Random Walk Based Capacitance Extraction for 3D ICs with Cylindrical Inter-Tier-Vias

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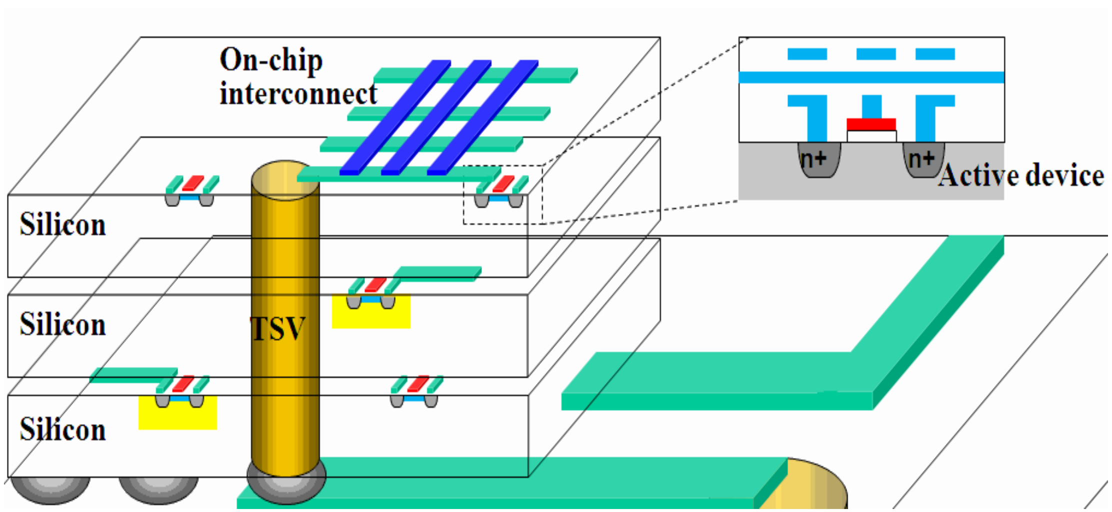
Outline

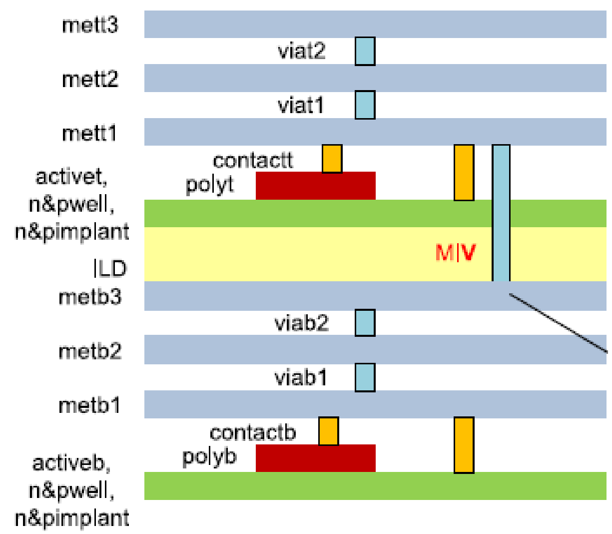
- Background
- Considered structures and motivation
- The floating random walk algorithm for capacitance extraction
- FRW based technique for the cylindrical ITVs
- Conclusions

Background

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



TSV in die-stacking 3D IC



MIV in monolithic 3D IC [1]

[1] **S. Panth**, et al., "High-density integration of functional modules using monolithic 3D-IC technology," ***ASP-DAC* 2013**

Background

- The problem
  - The inter-tier-vias (viz. TSV and MIV) play a critical role in 3D 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 ITV's equivalent model and its *MOS capacitance*, instead of the *electrostatic coupling* among ITVs 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

[1] **D. H. Kim**, et al., "Fast and accurate analytical modeling of through-silicon-via capacitive coupling," ***IEEE T-CPMT***, 2011

