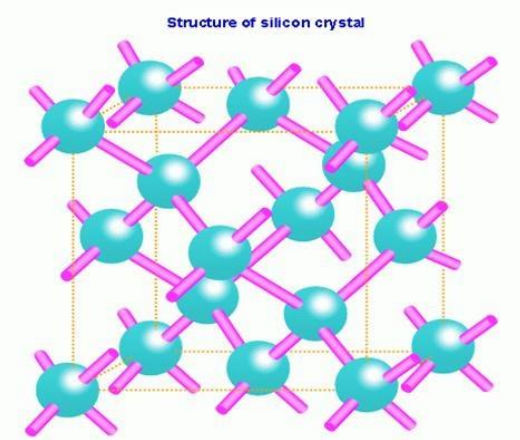

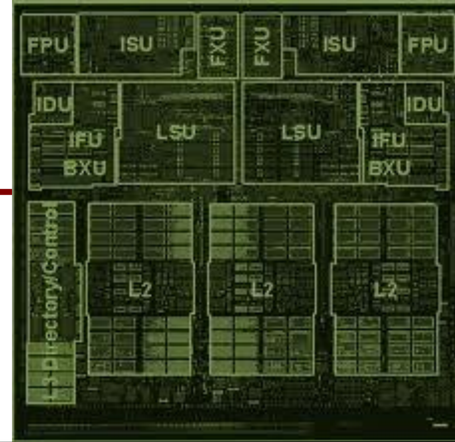

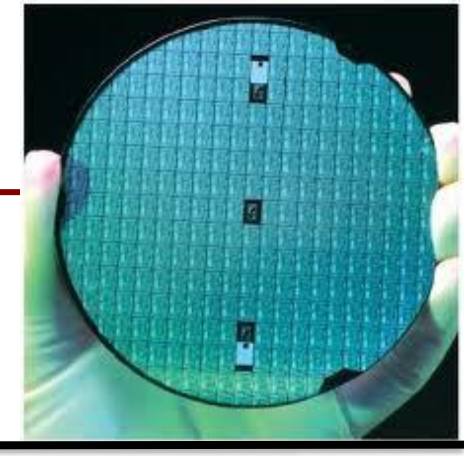

ECE 225

Lecture 11

Interconnect Design under Thermal, Power, Reliability, & Variability Constraints (Cont'd)

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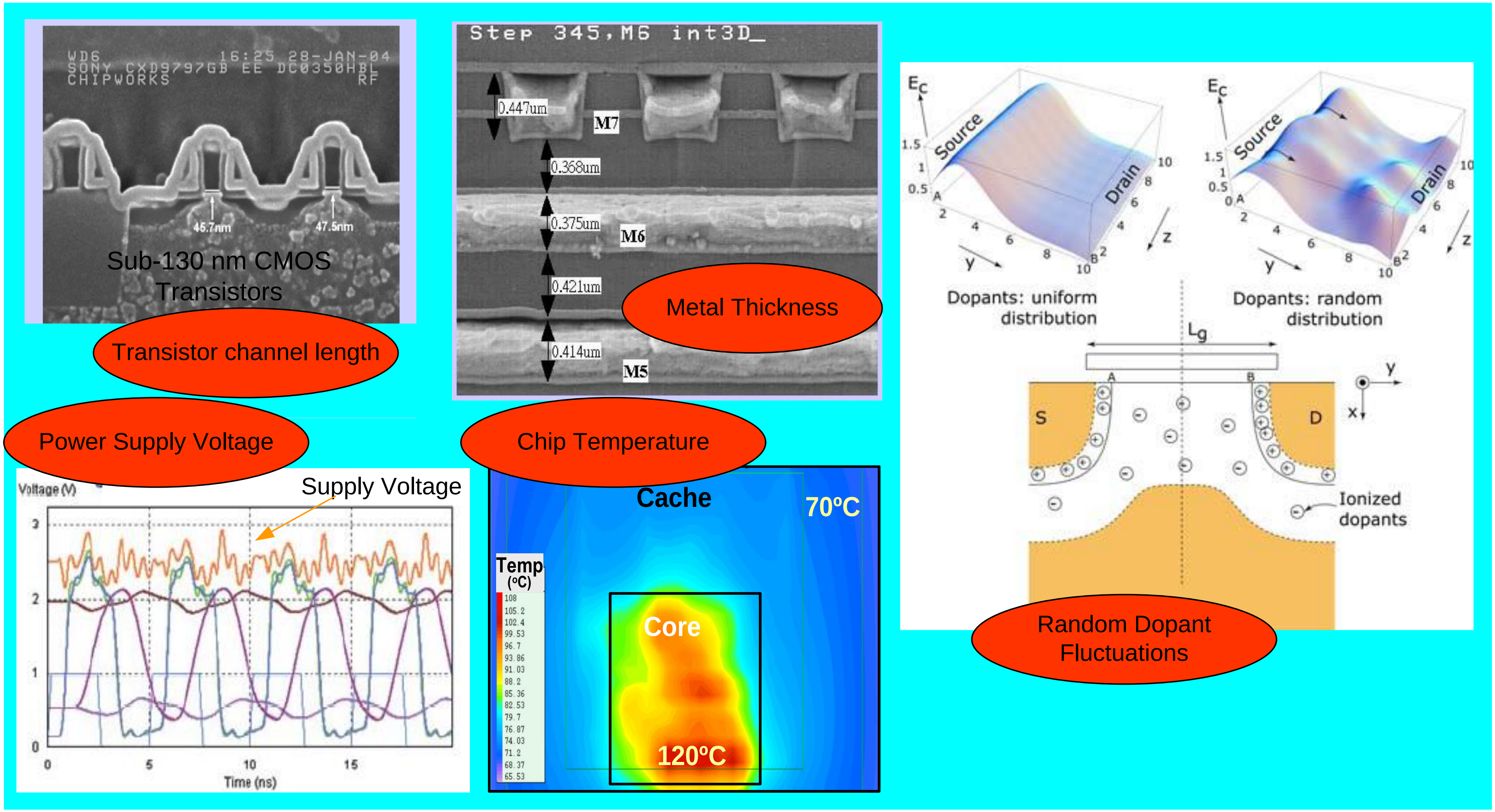
University of California, Santa Barbara

