Efficient Capacitance Modeling and Extraction for the Cylindrical Inter-Tier-Vias in 3-D ICs

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Dec. 16, 2017
Outline

- Background and motivation
- The floating random walk algorithm for capacitance extraction
- FRW based technique for the cylindrical ITVs
- Comprehensive modeling of TSVs in 3-D IC
- Conclusions
Background

- 3-D IC: a promising solution offering a path beyond the Moore’s law
- Two types of vertical integrating for 3-D IC
  - Die stacking using through-silicon-via (TSV)
  - Monolithic integration using monolithic inter-tier-via (MIV)

Background

- The problem
  - The inter-tier-vias (viz. TSV and MIV) play a critical role in 3-D ICs to deliver signal and power
  - Their related parasitics need accurate modeling (rising number of analog effects, narrowed performance margins)

- Extraction of ITV capacitances
  - Most works focused on TSV’s equivalent model and its *MOS capacitance*, instead of the *electrostatic coupling* among TSVs and horizontal wires
  - [T-CPMT 2011]¹ reveals the electrostatic cap. can be comparable to the MOS cap.; The *analytical* technique is based on square-shape TSV, and has >20% error

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Actual ITV is more like a cylinder in geometry
- TSV-first, TSV-last, TSV-middle, etc.
- Large size (diameter~5μm), large aspect ratio (~10)
- In exiting work, calculation of $C_{TT}$ and $C_{TD}$ investigated

Monolithic 3-D IC similar to TSV-first; smaller-size MIV
- Larger density of MIV; larger aspect ratio than local via

not considering the wires surrounded laterally and vertically
Background

- Cylindrical ITV, or square-shape ITV?
  - The error of square-shape approximation
  - Typical TSV and MIV structures

<table>
<thead>
<tr>
<th></th>
<th>( C_{\text{total}} ) (aF)</th>
<th>Err. ( C_{\text{total}} ) (%)</th>
<th>Error of ( C_{\text{couple}} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder</td>
<td>3740</td>
<td>5.9</td>
<td>-20 21</td>
</tr>
<tr>
<td>TSV-first</td>
<td>3866</td>
<td>5.2</td>
<td>-38 71</td>
</tr>
<tr>
<td>MIV</td>
<td>14.7</td>
<td>7.5</td>
<td>-1.6 9.1</td>
</tr>
<tr>
<td>Square</td>
<td>3962</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSV-last</td>
<td>4065</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The error of square-shape approximation of TSV and MIV structures. Square approximation overestimates \( C_{\text{total}} \), while causes large errors on \( C_{\text{couple}} \).
Background

- High-precision capacitance extraction -- Field Solver
  - Finite difference/finite element method
    - Stable, versatile; slow
  - Boundary element method
    - Fast for small/medium size cases
    - Polyhedron approximation; discretization
  - Floating random walk method
    - Stable (discretization-free); Scalable (low memory cost),
    - Only efficient for Manhattan structures
- None of the fast solvers directly and efficiently handle the structure with cylindrical ITVs

Our work

- The *first* capacitance field solver that can directly handle cylindrical ITVs without any geometric approximation.
- It can be *tens to hundreds times faster* than fast BEM solvers for TSV or large MIV structures, with great memory saving and more stable accuracy.
- It is used in modeling complete electro/semiconductor effects of TSV structures, which results in 47X speedup over a commercial simulator while keeping accuracy.
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The floating random walk alg.

- Integral formula for the potential calculation
  \[ \phi(r) = \int_{S_1} P_1(r, r^{(1)}) \phi(r^{(1)}) ds^{(1)} \]
  P_1 is called surface Green’s function, and can be regarded as a probability density function

- Monte Carlo method: \( \phi(r) = \frac{1}{M} \sum_{m=1}^{M} \phi_m \)
  \( \phi_m \) is the potential of a point on \( S_1 \), randomly sampled with \( P_1 \)

- What if \( \phi_m \) is unknown? expand the integral recursively
  \[ \phi(r) = \int_{S_1} P_1(r, r^{(1)}) \int_{S_2} P_1(r^{(1)}, r^{(2)}) \ldots \]
  \[ \int_{S_k} P_1(r^{(k-1)}, r^{(k)}) \phi(r^{(k)}) ds^{(k)} \ldots ds^{(2)} ds^{(1)} \]
  This spatial sampling procedure is called floating random walk
The floating random walk alg.

