Simulation Based Study of Wireless RF Interconnects for Practical CMOS Implementation

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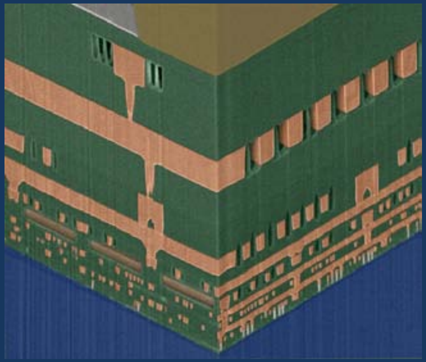
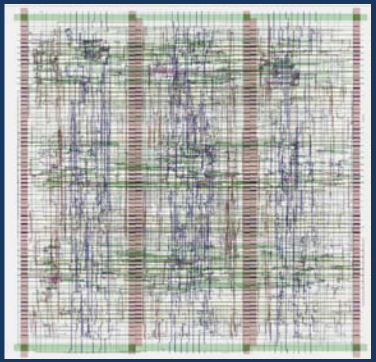
Global Wiring Paradigm

- **Problems due to DSM effects**
  - Time delay
  - Clock distribution
  - Maximum reachable distance
  - Inductance
  - Noise
  - Routing
  - Power distribution



Source: IBM



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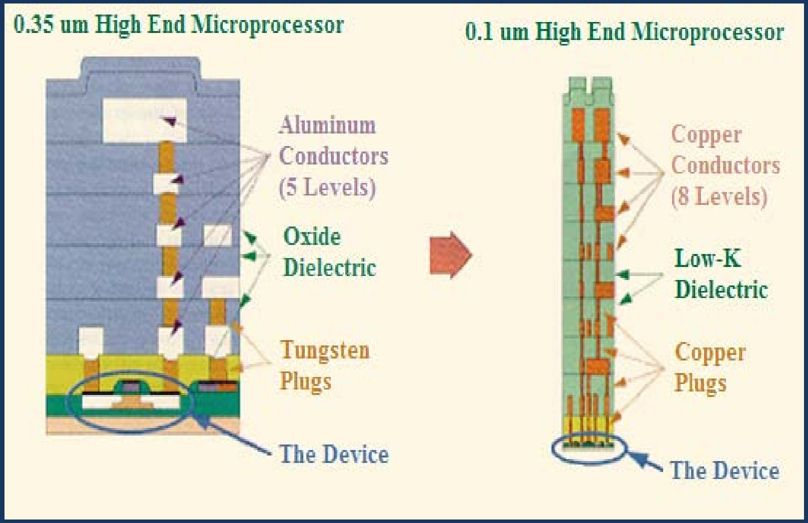


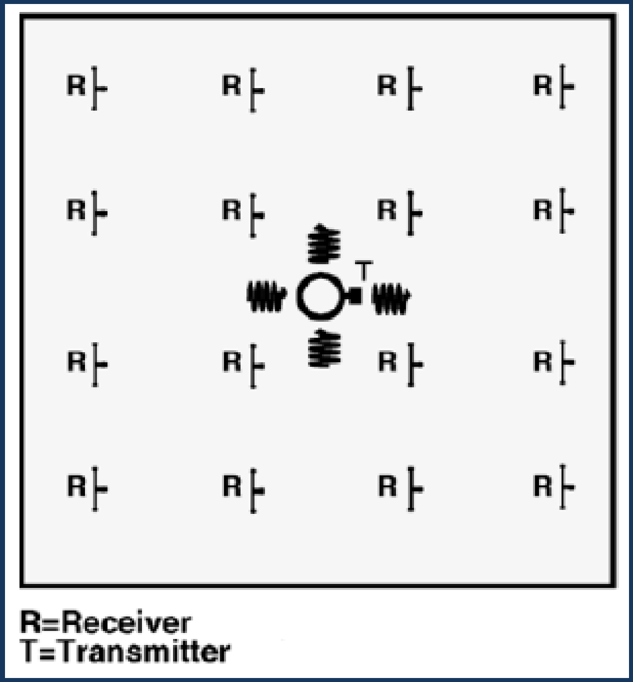
Source: Rabaey, et. al in “Digital Integrated Circuits”, Prentice Hall, 2nd edition

Improved Interconnects

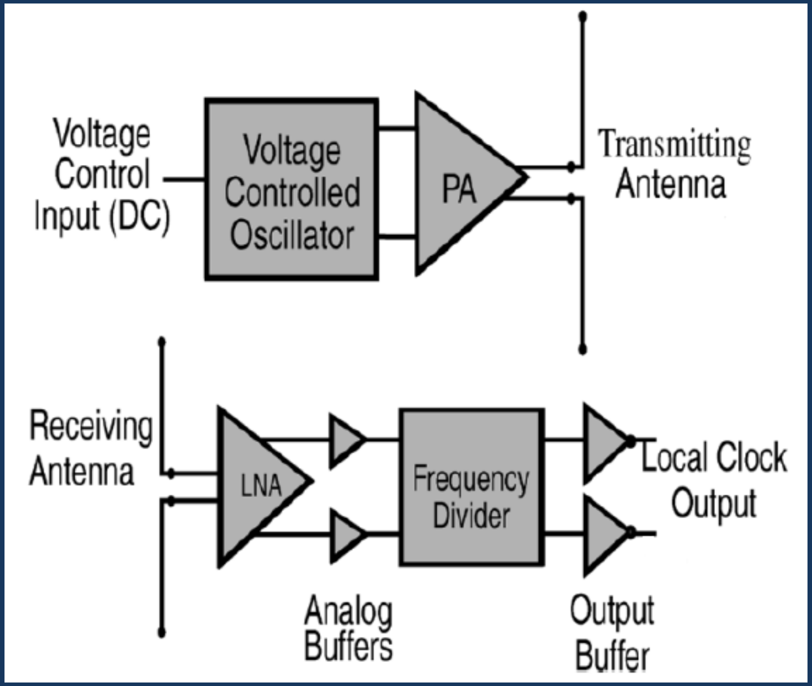
- Manufactory solutions
  - Changes to surrounding material
  - High conductivity metals
  - Reverse scaling
- Design solutions
  - Optical interconnects
  - Interconnects using nano-tubes
  - Radio frequency (RF) interconnects
    - Microstrip RF
    - Wireless RF

On-Chip Antennas

- **Concept**



Source: K. K. O et. al. in TED

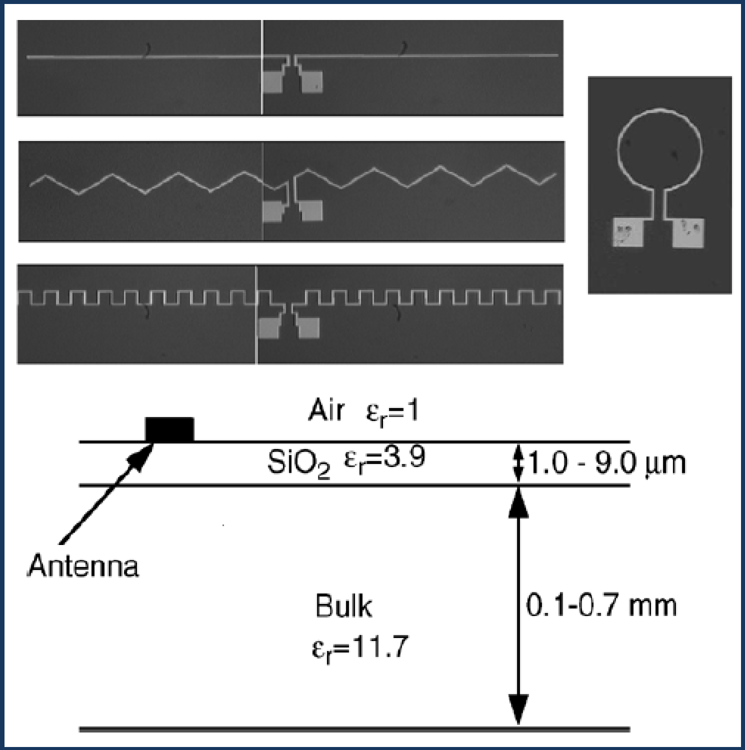


Source: K. K. O et. al. in TED

K. K. O et. al., "On-Chip Antennas in Silicon ICs and Their Application", IEEE Transactions on Electron Devices, vol. 52, pp. 1312 - 1319, July 2005.

Antenna Structures

- **Physical structure**
- **Simulation structure**



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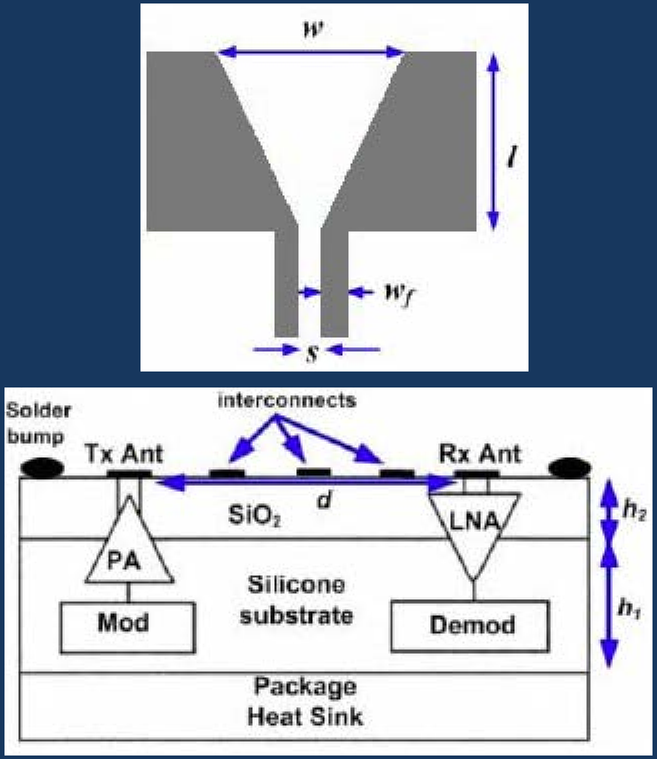

