

Lecture 13: Wires

Outline

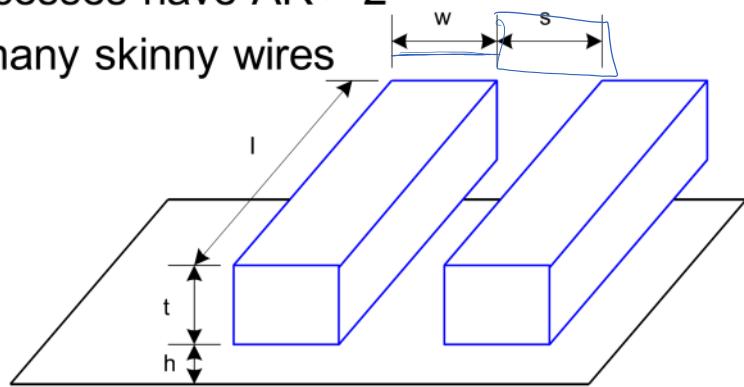
- Introduction
- Interconnect Modeling
 - Wire Resistance
 - Wire Capacitance
- Wire RC Delay
- Crosstalk
- Wire Engineering
- Repeaters

Introduction

- Chips are mostly made of wires called *interconnect*
 - In stick diagram, wires set size
 - Transistors are little things under the wires
 - Many layers of wires
- Wires are as important as transistors
 - Speed
 - Power
 - Noise
- Alternating layers run orthogonally

Wire Geometry

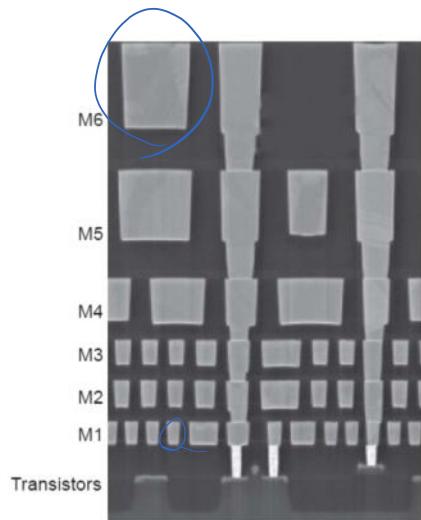
- Pitch = $w + s$
- Aspect ratio: $AR = t/w$
 - Old processes had $AR \ll 1$
 - Modern processes have $AR \approx 2$
 - Pack in many skinny wires



Layer Stack

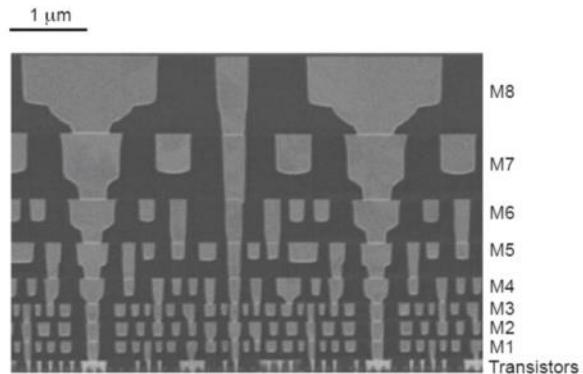
- AMI 0.6 μm process has 3 metal layers
 - M1 for within-cell routing
 - M2 for vertical routing between cells
 - M3 for horizontal routing between cells
- Modern processes use 6-10+ metal layers
 - M1: thin, narrow ($< 3\lambda$)
 - High density cells
 - Mid layers
 - Thicker and wider, (density vs. speed)
 - Top layers: thickest
 - For V_{DD} , GND, clk

Example



Intel 90 nm Stack

[Thompson02]



Intel 45 nm Stack

[Moon08]

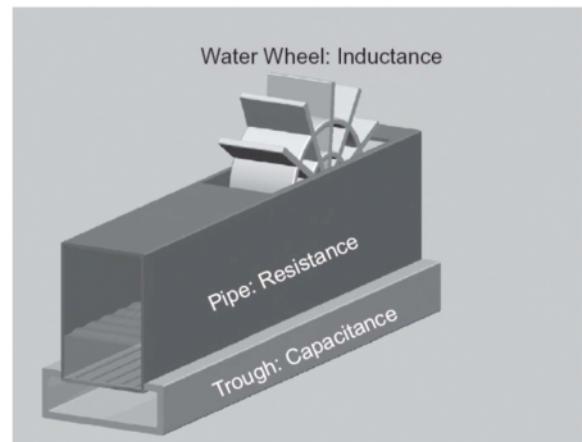
13: Wires

CMOS VLSI Design 4th Ed.

