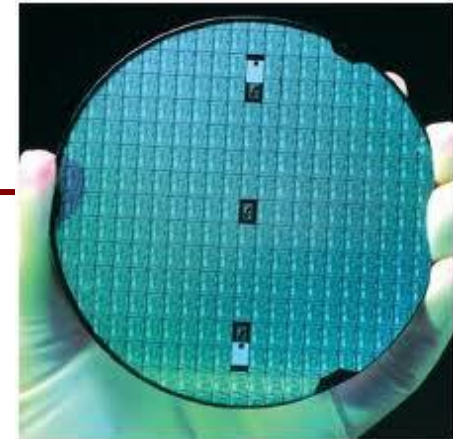
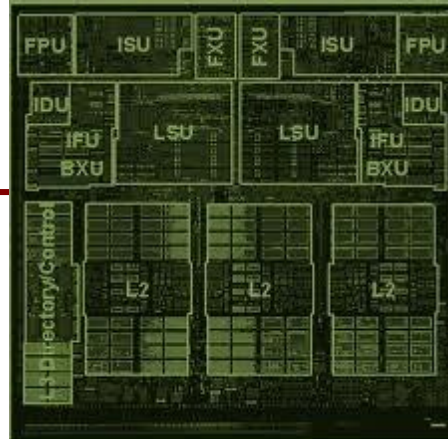
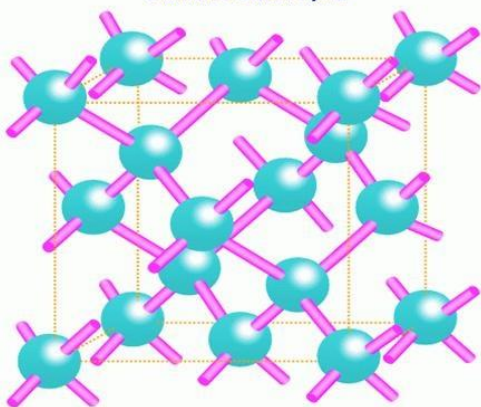