- The Markov random process + MC method prove the correctness of the FRW method
- A 2-D example with 3 walks
  - Use maximal cubic transition domain
- How to calculate capacitances?

Definition:

\[
\begin{bmatrix}
C_{11} & C_{12} & C_{13} \\
C_{12} & C_{22} & C_{23} \\
C_{13} & C_{23} & C_{33}
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
V_3
\end{bmatrix}
= \begin{bmatrix}
Q_1 \\
Q_2 \\
Q_3
\end{bmatrix}
\]

\[Q_1 = C_{11}V_1 + C_{12}V_2 + C_{13}V_3\]

Integral for calculating charge (Gauss theorem)

\[Q_1 = \int_{G_1} F(r) \cdot \hat{n} \cdot \nabla \phi(r) \, dr = \int_{G_1} F(r) \cdot \hat{n} \cdot \nabla \int_{S_1} P_1(r, r^{(1)}) \phi(r^{(1)}) \, dr^{(1)} \, dr\]

\[= \int_{G_1} F(r) g \int_{S_1} P_1(r, r^{(1)}) \phi(r^{(1)}) \omega(r, r^{(1)}) \, dr^{(1)} \, dr\]

weight value, estimate of coefficients C_{11}, C_{12}, C_{13}

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Techniques for cylindrical ITVs

- Runtime of FRW: $T_{\text{total}} = N_{\text{walk}} \cdot N_{\text{hop}} \cdot T_{\text{hop}}$

- The ideas
  - Manhattan transition cube $\rightarrow$ rotated transition cube
  - Larger probability to terminate; potentially smaller $N_{\text{hop}}$
  - If the rotated cube touching ITV is within the second smallest Manhattan cube, choose the rotated cube.

Simple extension of original FRW
Techniques for cylindrical ITVs

- The ideas
  - Traversing all cylinders increases $T_{hop}$ for cases with many ITVs!
  - Special space management
    - Add ITV's bounding boxes to the conventional space management structure
    - The nearest block is ITV's: may use the rotated cube
    - With the second nearest block, choose valid transition cube

By setting ITV's neighbor region, we can either get the second nearest block efficiently or have a large enough transition cube

Techniques for cylindrical ITV's

- The ideas
  - Optimized Gaussian surface and importance sampling for TSV structure
    - Setting Gaussian surface the equidistance positions is preferred, but induces large variance to the weight value
      \[ I_k = \int_{\Gamma_{j,k}} gF(r) \int_{S_{a}} -\frac{K_a}{gL(r)} q_a(r, r^{(1)}) \phi(r^{(1)}) dr^{(1)} dr \]
      Weight value: \[ \omega_a(r, r^{(1)}) = -\frac{K_a}{gL(r)} \]

    - With compensation of \( D(r) \), the variance largely reduced
    - Analytical integral is derived for \( A' = \int_{g_j} \frac{F(r)}{D(r)} dr \)
    - Sampling on Gaussian surface with new probability density function finally accelerates the convergence rate for 10X
# Techniques for cylindrical ITVs

