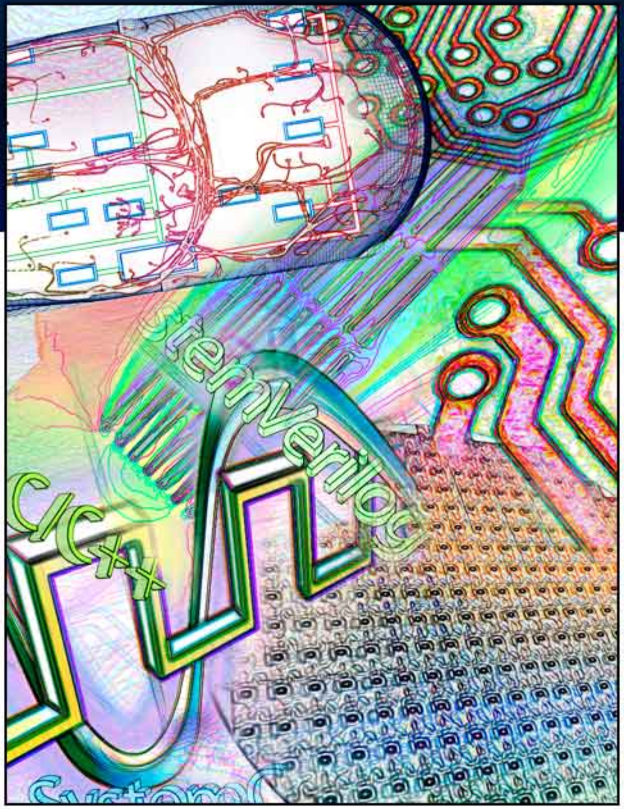
Equivalent Lumped Element Model for n-Port Through Silicon Via Networks



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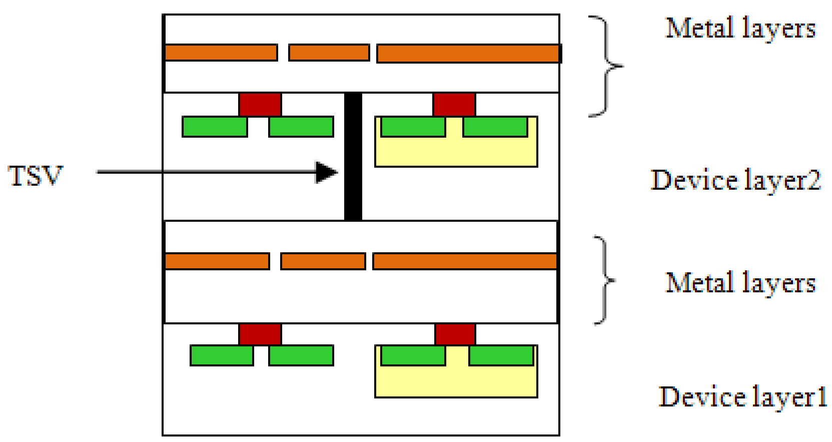
Introduction (1)

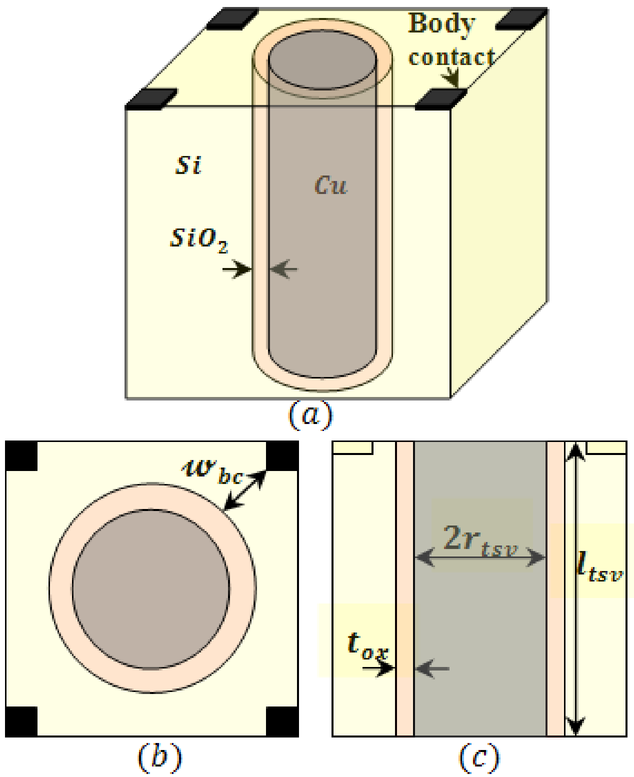
- Increased power consumption and delay due to increased wiring resistance and capacitance have become a major obstacle for further improving the performance of integrated circuits.
- 3D-integration using Through Silicon Vias (TSVs) is a promising solution for higher integration allowing for higher system speed and lower power consumption.
- TSV technology, also, provides other advantages such as:
  - high interconnect density,
  - small footprint, and
  - heterogeneous integration of the various materials and technologies.