Structure of silicon crystal



ECE 225

Lecture 8

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

Prof. Kaustav Banerjee

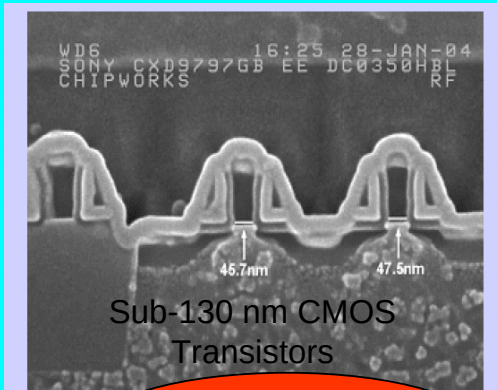
Electrical and Computer Engineering

University of California, Santa Barbara

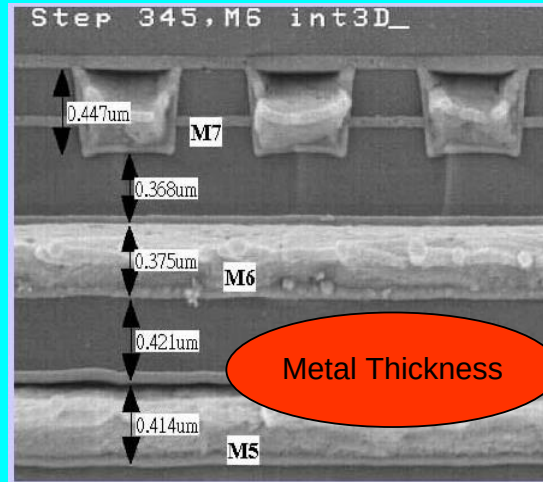
Implications of Parameter Variations

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

Parameter (P-V-T) Variations

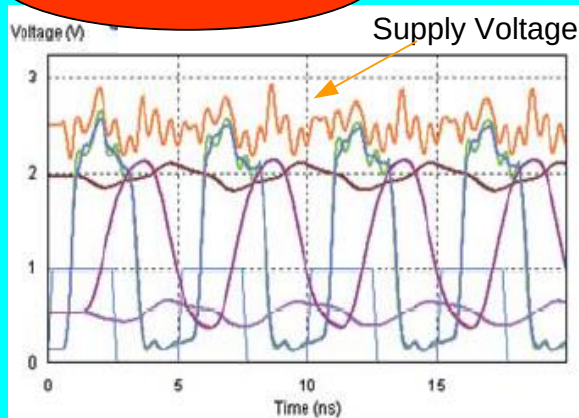


Transistor channel length

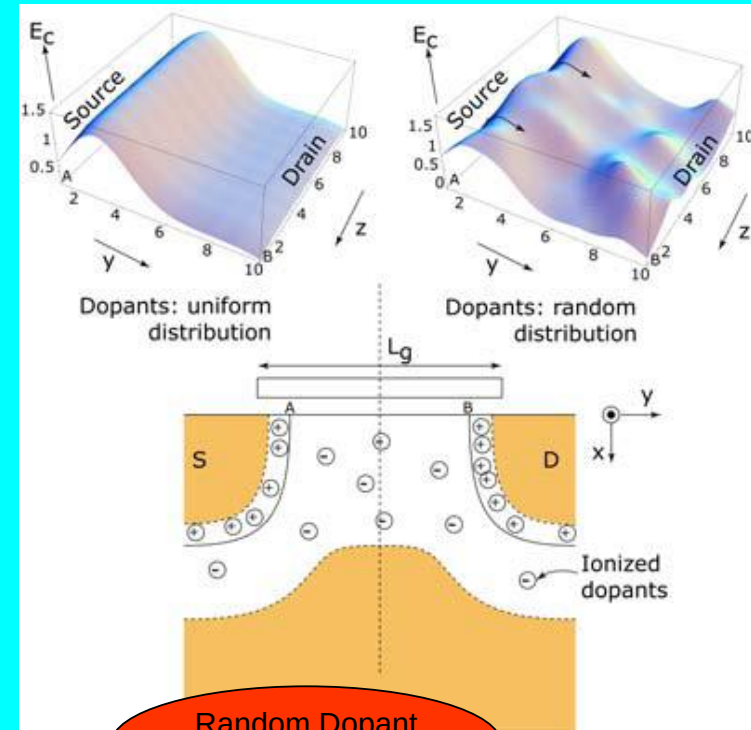
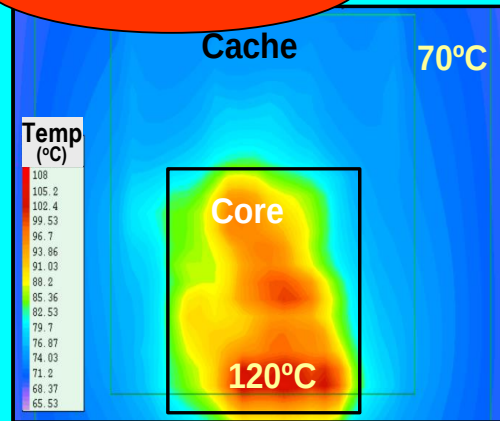


Metal Thickness

Power Supply Voltage



Chip Temperature

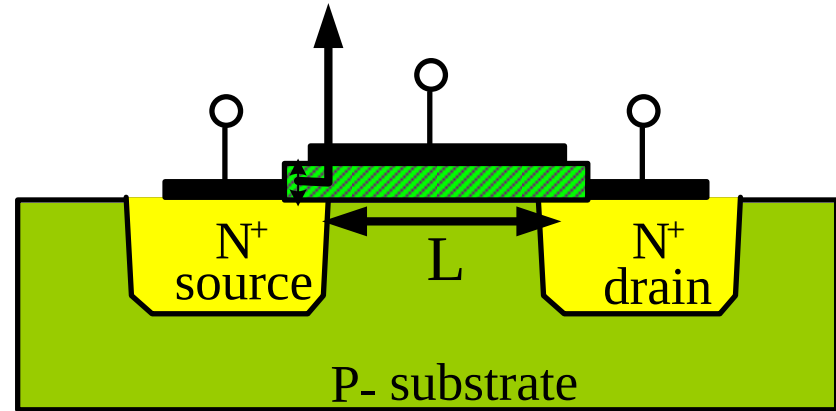


Random Dopant Fluctuations

Process Variations

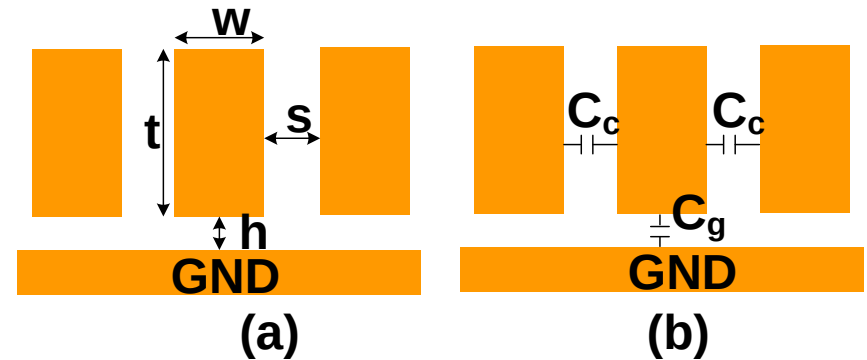
❑ Device Variations

- Channel Length (L)
- Oxide Thickness (t_{ox})
- Dopant Density (N_a)