Background

- High-precision capacitance extraction -- Field Solver
  - Finite difference/finite element method
    - Stable, versatile; slow

      Golden tool: **Raphael**
  - Boundary element method
    - Fast; not stable (discretization)

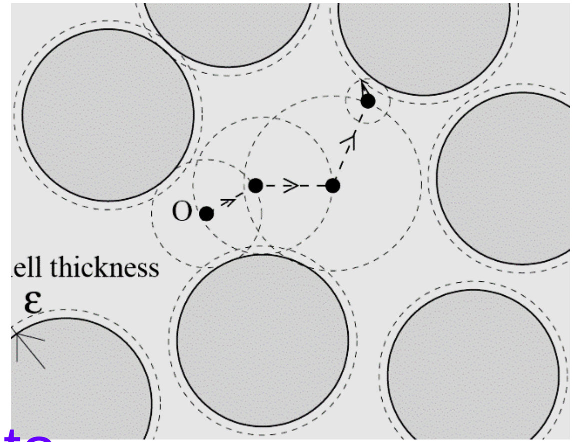
      FastCap, **Act3D** , **QBEM**[1]
  - Floating random walk method
    - Stable (discretization-free); restriction on geometry
    - Scalable/fast, parallelizable

      QuickCap/Rapid3D, **RWCap**[2]
- None of the fast solvers directly handles the *cylindrical* shape of ITVs

[1] **W. Yu**, et al., "Enhanced QMM-BEM solver for 3-D multiple-dielectric capacitance extraction within finite domain," ***IEEE T-MTT***, 2004
[2] **W. Yu**, et al., "RWCap: A floating random walk solver for 3-D capacitance extraction of VLSI interconnects," ***IEEE T-CAD***, 2013

Background

- The cylinder shape brings challenges
  - More effort on describing the geometry accurately
  - Fast BEM solver
    - Approximated by polyhedron / dense discretization
    - Increase runtime & memory cost, worsen stability
  - Fast FRW solver
    - Manhattan (square-shape) approximation causes error
    - General walk on sphere (WOS) method is not efficient enough



Enhance fast FRW capacitance solver to model the cylindrical ITVs accurately

Background

- The contributions
  - The *first* field solver that can directly handle cylindrical ITVs without any geometric approximation
  - The *first* work handling non-Manhattan geometries with the fast FRW method using cubic transition domains
  - With the *rotated transition cube* and *special space management*, the proposed method is 20X faster than a simple extension of original FRW;
    It's also >10X faster than fast BEM solvers with great memory saving

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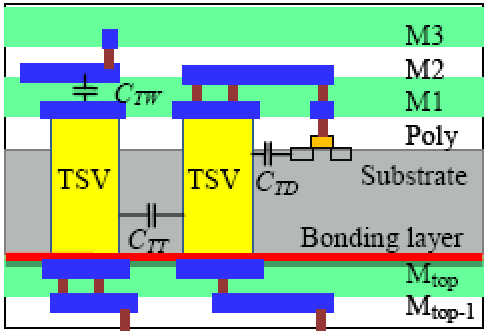
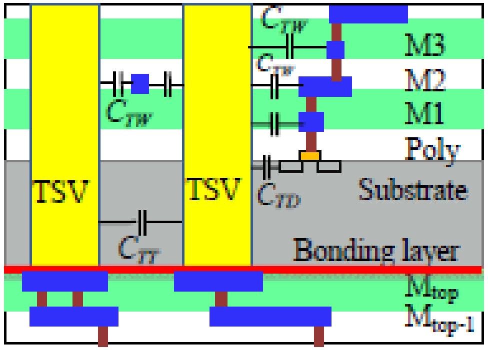
Modeling the ITVs in 3D IC

- Fabrication technologies of ITVs
  - TSV-first, TSV-last, TSV-middle, etc.
  - Large cylinder (diameter~5μm), large aspect ratio (~10)
  - Most works only considered calculation of C_{TT} and C_{TD}