Source: Bialkowski and Abbosh in APSURSI

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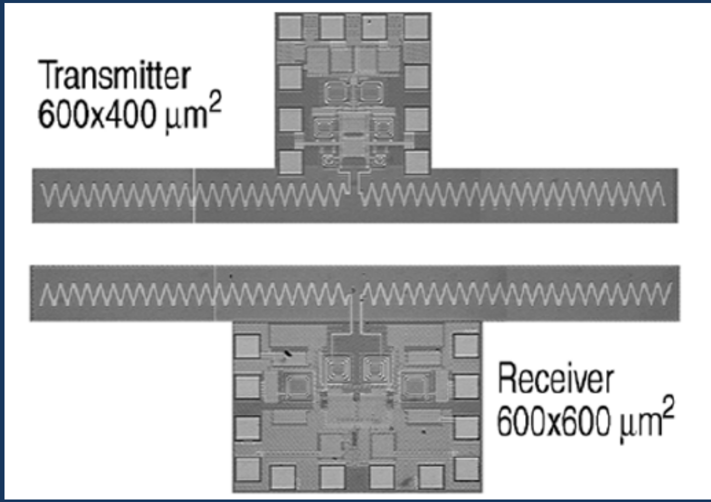
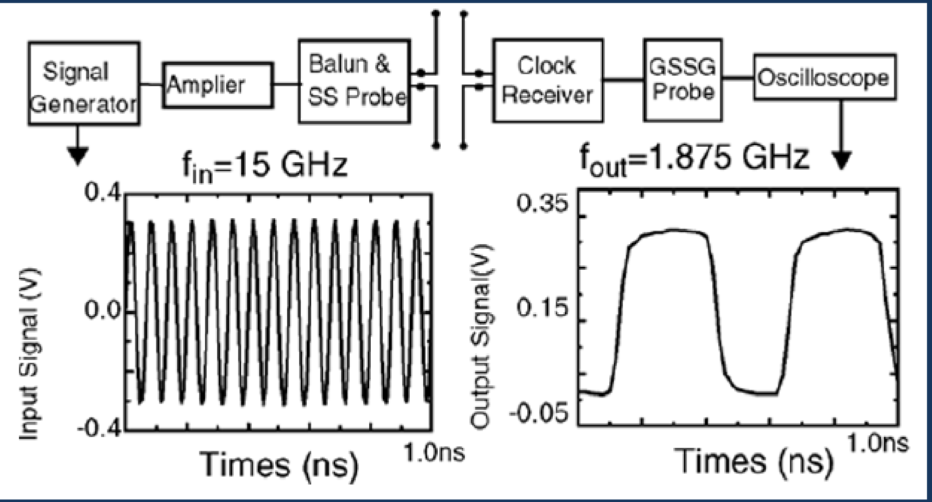
M. Bialkowski, and A. Abbosh, "Investigations into intra chip wireless interconnection for ultra large scale integration technology", International Symposium of Antennas and Propagation Society, June 2009.

Demonstration of Wireless Clock Transmission



Source: K. K. O et. al. in TED



Source: K. K. O et. al. in TED

Challenges for Wireless Interconnects

1. Antenna characteristics under high levels of integration
2. Radiation effects on metal interconnects
3. Radiation effects on circuit devices
4. Wireless system performance under switching noise
5. Performance comparison with metal interconnects
   - Footprint area
   - Power consumption
   - Delay
   - Clock skew and jitter
   - Bit-error rate

Objectives

- Effects of the electromagnetic radiations from the antennas on metal interconnects considering
  - Interconnects on different metal layers
  - Varying widths of the interconnect
  - Varying lengths of the interconnect
  - Varying distance of the interconnects from the transmitting antenna
- Effects of typical CMOS manufacturing processes on the antenna characteristics
  - Adherence to 90^{o} bend angles on antennas
  - Presence of high-conductivity epitaxial layer
  - Varying metal utilization factor

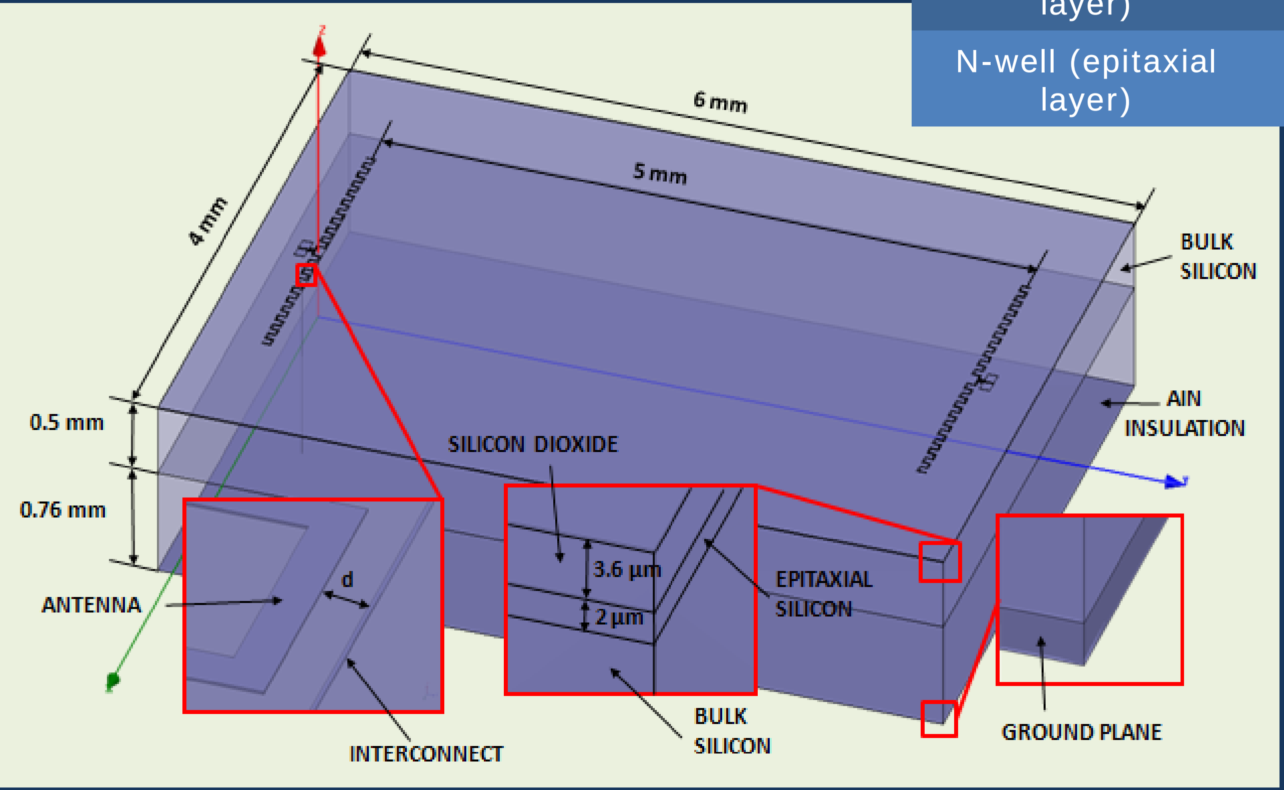
Wireless Interconnect Analysis

- 3D FEM based full wave electromagnetic analysis
- 250nm CMOS technology rules
- Die size of 6x4 mm^2
- Antenna characteristics:
  - Meander dipole antenna
  - 17GHz operation frequency
  - Arm length of 2.4mm
  - Antenna separation of 5mm

- Transmission gain used as the figure of merit

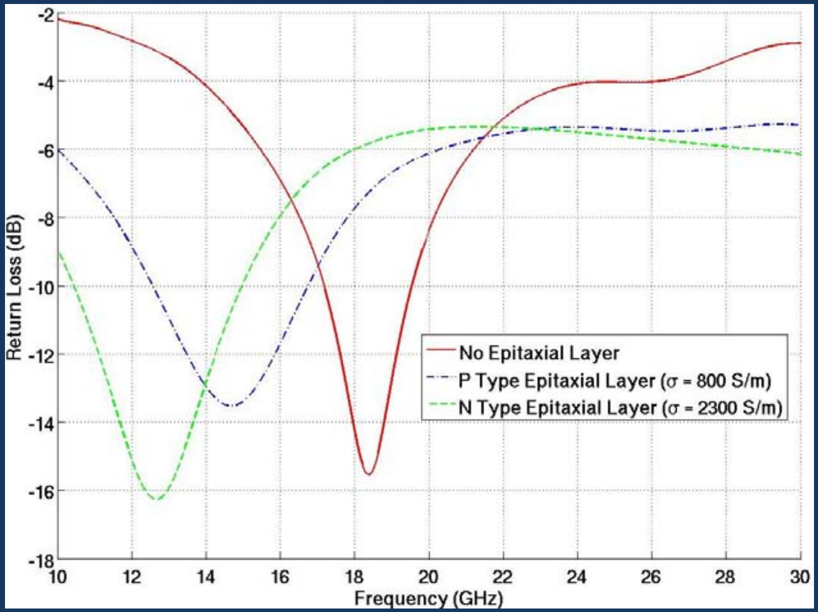
Simulation Model

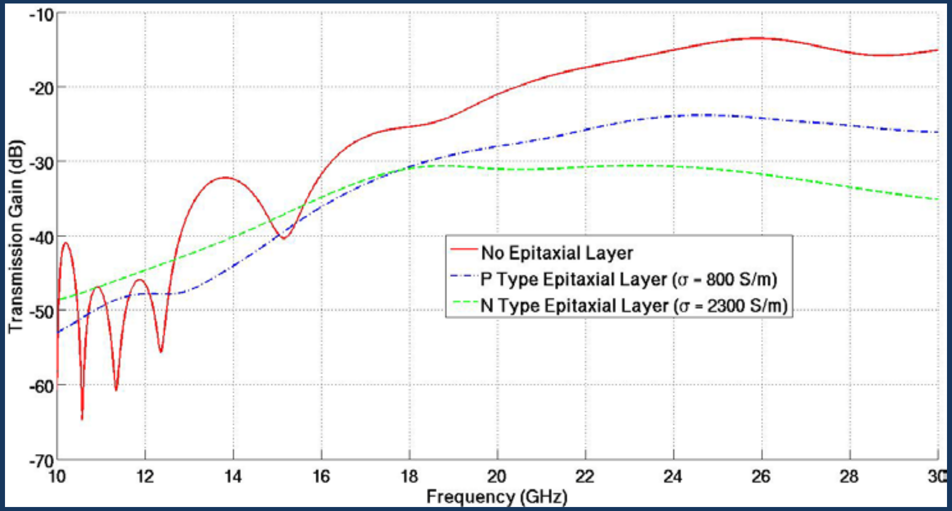
Material	Conductivity (S/m)	Relative permittivity
Silicon Dioxide	0	3.7
20 Ω-cm Substrate	5	11.9
P-well (epitaxial layer)	800	11.9
N-well (epitaxial layer)	2300	11.9