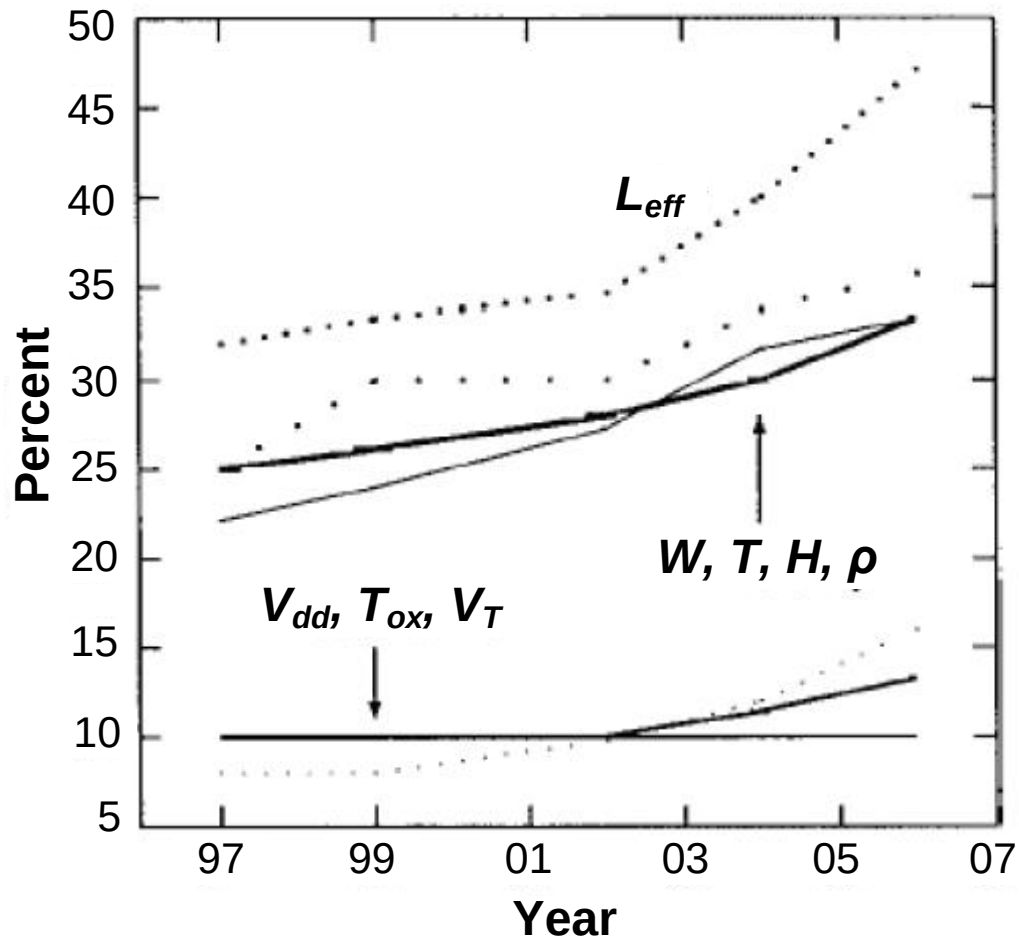


❑ Interconnect Variations

- Line Width (w)
- Spacing (s)
- Metal Thickness (t)
- Dielectric Thickness (h)

