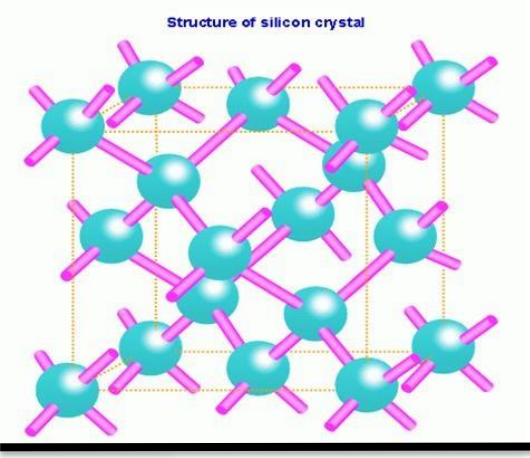

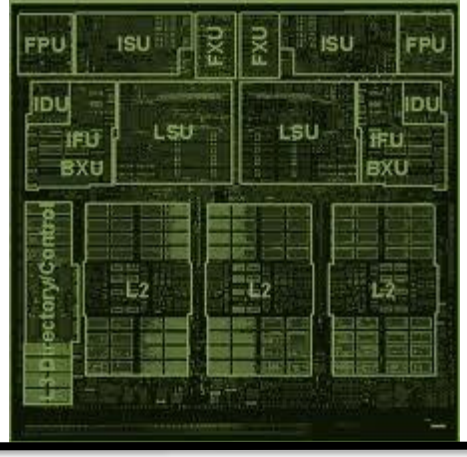

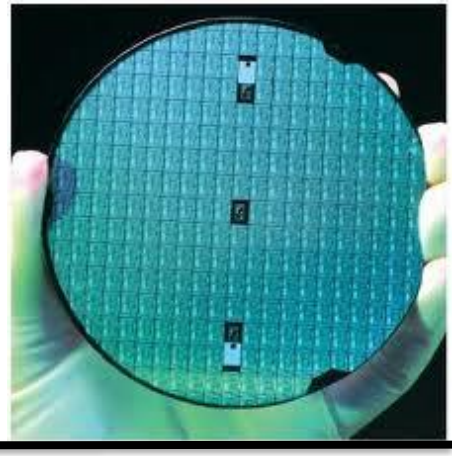

ECE 225

Lecture 10

On-chip Inductance Effects

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University of California, Santa Barbara