6

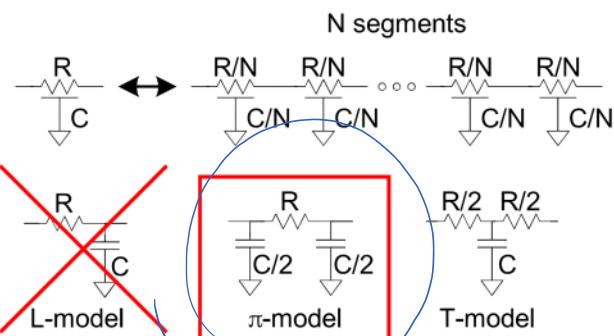
Interconnect Modeling

- Current in a wire is analogous to current in a pipe
 - Resistance: narrow size impedes flow
 - Capacitance: trough under the leaky pipe must fill first
 - Inductance: paddle wheel inertia opposes changes in flow rate
 - Negligible for most wires

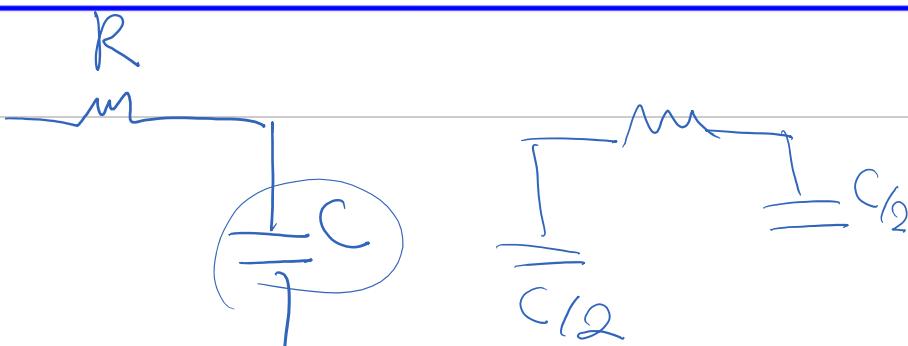


Lumped Element Models

- Wires are a distributed system
 - Approximate with lumped element models



- 3-segment π -model is accurate to 3% in simulation
- L-model needs 100 segments for same accuracy!
- Use single segment π -model for Elmore delay



Wire Resistance

- $\rho = \text{resistivity } (\Omega \cdot \text{m})$

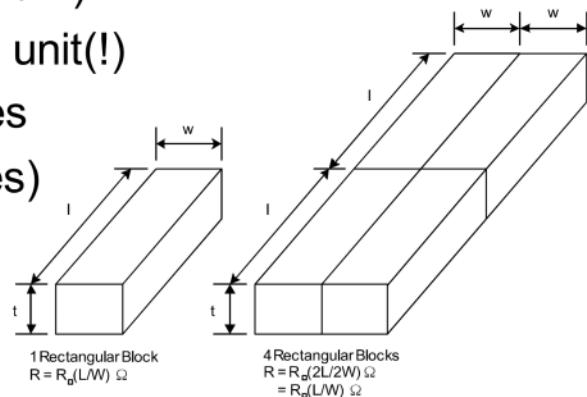
$$R = \frac{\rho}{t} \frac{l}{w} = R_w \frac{l}{w}$$

- $R_{\square} = \text{sheet resistance } (\Omega/\square)$

– □ is a dimensionless unit(!)