TSV-first



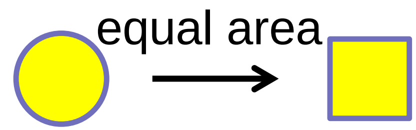
TSV-last

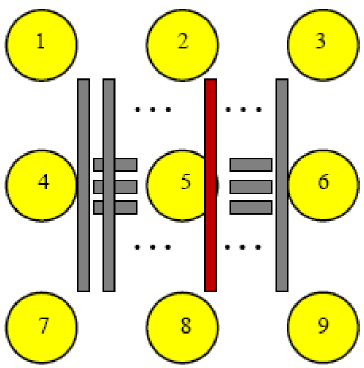
Surrounded by wires laterally and vertically

  - With similar topology as TSV-first, MIV has smaller size
  - Larger density of MIV; larger aspect ratio than local via

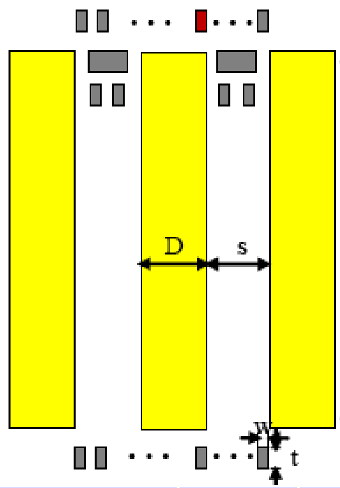
Modeling the ITVs in 3D IC

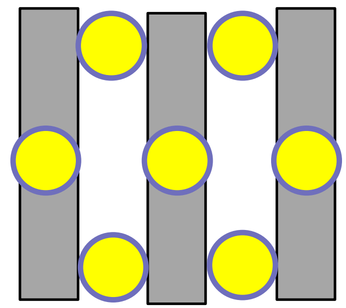
- The necessity of cylindrical geometry model
  - The error of square approximation of ITV cross-section
  - Typical TSV and MIV structures





(top view)





(top view of MIV)

Raphael simulation	C_{total} (aF)		Err. C_{total} (%)	Error of C_{couple} (%)	
	Cylinder	Square		min	max
TSV-first	3740	3962	5.9	-20	21
TSV-last	3866	4065	5.2	-38	71
MIV	14.7	15.8	7.5	-1.6	9.1

Square approximation overestimates C_{total}, while causes large errors on C_{couple}

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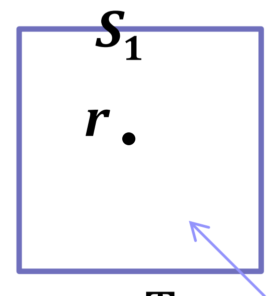
The floating random walk alg.

- Integral formula for the potential calculation

$$\Phi(r) = \oint_{S_1} P_1(r, r^{(1)})\Phi(r^{(1)})dr^{(1)}$$

P_1 is called surface Green's function, and can be regarded as a probability density function



