Electromigration-Lifetime Constrained Power Grid Optimization Considering Multi-Segment Interconnect Wires

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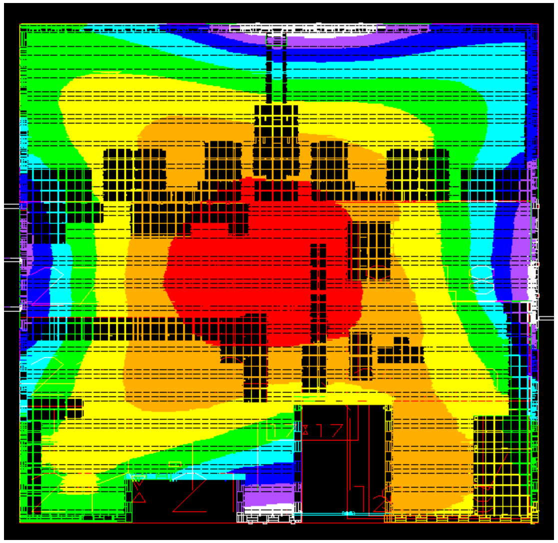
Outline

- Motivation
- Review of existing algorithms
- EM-immortality constrained P/G Optimization
- EM lifetime-constrained optimization
- Experimental results
- Conclusion

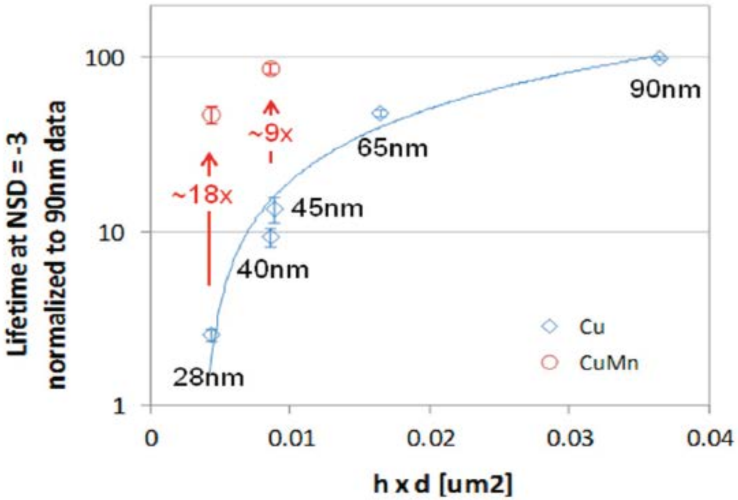
Motivation

- Power/ground networks deliver power supplies from the P/G pads on a chip to the circuit models.
- P/G grid design becomes critical.
  - P/G grids are more vulnerable for the EM wearout due to the unidirectional current flows
  - Excessive IR drops leads to timing failure
  - Both EM and IR drops get worse as technologies advance

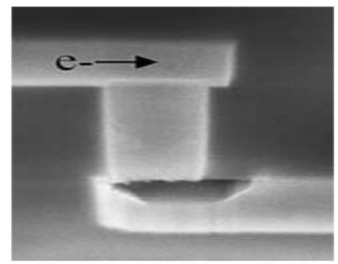


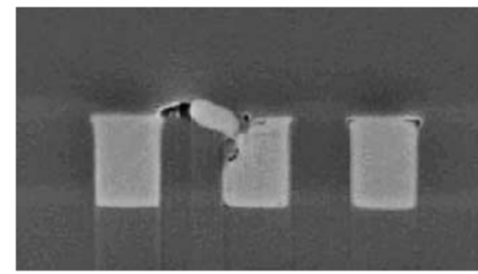
A real industrial chip
#cell instances: 0.5M
#P/G resistors: 0.6M

The EM crisis predicted for sub-10nm VLSI

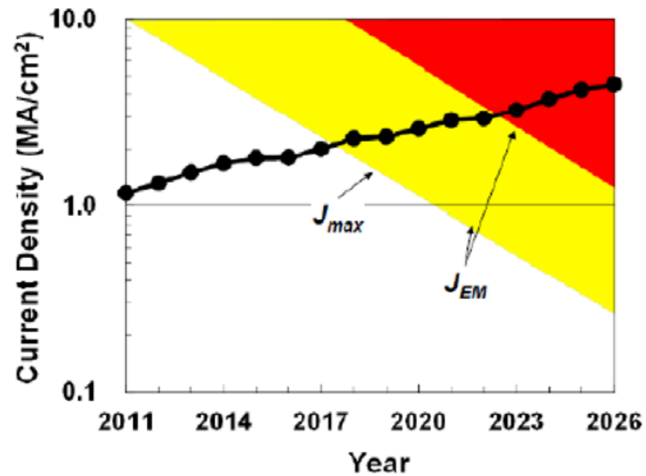


Gall et al, IRPS 2013, EM lifetime at about 0.1% cumulative failure as a function of the product of the line height h and via size d for various technologies.