Implications of Parameter Variations

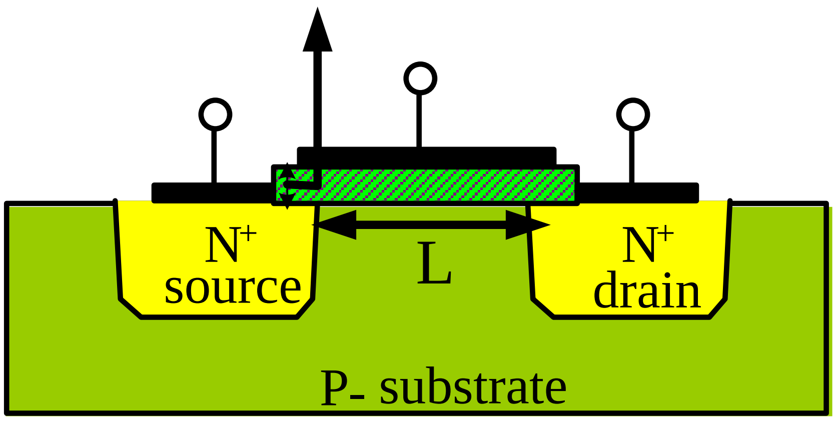
V. Wason and K. Banerjee, IEEE International Symposium on Low Power Electronic Design (ISLPED), 2005, pp. 131-136.