Effects of Epitaxial Layer on Antenna Characteristics

- **Return loss at the transmitting antenna**
  - High conductivity epitaxial layer decreases the frequency range of operation
  - P-type epitaxial layer is used for all other simulations (typical of most ICs)

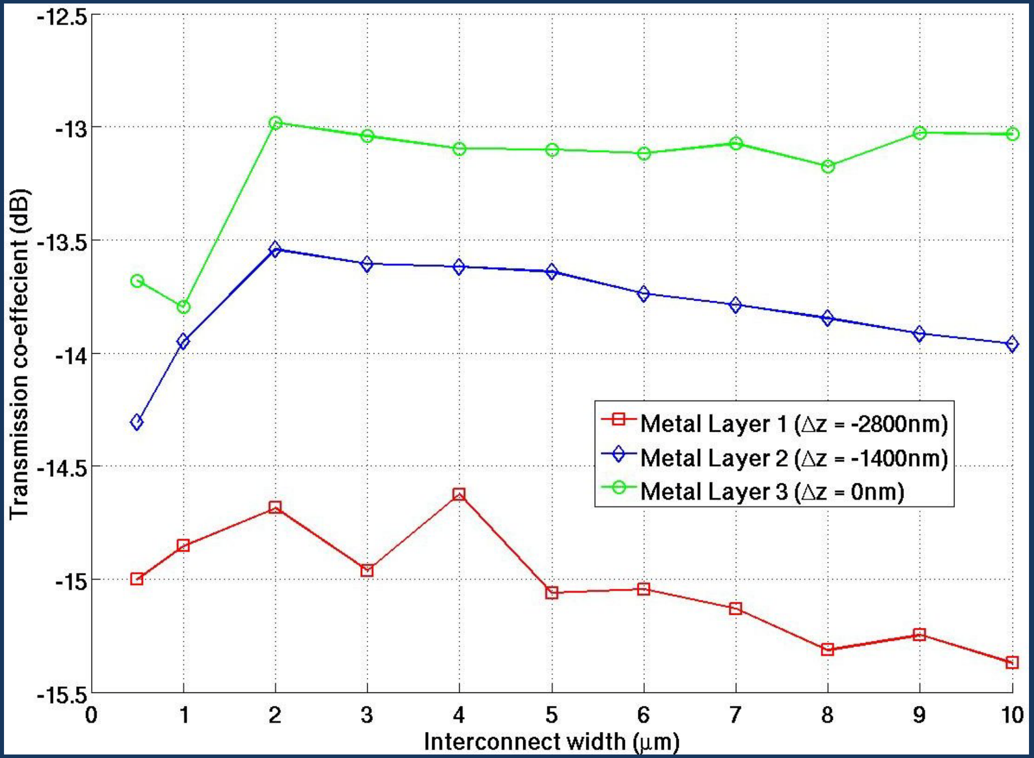




- **Transmission gain between the transmitting and receiving antenna**

Electromagnetic Coupling Between Antenna and Interconnects

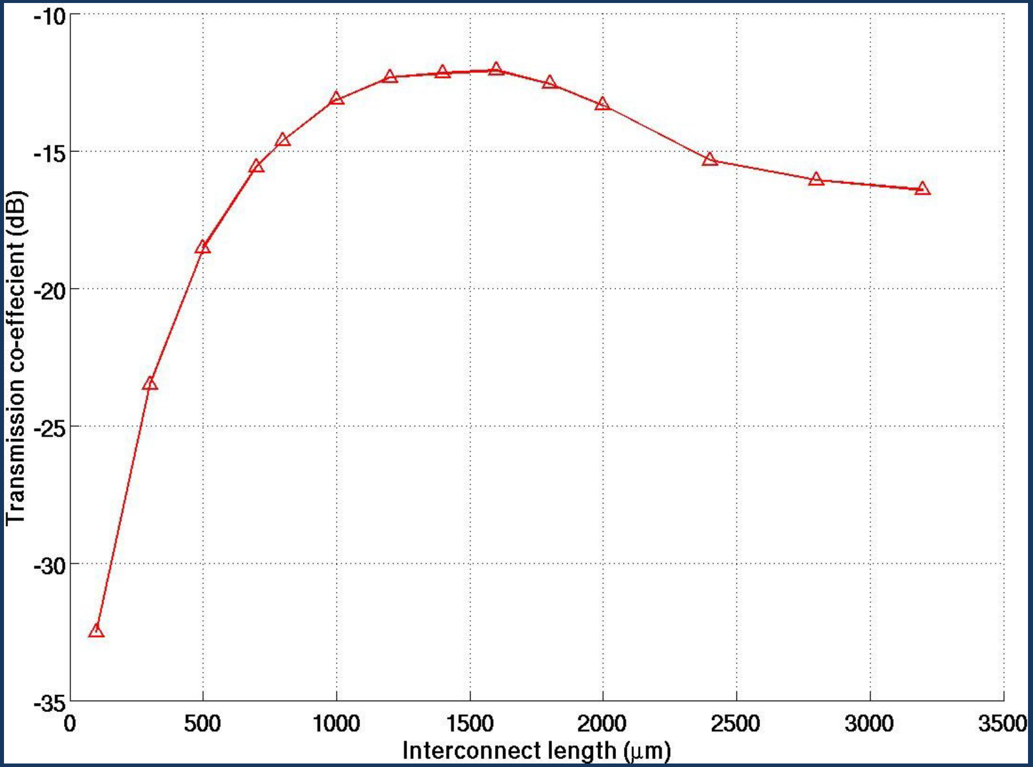
- **Variation with interconnect width and metal layer placement**
  - Relatively stable and low coupling with width
  - Decreases with a higher layer separation



(interconnect length = 1mm)

Electromagnetic Coupling Between Antenna and Interconnects

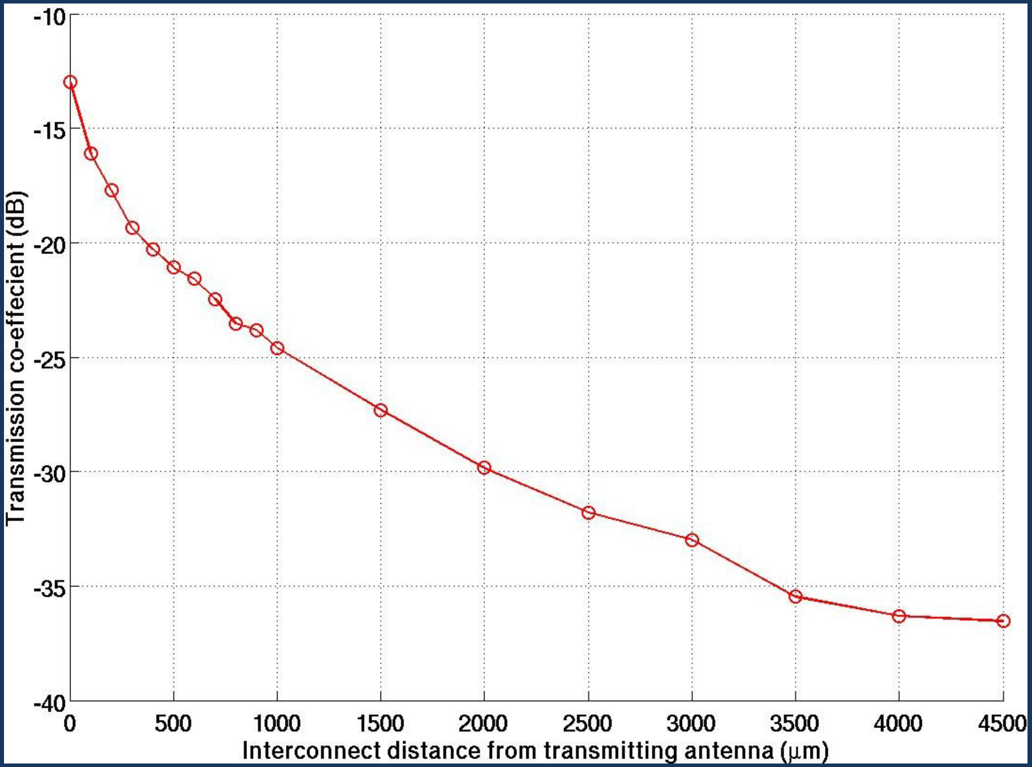
- **Variation with interconnect length**
  - Low coupling
  - Peaksat a length of quarter wavelength of the EM wave (=6.8mm/4 = 1.7mm)



(interconnect width = 2µm)