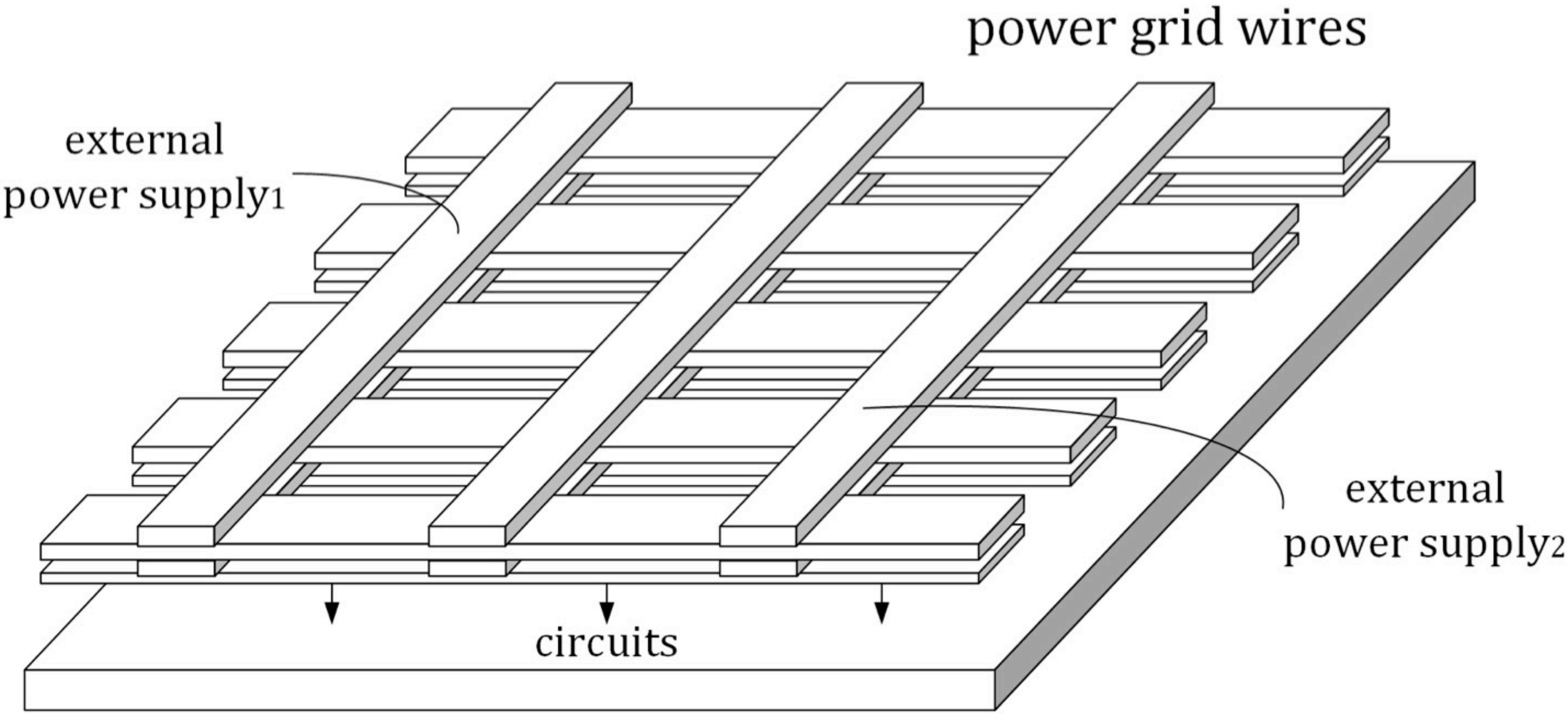


Both J_{max} and J_{EM} will increase over each generation due decreasing cross section and increased operation Frequencies.