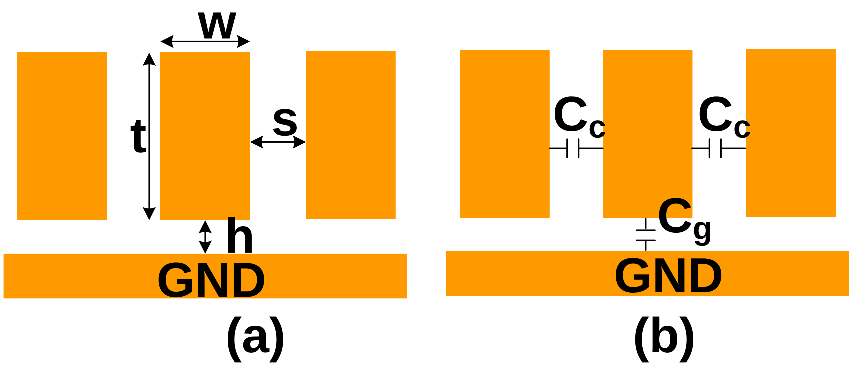
Parameter (P-V-T) Variations



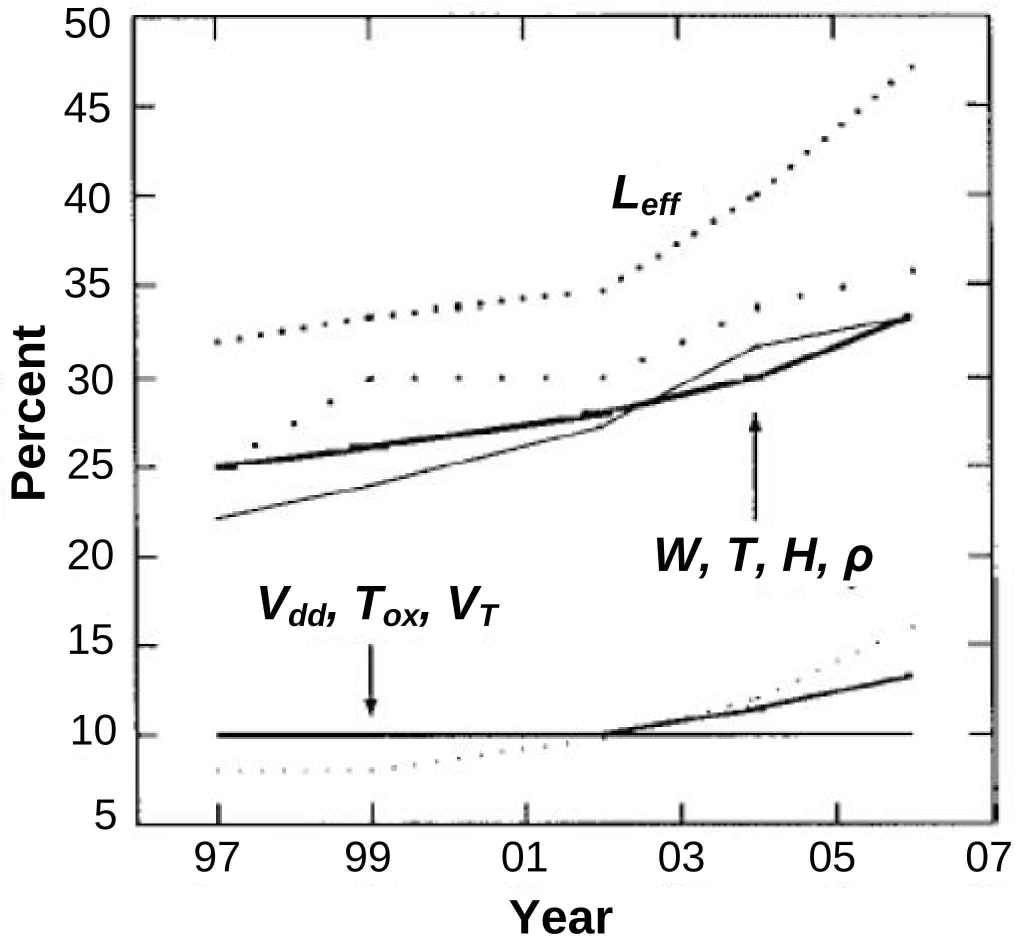
Process Variations

- Device Variations
  - Channel Length (L)
  - Oxide Thickness (t_{ox})
  - Dopant Density (N_a)
- Interconnect Variations
  - Line Width (w)
  - Spacing (s)
  - Metal Thickness (t)
  - Dielectric Thickness (h)



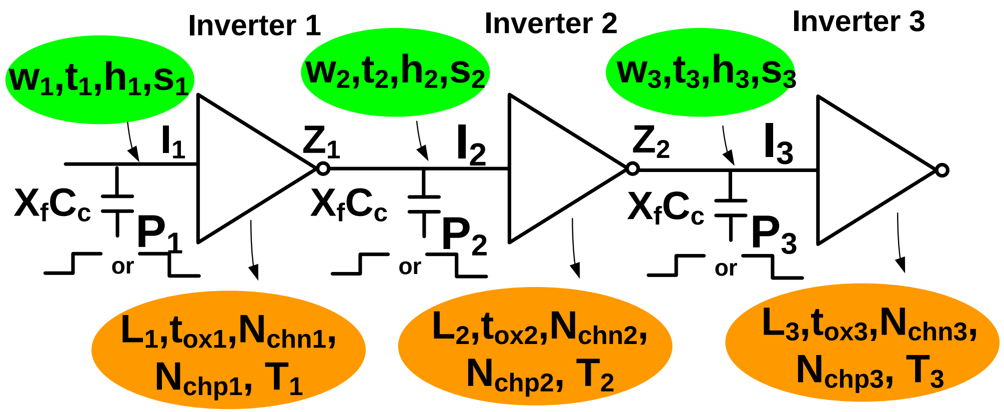


Device vs. Interconnect Variations



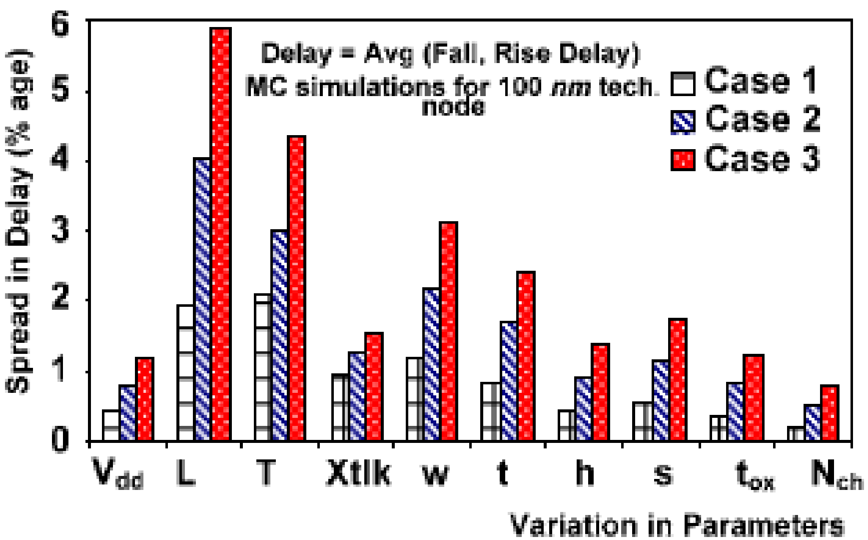
S. Nassif (IBM)