- Count number of squares

– $R = R_{\square} * (\# \text{ of squares})$



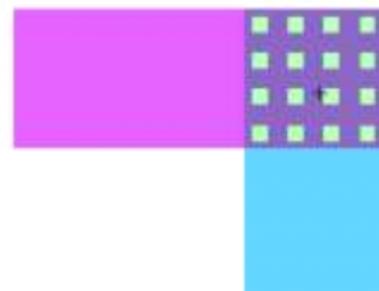
Choice of Metals

- Until 180 nm generation, most wires were aluminum
- Contemporary processes normally use copper
 - Cu atoms diffuse into silicon and damage FETs
 - Must be surrounded by a diffusion barrier

Metal	Bulk resistivity ($\mu\Omega \cdot \text{cm}$)
Silver (Ag)	1.6
Copper (Cu)	1.7
Gold (Au)	2.2
Aluminum (Al)	2.8
Tungsten (W)	5.3
Titanium (Ti)	43.0

Contacts Resistance

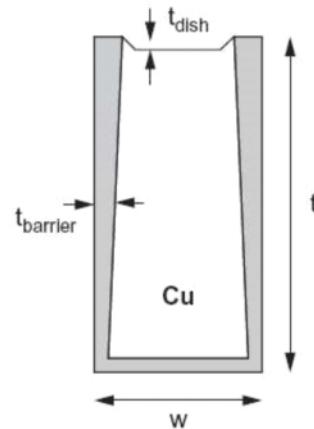
- Contacts and vias also have $2-20 \Omega$
- Use many contacts for lower R
 - Many small contacts for current crowding around periphery



Copper Issues

- Copper wires diffusion barrier has high resistance
- Copper is also prone to *dishing* during polishing
- Effective resistance is higher

$$R = \frac{\rho}{(t - t_{\text{dish}} - t_{\text{barrier}})} \frac{l}{(w - 2t_{\text{barrier}})}$$



Example

- Compute the sheet resistance of a $0.22 \mu\text{m}$ thick Cu wire in a 65 nm process. The resistivity of thin film Cu is $2.2 \times 10^{-8} \Omega\cdot\text{m}$. Ignore dishing.

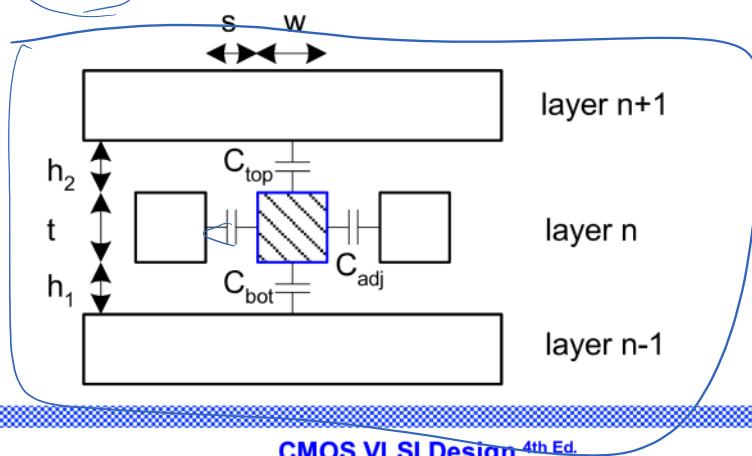
$$R_w = \frac{2.2 \times 10^{-8} \Omega\text{m}}{0.22 \times 10^{-6} \text{ m}} = 0.10 \Omega/\mu\text{m}$$

- Find the total resistance if the wire is $0.125 \mu\text{m}$ wide and 1 mm long. Ignore the barrier layer.

$$R = (0.10 \Omega/\mu\text{m}) \frac{1000 \mu\text{m}}{0.125 \mu\text{m}} = 800 \Omega$$

Wire Capacitance

- Wire has capacitance per unit length
 - To neighbors
 - To layers above and below
- $C_{\text{total}} = C_{\text{top}} + C_{\text{bot}} + 2C_{\text{adj}}$



Capacitance Trends

- Parallel plate equation: $C = \epsilon_{ox} A/d$
 - Wires are not parallel plates, but obey trends
 - Increasing area (W, t) increases capacitance
 - Increasing distance (s, h) decreases capacitance
- Dielectric constant
 - $\epsilon_{ox} = k\epsilon_0$
 - $\epsilon_0 = 8.85 \times 10^{-14} \text{ F/cm}$
 - $k = 3.9$ for SiO_2
- Processes are starting to use low-k dielectrics
 - $k \approx 3$ (or less) as dielectrics use air pockets