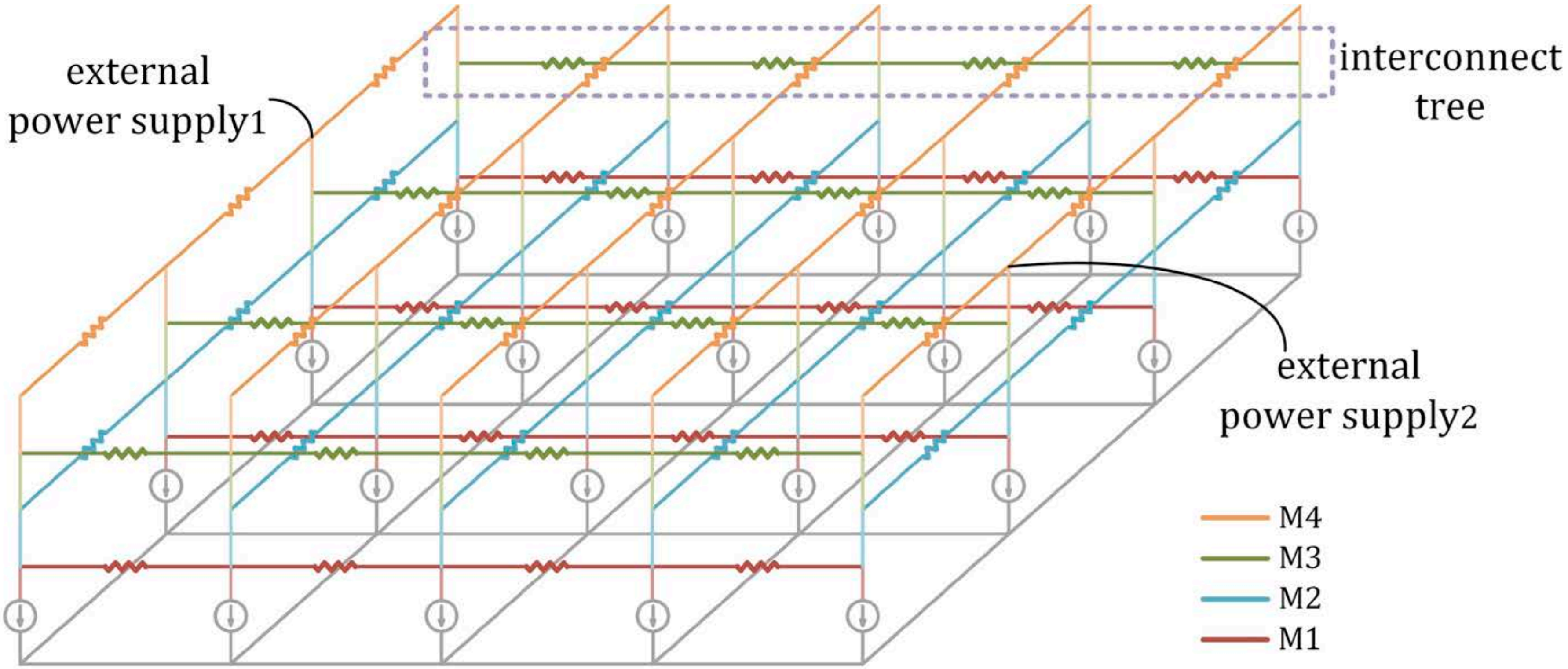


J_{max} is equivalent DC current density
J_{EM} is the maximum current density

Typical Power/Ground (P/G) Network



P/G Network Modeling

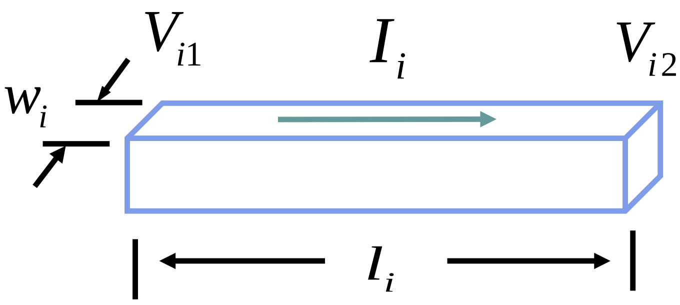


- P/G network can be modeled as linear time-invariant networks with independent current sources
- In our work, via and its resistances can be ignored as we do not change the via sizes.

P/G Network Modeling

- Assumption:
  - Currents (average or maximum) of each individual cell instance are known
  - Computed by using power models of cells in a design
- Existing optimization methods differ in the selection of variables.

Ohm's Law



$$R_i = \frac{V_{i1} - V_{i2}}{I_i} = \rho \frac{l_i}{w_i}$$

P/G wire sizing problem formulation

- Cost function

$$f(V,I) = \sum_{i \in B} l_i w_i = \sum_{i \in B} \rho \frac{I_i l_i^2}{V_{i1} - V_{i2}}$$

- Constraints
  - Voltage IR drop constraints
  - Minimum width constraints
  - Electro-migration constraints
  - Equal width constraints
  - Kirchoff's current law

Relevant algorithm review

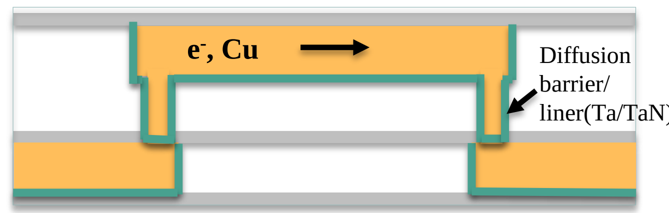
- Resistance values and branch currents are variables (*Chowdhury and Breuer'87*)
  - Both objective function and IR drop constraints are nonlinear
  - Solution: augmented Lagrangian method
- Resistance values are variables (*Dutta and Marek-Sadowska'89)*
  - All the constraints are nonlineat
  - Solution: feasible direction method
- Nodal voltage and branch current are variables (*Chowdhury'89)*
  - Only objective function is nonlinear
  - Solution: linear programming & conjugate gradient
- Sequence of Linear Programming, SLP (Tan's 1999)
  - Transform the nonlinear optimization into the sequence of linear programming (SLP) problems.
  - More efficient than all the previous method.
  - But it still use the old current-density EM constraint

New contributions in this work

- Proposed a new P/G wire sizing technique based on SLP and new EM immortality constraint.
  - Using the recently proposed EM immortality models for general multi-segment interconnect wires.
  - The new method can ensure the immortality of the whole P/G grid networks and still keep the efficiency of the SLP.
- Proposed a new life-time constrained P/G wire sizing technique consider the aging effects of P/G for the first time.
  - Allow some P/G wire failures to further relax the constraints.
  - Consider the aging effects at the targeted life time.