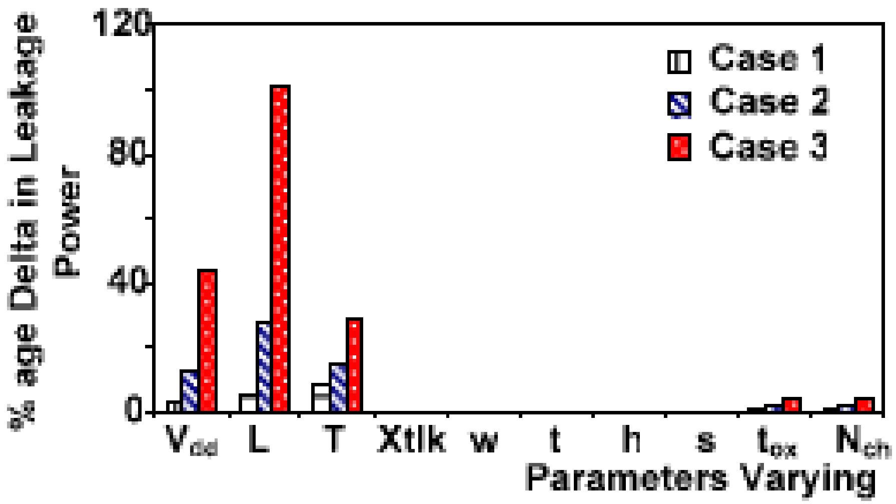
Sensitivity Analysis of Delay and Power



3 cases considered;
% variations increase
from case 1 to case 3

Wason and Banerjee, ISLPED 2005

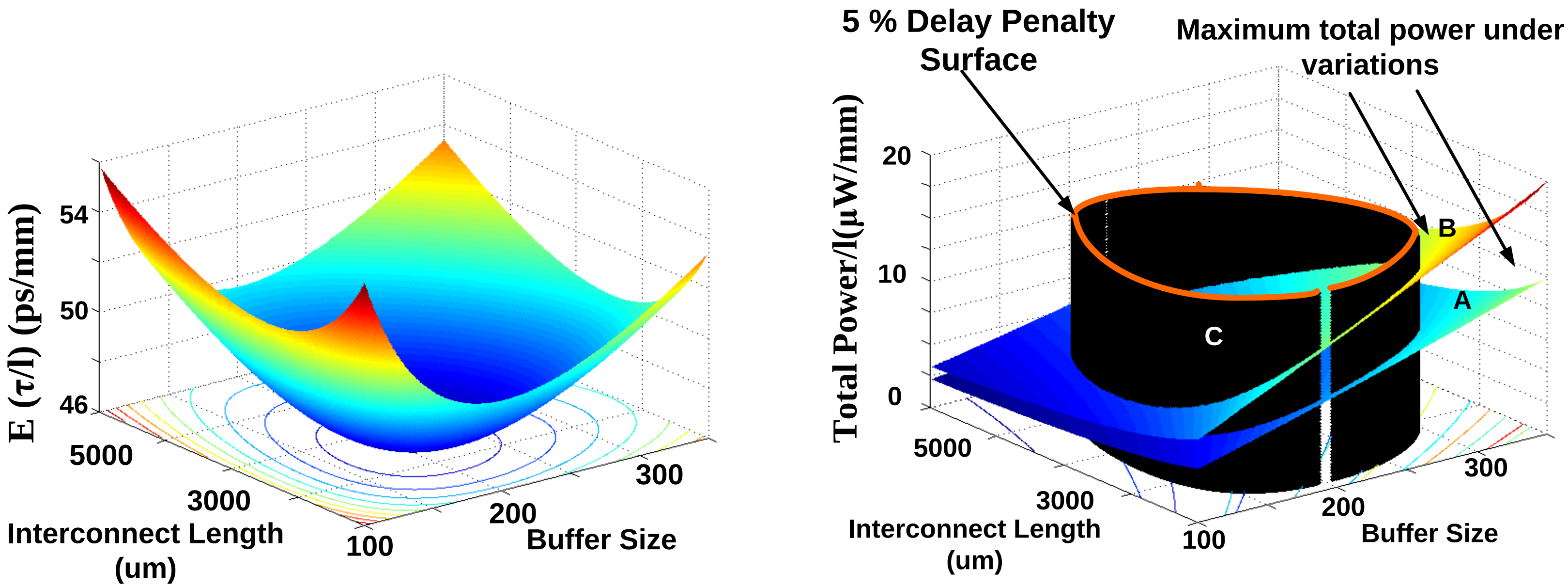




- Variations have significant impact on leakage power and delay

Interconnect Design Considering Variations

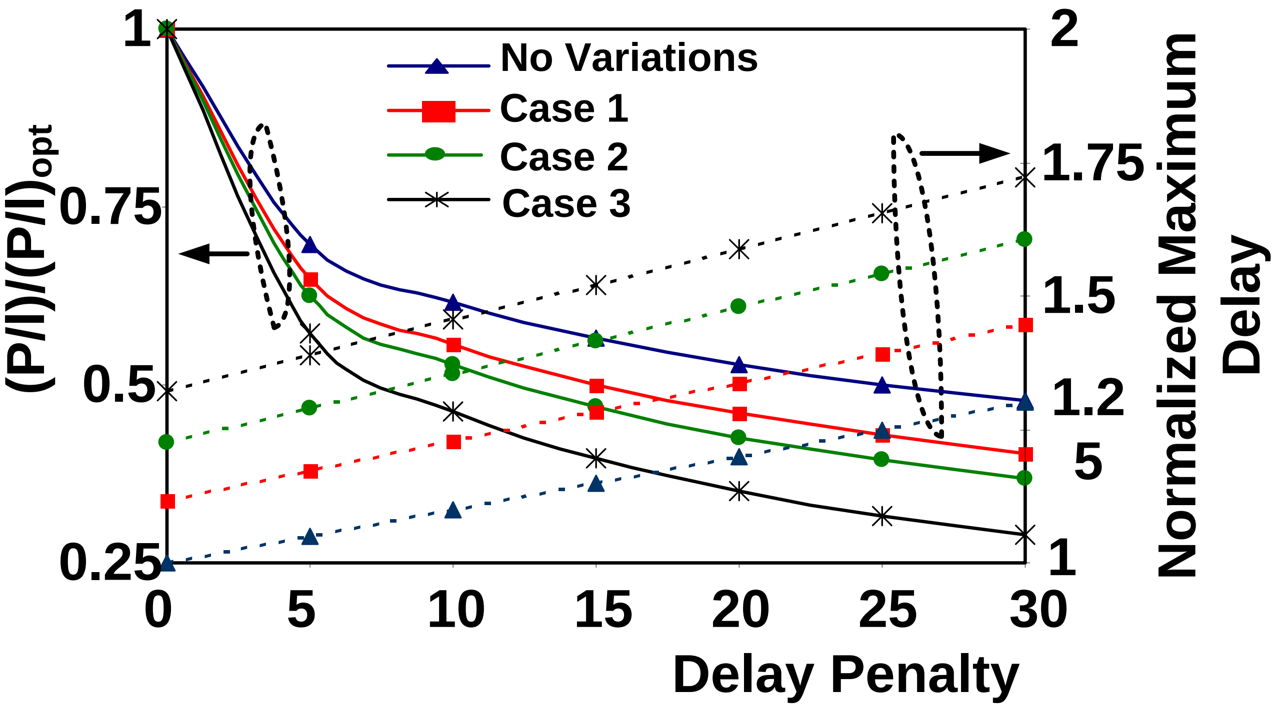
- Significant Implications for Interconnect Design
- Power-Optimal Repeater Insertion- tradeoff delay with power