## Experimental results

### Accuracy

<table>
<thead>
<tr>
<th></th>
<th>Raphael (aF)</th>
<th>newFRW (aF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSV-first(C&lt;sub&gt;t&lt;/sub&gt;)</td>
<td>3740 3962 5.9%</td>
<td>3793 1.4%</td>
</tr>
<tr>
<td>TSV-last(C&lt;sub&gt;t&lt;/sub&gt;)</td>
<td>3866 4065 5.1%</td>
<td>3885 0.5%</td>
</tr>
<tr>
<td>MIV(C&lt;sub&gt;t&lt;/sub&gt;)</td>
<td>14.7 15.8 7.5%</td>
<td>14.8 0.7%</td>
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<tr>
<td>TSV-first(C&lt;sub&gt;c&lt;/sub&gt;)</td>
<td>49.9 60.2 21%</td>
<td>50.0 0.2%</td>
</tr>
<tr>
<td>TSV-last(C&lt;sub&gt;c&lt;/sub&gt;)</td>
<td>48.2 58.6 22%</td>
<td>47.9 -0.6%</td>
</tr>
<tr>
<td>MIV(C&lt;sub&gt;c&lt;/sub&gt;)</td>
<td>2.06 2.24 8.7%</td>
<td>2.12 2.9%</td>
</tr>
</tbody>
</table>

#### 0.5% criterion

#### 1% criterion

### Runtime

<table>
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<tr>
<th></th>
<th>oldFRW</th>
<th>newFRW</th>
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<tbody>
<tr>
<td>TSV-first(C&lt;sub&gt;t&lt;/sub&gt;)</td>
<td>2.06 1.66 -19%</td>
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<tr>
<td>TSV-last(C&lt;sub&gt;t&lt;/sub&gt;)</td>
<td>2.01 2.79 39%</td>
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<tr>
<td>MIV(C&lt;sub&gt;t&lt;/sub&gt;)</td>
<td>0.61 1.88 3.1X</td>
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</tr>
<tr>
<td>TSV-first(C&lt;sub&gt;c&lt;/sub&gt;)</td>
<td>3.5 4.22 21%</td>
<td></td>
</tr>
<tr>
<td>TSV-last(C&lt;sub&gt;c&lt;/sub&gt;)</td>
<td>4.2 5.11 22%</td>
<td></td>
</tr>
<tr>
<td>MIV(C&lt;sub&gt;c&lt;/sub&gt;)</td>
<td>2.6 6.83 2.6X</td>
<td></td>
</tr>
</tbody>
</table>

- The proposed technique scarifies affordable runtime to achieve higher accuracy.
Techniques for cylindrical ITVs

- Experimental results
  - Comparison with fast BEMs
  
<table>
<thead>
<tr>
<th></th>
<th>FastCap*</th>
<th></th>
<th>QBEM*</th>
<th></th>
<th>newFRW</th>
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<tr>
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<td>Err</td>
<td>time(s)</td>
<td>Mem.</td>
<td>Err</td>
<td>time(s)</td>
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<td>TSV-last(C)&lt;sub&gt;c&lt;/sub&gt;</td>
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<td>79</td>
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- Scalability to large-scale cases

<table>
<thead>
<tr>
<th></th>
<th>FRW(non-rotate)</th>
<th>newFRW</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>N&lt;sub&gt;walk&lt;/sub&gt;</td>
<td>N&lt;sub&gt;hop&lt;/sub&gt;</td>
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<tr>
<td>TSV-first</td>
<td>2.3M</td>
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<tr>
<td>TSV-last</td>
<td>2.2M</td>
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<tr>
<td>MIV</td>
<td>224K</td>
<td>23.6</td>
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<tr>
<td>100TSV</td>
<td>6.0M</td>
<td>36.0</td>
</tr>
<tr>
<td>400TSV</td>
<td>6.0M</td>
<td>36.0</td>
</tr>
<tr>
<td>576MIV</td>
<td>149K</td>
<td>13.0</td>
</tr>
</tbody>
</table>

*approximate cylinder with 16-side prism

Favorable speedup
Huge memory save

random TSV layout
Techniques for cylindrical ITV

- **Experimental results**
  - For large-scale cases, Raphael and FastCap don’t work due to runtime and memory usage limitations
  - For case 576MIV, FRW is 192X faster than QBEM
  - Multi-dielectric cases
    - Speedup to QBEM is up to 143X
      - Verified accuracy with Raphael