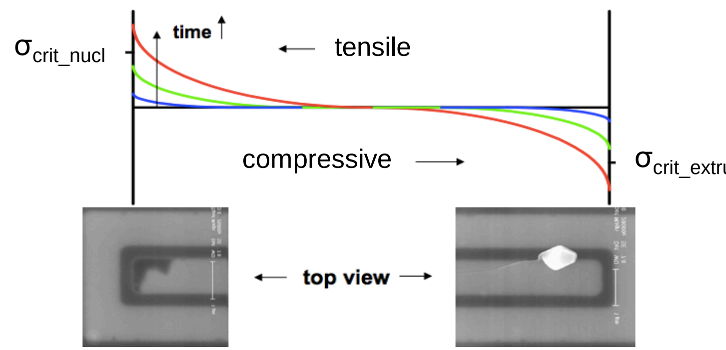
"Blech Limit" effect re-visited

- **Current induced diffusion**
  - ✧ Cu atoms diffuse with electron wind due to momentum transfer
  - ✧ liners block EM through vias
  - ✧ tensile failure (void) at cathode, compressive failure (hillock) at anode



- **Immortality in 'short' lines**
  - ✧ steady state
    - vanished atomic flux:
    - linear time-invariant stress along the line
  - ✧ failure will not occur if: $F_{EM} = F_{\nabla\sigma}$

$\sigma_{ss} < \sigma_{crit}$ or $(jL) < (jL)_{crit}$ *"Blech limit"*



C. V. Thompson, VMIC 2006, Fremont, CA, USA

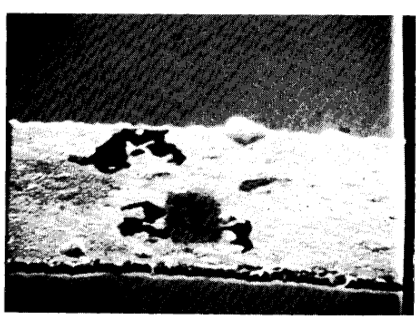
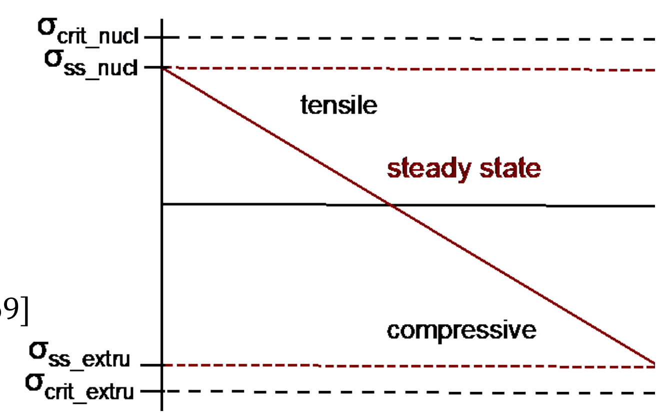


Fig. 3. Voids formed in a ½-mil wide small-grain Al film.

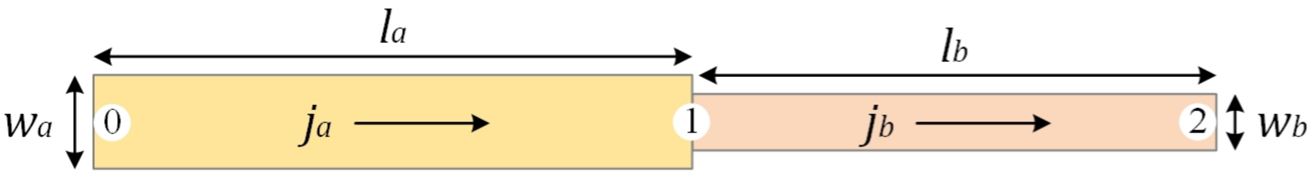
But it only works for single wire

[Black, IEEE Trans Device, 1969]



New steady-state EM modeling and "Blech Limit" for multi-segment wire [Sun, ICCAD'16][1]