Electromagnetic Coupling Between Antenna and Interconnects

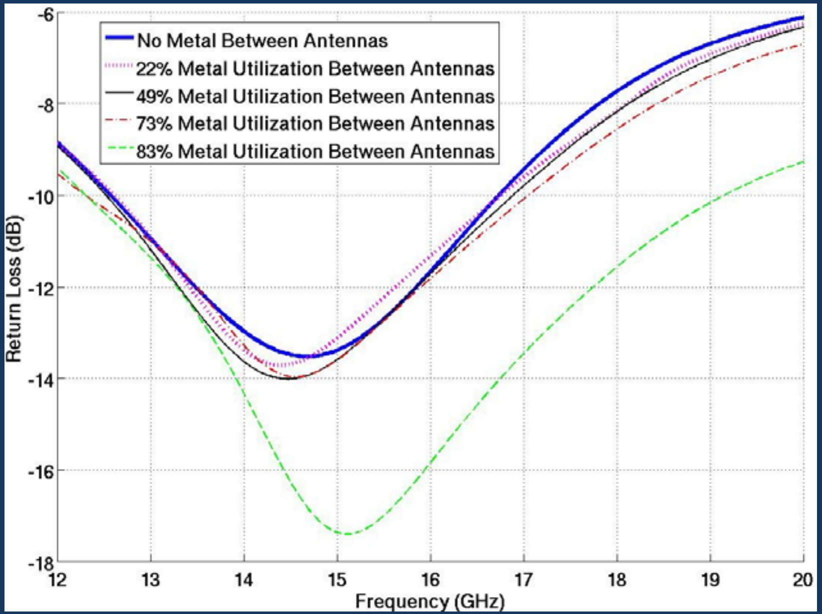
- **Variation with interconnect distance**
  - Low coupling
  - Decreases monotonously with a higher separation between the interconnect and the transmitting antenna

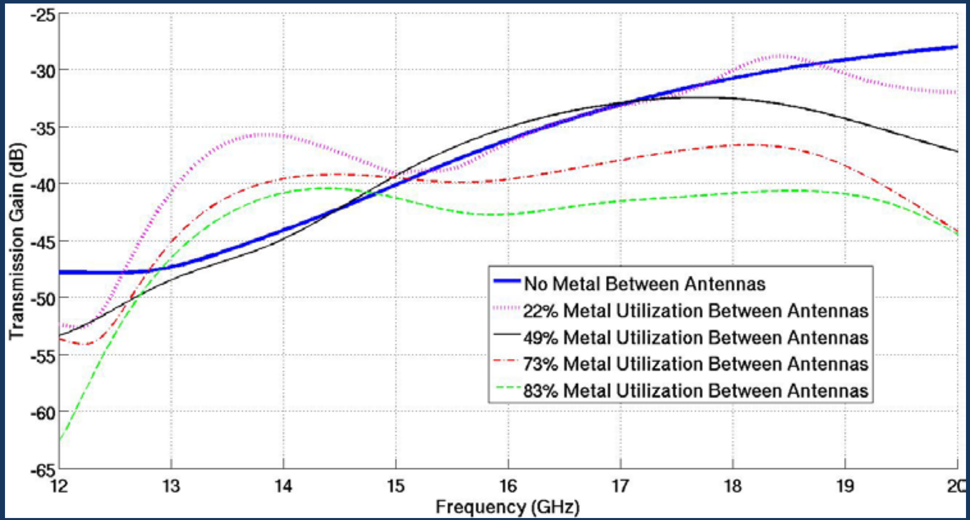


(int. length = 1mm; width = 2μm)

Effects of Metal Utilization on Antenna Characteristics

- **Return loss at the transmitting antenna**





- **Transmission gain between the transmitting and receiving antenna**
  - **High metal utilization can reduce the transmission gain between the antennas**

Conclusions 1/2

- The coupling with metal interconnect:
  - Is very low, not hindering wireless interconnect operation.
  - Decreases with placement in different metal layers
  - Isunaffected by varying widths of the interconnect
  - Is very low at small interconnect lengths
    - Peaks at interconnect length of approximately a quarter of the wavelength of the electromagnetic waves
  - Monotonously decreases with an increasing distance from the transmitting antenna

Conclusions 2 / 2

- The “essential” high conductivity epitaxial layer reduces the transmission gain between the antenna pair by approximately 12dB

- The transmission gain between the antenna pair varies depending on the percentage utilization of same metal layer of the antenna
  - Very high utilization ~80% a concern?

Thank You

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Supplementary Slides

References

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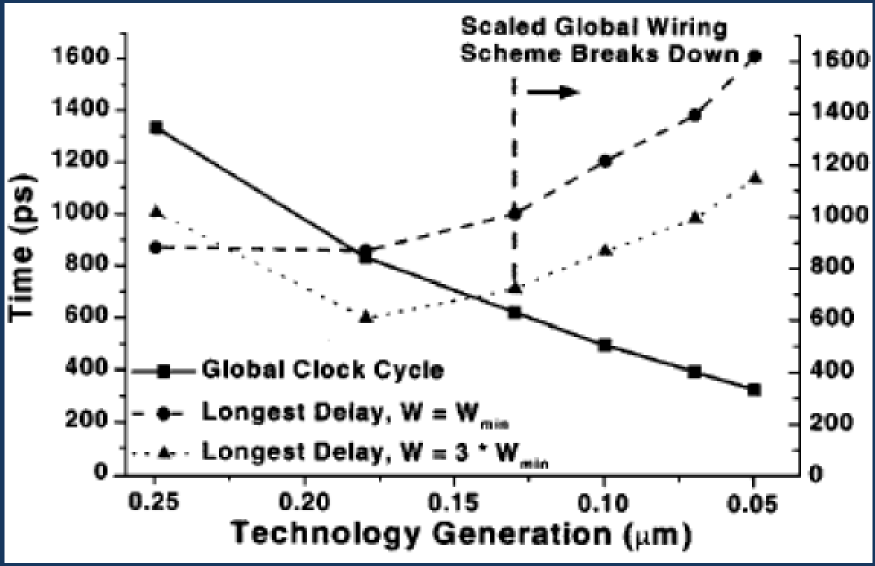
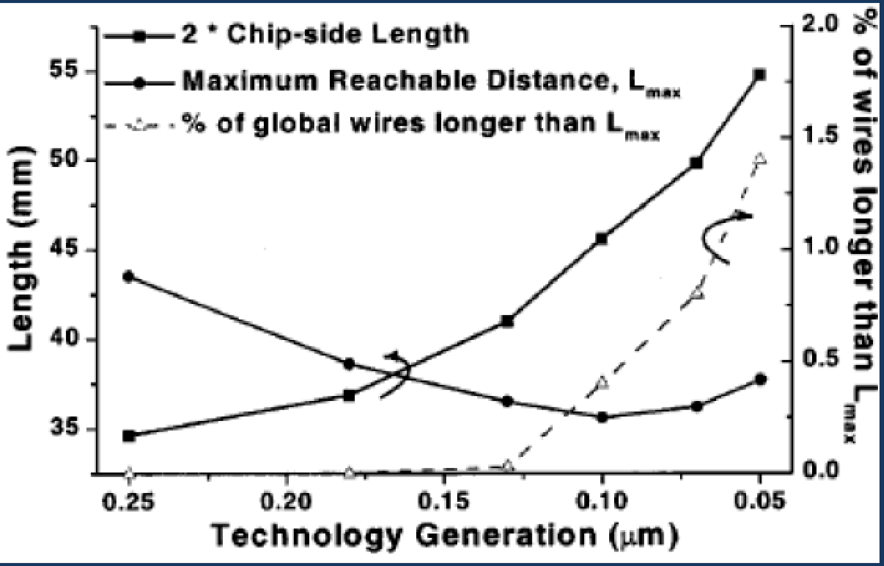
Technology Trends

- **Time delay** increases
- **Clock distribution** is more difficult

- **Maximum reachable distance** decreases



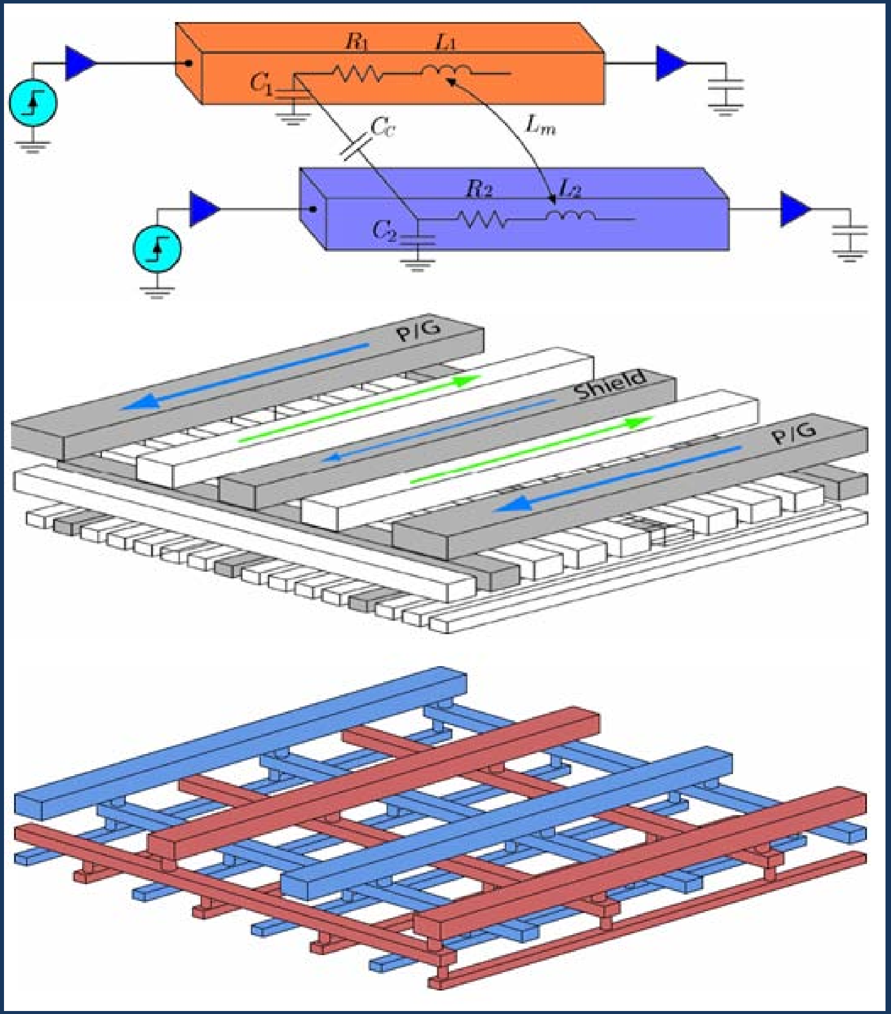
Source: Sylvester and K. Keutzer in TCAD