Introduction (2)

- The characteristics of a TSV are dependent on its geometrical and electrical parameters.
- There is a number of configurations for TSV-based 3D IC integration.



An Example of "stacked" 3D IC with TSV



Typical TSV structure

(a) 3D view, (b) top view and (c) side view

Objective

- The objective of this research is set to introduce a complete and robust model that accurately captures:
  - all the loss modes of a TSV,
    - In conductor (resistance and skin effect)
    - In substrate (resistance)
  - coupling parasitics (R, L and C) between TSVs,
  - the TSV nonlinear capacitance and resistance of the depletion region (MOS) effect.

Modeling Methodology

(a) propose a physics-based lumped element model for two adjacent TSVs,

(b) simulate the structure of the two adjacent TSVs using EM simulation

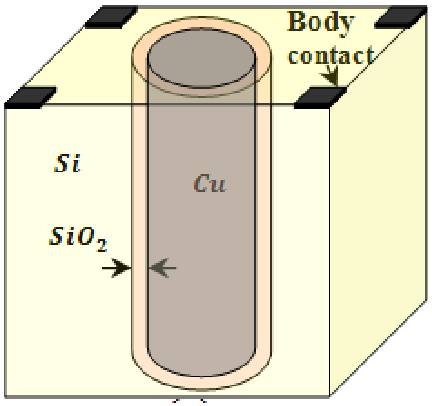
(c) use the results of EM simulator to optimize the physics-based lumped-element values under a number of different setups

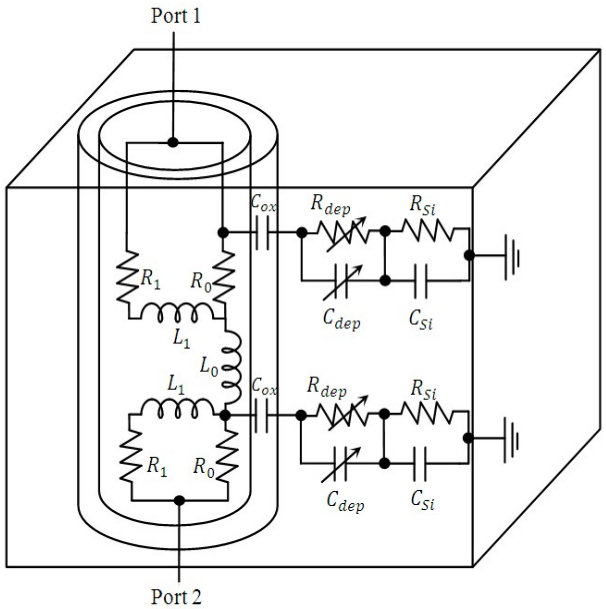
(d) use the dimensional analysis method to develop closed-form expressions for the values of model lumped elements

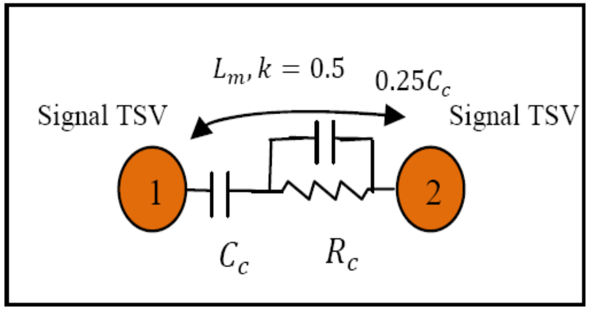
(e) use the results of step (c) to optimize the coefficients of the closed-form expressions from (d)

(f) validate the model with its elements' value using the closed-form expressions of step (e) against EM simulation.