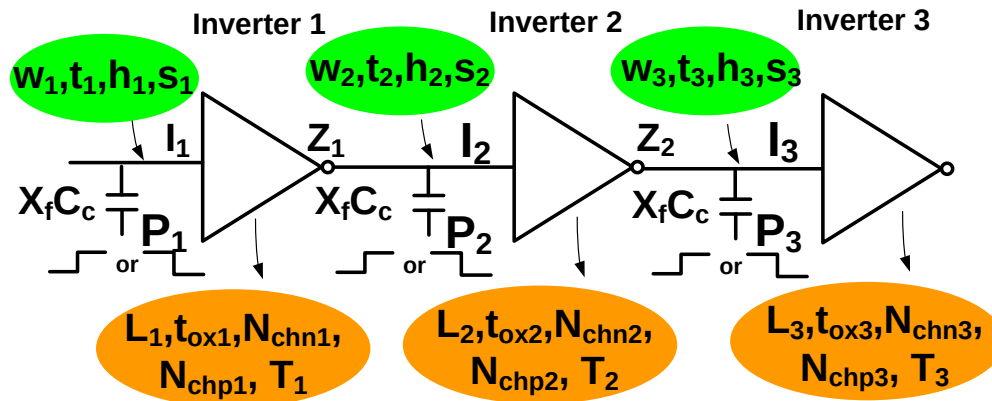


Device vs. Interconnect Variations



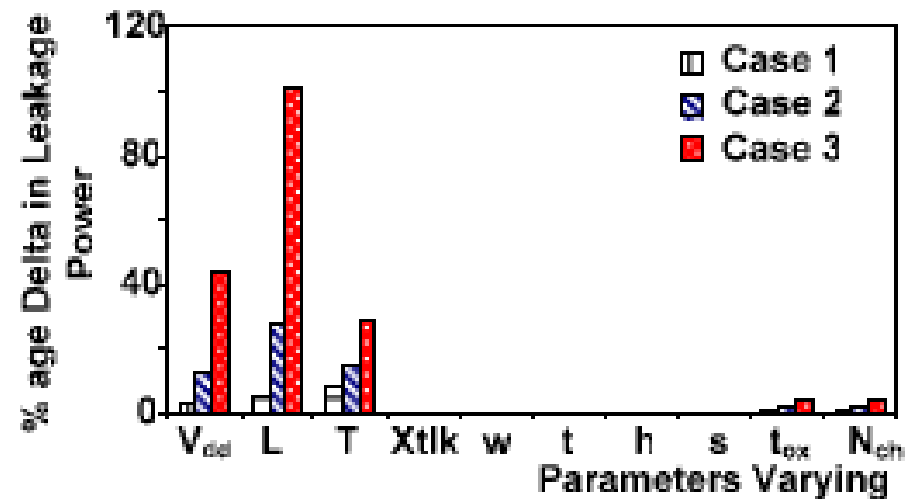
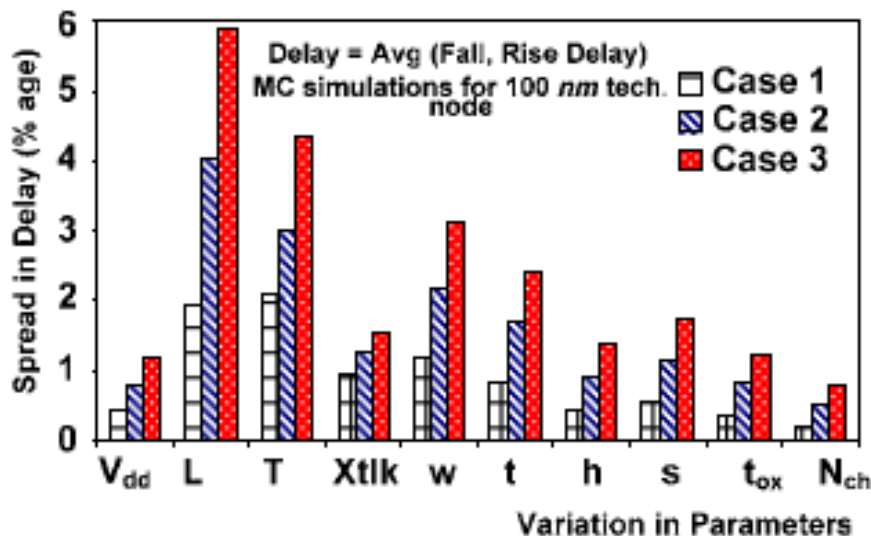
S. Nassif (IBM)

Sensitivity Analysis of Delay and Power



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

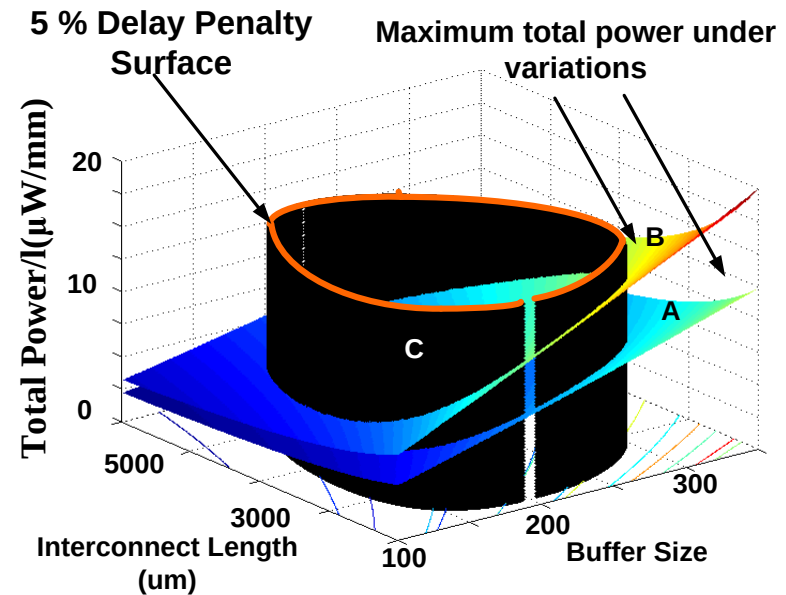
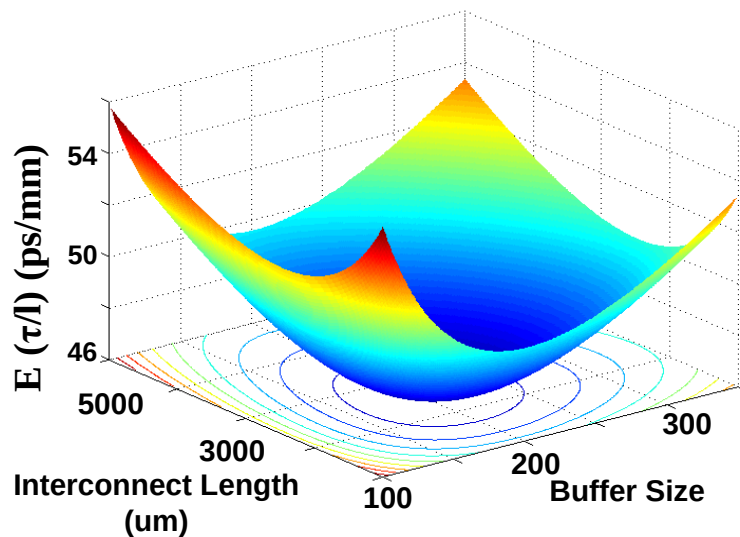
Wason and Banerjee, ISLPED 2005