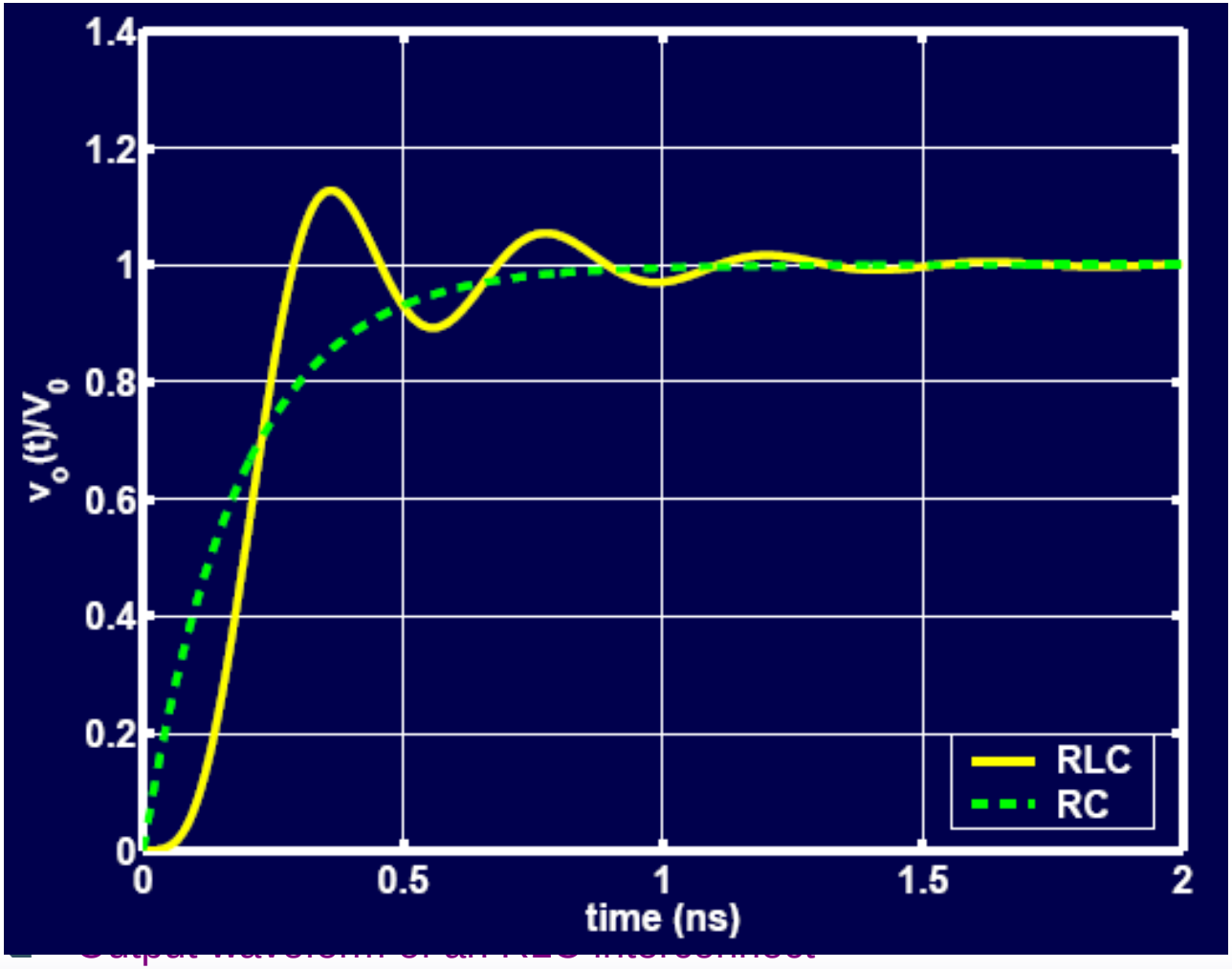
On-Chip Inductance Effects

K. Banerjee and A. Mehrotra, IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, Vol. 21, No. 8, pp. 904-915, August 2002.

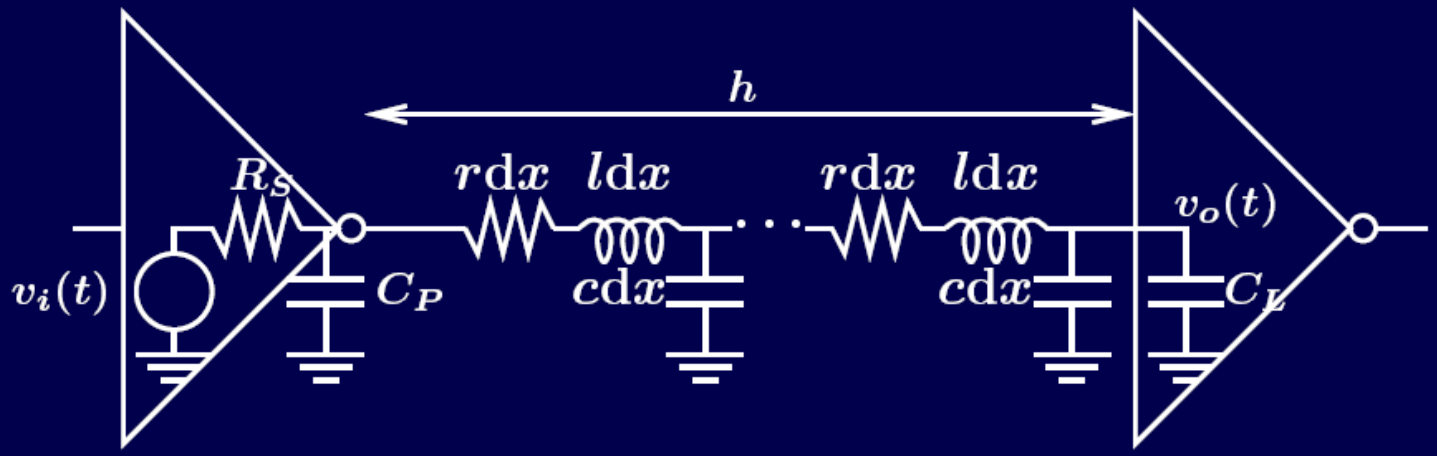
On-Chip Inductance Effects

- *Increasing clock speeds and decreasing rise times cause inductive effects*
- *Low resistance wires more susceptible to inductive effects*
  - *Global wires that are usually wide*
  - *introduction of Cu: lower resistivity*
- *Line inductance depends on current return path*
  - *strongly dependent on circuit topology*
  - *difficult to extract accurately*
  - *large variations*