Transition domain

- Monte Carlo method: $\Phi(r) = \frac{1}{M}\sum_{m=1}^{M}\Phi_m$

Φ_m is the potential of a point on S_1, randomly sampled with P_1

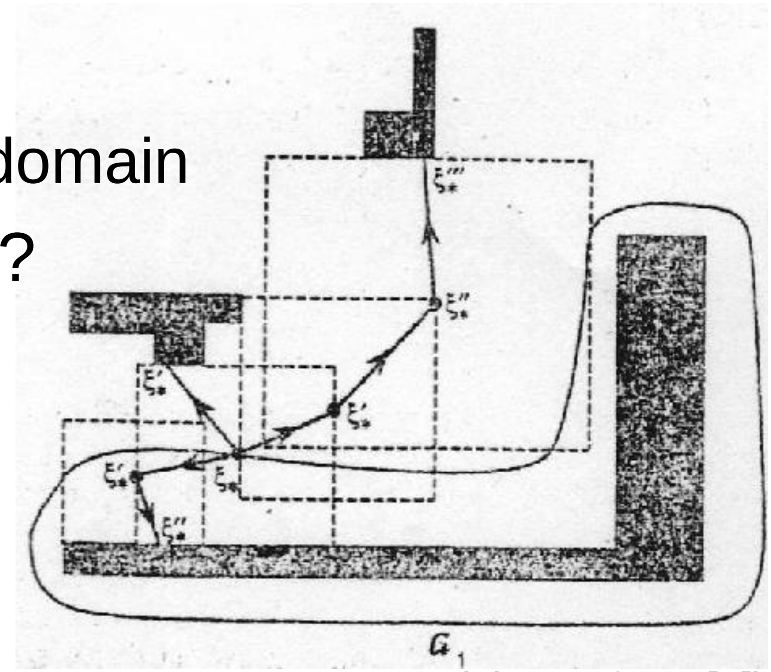
- What if Φ_m is unknown? expand the integral recursively

$$\Phi(r) = \oint_{S_1} dr^{(1)} P_1(r, r^{(1)}) \oint_{S_2} dr^{(2)} P_2(r^{(1)}, r^2)$$
$$\times \cdots \times \oint_{S_n} dr^{(n)} P_n(r^{(n-1)}, r^{(n)})\Phi(r^{(n)})$$

This spatial sampling procedure is called **floating random walk**

The floating random walk alg.

- A 2D example with 3 walks
  - Use maximal cubic transition domain
- How to calculate capacitances?



(picture from [1])

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

$$\Rightarrow \boldsymbol{Q_1 = C_{11}V_1 + C_{12}V_2 + C_{13}V_3}$$

Integral for calculating charge (Gauss theorem)

$$Q_1 = \oint_{G_1} F(\mathbf{r}) \cdot \hat{n} \cdot \nabla \phi(\mathbf{r}) d\mathbf{r} = \oint_{G_1} F(\mathbf{r}) \cdot \hat{n} \cdot \nabla \oint_{S_1} P_1(\mathbf{r}, \mathbf{r}^{(1)}) \phi(\mathbf{r}^{(1)}) d\mathbf{r}^{(1)} d\mathbf{r}$$

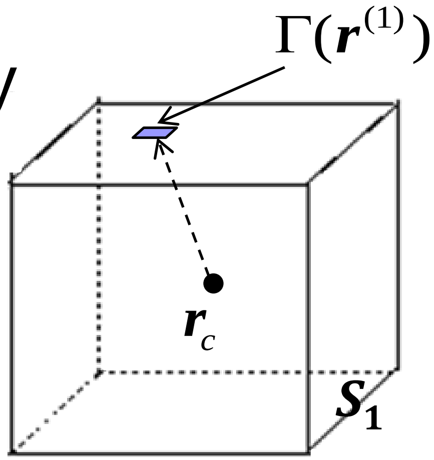
$$= \oint_{G_1} F(\mathbf{r}) g \oint_{S_1} P_1(\mathbf{r}, \mathbf{r}^{(1)}) \phi(\mathbf{r}^{(1)}) \omega(\mathbf{r}, \mathbf{r}^{(1)}) d\mathbf{r}^{(1)} d\mathbf{r}$$

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

[1] **Y. Le Coz**, et al., "A stochastic algorithm for high speed capacitance extraction in integrated circuits," ***Solid-State Electronics***, 1992

The floating random walk alg.