Source: Sylvester and K. Keutzer in TCAD

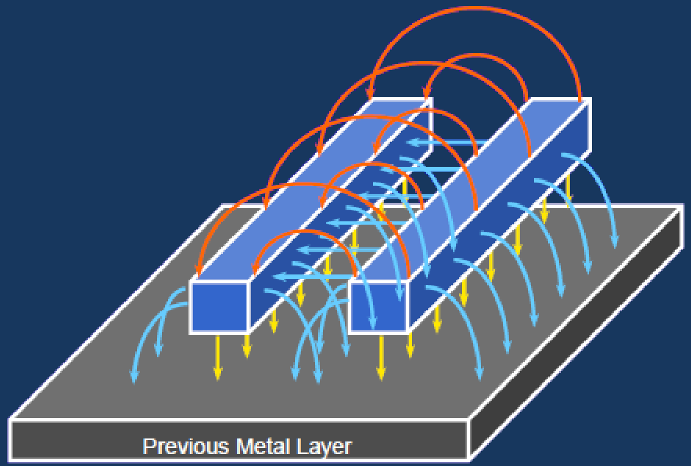
Interconnect Networks

- **Inductance** effect increases
- **Noise** increases
- **Routing** density is reduced
- **Power distribution** suffers from higher voltage drops



Source: Friedman in 1st NoC Workshop

Interconnect Capacitive Coupling

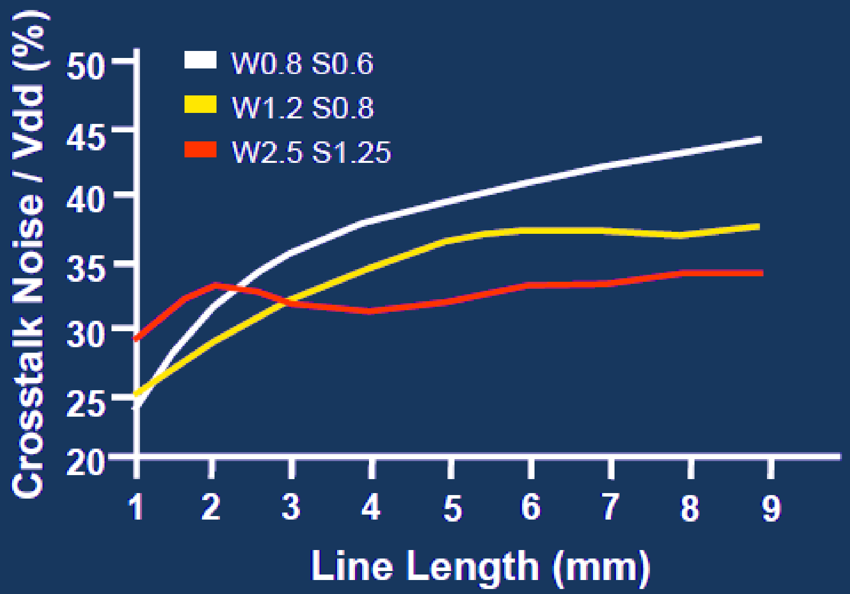


Source: Friedman in 1st NoC Workshop

- **Fringing capacitance increases with scaling**
  - **Spacing between lines decreases**

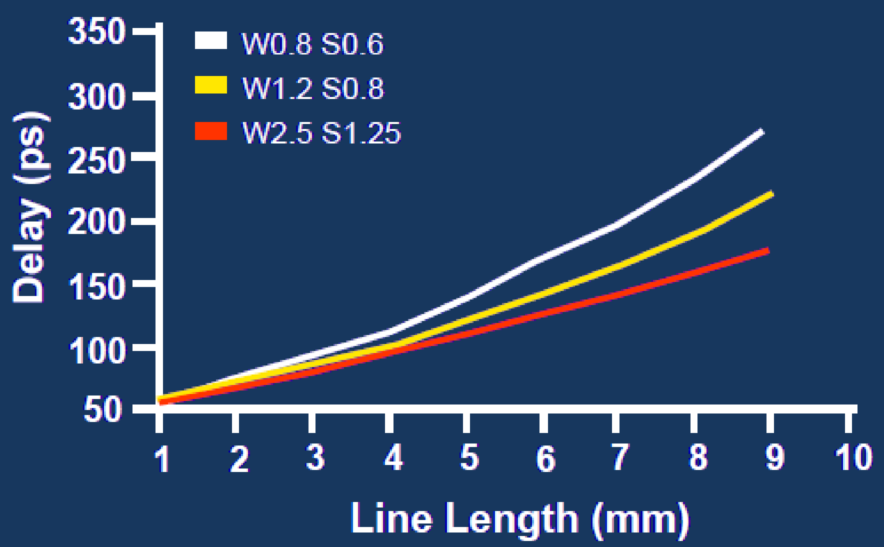
Geometric Wire Characteristics

- **Narrow lines**
  - RC dominant
  - Quadratic delay with line length



Source: Friedman in 1st NoC Workshop

- **Wide lines**
  - Less noise at the far end
  - Linear Delay with line length



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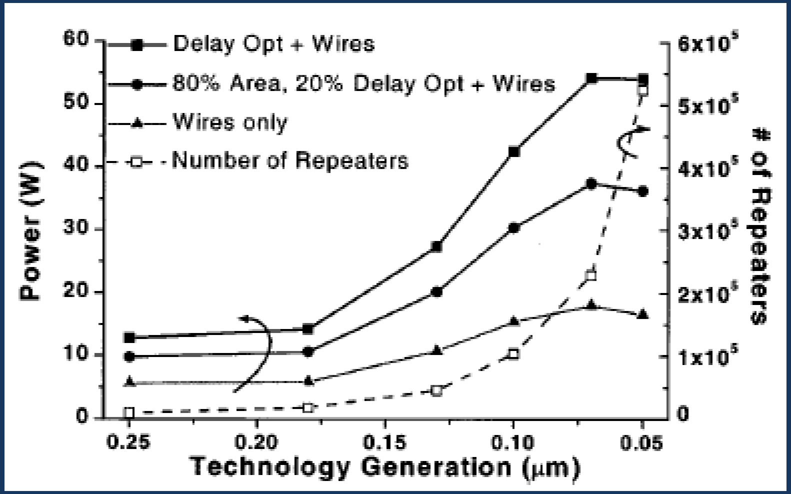
Use of Repeaters in Interconnects



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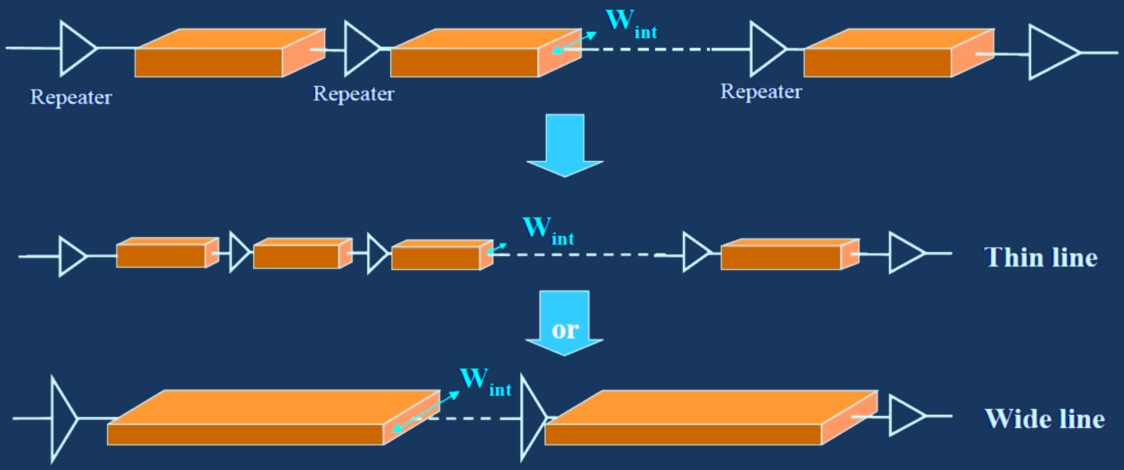
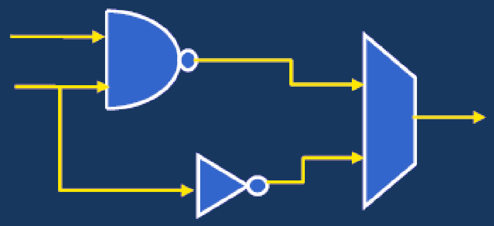