Step Response of an RLC Line



Time-Domain Response of RLC Segment



$$H(s) = \frac{1}{[1+sR_S(C_P+C_L)]\cosh(\theta)+\left[\frac{R_S}{Z_0}+sC_LZ_0+s^2R_SC_PC_LZ_0\right]\sinh(\theta)}$$

$$\approx \frac{1}{1 + sb_1 + s^2b_2 + s^3b_3 + s^4b_4}$$

$$Z_0 = \sqrt{\frac{r+sl}{sc}} \qquad \theta = \sqrt{(r+sl)sch}$$

Critical Inductance

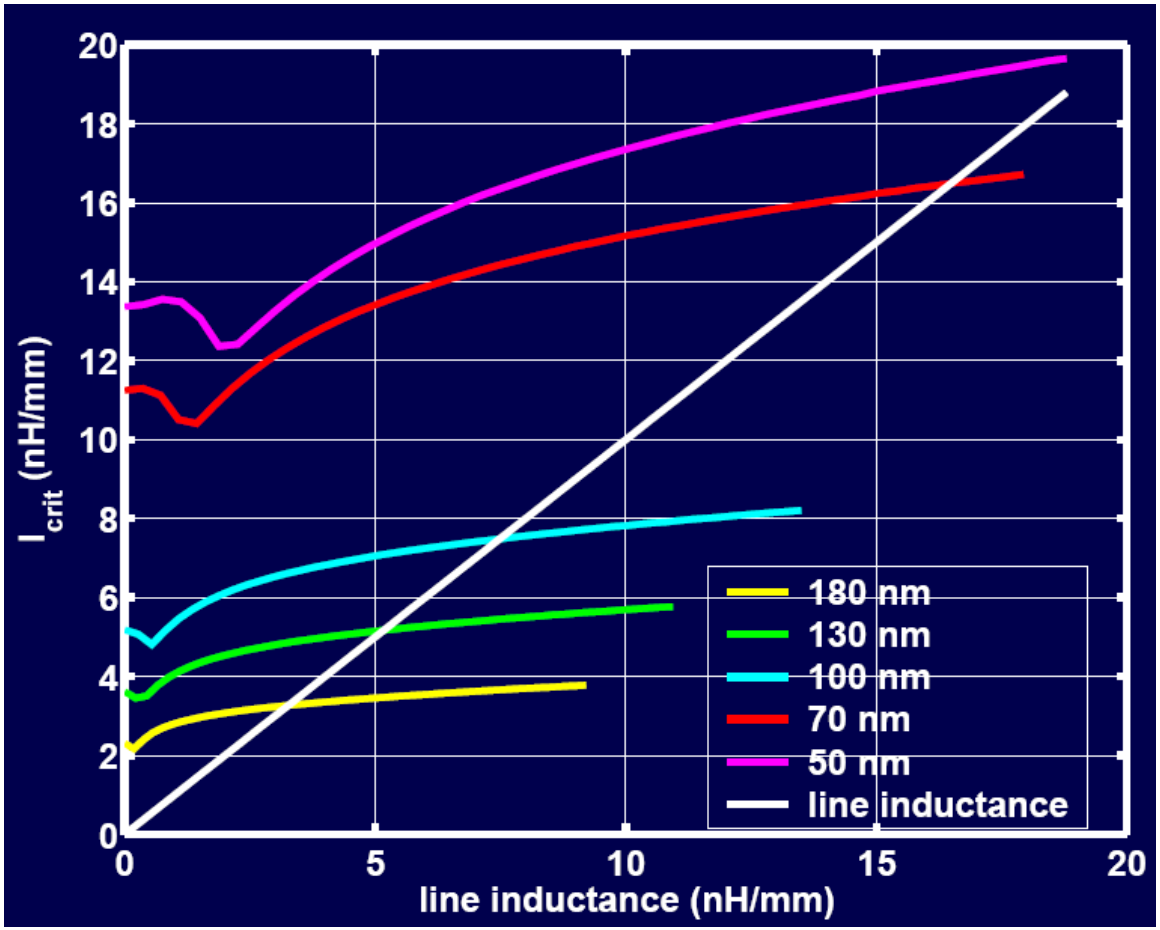
- Second order Padé expansion of $H(s)$

$$H(s) \approx \frac{1}{1 + b_1 s + b_2 s^2}$$

- System overdamped, critically damped or underdamped when $b_1^2 - 4b_2$ is $>, =, < 0$.
- At optimum buffer size and interconnect length, find l_{crit} for which the system is critically damped.
- For l $<, =, >$ l_{crit}, the system is overdamped, critically damped or underdamped