Wason and Banerjee, ISLPED 2005

Variations can significantly impact power-optimal repeater insertion

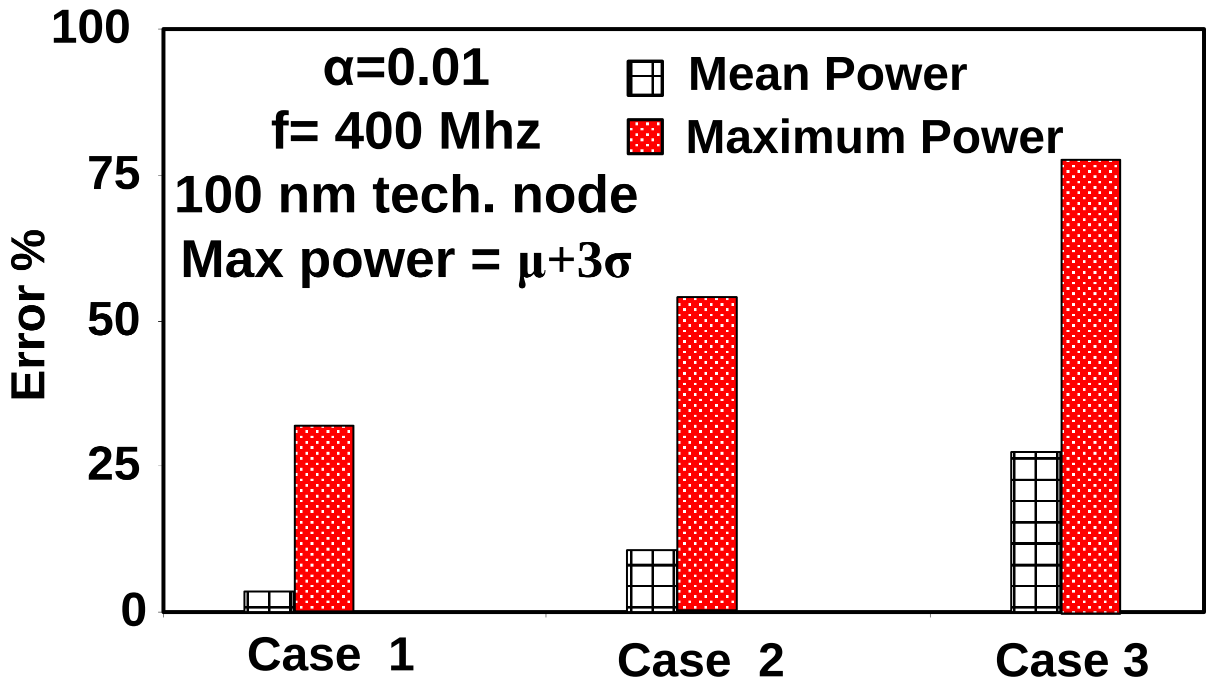
Optimization under Parameter Variations



Wason and Banerjee, ISLPED 2005

- The normalized delay increases under variations
- Power savings are higher for the same penalty in delay, as variations increase
- Importance of power-optimal repeater insertion increases

Implications for Power Estimations



- Error in power estimation can be significant if variations are neglected

Interconnect Thermal Effects and Reliability

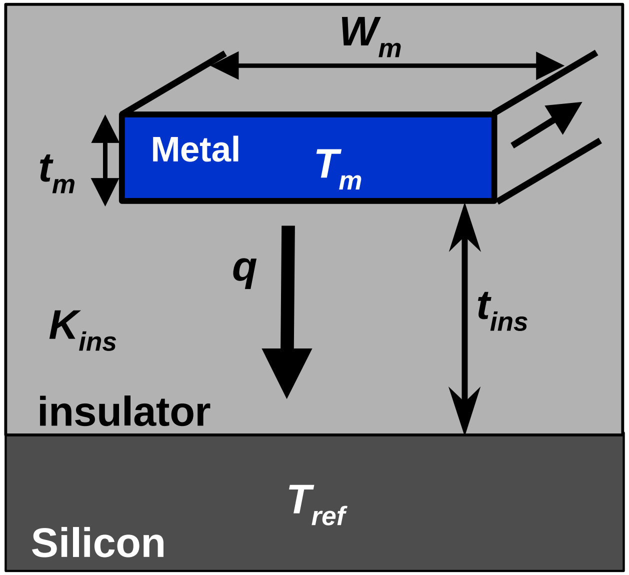
K. Banerjee and A. Mehrotra, IEEE Circuits and Devices Magazine, pp. 16-32, Sept. 2001.