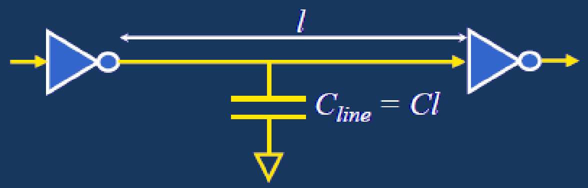
Source: Friedman in 1st NoC Workshop

History of Interconnect Modeling

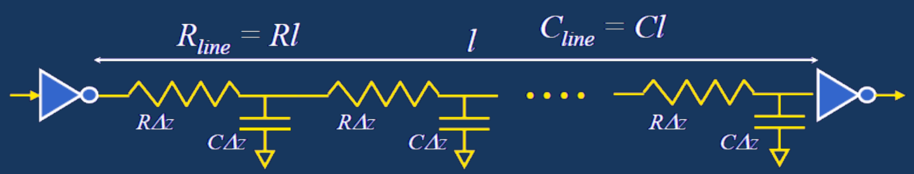
- Gate delay was dominant



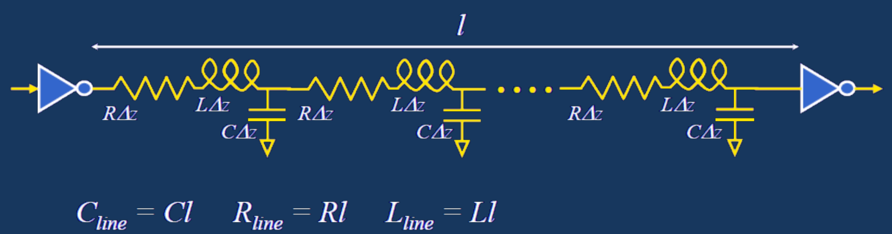
- Capacitive only



- Resistive and capacitive

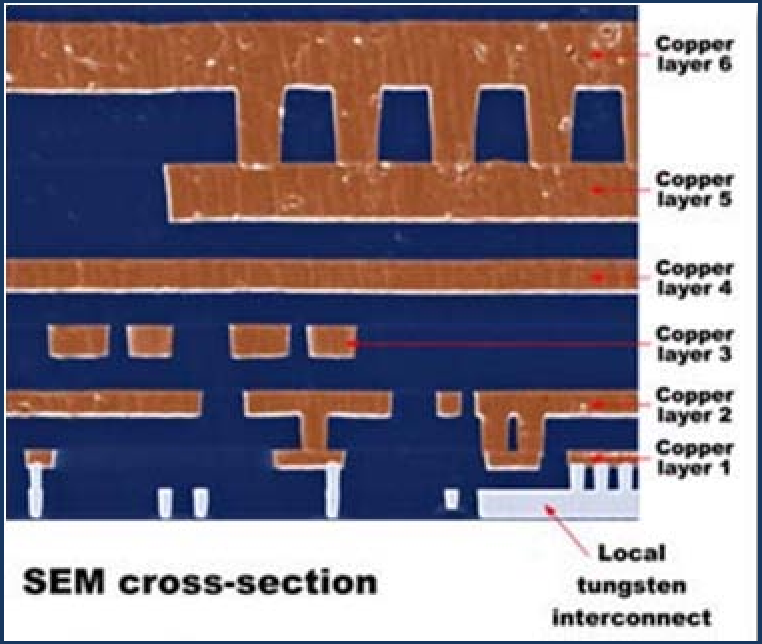


- Resistive, capacitive and inductive



Source: Friedman in 1stNoC Workshop

Wave Propagation



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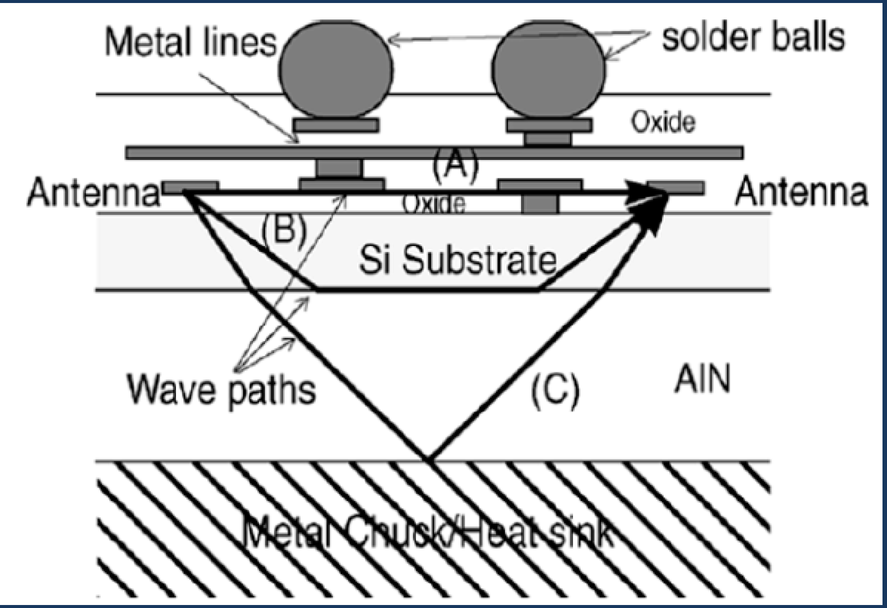
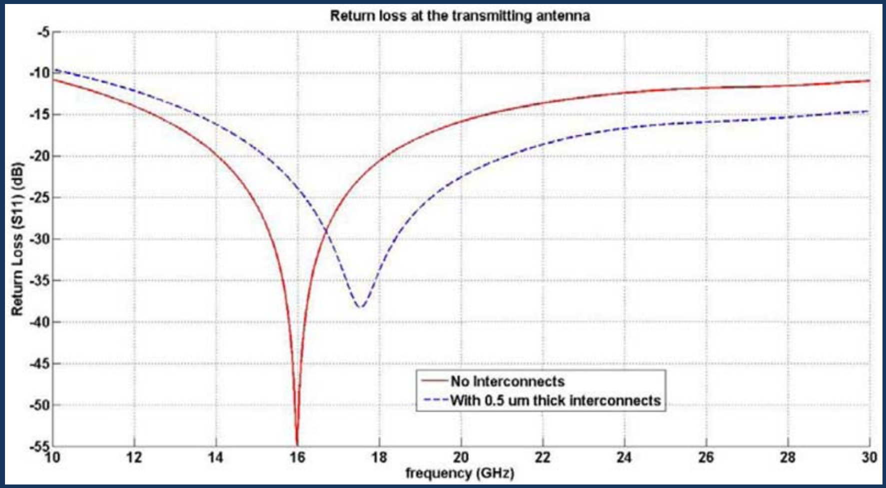
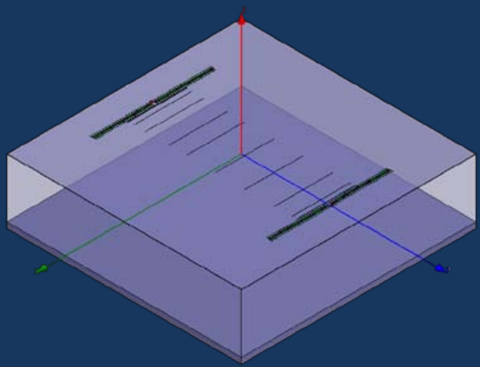
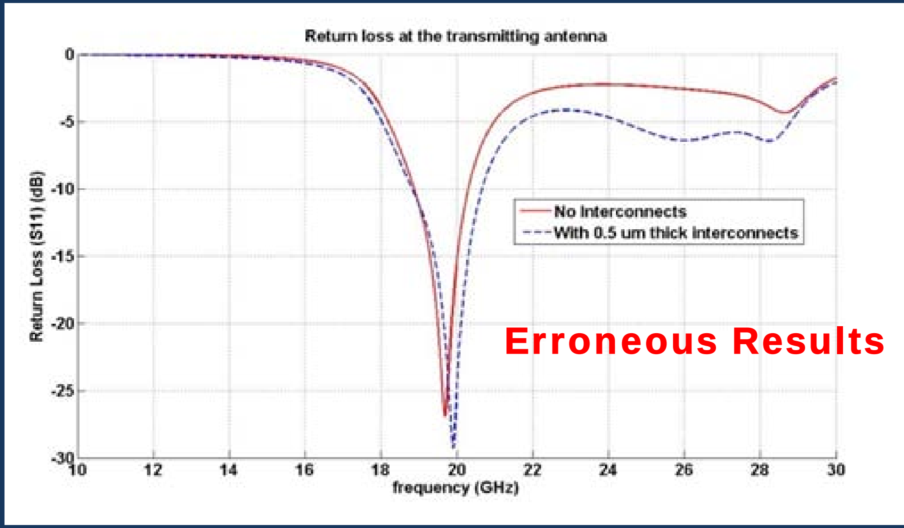