Impact of Scaling: Case 1

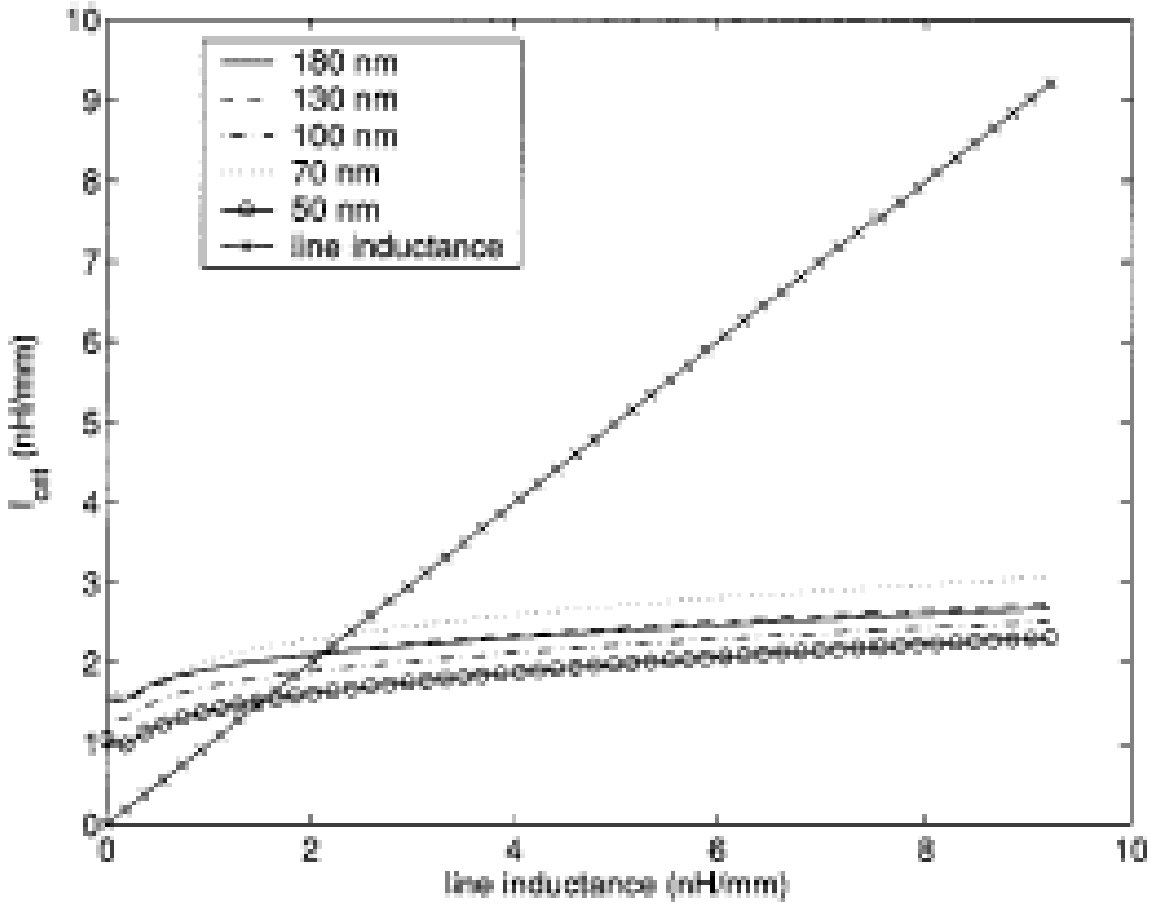
Minimum Width Global Wires



- ***As technology scales, $l < l_{crit}$ over larger range of line inductance***
- ***Hence, impact of inductance reduces with scaling***

Impact of scaling: Case 2

Unscaled Global Wires



- ***As technology scales, $l > l_{crit}$ over larger range of line inductance***
- ***Hence, impact of inductance increases with scaling***