■ Variations have significant impact on leakage power and delay

Interconnect Design Considering Variations

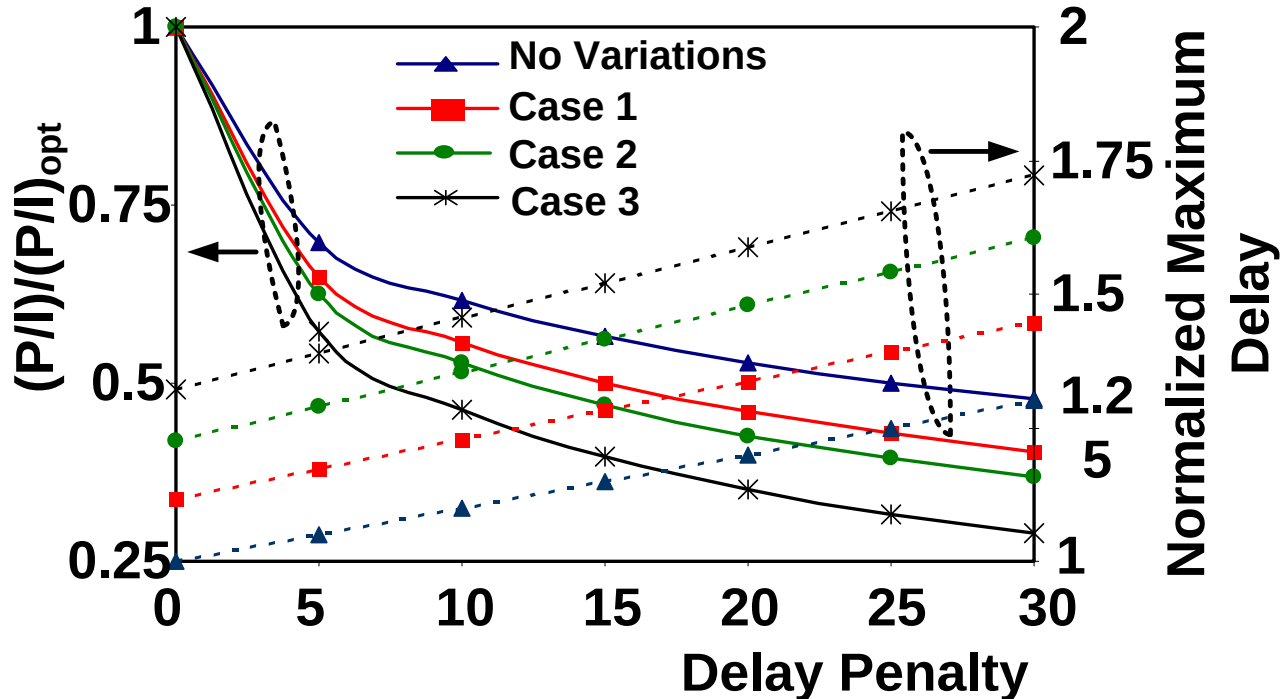
- Significant Implications for Interconnect Design
- Power-Optimal Repeater Insertion- tradeoff delay with power



Wason and Banerjee, ISLPED 2005

Variations can significantly impact power-optimal repeater insertion

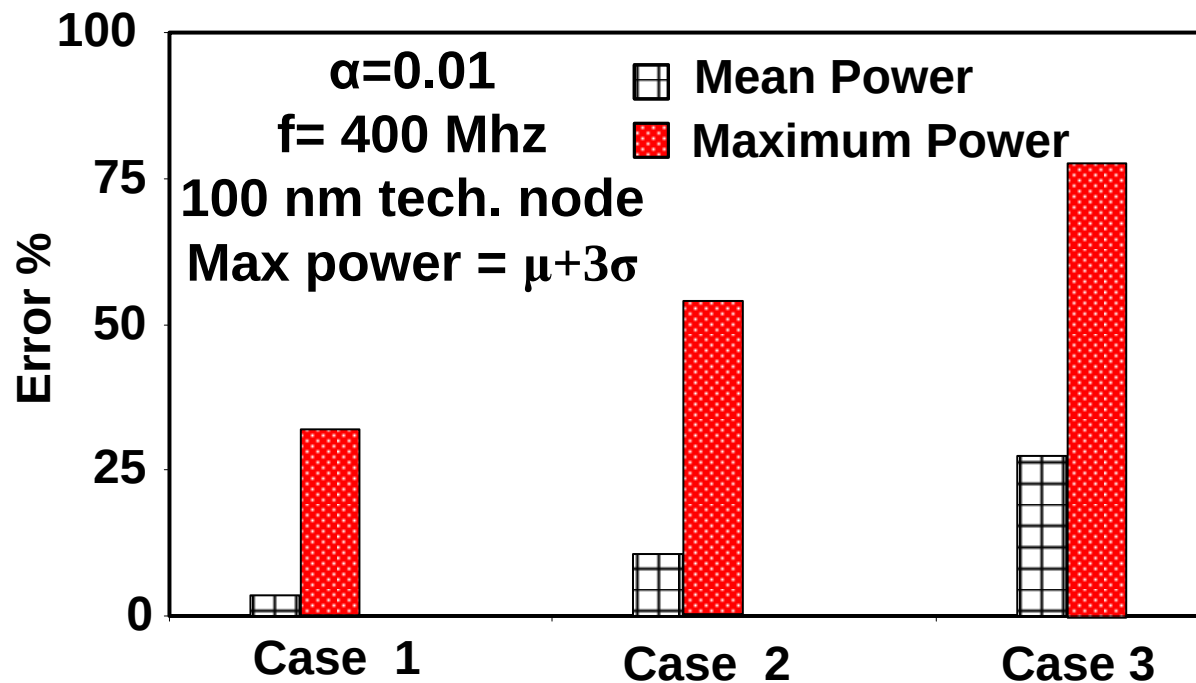
Optimization under Parameter Variations



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.

