacts.

$$C_{dep} = \frac{2\pi\varepsilon_0\varepsilon_{si} l_{tsv}}{\ln\left(1+\frac{t_{ox}+w_{dep}}{r_{tsv}}\right)\sqrt{1+\frac{V_{tsv}}{V_{th}}}} \quad (22)$$

$$R_{dep} = \frac{\ln\left(1+\frac{t_{ox}+w_{dep}}{r_{tsv}}\right)\sqrt{1+\frac{V_{tsv}}{V_{th}}}}{2\pi\sigma_{si} l_{tsv}} \quad (23)$$

These closed form expressions represent accurate and direct extraction of the TSV for any technology parameters and TSV geometry as well as body contacts' distance and number for frequency range:(0 GHz -10 GHz).

IV. Proposed Lumped Element Model Validation

The closed form equations of the proposed lumped element model of the TSV have been validated versus electromagnetic simulations and the results are shown in Fig. 3. The model shows good correlation and the percent error is less than 1% for S21. The maximum percent error is less than 5% for S21.Extracted values for R, L, and C of the TSV from the closed form formulas are shown in Table II. The values of C_{si} and R_{si} are the only affected parameters by changing the number of body contacts, where the capacitance increases as the body contacts' number increases.

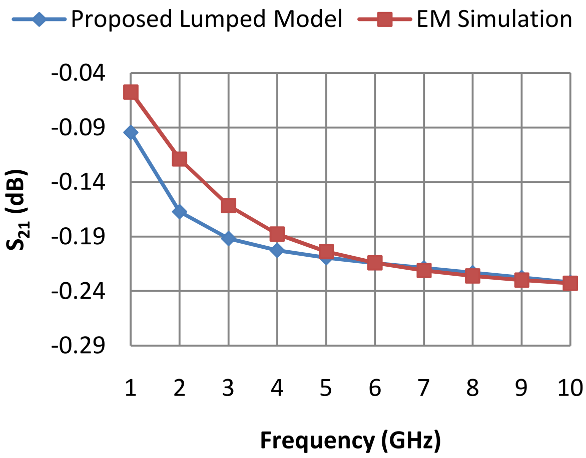

Fig. 3 A comparison of the quasi-static EM simulations against the proposed lumped element model simulations.

TABLE II
EXTRACTED VALUES FOR *R, L,* AND *C* OF A TSV FROM THE CLOSED FORM FORMULAS ($2r_{tsv} = 5\mu m, l_{tsv} = 50\mu m, V_{tsv} = 0.3V, w_{bc} = 5\,\mu m$)

Body contacts	$R(\Omega)$		$C(fF)$		$L(pH)$	
$n_{bc}=0$ (no body contacts around the TSV)	R_0	$63m$	C_{ox}	37	L_0	14
	R_1	$38m$	C_{si}	7	L_1	5
	R_{si}	$1.4K$	C_{dep}	78		
	R_{dep}	124				
$n_{bc}=1$ (one body contact around the TSV)	R_0	$63m$	C_{ox}	37	L_0	14
	R_1	$38m$	C_{si}	68	L_1	5
	R_{si}	155	C_{dep}	78		
	R_{dep}	124				
$n_{bc}=4$ (four body contact around the TSV)	R_0	$63m$	C_{ox}	37	L_0	14
	R_1	$38m$	C_{si}	250	L_1	5
	R_{si}	42	C_{dep}	78		
	R_{dep}	124				

V. Conclusion

In this paper a TSV modeling methodology is proposed. The methodology fits a proposed lumped element model to the complete frequency dependent TSV empirical data obtained from a field solver. Both 3D full-wave (HFSS) and 3D Quasi-static (Q3D) field solvers were considered. Comparison between those two field solvers from few Hz to 10 GHz showed that the difference in accuracy is less than 5%, hence, the 3D Quasi-static (Q3D) field solver was used. The parameters' values of this proposed lumped element model were fitted to the field solver simulation. Dimensional analysis was used to obtain closed form formulas for the lumped elements that achieved S-parameter matching with less than 5% error. It was shown that the capacitance of the TSV is highly dependent on the body contact positions. Coupling between TSVs will be handled in another paper.

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