High-Frequency Issues

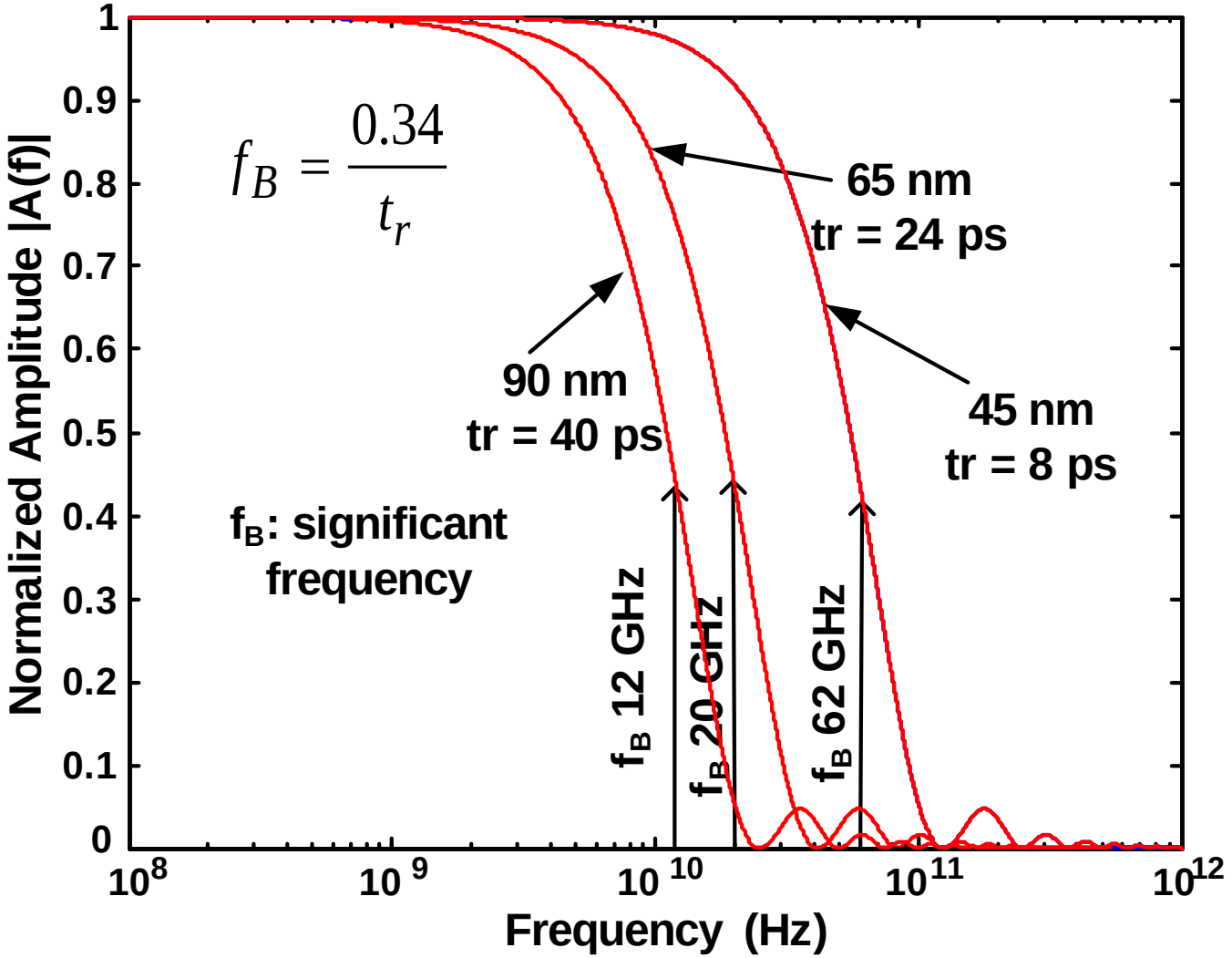
K. Banerjee, S. Im and N. Srivastava, Proc. Advanced Metallization Conf., 2005.

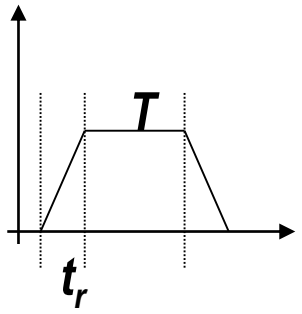
S. Suaya, R. Escovar, S. Ortiz, K. Banerjee and N. Srivastava, Proc. Advanced Metallization Conf., 2006.

High-Frequency Effects

- Frequency of signals on interconnects is rising rapidly
- Frequency dependent impedance extraction is a major hurdle
  - Field solvers are unable to handle the complexity of VLSI interconnects
- Need to develop models for interconnect geometry dependent calculation of high frequency impedance

Signal Frequency on Interconnects





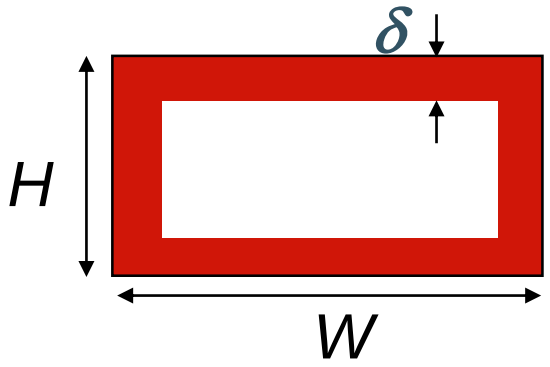
Digital signal composed of various frequency components.