Self-Heating or Joule Heating

$$\Delta T_{self-heating} = \left(T_m - T_{ref}\right) = I_{rms}^2 R\, \theta_j$$

θ_j **is the effective thermal impedance:**

$$\theta_j = \frac{t_{ins}}{K_{ins} L W_{eff}}$$

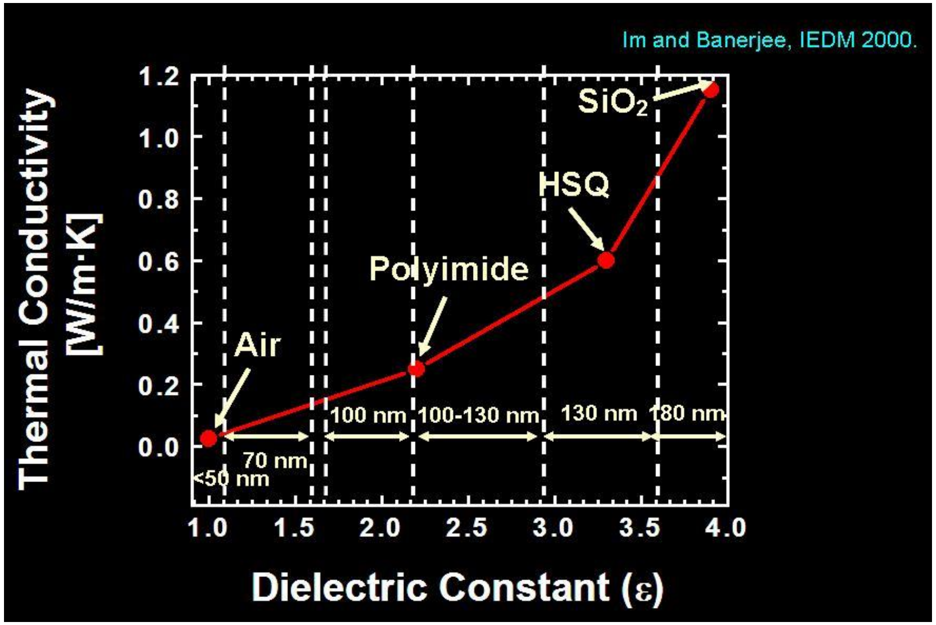


W_{eff} **is the effective metal width to account for quasi-2D heat conduction.**

Interconnect Scaling Trends

Implications of Technology Scaling on Thermal Effects

- Low-k materials have lower thermal conductivity than silicon dioxide.
- Scaling trends that cause increasing thermal effects are:
  - increasing current density
  - increasing interconnect levels
  - low-k dielectrics
  - increasing thermal coupling

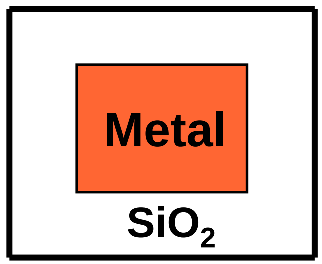


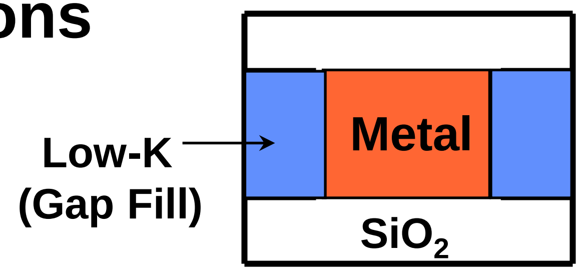
Interconnect Scaling Trends

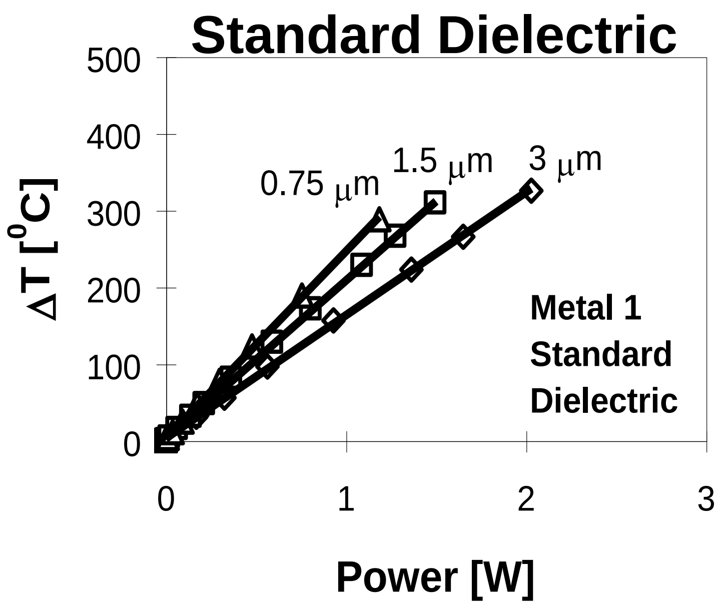
Impact of Line Width Scaling Using Low-k

