The Pressing Need for Electromigration-Aware Physical Design

Jens Lienig, Matthias Thiele
Dresden University of Technology
Dresden, Germany
www.ifte.de
<table>
<thead>
<tr>
<th>Year</th>
<th>2018</th>
<th>2020</th>
<th>2022</th>
<th>2024</th>
<th>2026</th>
<th>2028</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate length (nm)</td>
<td>12.8</td>
<td>10.65</td>
<td>8.87</td>
<td>7.39</td>
<td>6.16</td>
<td>5.13</td>
</tr>
<tr>
<td>On-chip local clock frequency (GHz)</td>
<td>6.69</td>
<td>7.24</td>
<td>7.83</td>
<td>8.47</td>
<td>9.16</td>
<td>9.91</td>
</tr>
<tr>
<td>DC equivalent maximum current (μA)</td>
<td>6.92</td>
<td>4.41</td>
<td>2.33</td>
<td>2.98</td>
<td>3.56</td>
<td>4.24</td>
</tr>
</tbody>
</table>

**Metal 1 properties**

| Cross-sectional area (nm²) | 302.4 | 170.1 | 79.2 | 79.2 | 79.2 | 79.2 |
| DC equivalent current densities (MA/cm²) |       |       |      |      |      |      |
| Maximum tolerable current density (w/o EM degradation) | 1.8 | 1.1 | 0.7 | 0.4 | 0.3 | 0.2 |
| Maximum current density (beyond no known solutions) | 9.5 | 5.8 | 3.5 | 2.1 | 1.3 | 0.8 |

*Manufacturable EM-robust solutions are NOT known*

*Interconnect is EM-affected*
Current density needed to drive four inverter gates

Contents

1 Introduction to Electromigration (EM)

2 Mitigating EM in Physical Design – What are Today’s Options?

3 Outlook – What to Do in the “Red Area”?

4 Summary
Electromigration (EM):

Electromigration is the forced movement of metal ions due to an electric field

\[ F_{\text{total}} = F_{\text{direct}} + F_{\text{wind}} \]

- Direct action of electric field on metal ions
- Force on metal ions resulting from momentum transfer from the conduction electrons

\[ \text{Anode} \quad + \quad \text{Cu}^+ \quad \rightarrow \quad \text{Cathode} \quad - \]

Effects of electromigration in metal interconnects:

- **Atomic depletion (voids):**
  - \( \rightarrow \) Slow reduction in connectivity
  - \( \rightarrow \) Interconnect failure

- **Atomic deposition**
  (hillocks, whiskers):
  - \( \rightarrow \) Short-cuts
Black’s Equation:
Median time to failure (MTF) of a single segment due to electromigration

\[ MTF = \frac{A}{j^n} \exp \left( \frac{E_a}{k \cdot T} \right) \]

- Current density
- Cross-sectional-area-dependent constant
- Activation energy for electromigration
- Temperature
- Boltzmann constant
- Scaling factor (usually set to 2)

⇒ Current density is key to addressing electromigration during physical design

Maximum Tolerable Current Densities

- Conventional metal wires (house wiring, etc.)
  - Al ≈ 19,100 A/cm²
  - Cu ≈ 30,400 A/cm²
  … reaching melting temperature due to Joule heating

Melting temperature limits maximum current densities

- Thin film interconnect on integrated circuits can sustain current densities up to \(10^{10}\) A/cm² before reaching melting temperature,
  - Al \(\approx 200,000\) A/cm²
  - Cu \(J_{\text{max}}(Cu) = 5 \cdot J_{\text{max}}(Al) \approx 1,000,000\) A/cm²
  … it reaches its maximum value due to the occurrence of electromigration

Electromigration limits maximum current densities
Maximum Tolerable Current Densities

- Rule of Thumb for Copper IC Interconnects
  - Electromigration to be considered \( \approx 10,000 - 100,000 \) A/cm\(^2\)
  - Effects visible \( \approx 500,000 \) A/cm\(^2\)
  - Rapid destruction \( \approx 30,000,000 \) A/cm\(^2\)

(25°C, Source: AMD Saxony)

Electromigration limits maximum current densities

Contents

1 Introduction to Electromigration (EM)

2 Mitigating EM in Physical Design – What are Today’s Options?

3 Outlook – What to Do in the “Red Area”?

4 Summary
Mitigating EM in Physical Design – What are Today’s Options?

- Local current density
- Surface diffusion in Cu
- Bamboo effect
- Short-length effects
- Impact of voids
- Reservoir effect
- Damage-healing (self-healing) effect

- Wire widths, double/multiple vias
- Surface coating, metal capping
- Wire widths
- Segment lengths
- Via-above/via-below configurations
- (Metal-via) overlaps, multiple vias
- Frequency of the current