Significant Frequency:

Frequency used for interconnect analysis

Frequency Dependence of R

- At high enough frequencies, R can increase due to ***skin effect***
- Current flow constrained in a thin layer along the surface of the conductor: **R increases**
- The current falls off exponentially with depth into the interconnect
- **Skin depth**, δ is defined as the depth at which current falls of to a value of 1/e of its nominal value



$$\delta = \sqrt{\frac{\rho}{\pi f \mu}}$$

μ is the permeability of the surrounding dielectric

Resistance per unit length:

$$r(f) = \frac{\sqrt{\pi f \mu \rho}}{2(H+W)}, \quad for\ W, H >> \delta$$

Skin Effect

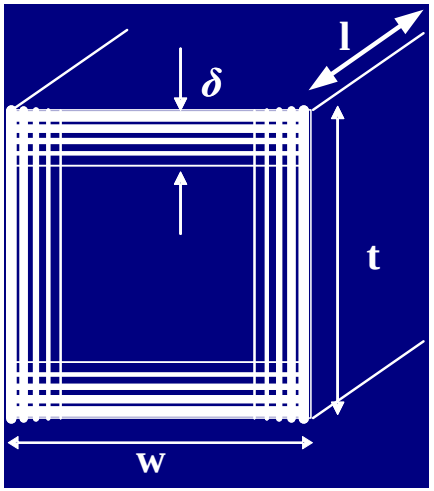
- Onset of skin effect: at $f=f_s$, δ =1/2 x smallest dimension

$$f_s = \frac{4\rho}{\pi\mu\left(\min\left(W,H\right)\right)^2}$$

- For Cu wires:

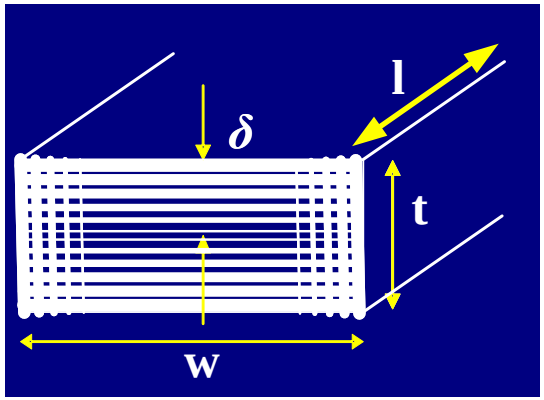
Freq	1 GHZ	5 GHZ	10 GHZ	15 GHZ	20 GHZ
Skin depth (μm)	2.08	0.93	0.66	0.53	0.46