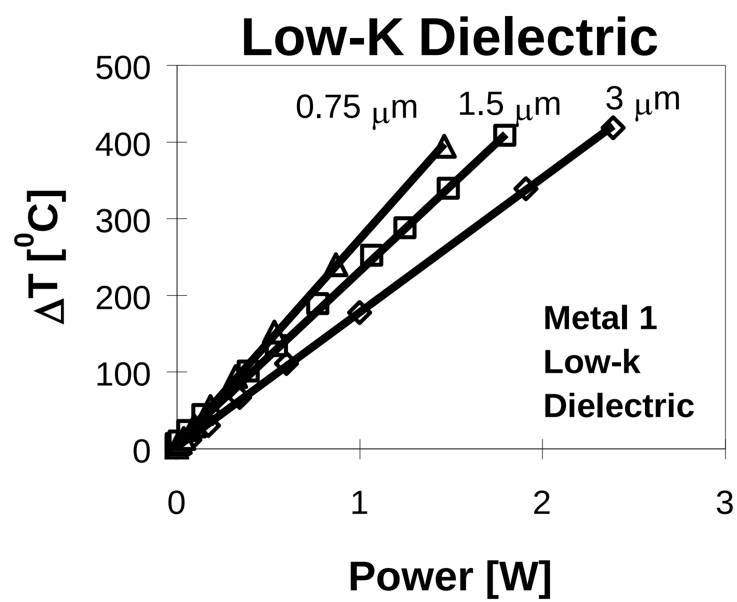
Banerjee et al., IEDM, 1996

DC Conditions









- As W decreases SH increases.
- Low-k increases SH by 10-15%

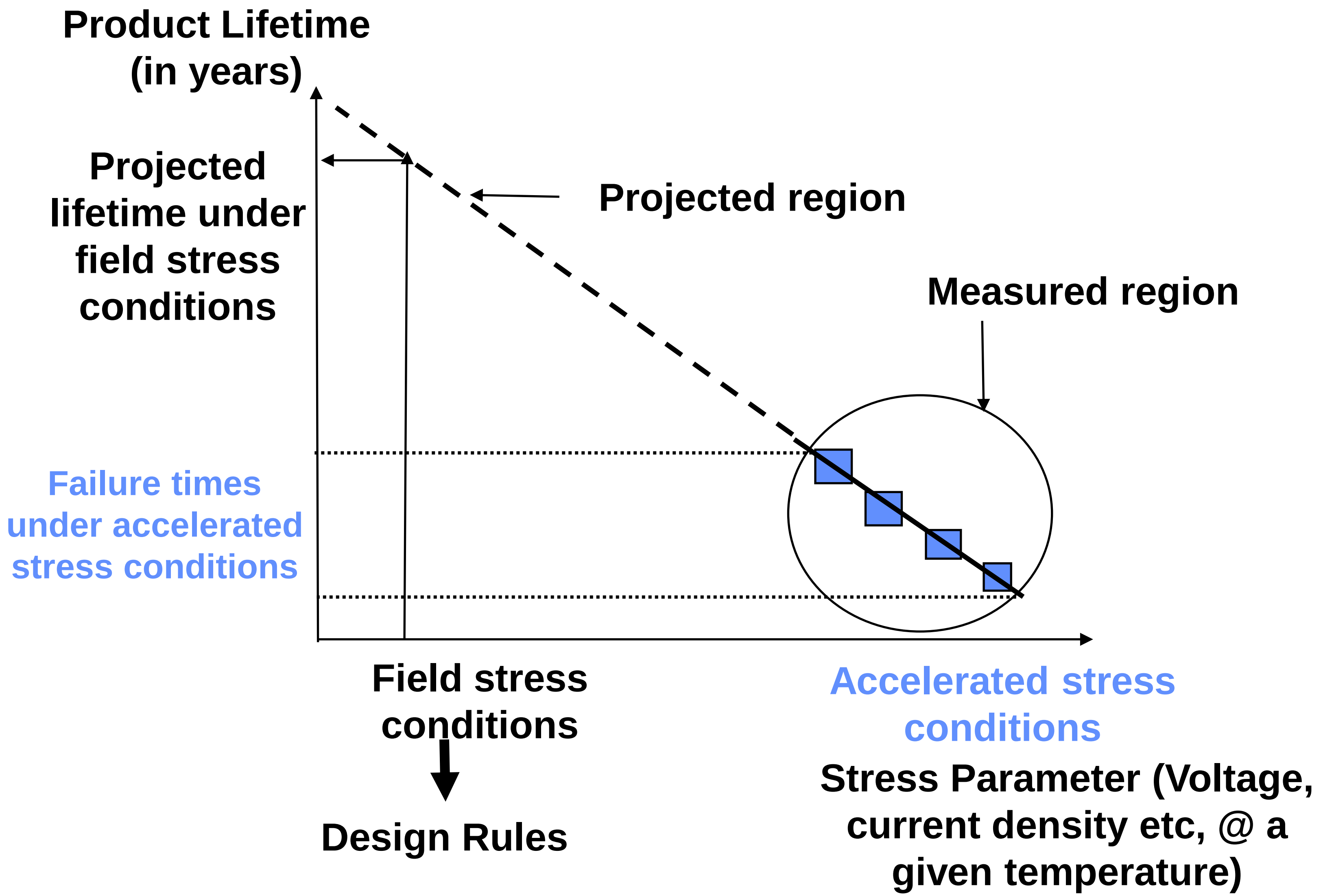
Electromigration Reliability

- **Transport of mass in metal interconnects under an applied current density**
- **EM lifetime reliability modeled using Black's equation given by,**

$$TTF = A\, j_{avg}^{-2}\, exp\left(\frac{Q}{k_B T_m}\right)$$

- **EM stress data gives a technology limit of the current density (j_{avg}) - - *for a required failure rate and a desired lifetime at a reference temperature T_{ref} (~ 100 ^{0}C)***
- **The j_{avg} limit does not comprehend self-heating**

VLSI Reliability: Lifetime Estimation and Design Rule Generation



Self-Consistent Design

Typical EM Analysis

- Accelerated EM stress data yields *A, Q*, and *n* in Black's equation, and a value of log-normal σ_{LN}.
- EM stress data + Black's equation gives a technology limit to the maximum allowed current density (j_{avg}) for the required failure rate and a desired lifetime at a reference temperature T_{ref} (~ 100 ^{0}C).
- Typical goal: achieve a 10 year lifetime.
- The j_{avg} limit does not comprehend self heating, and is therefore not self-consistent.