- Make random sampling with P_1 probability
  - Available for cubic transition domain
  - Pre-calculate the probabilities from center to surface panels (GFT)
  - $\omega(\boldsymbol{r}, \boldsymbol{r}^{(1)})$ is also pre-calculated (WVT)



- Secrets of fast FRW algorithm for Manhattan geometry
  - Load GFT/WVT for cubic transition domain to perform fast random walks
  - Maximum transition cube: terminate a walk quickly; easy to design spatial structure for fast calculation of it[1]
- Runtime of FRW: $T_{total} = N_{walk} \cdot N_{hop} \cdot T_{hop}$

[1] **C. Zhang**, et al., "Efficient space management techniques for large-scale interconnect capacitance extraction with floating random walks," ***IEEE T-CAD***, 2013

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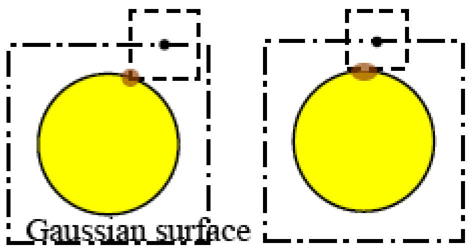
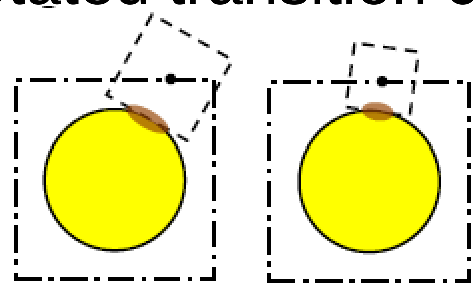
Techniques for Cylindrical ITVs

- Aim: modify the FRW algorithm to accurately handle circular ITV cross section while keeping high efficiency
- The ideas
  - Manhattan transition cube → rotated transition cube