Skin and Proximity Effects



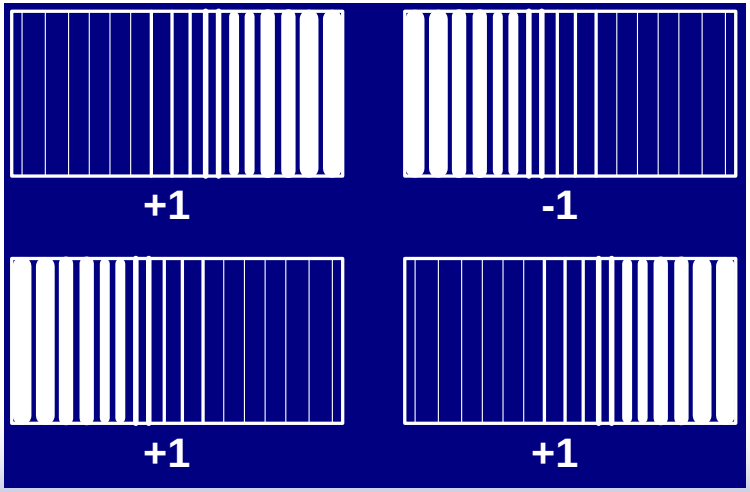
Isolated Wire 5um x 5um

Skin Effect in Isolated Conductors

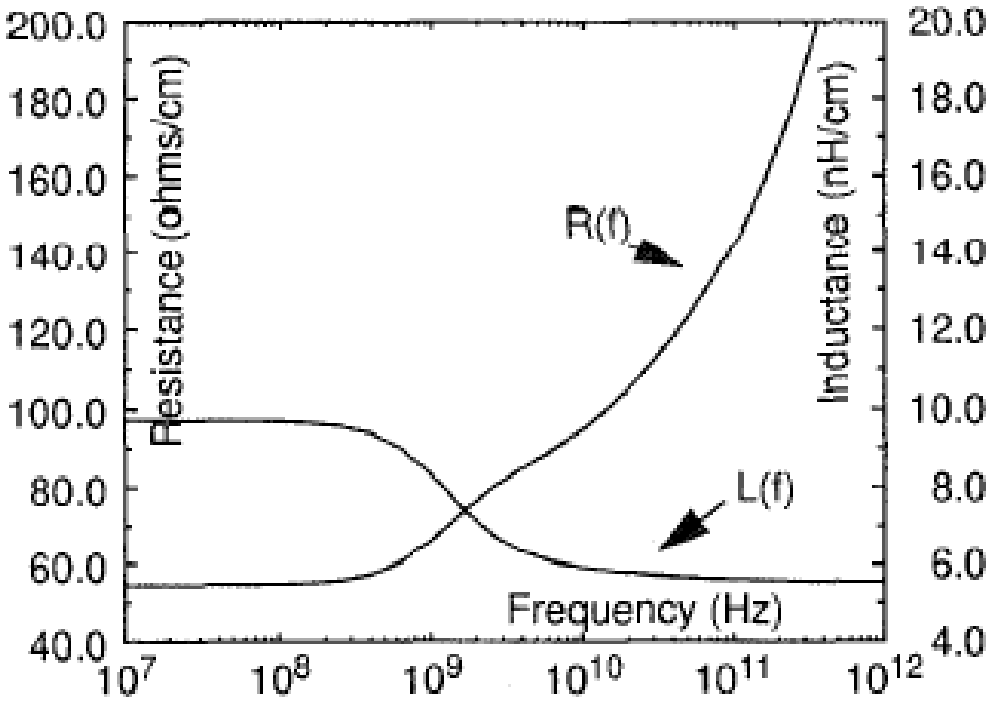


Isolated Wire 5um x 1um

Proximity Effect in Coupled Conductors



Frequency Dependence of R and L

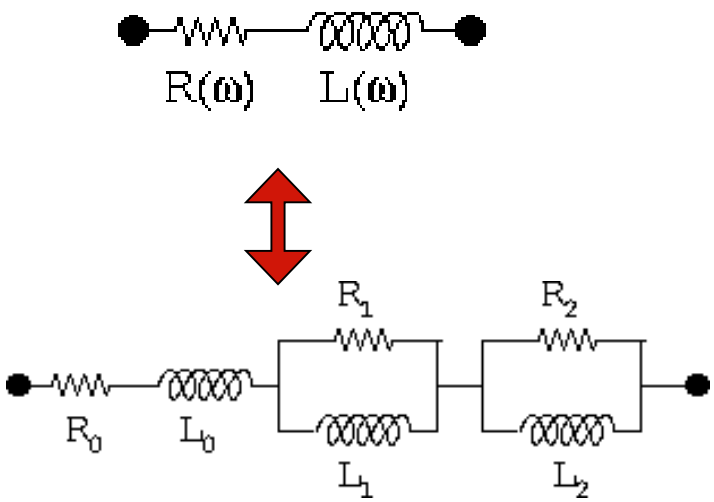


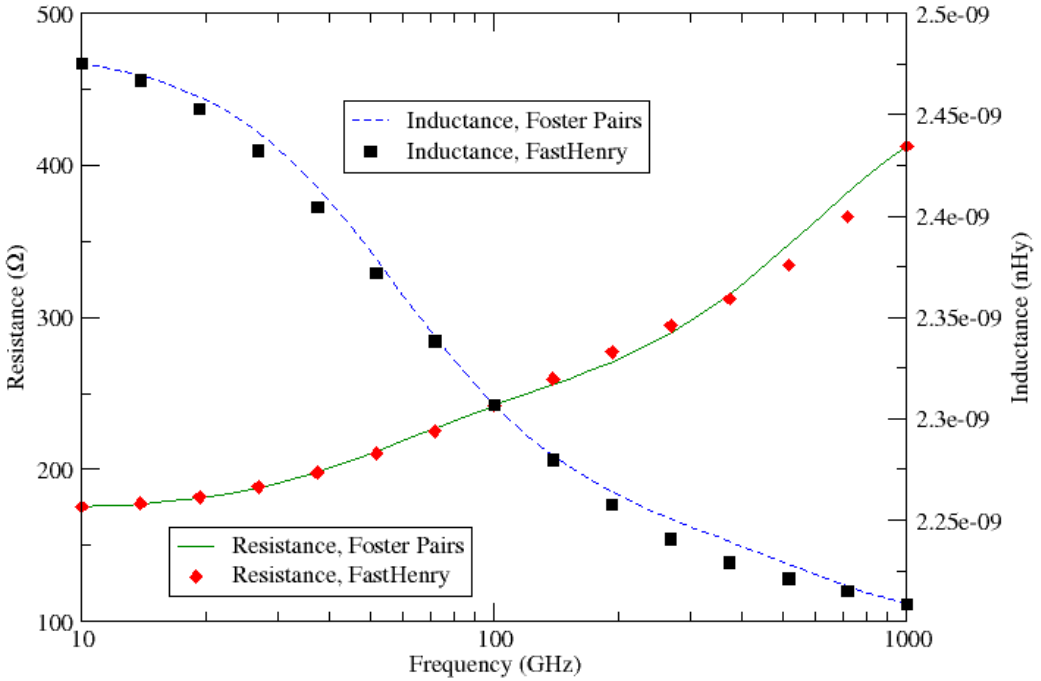
B. Krauter and S. Mehrotra, DAC, 1998.