Self-Consistent Design

Current Density Definitions

- **Peak, Average, and RMS current densities:**

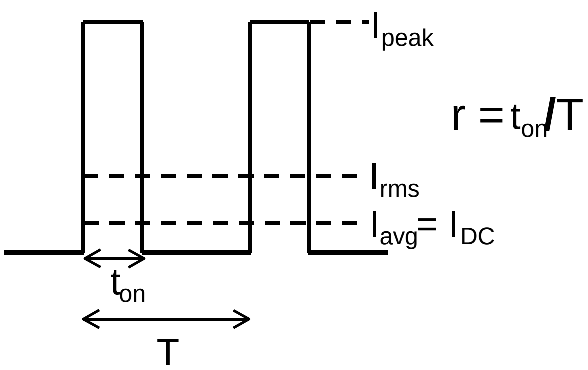
$$j_{peak} = \frac{I_{peak}}{A} \qquad j_{avg} = \frac{1}{T}\int_0^T j(t)\,dt \qquad j_{rms} = \sqrt{\frac{1}{T}\int_0^T j^2(t)\,dt}$$

A **is the cross sectional area of interconnect,** ***T*** **is the time period of the current waveform.**

- **For an unipolar waveform:**

$$j_{avg} = r\, j_{peak} \qquad j_{rms} = \sqrt{r}\, j_{peak}$$

r **is the duty factor**



- **EM is determined by** j_{avg}**, and self-heating by** j_{rms}**.**

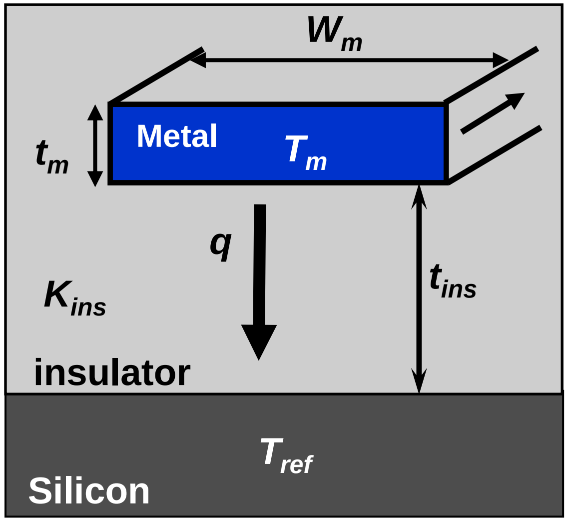
Self-Consistent Design

Impact of Self-Heating on EM

- EM lifetime given by: $TTF = A\, j^{-n} \exp\left(\frac{Q}{k_B T_m}\right)$
- Due to self-heating: $T_m = T_{ref} + \Delta T_{self\text{-}heating}$

$$\Delta T_{self-heating} = (T_m - T_{ref}) = I_{rms}^2 R R_\theta$$

$$j_{rms}^2 = \frac{(T_m - T_{ref}) K_{ins} W_{eff}}{t_{ins} t_m W_m \rho_m (T_m)} \quad (1)$$



R_θ is the effective thermal impedance given by,

$$R_\theta = \frac{t_{ins}}{K_{ins} L W_{eff}}$$

W_{eff} is the effective metal width to account for quasi-2D heat conduction.

Self-Consistent Design

What is Self-Consistent Design?

- Typically, design rules specify j_{avg} from EM and j_{rms} from self-heating separately.
- Self-consistent approach: comprehends EM and self-heating simultaneously.
- In order to achieve an EM reliability lifetime goal mentioned earlier, the lifetime at any j_{avg} and metal temperature T_m, should be equal to or greater than the lifetime value (e.g., 10 year) under the design rule current density (j_0).

$$\frac{\exp\left(\frac{Q}{k_B T_m}\right)}{j_{avg}^2} \geq \frac{\exp\left(\frac{Q}{k_B T_{ref}}\right)}{j_0^2} \qquad (2)$$

Self-Consistent Design

What is Self-Consistent Design?

- Using the relationship between j_{avg}, j_{rms}, j_{peak} and r for an unipolar waveform described earlier, it can be shown that,

$$\frac{j_{avg}^2}{j_{rms}^2} = r \qquad (3)$$

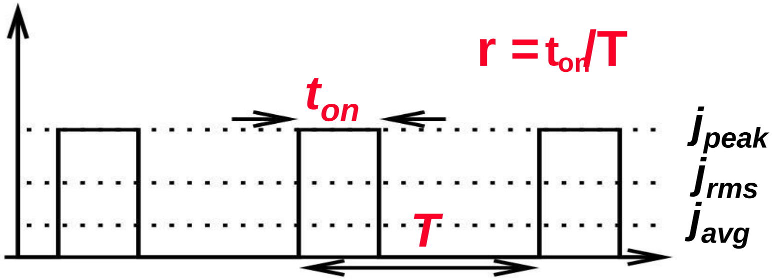
- Incorporating the j^2_{rms} and j^2_{avg} values from (1) and (2) in (3) yields the self-consistent equation,

$$r = j_0^2 \frac{\exp\left(\dfrac{Q}{k_B T_m}\right)}{\exp\left(\dfrac{Q}{k_B T_{ref}}\right)} \frac{t_{ins}\, t_m\, W_m\, \rho_m(T_m)}{(T_m - T_{ref}) K_{ins} W_{eff}}$$

This is a single equation in the single unknown temperature T_m. Once the self-consistent T_m is obtained, the corresponding j_{rms} and j_{peak} and j_{avg} values can be calculated.

Coupled Analysis

Unipolar Case:



- **Coupled equation:**

$$\frac{j_{avg}^2}{j_{rms}^2} = r$$

$$r = j_0^2 \frac{\exp\left(\frac{Q}{k_B T_m}\right)}{\exp\left(\frac{Q}{k_B T_{ref}}\right)} \frac{t_{ins} t_m W_m \rho_m (T_m)}{(T_m - T_{ref}) K_{ins} W_{eff}}$$

Once T_m is calculated, j_{rms} and j_{peak} can be obtained

Coupled Analysis

Unipolar Case: **Metal 6, 180 nm node, j_0 = 0.6 MA/cm^2**