- EM voltage
  - $V_E = \frac{1}{2A} \sum_{k \neq g} a_k V_k$



  - $V_E = \frac{V_0 A_0 + V_1 A_1 + V_2 A_2}{2A} = \frac{V_0 \cdot (l_a w_a) + V_1 \cdot (l_a w_a + l_b w_b) + V_2 \cdot (l_b w_b)}{2[(l_a w_a) + (l_a w_a + l_b w_b) + (l_b w_b)]}$
- Critical EM voltage
  - $V_{crit,EM} = \frac{1}{\beta}(\sigma_{crit} - \sigma_{init}) \approx 3.69\text{mV}$
- Immortal condition
  - $V_{crit,EM} > V_E - V_i \Longrightarrow V_{crit,EM} > V_E - V_{cat}$

[1] Z. Sun, E. Demircan, M. Shroff, T. Kim, X. Huang, S. X.-D. Tan, "Voltage-based electromigration immortality check for general multi-branch interconnects", *Proc. IEEE/ACM International Conf. on Computer-Aided Design* (ICCAD'16), Austin, TX, Nov. 2016

P/G wire sizing constraints

- Voltage IR drop constraints

$$V_i \geq V_{min} \text{ for power nodes}$$
$$V_i \leq V_{max} \text{ for ground nodes}$$

- Minimum width constraints

$$w_i = \rho \frac{I_i l_i}{V_{i1} - V_{i2}} \geq w_{i,min}$$

- EM constraints

$$\boldsymbol{V_{EM} - V_{cat,m} < V_{crit,EM}}$$

- Equal width constraints (for branches in an interconnect tree)

$$w_i = w_k \Rightarrow \frac{V_{i1} - V_{i2}}{I_i l_i} = \frac{V_{k1} - V_{k2}}{I_k l_k}$$

- Kirchhoff's current law

$$\sum_{k \in B(j)} I_k = 0$$

Relaxed two-step SLP solution—P-V phase

- $f(V) = \sum_{i \in B} \frac{\alpha_i}{V_{i1} - V_{i2}}, \alpha_i = \rho I_i l_i^2$
  - linearize the objective function
    - $g(V) = \sum_{i \in B} \frac{2\alpha_i}{V_{i1}^0 - V_{i2}^0} - \sum_{i \in B} \frac{\alpha_i}{\left(V_{i1}^0 - V_{i2}^0\right)^2} (V_{i1} - V_{i2})$
    - $\xi \left| V_{i1}^0 - V_{i2}^0 \right| < |V_{i1} - V_{i2}|, \xi \epsilon (0,1)$
  - voltage IR drop constraints
  - minimum width constraints
  - EM constraints
  - equal width constraints
  - current direction constraints
    - $\frac{V_{i_1} - V_{i_2}}{I_i} \geq 0$

Relaxed two-step SLP solution—P-I phase

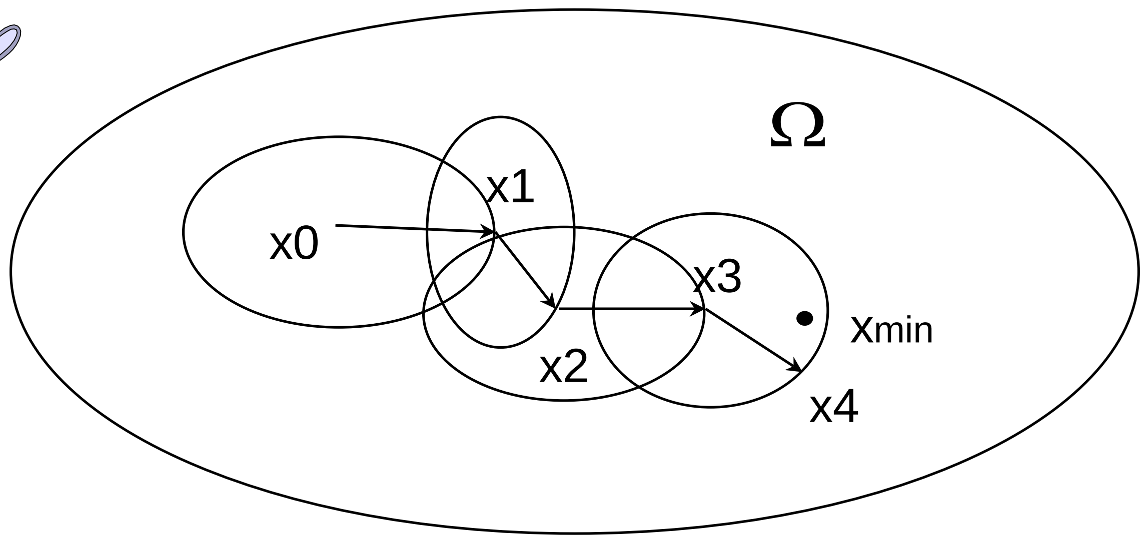
- $f(I) = \sum_{i \in B} \beta_i I_i, \beta_i = \frac{\rho l_i^2}{V_{i1} - V_{i2}}$
  - minimum width constraints
  - equal width constraints
  - KCL constraints
  - current direction constraints
    - $\frac{I_i}{V_{i_1} - V_{i_2}} \geq 0$

Immortality constrained SLP

- New P/G Optimization Algorithm
  1. Obtain an initial solution V^k, I^k for a given P/G network
  2. Build all the constraints for linearized problem P-V
  3. Solve P-V by sequence of linear programmings and record the result as V^{k+1}
  4. Build all the constraints based on V^{k+1} of step (3) for the problem P-I
  5. Solve P-I by linear programming and record the result as I^{k+1}
  6. Stop if improvement over previous result is small. Otherwise, go to step (2)

SLP illustration

- There exists a ξ so that step (3) always converges to the global minimum in the convex problem space of original P-V.

