Thermal and Power Integrity based Power/Ground Networks Optimization

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Outline

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P/G Network Design

- Power/Ground (P/G) distribution systems are designed to provide needed voltages and currents to the transistors that perform the logic functions of a chip.

P/G Design Challenges

- Power/Ground Network Design
  - Cost
  - Reliability
  - Performance
  - Minimize: Wire Area
  - Subject to: 1) IR-Drop constraint
    2) EM constraint
    3) Minimum-Width constraint

Chip Area
  - Electromigration
  - IR-Drop
Electromigration

- The mass transport of a metal due to the momentum transfer between conducting electrons and diffusing metal atoms.
- Main reliability concern of IC design.
- Modeled by Block’s equation for mean-time-failure

\[ MTF = \frac{A}{J_{\text{EM eff}}^2} \exp\left(\frac{E_u}{k_B T_m}\right) \]

- \( T_m \) – Metal Temperature
- \( J_{\text{EM eff}} \) – Effective ac value of Current Density

- EM constraint limits current density

\[ J_{\text{EM eff}} \leq J_{\text{EM max}} \]

Figure: Dept. of Surface and Microarea Analysis, Leibniz Inst. for Solid State & Materials Research Dresden

Existing Approaches

- Nonlinear programming methods
  - Not convex, nonlinear
  - Slow runtime, small problem size
  - Augmented Lagrangian method
    (S. Chowdbury, M. A. Breuer in TCAS 1987, TCAD 1988)
  - Feasible Direction method
    (R. Dutta, M. Marek-Sadowska in DAC 1989)
Existing Approaches – cont.

- Relaxed two-phase optimization method
  - phase 1 – current fixed, convex, nonlinear
  - phase 2 – voltage fixed, linear programming problem
  - conjugate gradient method (S. Chowdbury in DAC 1989)
  - sequence of linear programming problems
    (X. Tan, C.-J. Richard Shi, et. al., in DAC 1999, DAC 2001)
  - sequence of network simplex problems
    (T.-Y. Wang, Charlie Chen in ISQED 2002)
  - much faster

- Heuristic method based on minimizing average power consumption and wire area
  - convex
    (S. Boyd, S. Yun, et. al. in ISPD 2001)
  - faster than two-phase method
  - with optimal solution, each wire has either same current density or zero width
Robustness Issues of Existing Methods

Power/Ground Network Design

Cost

Reliability

Performance

Chip Area

Minimize: Wire Area

Subject to: 1) IR-Drop constraint

2) EM constraint

3) Minimum-Width constraint

What's Wrong? Thermal Problems

- Wire temperature is governed by Self-Heating (SH).
- In the EM constraint,
  - Reliability is guaranteed only by limiting current density.
  - However, lifetime is also dependent on wire temperature.
  - Therefore, wire widths are overestimated (area cost) or underestimated (lifetime degradation).
- Need a new constraint: EM + SH.
- In the objective function,
  - Minimize total wire area
  - However, smaller the wire area → larger the power consumption in the network.
  - Therefore, wire has higher temperature (SH).
- Need to minimize weighted sum of total wire area and power consumption.
Proposed methods

- Thermal-aware P/G networks design methodology:
  - Consider thermal issues in optimization process.
  - A self-consistent constraint (EM + SH) is used to replace the EM constraint.
  - Minimize the sum of each wire’s weighted sum of average power dissipation and wire area.

\[
\text{Minimize: } \sum (R + \mu_k A_k)
\]

\[
\text{Subject to: } 1) \text{ IR-Drop constraint} \\
2) \text{ self-consistent constraint} \\
3) \text{ minimum-width constraint}
\]

Self-Consistent Constraint

- In the EM constraint,
  - Maximum current density is dependent on wire temperature

\[
J_{EM,ref} = J_{EM,ref}e^{\left(\frac{F_e}{2\lambda_{ref}^2} + \frac{F_r}{2\lambda_{ref}^2}\right)} = J_{max}(T_m)
\]

- Self-Heating (SH) effect:
  - Current flowing through metal wires dissipates heat and increases the wire temperature

\[
J_{SH,SH} = \Delta T_{SH}K_{ins}W_{m}\rho_{m}(T_m)
\]

- Self-consistent constraint:
  - Find the maximum current density of each wire satisfying both EM and SH (W. R. Hunter in Trans. ED 1997)

\[
J_k \leq J_{SC}
\]
Objective Function

- To minimize the sum of each wire’s weighted sum of area and power consumption.
  \[ \sum_k [P_k + \mu_k A_k] \]
  - Purpose: control the power consumption in P/G network
  - Control power consumption \(\rightarrow\) Control temperature
  - \(\mu_k > 0\) is defined as ohmic power density
  - Trade-off between wire area and power consumption -- control \(\mu_k\)

Optimization Approach

- Thermal-aware optimization problem solves
  - Minimize: \(\sum [P_k + \mu_k A_k]\)
  - Subject to:
    1) IR-Drop constraint
    2) self – consistent constraint
    3) minimum-width constraint

- Instead, we solve the following thermal-aware optimization problem (TOP)
  - Minimize: \(\sum [P_k + \mu_k A_k]\)
  - Subject to: \(w_k \geq 0\)
  - Convex, nonlinear function.
  - Can be solved efficiently.
  - Under optimal solution \(\rightarrow\) either \(w_k = 0\) or \(J_{k,\text{rms}} = \frac{1}{n} \sqrt{\frac{\mu_k}{\rho}}\)
  - Wire with current density \(J_{k,\text{rms}}\) assigned \(\mu_k\) by \(\mu_k = \rho_s (J_{k,\text{rms}})^3 w_k^2\)
Constraints Satisfaction

- Self-consistent constraint:
  - Calculate self-consistent current density $J_{sc}$
  - To have wire with current density $J_k$ (satisfy $J_k \leq J_{sc}$) is guaranteed by setting $\mu_k = \rho_s (J_k)^2_{rms}$

- Problem TOP is solved with logarithmic barrier method

- IR-drop and minimum-width constraints:
  - Scaling ($\lambda$): $w = \{ w_1, \ldots, w_n \} \leftrightarrow \mu = \{ \mu_1, \ldots, \mu_n \}$
    \[ \lambda w \leftrightarrow \mu / \lambda^\lambda \]
  - IR-drop scaling $\lambda = V / V_{max}$
  - Minimum-width scaling $\lambda = w_{min} / w$

Experimental Results

- Without thermal consideration, the lifetime of wires in hot spots may be less than 10 years (expected).
- Since the self-consistent current density of wires in hot spots is small, these wires need to be widen to satisfy 10 years of reliability.
There are 372 wires violating the 10 years of reliability and the minimum lifetime is 2 years without considering thermal effects.

With thermal-aware optimization design, each wire is within 5% of expected 10 years.

Compare to the design without thermal concern, the increase of the wire area of thermal-aware design is only 5.4%
In this paper, we propose a new approach of P/G network design, satisfying power-delivery and thermal integrity.
- Define a self-consistent constraint to comprehend EM with thermal reliability.
- Propose a new objective function to guarantee lifetime through power consumption and wire are control.

The resulted design improves the power-delivery quality and thermal reliability from the comparison of wire lifetime, voltage distribution, and current density distribution.