Physics-Based Proposed Model



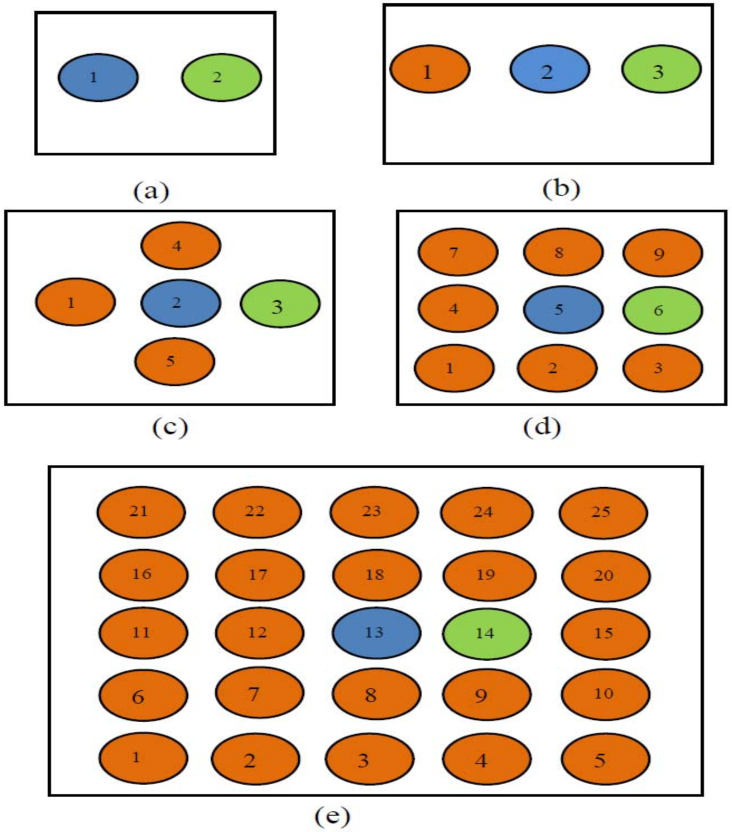




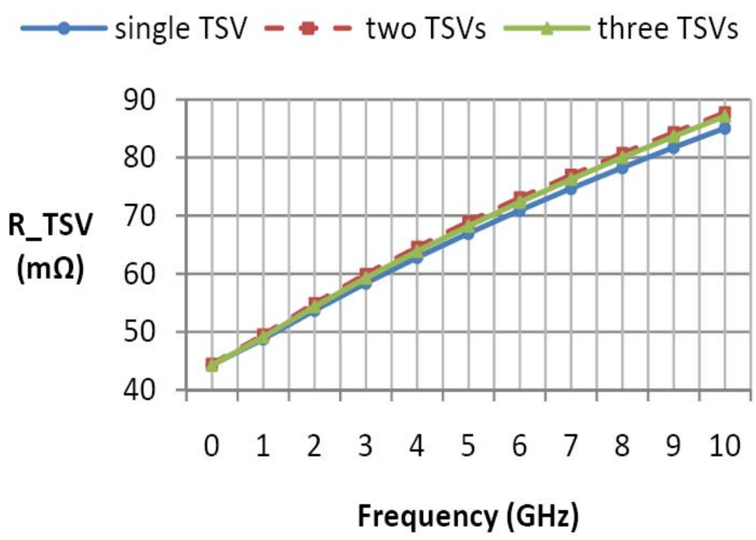
Circuit element	Physical meaning
R_0, L_0	Ohmic loss of the conductor
R_1, L_1	Skin effect of the conductor
C_{ox}	Capacitance of the oxide
C_{dep}, R_{dep}	Silicon substrate depletion region capacitance and resistance
C_{si}, R_{si}	Silicon substrate capacitance and resistance
C_c, R_c, L_m	Capacitive, resistive , and inductive coupling