Source: K. K. O et. al. in TED

Effect of Substrate Model







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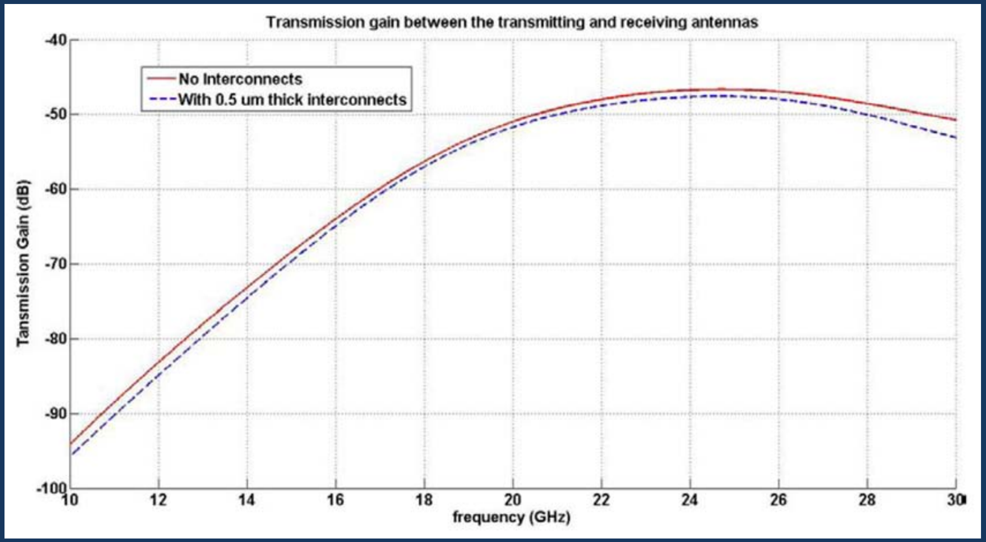
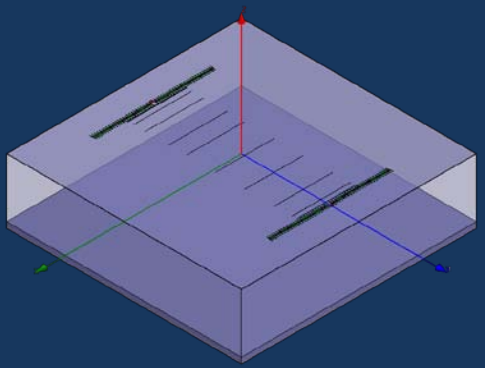
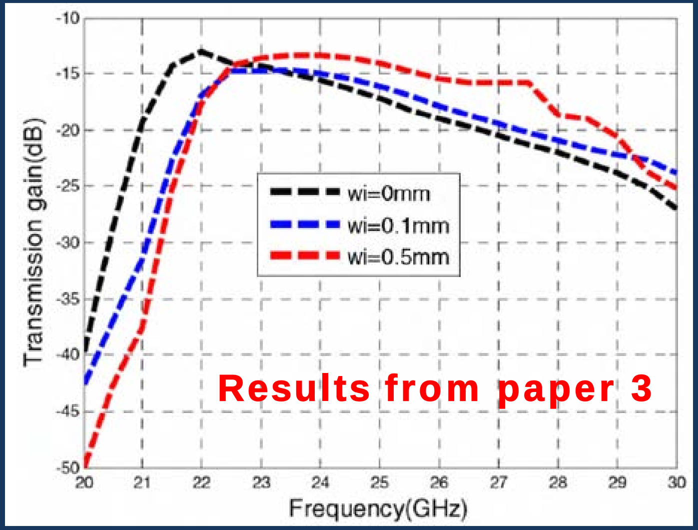
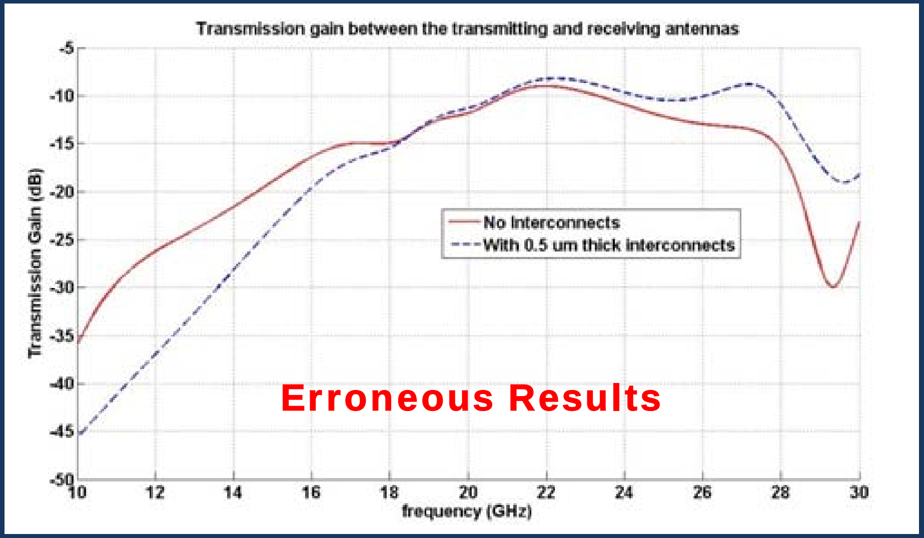








Source: Bialkowski and Abbosh in APSURSI

Simulation Profile: Antenna with Interconnects

- **Objectives:**
  - To study interference effects on antenna characteristics
  - To study radiation effects on metal interconnects

- **Methodology:**
  - Measure scattering parameters (s-parameters)
  - Calculate transmission gain
  - Variance of transmission s-parameter between transmitting antenna and metal interconnects with distance

Simulation Profile: Antenna with Inverters

- **Objectives:**
  - To study interference effects on circuit devices

- **Methodology:**
  - Measure electric fields across gate
  - Measure electric fields across channel
  - Compute radiation induced gate to source and drain to source voltages
  - Compute leakage current

Antenna Characterization

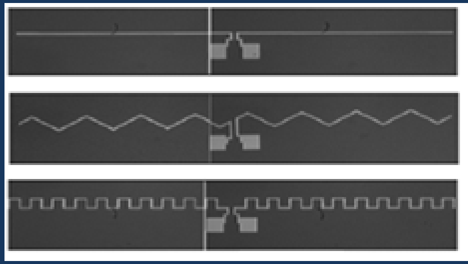
- **Antenna transmission gain, G_a**

$$G_a = \frac{|S_{21}|^2}{\left(1-|S_{11}|^2\right)\left(1-|S_{22}|^2\right)} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 e^{-2\alpha R}$$

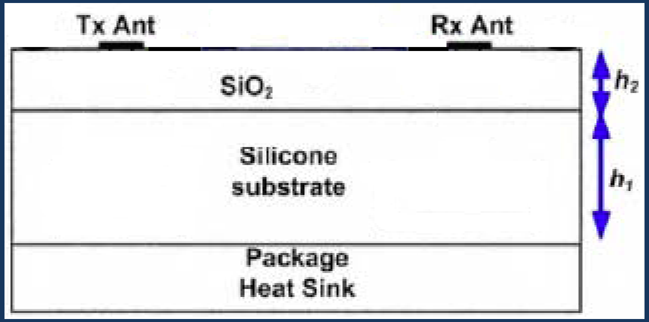
  – Where
    - G_t → gain of transmitting antenna
    - G_r → gain of receiving antenna
    - λ → wavelength
    - α → attenuation constant
    - R → separation between antennas
    - S_{21}, S_{11}, S_{22} → elements of the scattering parameter matrix

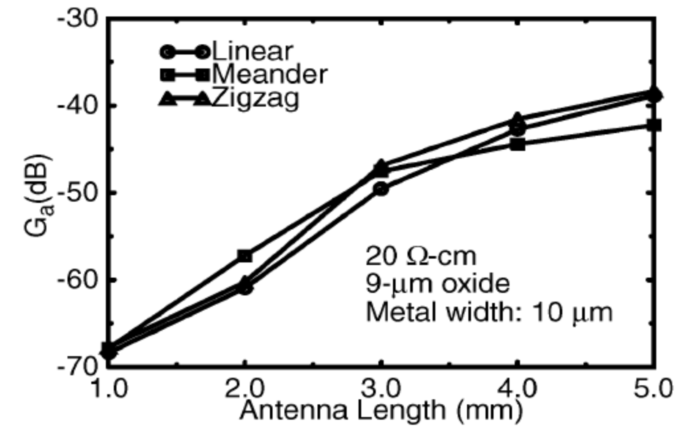
Antenna Characteristics

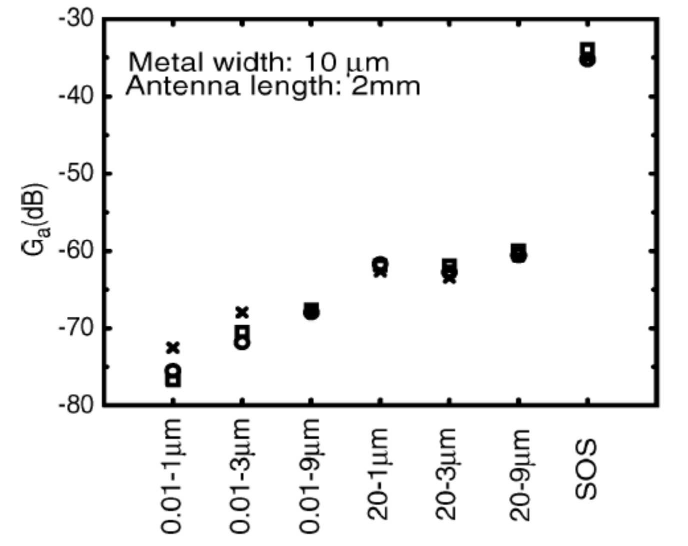
- Transmission gain increases with antenna length



- Transmission gain increases with substrate resistivity and oxide thickness





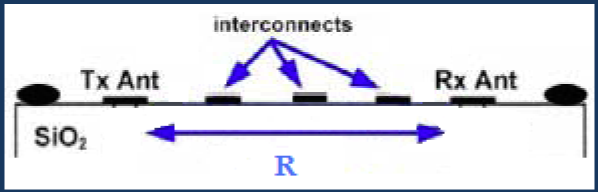


Source: K. K. O et. al. in TED

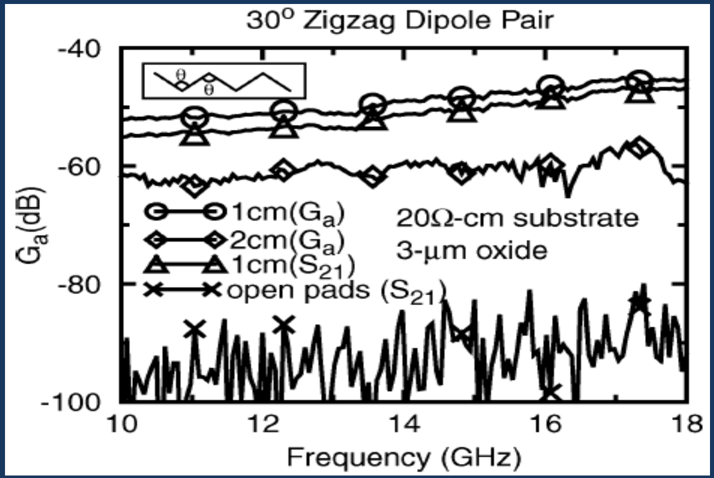
Antenna Characteristics

- **Transmission gain decreases with increasing antenna separation**
  - **Physical structure**