<table>
<thead>
<tr>
<th></th>
<th>QBEM</th>
<th></th>
<th></th>
<th>newFRW</th>
<th></th>
<th></th>
<th>Sp.</th>
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<tbody>
<tr>
<td></td>
<td>Cap.</td>
<td>Mem.</td>
<td>Time(s)</td>
<td>Cap.</td>
<td>Error</td>
<td>Mem.</td>
<td>Time(s)</td>
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<td>TSV-first2</td>
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<td>1.9%</td>
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<td>144MIV</td>
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<td>576MIV</td>
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<td>344</td>
<td>0.291</td>
<td>--</td>
<td>25MB</td>
<td>5.69</td>
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</tbody>
</table>

For pre-built GFTs and WVTs
Outline

- Background and motivation
- The floating random walk algorithm for capacitance extraction
- FRW based technique for the cylindrical TSVs
- Comprehensive modeling of TSVs in 3-D IC
- Conclusions
Comprehensive modeling of TSVs

- RC circuit model for analyzing the signal integrity on TSVs (e.g. on a “victim” TSV)
  - Considers both electrostatic and semiconductor effects

\[ R_{si} = \frac{\varepsilon_{si}}{\sigma_{si} C_{si}} \]

- \( C_{si} \): electrostatic cap.
- \( C_{tsv} \): MOS cap.

Couplings among 'A' TSVs not shown
Comprehensive modeling of TSVs

- **Extraction algorithm flow**
  - Input geometry/material information, the voltages of TSVs
  - Extract $C_{si}$’s with the FRW based capacitance solver
  - Extract $C_{TSV}$’s with an analytical method

- An algorithm calculating the total lump capacitance of a victim TSV

---

**Input:** Equivalent RC circuit of the structure, signal frequency $\omega$;  
**Output:** The total lump capacitance of victim TSV $C_1$.

1. $Y_m = j\omega C_{si} + 1/R_{si}$;
2. For ($i=2$; $i \leq n$; $i++$) // $n$ is the number of TSVs
   
   $Y_i = j\omega C_{tsv,i} + j\omega C_{sig,i} + 1/R_{sig,i}$;
   
   $Y_m = Y_m + (j\omega C_{si,i} + 1/R_{si,i}) Y_i / (j\omega C_{si,i} + 1/R_{si,i} + Y_i)$;
   
   EndFor;
3. $Y_1 = j\omega C_{tsv,1} Y_m / (j\omega C_{tsv,1} + Y_m)$;
4. $C_1 = \text{real}(Y_1 / (j\omega))$;

Suitable for arbitrary TSV/interconnect layout

Comprehensive modeling of TSVs

- Experimental results
  - Copper TSVs embedded in a P-Si substrate
    - \[
    \begin{array}{c|c|c|c}
    R_{\text{metal}} (\mu m) & R_{\text{ox}} (\mu m) & l_{\text{TSV}} (\mu m) & N_a (\text{cm}^{-3}) \\
    \hline
    2.5 & 2.6182 & 20 & 2 \times 10^{15} \\
    \end{array}
    \]
  - Compared with Sdevice, using FEM for electro/semi simulation

- Results for structures with multiple TSVs
  - Capacitance trends vs. f and \(V_{\text{TSV}}\)
  - Error is within 5%

\[\sim 47X \text{ speedup in runtime comparison}\]
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Conclusions

- Extend the FRW algorithm to fast and accurately extract the capacitances of high-density ITVs in 3-D ICs
  - With the *rotated transition cube, a special space management* and *an optimized importance sampling* techniques, the proposed method can be over 200X faster than a simple extension of original FRW solver
- The solver is combined with analytical model to simulate electrostatic/semiconductor effects of TSV structures
- Reference
Thank You!

Wenjian Yu / Tsinghua University, China

Codes are shared on
http://numbda.cs.tsinghua.edu.cn
Email: Yu-wj@tsinghua.edu.cn