A Set of Test Multi-TSV Arrangements

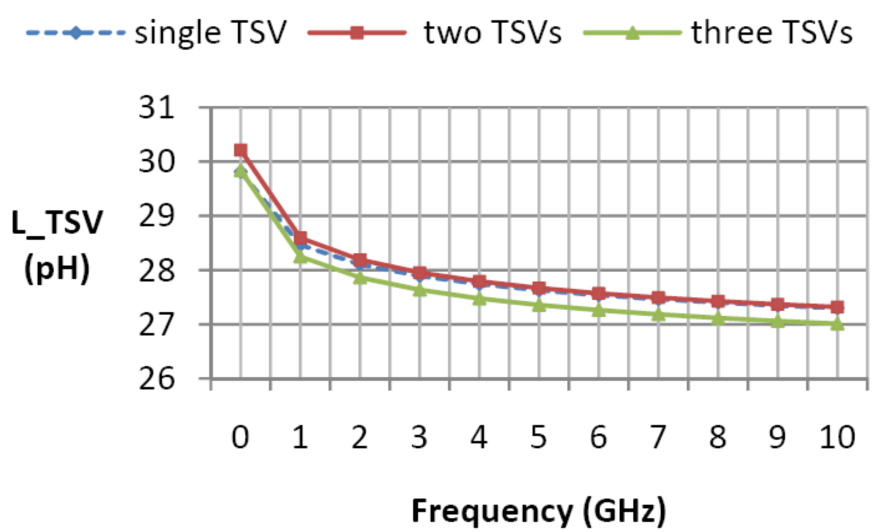
- The parasitics of two adjacent TSVs are investigated under different arrangements as shown below



Characteristics of Multi-TSV Structures(2)



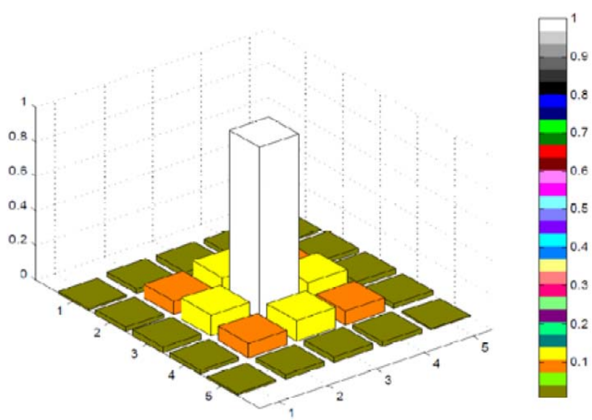
The equivalent resistance of a TSV for three test cases.



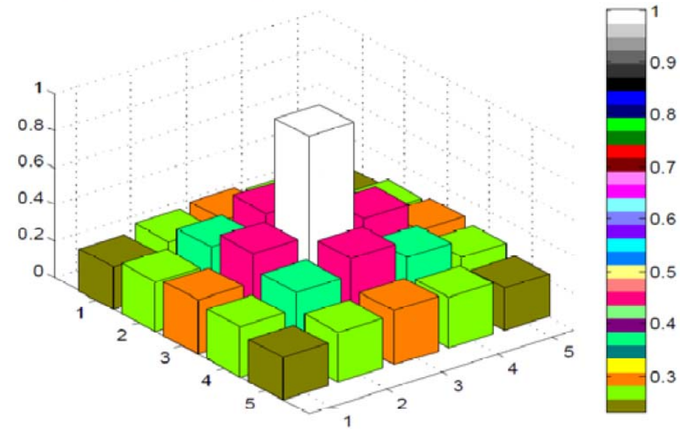
The equivalent Inductance of a TSV for three test cases

➔ Results show that the TSV self resistance and inductance slightly affected (negligible) by the arrangement of the TSVs around it.`