Bamboo Effect

$\text{MTF} \ [h]$

$w < \emptyset \ \text{Grains (Bamboo Wires)}$

$w \approx \emptyset \ \text{Grains}$

$w_{\text{MTF}_{\text{min}}}$

$\text{Wire Width } w \ [\mu m]$

$I = \text{constant} \quad T = \text{constant}$

### Bamboo Effect

**MTF [h]**

- **Diffusion**
- **Grain Boundary**
- **Practical Applications**
  - \( w \leq 850 \text{ nm} \)
  - *Damascene Copper [Ar99]*

#### Practical Applications

- \( w = \varnothing \text{ Grains (Bamboo Wires)} \)

### Short-Length Effects: (1) Blech Immortality Condition

- **Electromigration (EM)**
- **Stress Migration (SM)**

**Equilibrium between EM and SM**

- If \( L_{\text{segment}} < \text{“Blech length”} \)

\( F_{x1}, F_{x2}, F_{x3}, F_{x4}, F_{x5} \)
Short-Length Effects: (1) Blech Immortality Condition

Electromigration (EM) ↔ Stress Migration (SM)

Practical Applications:

L_{segment} ≤ 5 - 50 µm

Equilibrium between EM and SM if L_{segment} < 'Blech length'

Short-Length Effects: (2) Void Growth Saturation

Electromigration (EM) ↔

Tensile Compressive Stress

Void

Cap Layer Liner Layer

Metal (Cu) Metallic Barrier (Liner) Dielectric Passivation (Cap Layer)
Short-Length Effects: (2) Void Growth Saturation

Void growth saturation due to mechanical stress buildup if $J_{L_{\text{segment}}} < J_{L_{\text{saturation}}}$

Practical Applications*

$(JL)_{\text{saturation}} = 375 \text{ A/cm (Cu, low-k)} \ldots 3,700 \text{ A/cm (Cu, high-k)}$

$L \leq 7.5 \mu m \ldots 74 \mu m$

Via-below and Via-above Configuration

Via-below

Cap Layer
Liner Layer
Void

Via-above

Cap Layer
Liner Layer
Void

Practical Applications*

\[ J = 3,700 \text{ A/cm} \]
\[ L \leq 74 \mu\text{m} \]

\[ J = 1,500 \text{ A/cm} \]
\[ L \leq 30 \mu\text{m} \]

*\[ J = 5 \times 10^5 \text{ A/cm}^2, \text{Cu, high-}k, \text{[LE02][HR02]} \]
Double/Multiple Vias

[Diagram showing double/multiple vias with overstrained via]

Self-Healing Effect

[Graph showing lifetime vs. frequency with annotations: 10 Hz ... 10 kHz, 500-fold increase in MTF for Cu interconnect]


Self-Healing Effect

Practical Implication
(At least) two different current density limits:
- Nets with $f > 10 \text{ kHz}$
- Remaining (DC) nets

Contents

1 Introduction to Electromigration (EM)

2 Mitigating EM in Physical Design – What are Today’s Options?

3 Outlook – What to Do in the “Red Area”?

4 Summary
Outlook: Critical Length Effect

Critical length limits
Actual mean segment lengths
Length in µm

Blech lengths increasingly exceeded

Values from ITRS 2014, calculated for respective technology node

Outlook: EM-Robust Layout Elements

Current density

New constraint in physical design

"Forbidden elements"

EM-robust layout elements
Outlook: Pattern Generator

- Design Technology
- Technology Corners
- EM Design Rule Derivation
- Pattern Generator
- EM Verification
- Routing Elements
- EM-robust layout elements

Outlook: Constraint-Driven Design

- Design Technology
- Technology Corners
- EM Design Rule Derivation
- Pattern Generator
- EM Verification
- Routing Elements
- Physical Design
  - Layout Synthesis
  - Physical Verification
Pattern library contains meta-models, that are mathematical relations between FE model constraints (boundary conditions) and result quantities, e.g. maximum current density.

Maximum current densities are calculated from the boundary conditions (currents) of the layout.

Full-chip current-density analysis is possible as only the meta models are calculated.

Outlook: New Materials

- Carbon nanotube (CNT)
- Graphene structure
### Summary

> Electromigration is fast becoming a physical design problem due to increased current densities driven by IC down-scaling.

> Need to increase current density limits by putting in place EM-inhibiting measures, such as short-length and reservoir effects.

> Future design flows: using the dependence between current density limits and the specific layout geometry

<table>
<thead>
<tr>
<th></th>
<th>Cu</th>
<th>Single-wall CNTs</th>
<th>Multi-wall CNTs</th>
<th>Cu-CNT Composites</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum current density (A/cm²)</strong></td>
<td>&gt; 1·10⁶</td>
<td>&gt; 1·10⁸</td>
<td>&gt; 1·10⁹</td>
<td>&gt; 6·10⁸</td>
</tr>
<tr>
<td><strong>Thermal conductivity @300K (W/m·K)</strong></td>
<td>385</td>
<td>3,000-10,000</td>
<td>3,000</td>
<td>~ 800</td>
</tr>
</tbody>
</table>


https://doi.org/10.1145/3177540.3177560

> Restricting physical design to EM-robust structures can provide relief from severe reliability constraints in future technologies.


https://doi.org/10.1145/3177540.3177560