  - **Simulation structure**



$$G_a = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 e^{-2\alpha R}$$



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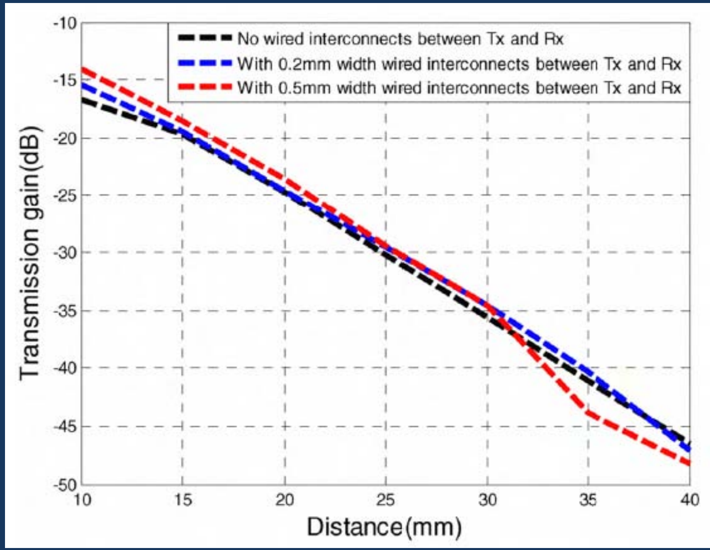
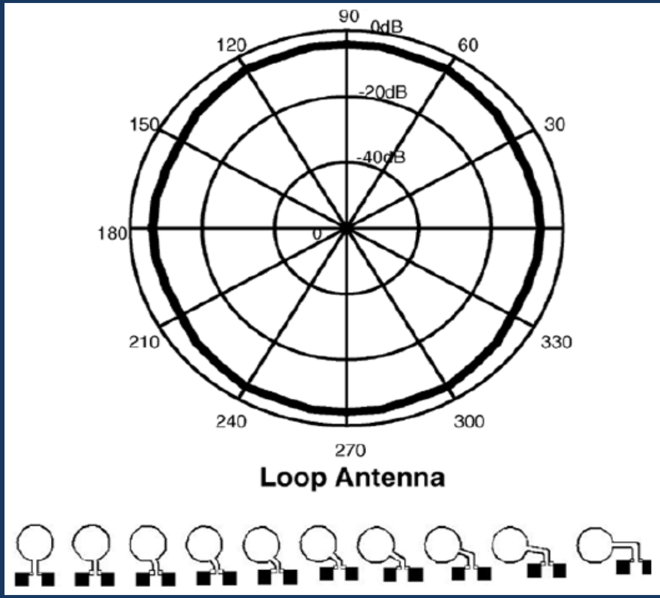


Source: Bialkowski and Abbosh in APSURSI

Loop Antenna

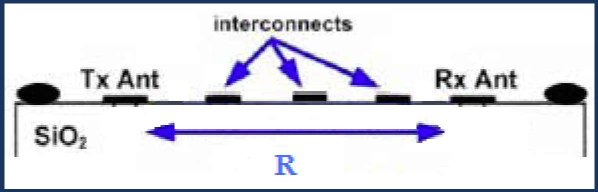
- **Antenna Characteristics**
  - Isotropic radiation pattern of loop antenna

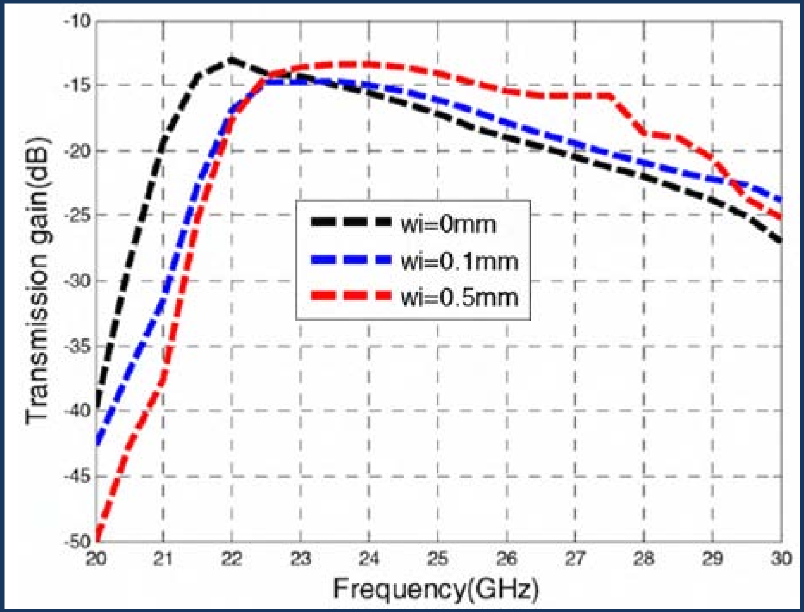


Source: K. K. O et. al. in TED

Variation with Presence of Metal Interconnects

- Minimal affect on transmission gain in presence of metal interconnects
- Center frequency shifted to a higher range in presence of metal interconnects





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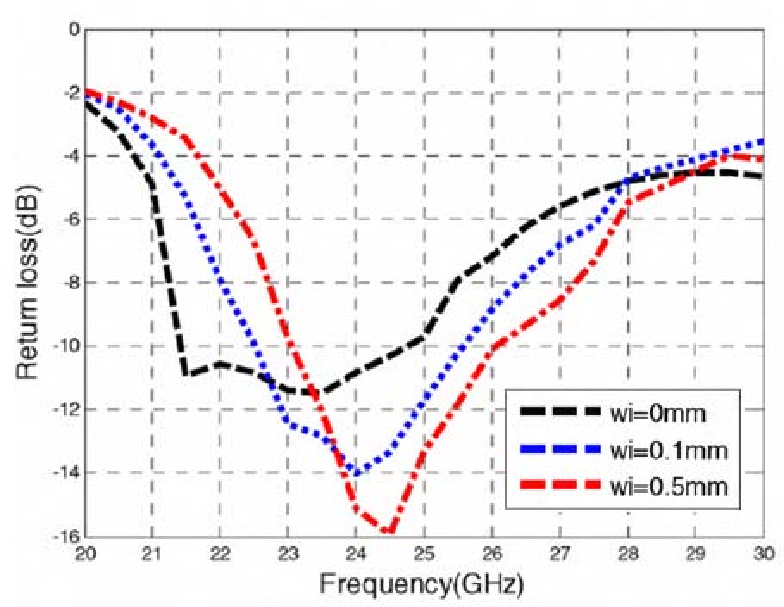
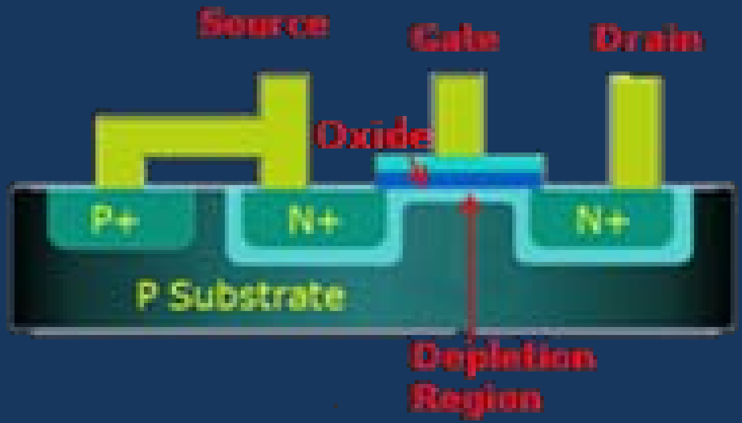


Source: Bialkowski and Abbosh in APSURSI

Simulation Profile: Antenna with Inverters

- Key equations:
  - Radiation induced voltage

$$[v]_{RAD} = [E_f]_{RAD} L$$



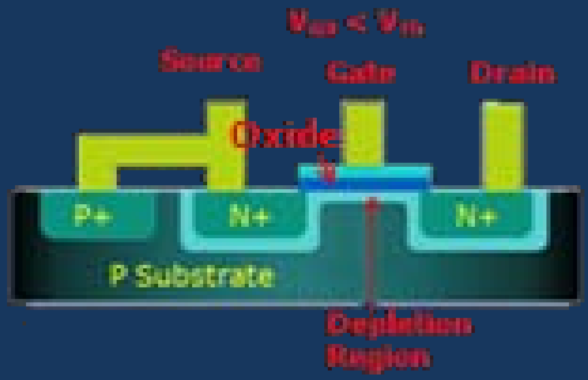
Where

- $[v]_{RAD}$ ➔ radiation induced voltage
- $[E_f]_{RAD}$ ➔ electric field from antenna radiation
- L ➔ length of element

Simulation Profile: Antenna with Inverters

- **Key equations:**
  - **Leakage current in sub-threshold region of operation**

$$I_D = I_S e^{qV_{GS}/nkT}\left(1 - e^{-qV_{DS}/kT}\right)\left(1 + \lambda V_{DS}\right)$$



Where

- I_S → reverse saturation current (≈ 10^{-14})
- q → charge on an electron
- k → Boltzman constant
- T → temperature (in Kelvins)
- λ → channel length modulation (ignored)
- n → empirical constant
- V_{DS} → drain to source voltage
- V_{GS} → gate to source voltage
- I_D → leakage current (in sub-threshold region of MOSFET)

Material properties

Material	Conductivity (S/m)	Relative permittivity
Aluminum	$3.8*10^7$	1
Silicon Dioxide	0	3.7
20 Ω-cm Substrate (lightly doped silicon)	5	11.9
P-well (epitaxial layer)	800	11.9
N-well	2300	11.9
P^+/N^+ (active regions)	62500	11.9