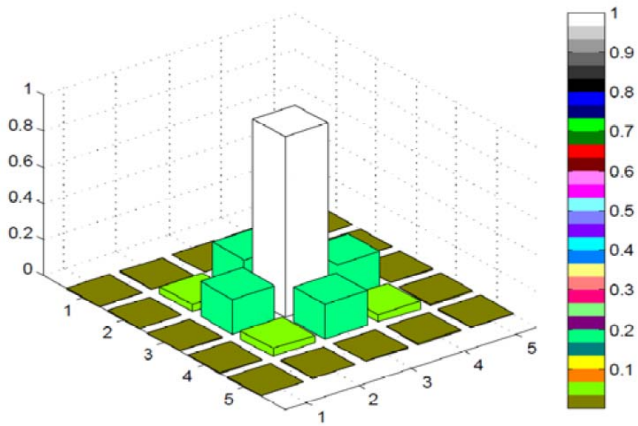
Characteristics of Multi-TSV Structures(3)



Capacitive coupling normalized w.r.t. the total capacitance of the TSV in the center.



Inductive coupling normalized w.r.t. the total inductance of the central TSV.

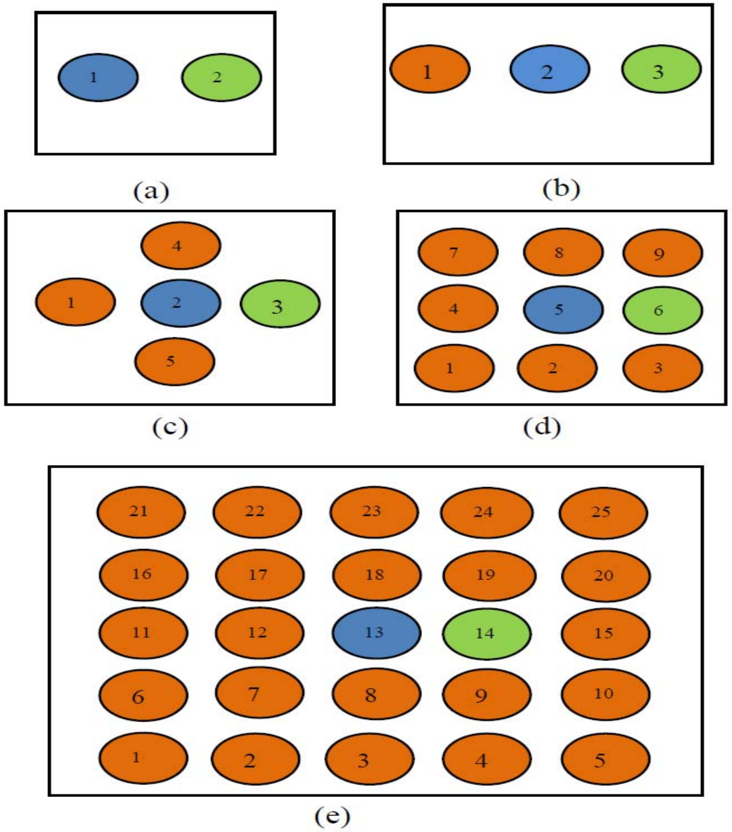


Resistive coupling normalized w.r.t. the total resistance of the TSV in the center.

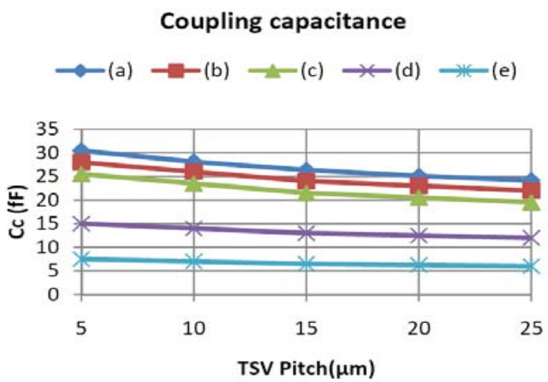
- ➔ Capacitive and resistive coupling are **weak** → insignificant beyond the 1st line of neighbors around the TSV in center.
- ➔ Inductive coupling is **strong** → significant coupling extends to the 2nd line of neighbors around the TSV in center.