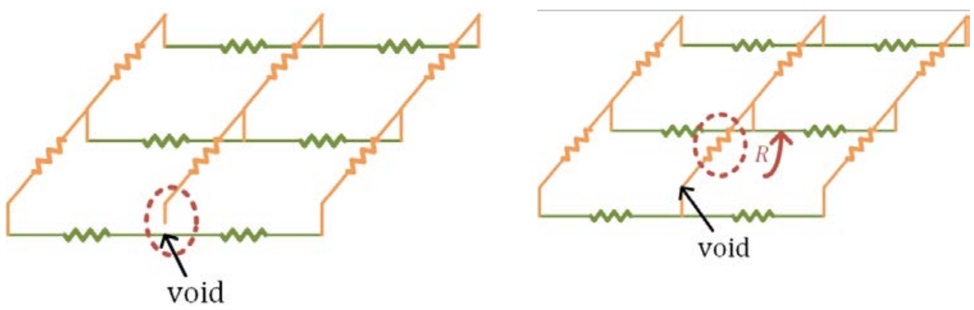


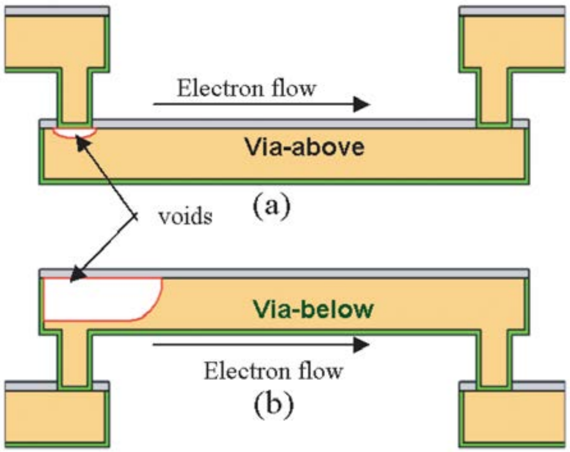
Weakness of the immortality constrained P/G sizing

- Too constrictive as immortality is over-constrained.
  - We may just need the P/G grids have a targeted lifetime like 10 years.
  - We should allow some wire segment to fail (with increased resistance).
  - Aging-aware P/G wire sizing will be more realistic and area-efficient.

Need a more accurate EM timer

- Wire is nucleated if $V_E - V_{cat} > V_{crit,EM}$
- $t_{life} < t_{target}$
  - **wire disconnection** at cathode node for early failure
  - **resistance change** for late failure





- $t_{life} > t_{target}$
  - **constraint relaxation**: $V_{crit,EM} = V_{E,m} - V_{cat,m}$ for the mth tree in the next round of optimization