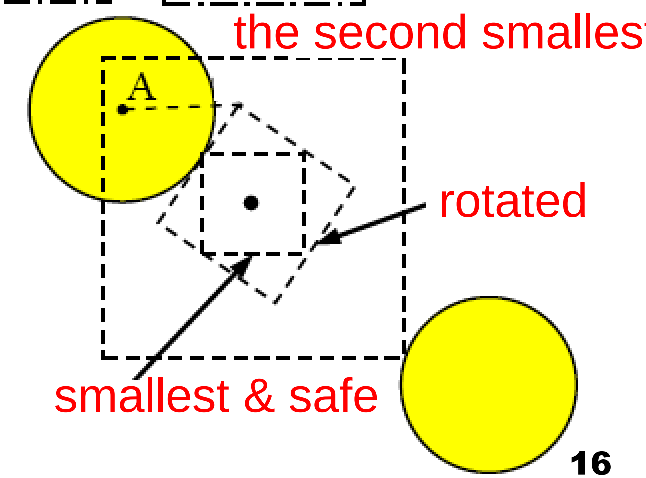
Top view





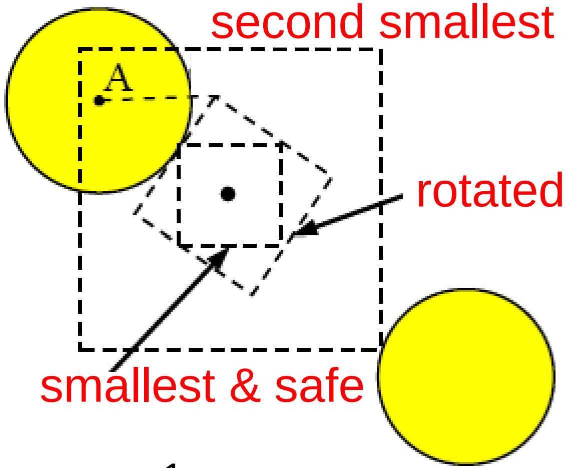
Simple extension of original FRW

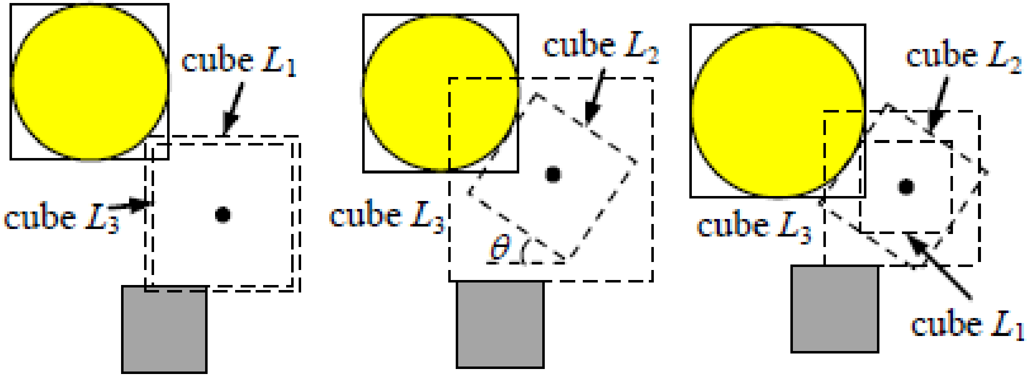
  - Larger probability to terminate; potentially smaller N_{hop}
  - Traverse all cylinders; if the rotated cube touching ITV < the second smallest cube, choose the rotated



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[1]
    - The nearest block is ITV's: may use cylinder-touching cube
    - With the second nearest block, choose valid transition cube





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

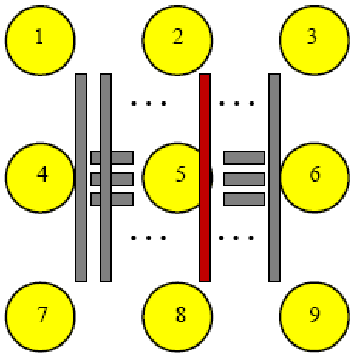
[1] **C. Zhang**, et al., "Efficient space management techniques for large-scale interconnect capacitance extraction with floating random walks," ***IEEE T-CAD***, 2013

Techniques for Cylindrical ITVs

- Performance of the new FRW solver
  - Accuracy

	Raphael (aF)			newFRW(aF)	
	cylinder	square	Err	cylinder	Err
TSV-first(C_t)	3740	3962	5.9%	3778	1.0%
TSV-last(C_t)	3866	4065	5.1%	3908	1.1%
MIV(C_t)	14.7	15.8	7.5%	14.9	1.4%
TSV-first(C_c)	49.9	60.2	21%	50.3	0.8%
TSV-last(C_c)	48.2	58.6	22%	48.1	-0.2%
MIV(C_c)	2.06	2.24	8.7%	2.10	1.9%

0.5% criterion (total capacitance rows C_t); 1% criterion (coupling capacitance rows C_c)



  - Runtime

	oldFRW	newFRW	
	square	cylinder	Inc.
TSV-first(C_t)	2.06	13.4	6.5X
TSV-last(C_t)	2.01	12.7	6.3X
MIV(C_t)	0.61	1.88	3.1X
TSV-first(C_c)	3.5	4.51	29%
TSV-last(C_c)	4.2	5.43	29%
MIV(C_c)	2.6	8.01	3.1X

- #TSV is much less than #wires
- The proposed technique scarifies affordable runtime to achieve high accuracy

Techniques for Cylindrical ITVs

- Performance of the new FRW solver
  - Comparison with fast BEMs

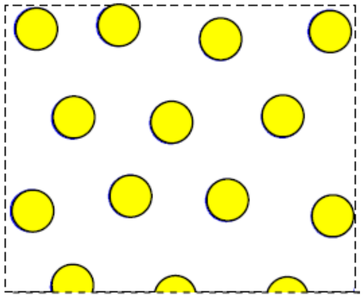
Favorable speedup
Huge memory save

	FastCap*			QBEM*			newFRW			
	Err	time(s)	Mem.	Err	time(s)	Mem.	time(s)	Mem.	Sp1	Sp2
TSV-first(C_t)	-0.8%	67.3	1.8GB	-3.7%	402	7.6GB	12.9	~1MB	5.0	30
TSV-last(C_t)	-3.4%	79	1.9GB	-4.1%	404	7.7GB	12.2	~1MB	6.2	32
TSV-first(C_c)	30%	67.3	1.8GB	-3.8%	298	5.9GB	4.51	~1MB	15	66
TSV-last(C_c)	34%	79	1.9GB	-4.4%	299	6.0GB	5.43	~1MB	15	55