A Set of Test Multi-TSV Arrangements

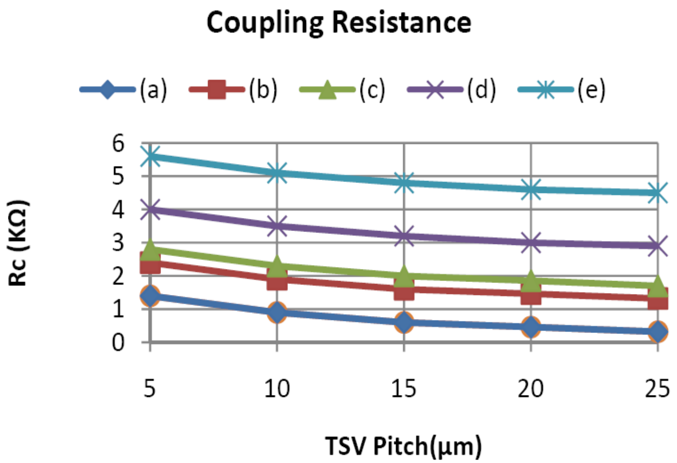
- The parasitics of two adjacent TSVs are investigated under different arrangements as shown below



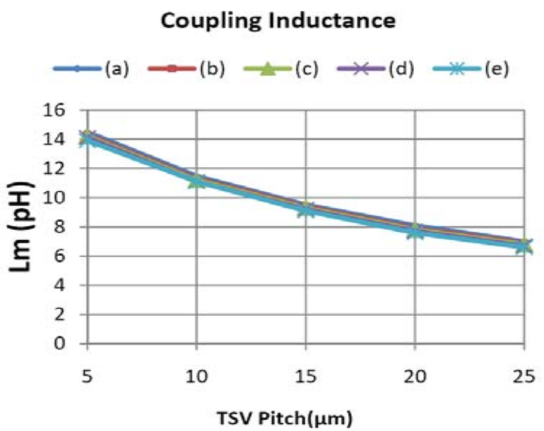
Characteristics of Multi-TSV Structures(4)



coupling capacitance for different TSV arrangements



coupling resistance for different TSV arrangements



coupling inductance for different TSV arrangements

➔ Coupling capacitance and resistance showed clear dependency on TSV arrangement, while coupling inductance remains “almost“ constant.

Closed Form Expressions for the Model Elements

- Using the dimensional analysis, we developed the following closed form expressions

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

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

$$C_c = \frac{1.6\pi\varepsilon_0\varepsilon_{si} l_{tsv}}{\alpha_3 ln\left(1+\frac{p_{tsv}}{r_{tsv}}\right)}$$

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

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

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

$$R_{si} = \frac{\left(\frac{p_{tsv}}{r_{tsv}}\right)^{\alpha_2}\ln\left(1+\frac{w_{bc}}{r_{tsv}}\right)}{0.5\pi(8n_{bc}+1)\sigma_{si} l_{tsv}}$$

$$L_m = \frac{434\mu_0 r_{tsv}}{2\pi} ln\left(1+0.02\frac{l_{tsv}}{p_{tsv}}\right)$$

$$C_{si} = \frac{0.5\pi\left(\frac{p_{tsv}}{r_{tsv}}\right)^{\alpha_1}(8n_{bc}+1)\varepsilon_0\varepsilon_{si} l_{tsv}}{\ln\left(1+\frac{w_{bc}}{r_{tsv}}\right)}$$