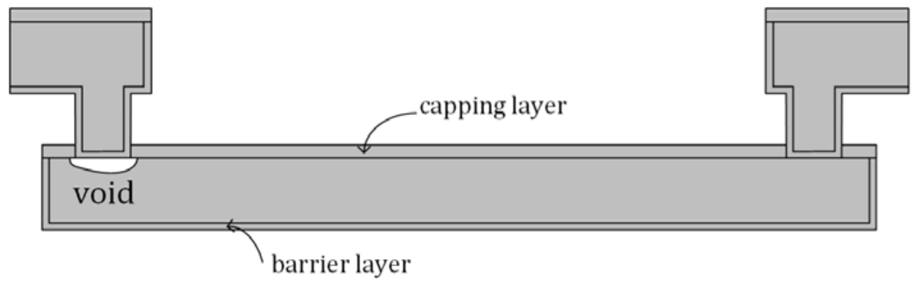
Transient EM-induced stress estimation

——Nucleation phase

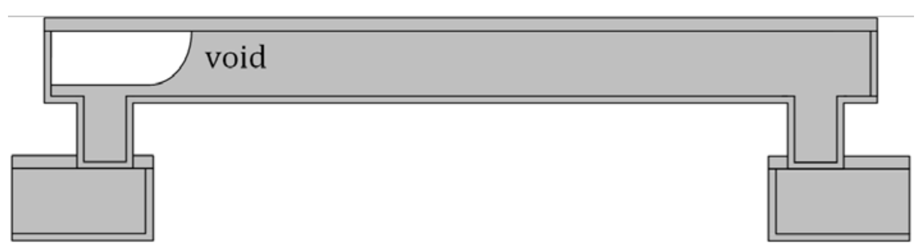
- $TTF = t_{life} = t_{nuc} + t_{growth}$
- Nucleation time, t_{nuc} can be obtained by solving Korhonen's equation
  - $\frac{\partial\sigma(x,t)}{\partial t} = \frac{\partial}{\partial x}\left[\kappa\left(\frac{\partial\sigma(x,t)}{\partial t}\right) + \Gamma\right]$
    - use integral transformation method to discretize the equation
  - Finite difference method [Chase, SMACD'16]
  - Eigen-function method [Wang, DATE'17. Wang, ICCAD'17]
    - $\sigma(x,t) = \sum_{m=1}^{\infty} \frac{\psi_m(x)}{N(\lambda_m)} \bar{\sigma}(\lambda_m, t)$
- If $\sigma(x,t) > \sigma_{crit}$, then $t_{nuc} = t$

Transient EM-induced stress estimation
——Growth phase

- early failure
  - $t_{growth} = \frac{\Delta L_{crit}}{v_d}$



- late failure
  - $t_{growth} = \frac{\Delta L_{crit}}{v_d} + \frac{\Delta r(t)}{v_d\left[\frac{\rho_{Ta}}{h_{Ta}(2H+W)} - \frac{\rho_{Cu}}{HW}\right]}$
- void saturation
  - If $L_{SS} < \Delta L_{crit}$, void can saturate
    - wire is immortal or its lifetime is larger than the targeted lifetime
  - $L_{SS} = L_{line} \times \left[\frac{\sigma_T}{B} + \frac{eZ\rho jL}{2B}\right]$



Lifetime/resistance change analysis for an interconnect tree

1. Compute the initial current density for time $t = 1000$ years, and then use bi-section method to find the first nucleation time t_{nuc}.
2. If the void can saturate, then $t_{growth} = \infty$, $\Delta R = 0$, else determine the growth phase failure mode.
   - If in early failure mode, then compute $t_{growth} = \frac{\Delta L_{crit}}{v_d}$ and set $\Delta R = \infty$.
   - If in late failure mode, then compute t_{growth} assuming $\Delta R = 10\% R$ or compute ΔR so that $t_{nuc} + t_{growth} = t_{target}$.
3. $t_{life} = t_{nuc} + t_{growth}$.

EM lifetime-constrained optimization flow

1. Run immortality constrained SLP. If we can get optimized results at first round, then stop.
2. Compute lifetime of those nucleated wires (if fail due to EM constraint), go to step (1).
   - If $t_{life} > t_{target}$, then relax the EM constraint.
   - If $t_{life} \leq t_{target}$ and in early failure mode, then disconnect segment and disable the EM constraint for certain trees.
   - If $t_{life} \leq t_{target}$ and in late failure mode, then change resistance and disable the EM constraint for certain trees.
3. Compute lifetime of wires whose resistance changed. If $\Delta R_{new} > \Delta R_{old}$, go to step (2-3), else stop.

Experimental results

- languages: C/C++
- Benchmarks: IBM benchmark and self-generated ones
- Parameters:

V_{dd}	1.8V	σ_{crit}	500MPa	T	323K
IR drop/V_{dd}	10%	V_{crit}	3.69mV	E_a	0.8eV
w_{min}	0.1μm	Z	10	D_0	5.55×10^{-8}m²/s
V_{target}	10years	Ω	1.18×10^{-29}m^3	ρ_{Cu}	1.9×10^{-8}Ω·m
		B	140GPa	ρ_{Ta}	1.35×10^{-7}Ω·m

Experimental results

ckt	# node	# bch	# tree	max # tree bch	area (mm^2)	VBEM	CBEM	
						area reduced (%)	area reduced (%)	$t_{life,min}$ (yrs)
ibmpg1	11572	5580	689	30	158.43	35.66	72.29	13.57
ibmpg2	61797	61143	462	192	60.38	77.55	91.35	8.16
ibmpg3	407279	399201	7388	965	697.71	22.60	57.98	9.64
ibmpg4	474836	384709	9358	571	210.44	18.42	29.70	7.61

CBEM – traditional current density based method
VBEM – newly proposed voltage-based EM method

Life-time violation occurs

- area reduced (VBEM) < area reduced (CBEM)
- immortal, no violation
- ibmpg2
  - 120 voltage sources + 18963 current sources

Experimental results

ckt	# nucleated tree	before opt	after opt		area reduced (%)
		$t_{life-min}$ (yrs)	$t_{life-min}$ (yrs)	$V_{crit-max}$ (mV)	
pg5x10	1	-	immortal	-	76.51
pg10x10	5	80.68	77.39	4.307	38.29
pg30x50	11	5.53	19.88	56.1	26.68
pg20x100	8	>100	>100	72.2	46.62

- Note: the area improvement strongly depends on the original layouts
- For $V_E - V_{cat} \gg V_{crit,EM}$, it is difficult to optimize successfully for the first time. With the lifetime-constrained optimization flow, the optimization results can always be achieved after several iterations so that the lifetime targeted can be met.