*approximate cylinder with 16-side prism

  - Scalability to large-scale cases

	FRW(non-rotate)			FRW(rotate)			
	N_{walk}	N_{hop}	time(s)	N_{walk}	N_{hop}	time(s)	Sp.
TSV-first	2.3M	37.6	41.9	2.3M	11.8	13.7	**3.1**
TSV-last	2.2M	37.4	36.9	2.2M	11.8	13.3	**2.8**
MIV	224K	23.6	2.14	241K	16.7	1.93	**1.1**
100TSV	6.0M	36.0	228	6.0M	11.5	35.3	**6.5**
400TSV	6.0M	36.0	710	5.9M	11.5	35.2	**20**
576MIV	149K	13.0	11.4	152K	11.2	1.5	**7.7**



random TSV layout

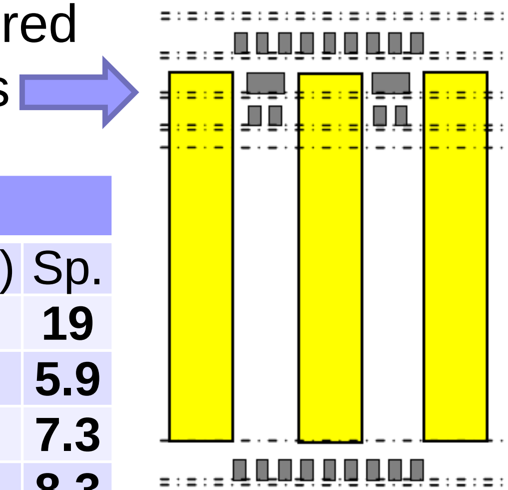
Techniques for Cylindrical ITVs

- Performance of the new FRW solver
  - For large-scale cases, Raphael and FastCap don't work due to runtime and memory usage limitations
  - QBEM works for case 576MIV, but 180X slower than FRW
  - Multi-dielectric cases
    - Speedup to QBEM is up to 61X

	QBEM			newFRW				
	Cap.	Mem.	Time(s)	Cap.	Error	Mem.	Time(s)	Sp.
TSV-first	32.56	11GB	534	33.9	1.5%	22MB	28.5	**19**
TSV-last	30.96	5.2GB	188	33.2	0.9%	22MB	32.7	**5.9**
MIV	0.146	581MB	18.4	0.148	1.4%	22MB	2.53	**7.3**
TSV-first2	31.88	8.8GB	400	33.5	1.9%	22MB	48.0	**8.3**
144MIV	0.276	856MB	35.9	0.292	--	23MB	6.31	**5.7**
576MIV	0.29	6.7GB	344	0.291	--	25MB	5.67	**61**

    - Verified accuracy with Raphael

Multi-layered dielectrics



For pre-built GFTs and WVTs

Techniques for Cylindrical ITVs

- Remarks got from the experiments
  - Show the capacitance error brought by the square approximation again: > 5% on the ITV total capacitance; > 20% on ITV-wire coupling capacitance
  - Compared with solving square-shape approximation, reduce error by 10X with affordable runtime overhead
  - The accuracy of BEM based solvers is not stable, especially for coupling capacitance. The efficiency of BEM is good for small MIV structures, but can be tens times slower than the FRW method for larger cases
  - By using rotated transition cubes and specific space management, up to 20X speedup achieved

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Conclusions

- Extend the FRW capacitance solver to tackle the challenge of accurate extraction brought by high-density ITVs in 3D IC
  - Rotated transition cubes better touching cylindrical
  - Tailored space management to handle large-scale case
  - The proposed method is accurate and versatile, and shows advantages over fast BEM based solvers
- Future work
  - Collaborate with the ITV model considering the semiconductor effect
  - Extend FRW for more general non-Manhattan geometry

Thank You !