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

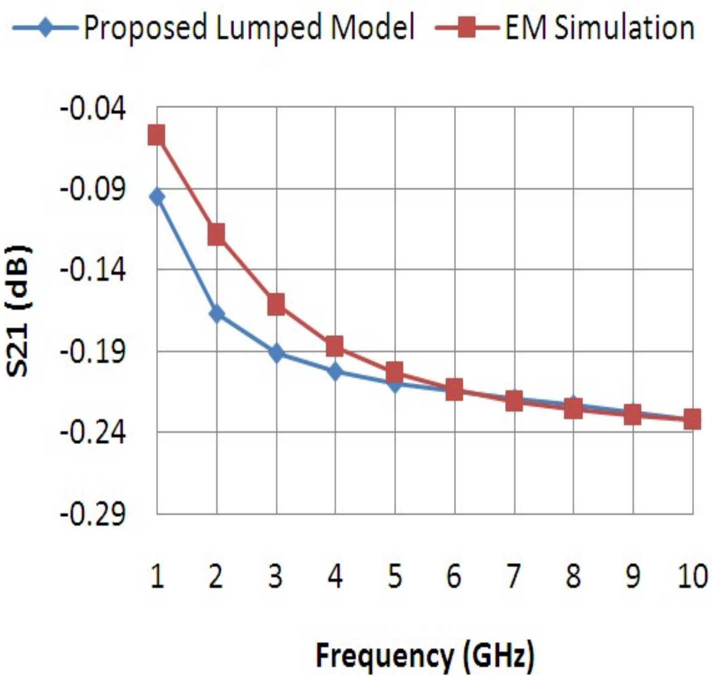
$$K_i = \frac{1}{2i}$$

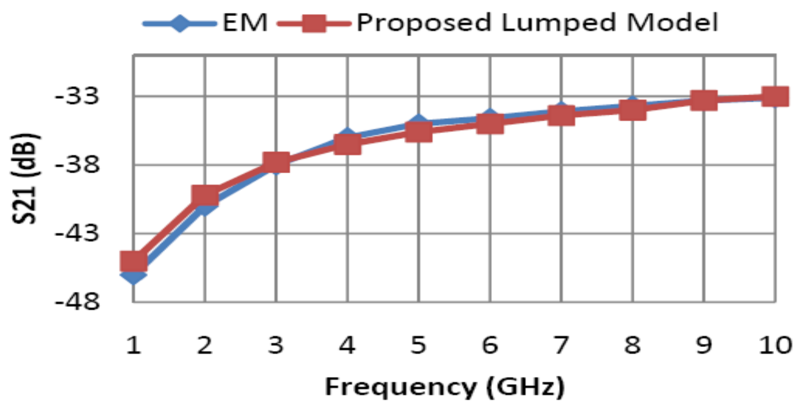
$$C_{dep} = \frac{2\pi\varepsilon_0\varepsilon_{si} l_{tsv}}{\ln\left(1+\frac{t_{ox}+w_{dep}}{r_{tsv}}\right)\sqrt{1-\frac{V_{tsv}}{V_{th}}}}$$

$$R_c = \frac{\alpha_4 ln\left(1+\frac{p_{tsv}}{r_{tsv}}\right)}{0.75\pi\sigma_{si} l_{tsv}}$$

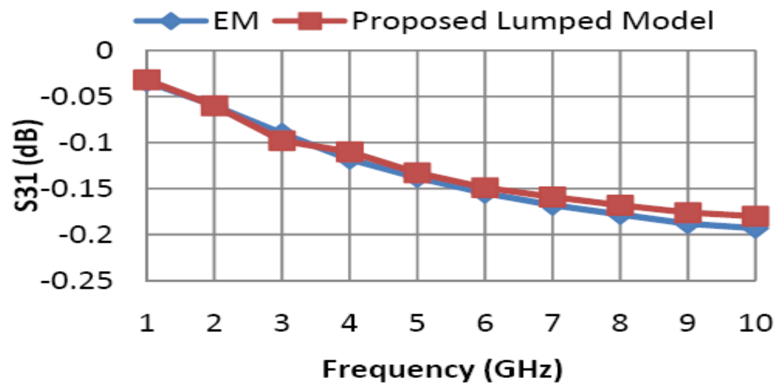
Test-case	α_1	α_2	α_3	α_4
(a)	1.6	1.2	1	1
(b)	1.8	1.3	1.6	1.5
(c)	1.95	1.4	1.7	1.55
(d)	3	1.6	1.8	1.6
(e)	3.5	1.8	1.9	1.8

TSV Model Validation Against EM Simulation





(a)