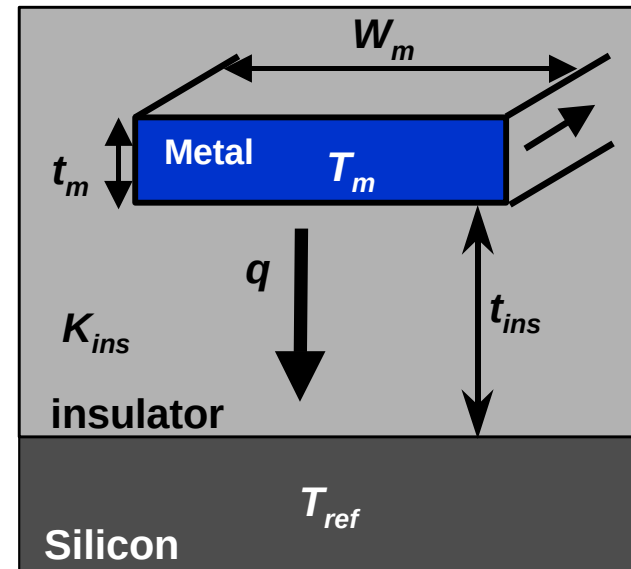
Self-Heating or Joule Heating

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

θ_j is the effective thermal impedance:

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

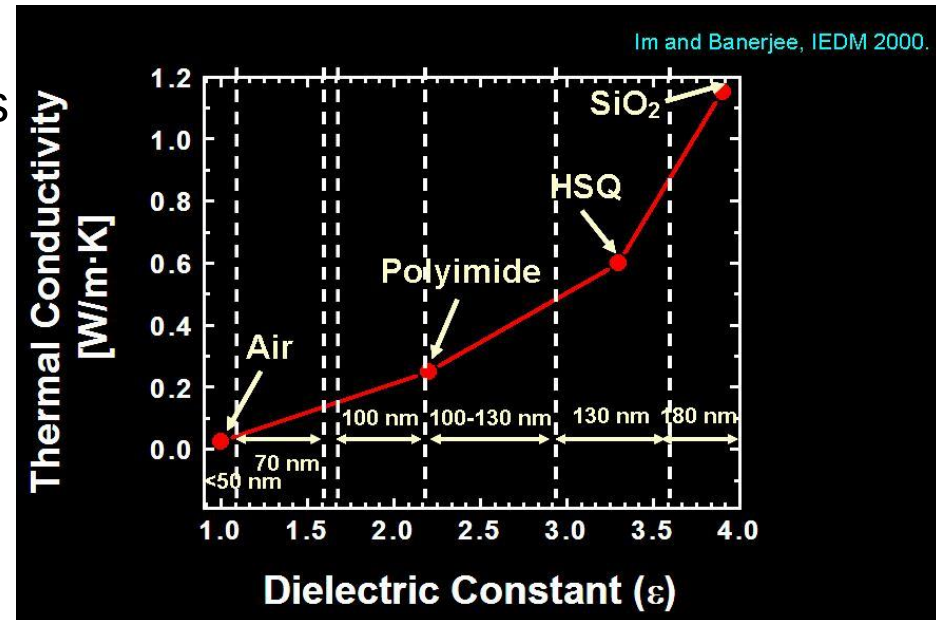
W_{eff} is the effective metal width to account for quasi-2D heat conduction.



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

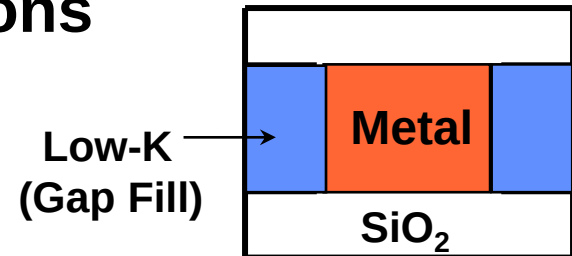
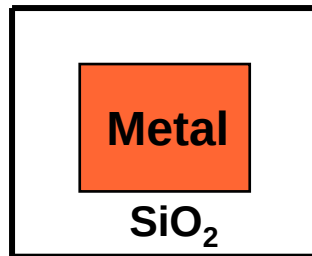