- ***Resistance increases due to skin effect***
- ***For lower frequencies, current return path is distributed between all ground lines---thus loop inductance is higher and return path resistance is smaller…..***
- ***For higher frequencies, current returns through closest ground paths---thus loop area is smaller, hence loop inductance reduces and return path resistance increases***

Modeling Frequency Dependent Behavior

Replacing $R(\omega), L(\omega)$ with Foster Pairs

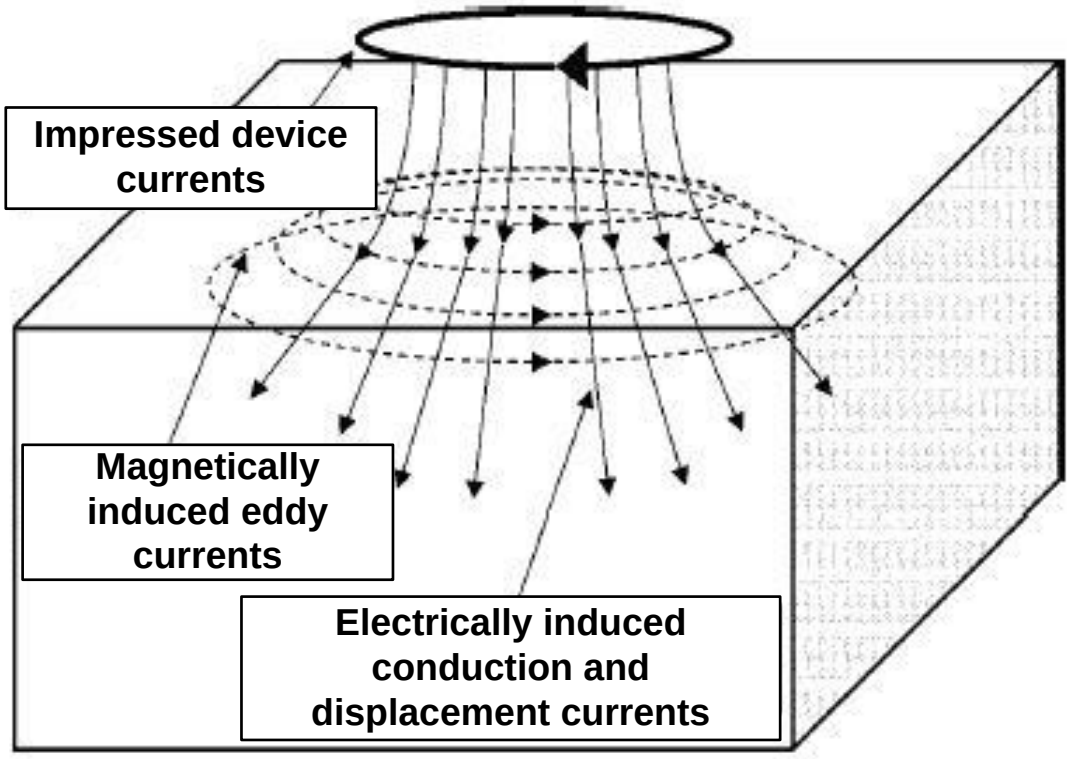




Note that at smaller frequencies L_1 ($Z=j\omega L$) will short R_1
R_0 and $L_0+L_1+L_2$ are low-frequency values of R and L
At higher frequencies some current flows through R_1 and R_2, hence R increases with frequency and effective inductance decreases

Suaya et al., Advanced Metallization Conf. 2006

Substrate Effects



Impacts interconnect impedance extraction

A. M. Niknejad and R. G. Meyer, IEEE Trans. on Microwave Theory and Techniques, 2001