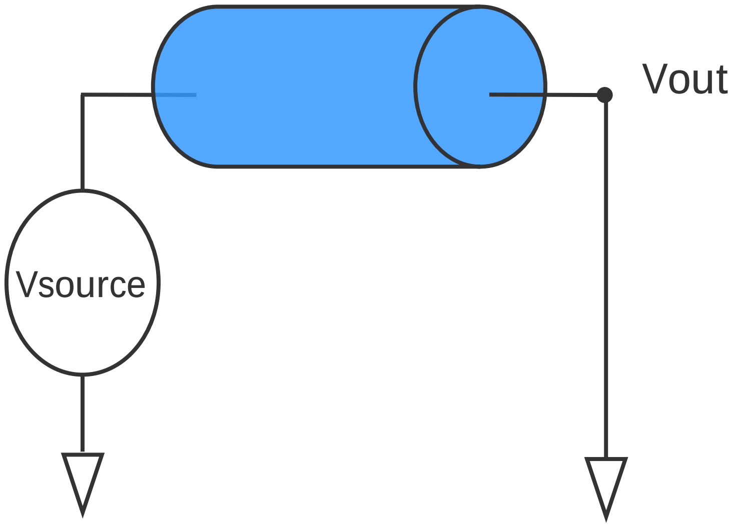


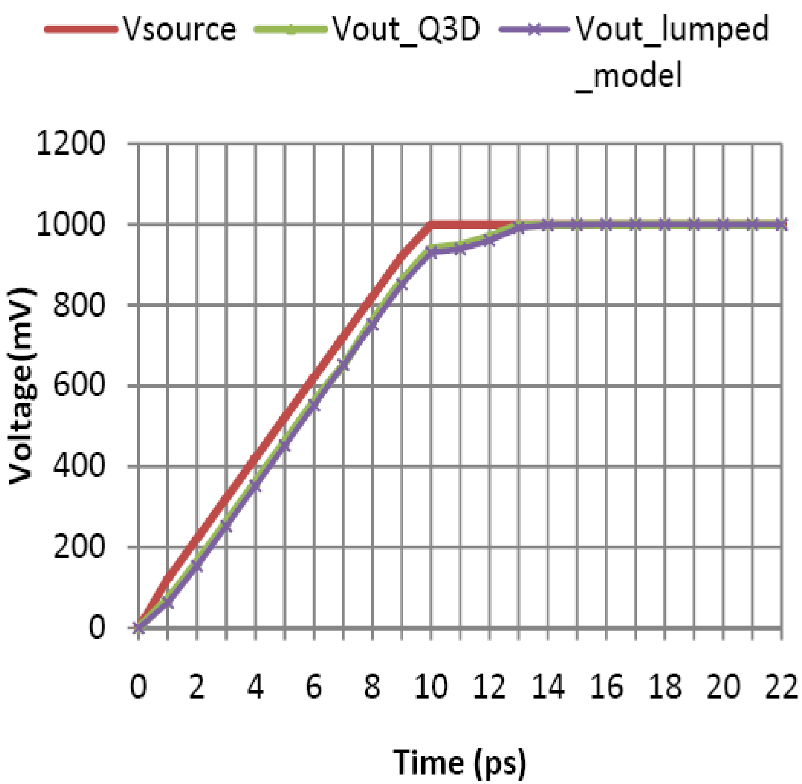
(b)

Single TSV.

Two TSV.

Model Usage Time Domain





A comparison of the quasi-static EM simulations against the proposed exact lumped element model simulations for a single TSV

Conclusion

- An equivalent lumped element model of multiple TSVs is introduced,
- Closed-form expressions for the values of the model elements (R, L and C) of different TSVs structures are presented.
- Results showed that:
  - the self resistance and inductance of a TSV are “almost” independent of the TSV arrangement.
  - coupling capacitance and resistance are **clearly dependant** on the TSV arrangement, while the coupling inductance are **“almost” independent** of the TSV arrangement.
  - Capacitive and resistive coupling are **weak** → insignificant beyond the 1st line of neighbors around the TSV in center.
  - Inductive coupling is **strong** → significant coupling extends to the 2nd line of neighbors around the TSV in center.

QUESTIONS?