Interconnect Scaling Trends

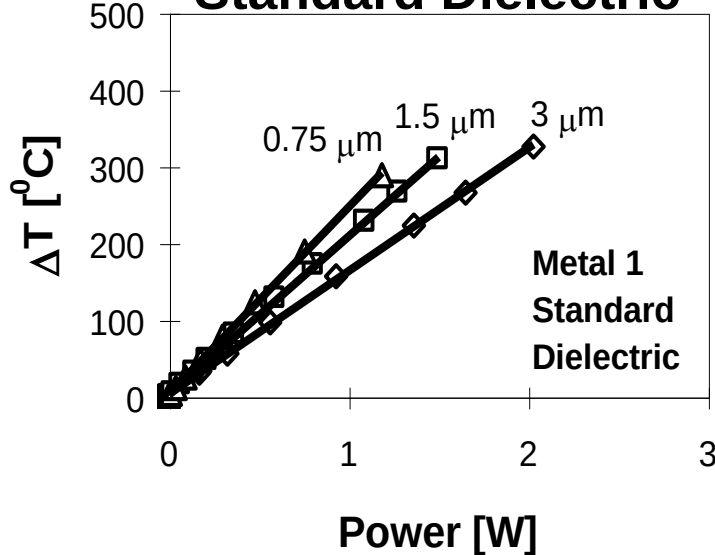
Impact of Line Width Scaling Using Low-k

Banerjee et al., IEDM, 1996

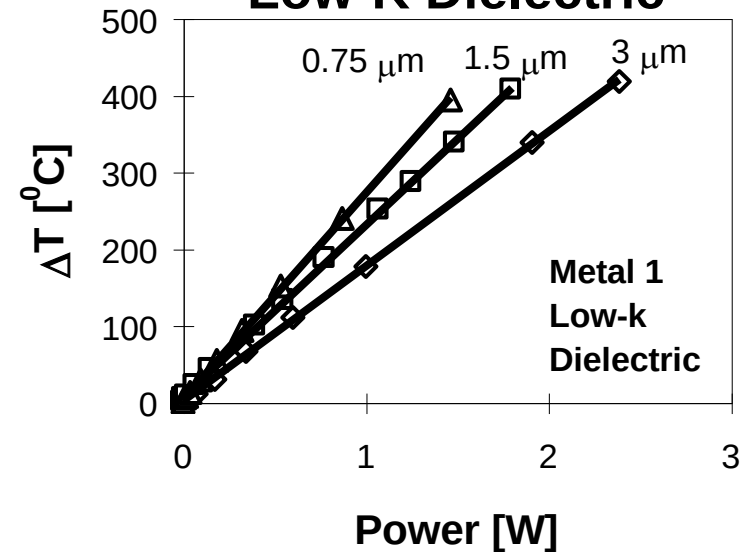
DC Conditions



Standard Dielectric



Low-K Dielectric



■ As **W** decreases **SH** increases.