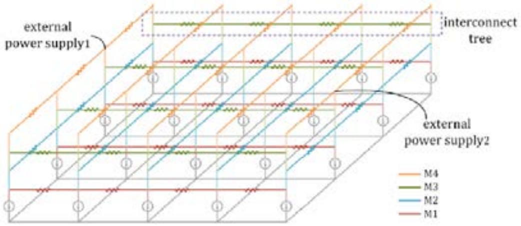
Conclusion

- The new EM-constrained P/G optimization problem
  - can still be formulated as a SLP problem.
  - It ensures that all the wires will not fail if all the constraints are satisfied.
- The lifetime-constrained P/G optimization method
  - allows some short-lifetime wires to fail so that it mitigates over-conservation issue.
- Numerical results
  - show that the new method can effectively reduce the area of P/G network while ensuring reliability in terms of both immortality or targeted lifetime.

Questions???

Electromigration-Lifetime Constrained Power Grid Optimization Considering Multi-Segment Interconnect Wires

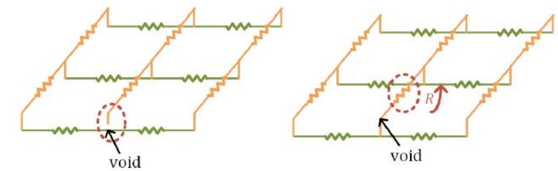
- ## P/G modeling



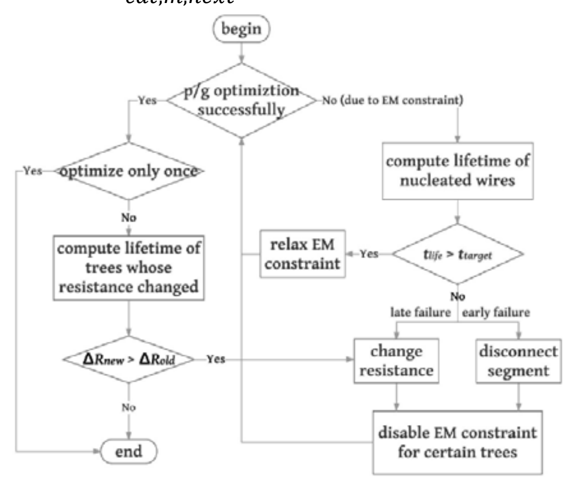
- ## Contribution
  - Size wire width of the power grid strips with recently proposed EM models
  - Considering EM aging effects

- ## EM-immortality constrained P/G optimization method
  - Objective function
    - $f(V,I) = \sum_{i \in B} l_i w_i = \sum_{i \in B} \rho \frac{I_i l_i^2}{V_{i1} - V_{i2}}$
  - Constraints
    - Voltage IR drop: $V_i \geq V_{min}$, $V_i \leq V_{max}$
    - Minimum width: $w_i = \rho \frac{I_i l_i}{V_{i1} - V_{i2}} \geq w_{i,min}$
    - **Electromigration: $V_{E,m} - V_{cat,m} < V_{crit,EM}$**
    - Equal width: $\frac{V_{i1} - V_{i2}}{I_i l_i} = \frac{V_{j1} - V_{j2}}{I_j l_j}$
    - KCL: $\sum_{i \in B(j)} I_i = 0$

- ## EM-lifetime constrained P/G optimization method
  - If $V_{E,m} - V_{cat,m} > V_{crit,EM}$ and $t_{life,m} < t_{target}$
    - wire disconnection (early failure)
    - resistance change (late failure)



  - If $V_{E,m} - V_{cat,m} > V_{crit,EM}$ and $t_{life,m} > t_{target}$
    - constraint relaxation
      - $V_{E,m} - V_{cat,m} < V_{E,m,next} - V_{cat,m,next}$



- ## Experimental Results

ckt	# bch	# tree	area (mm^2)	voltage-based EM constraint area reduced (%)	current density EM constraint area reduced (%)	current density EM constraint $t_{life-min}$ (yrs)
ibmpg1	5580	689	158.43	35.66	72.29	13.57
ibmpg2	61143	462	60.38	77.55	91.35	8.16
ibmpg3	399201	7388	697.71	22.60	57.98	9.64
ibmpg4	384709	9358	210.44	18.42	29.70	7.61

ckt	# tree	# nucleated wires	before optimization $t_{life-min}$ (yrs)	after optimization $t_{life-min}$ (yrs)	after optimization $V_{crit-max}$ (V)	# iter	area reduced (%)
pg5×10	15	1	-	immortal	-	1	76.51
pg10×10	20	5	80.68	77.39	4.307×10^{-3}	2	38.29
pg30×50	80	11	5.53	19.88	5.61×10^{-2}	5	26.68
pg20×100	120	8	>100	>100	7.22×10^{-2}	3	46.62