■ **Low-k** increases **SH** by 10-15%

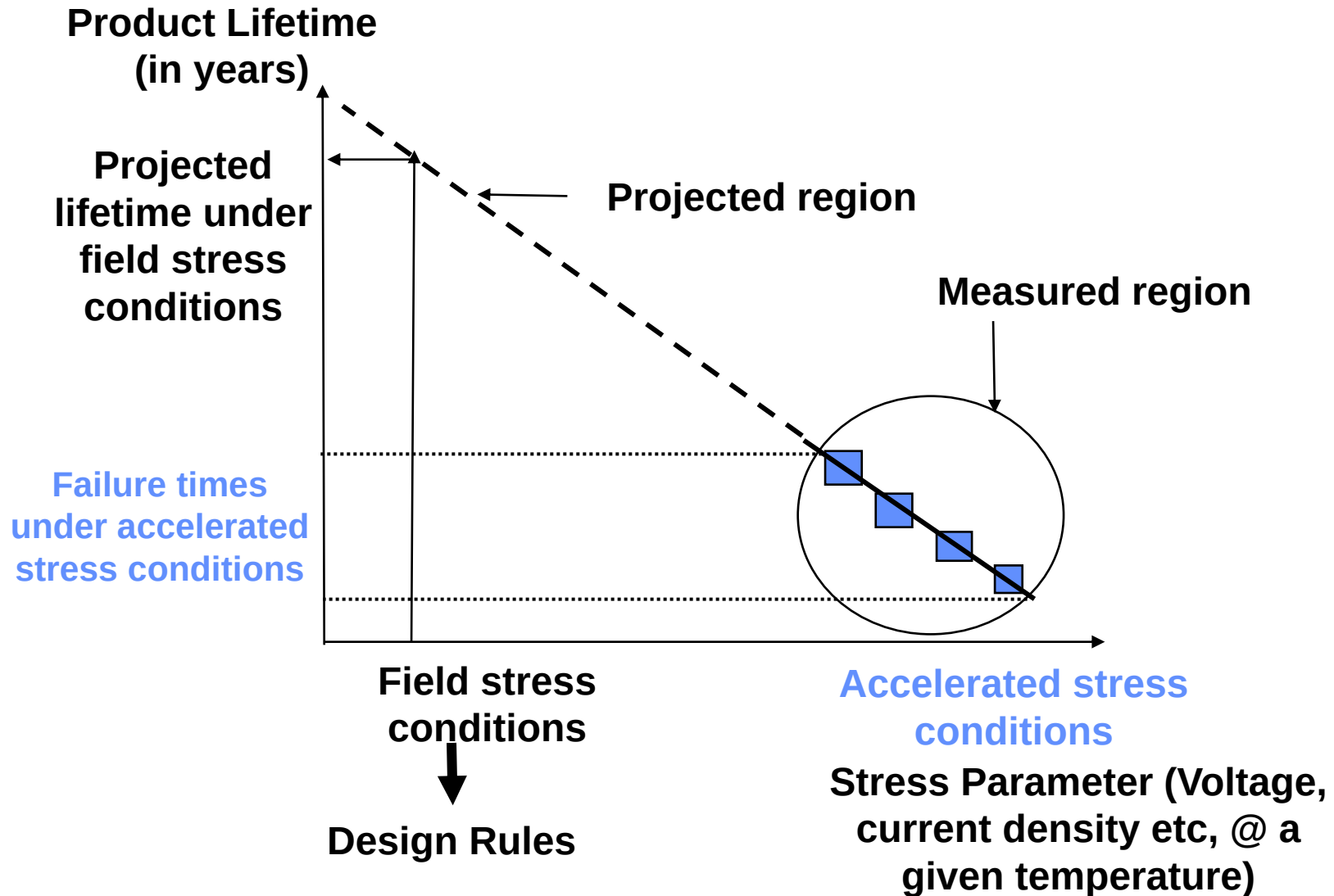
Electromigration Reliability

- 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} ($\sim 100^\circ\text{C}$)*
- 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} ($\sim 100^\circ\text{C}$).
- 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:

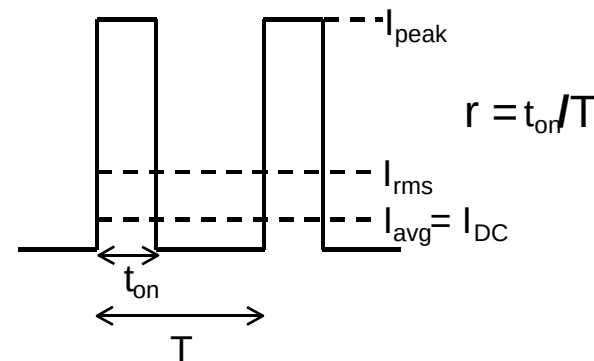
$$j_{peak} = \frac{I_{peak}}{A} \quad j_{avg} = \frac{1}{T} \int_0^T j(t) dt \quad j_{rms} = \sqrt{\frac{1}{T} \int_0^T j^2(t) dt}$$

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

■ For an unipolar waveform:

$$j_{avg} = r j_{peak} \quad j_{rms} = \sqrt{r} j_{peak}$$

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: $T_m = T_{ref} + \Delta T_{self-heating}$

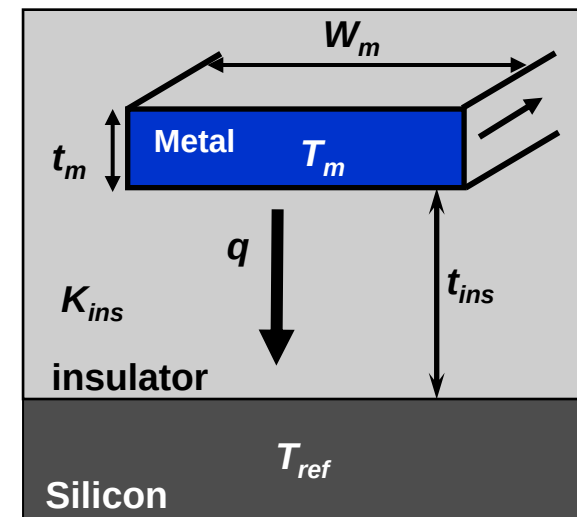
$$\Delta T_{self-heating} = (T_m - T_{ref}) = I_{rms}^2 R R_\theta$$

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

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).

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

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,

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

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

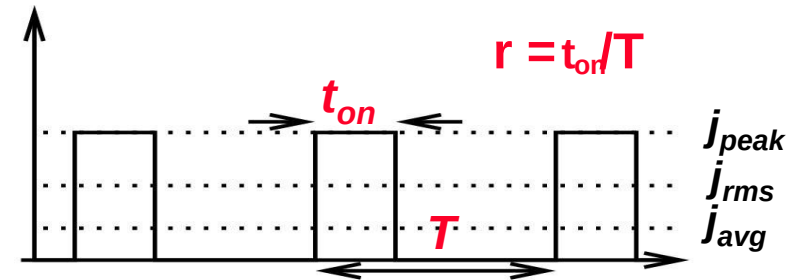
$$r = j_0^2 \frac{\exp\left(\frac{Q}{k_B T_m}\right)}{\exp\left(\frac{Q}{k_B T_{ref}}\right)} \frac{t_{ins} t_m W_m \rho_m (T_m)}{(T_m - T_{ref}) K_{ins} W_{eff}}$$

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, $j_0 = 0.6 \text{ MA/cm}^2$