Capacitance Formula

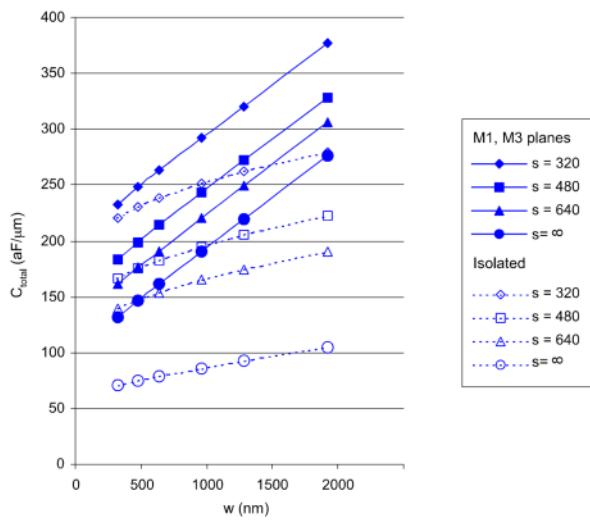
- Capacitance of a line without neighbors can be approximated as

$$C_{tot} = \epsilon_{ox} l \left[\frac{w}{h} + 0.77 + 1.06 \left(\frac{w}{h} \right)^{0.25} + 1.06 \left(\frac{t}{h} \right)^{0.5} \right]$$

- This empirical formula is accurate to 6% for AR < 3.3

M2 Capacitance Data

- Typical dense wires have $\sim 0.2 \text{ fF}/\mu\text{m}$
 - Compare to 1-2 $\text{fF}/\mu\text{m}$ for gate capacitance



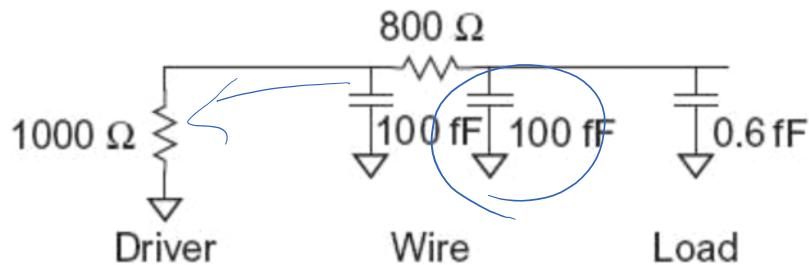
Diffusion & Polysilicon

- Diffusion capacitance is very high ($1\text{-}2 \text{ fF}/\mu\text{m}$)
 - Comparable to gate capacitance
 - Diffusion also has high resistance
 - Avoid using diffusion *runners* for wires!
- Polysilicon has lower C but high R
 - Use for transistor gates
 - Occasionally for very short wires between gates

Wire RC Delay

- Estimate the delay of a 10x inverter driving a 2x inverter at the end of the 1 mm wire. Assume wire capacitance is $0.2 \text{ fF}/\mu\text{m}$ and that a unit-sized inverter has $R = 10 \text{ K}\Omega$ and $C = 0.1 \text{ fF}$.

- $t_{pd} = (1000 \Omega)(100 \text{ fF}) + (1000 + 800 \Omega)(100 + 0.6 \text{ fF}) = 281 \text{ ps}$

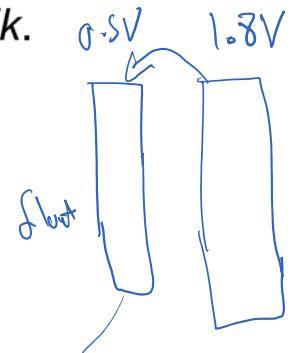


Wire Energy

- Estimate the energy per unit length to send a bit of information (one rising and one falling transition) in a CMOS process.
- $E = (0.2 \text{ pF/mm})(1.0 \text{ V})^2$
= 0.2 pJ/bit/mm
= 0.2 mW/Gbps/mm

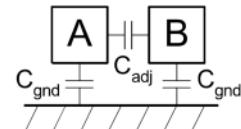
Crosstalk

- ❑ A capacitor does not like to change its voltage instantaneously.
- ❑ A wire has high capacitance to its neighbor.
 - When the neighbor switches from 1-> 0 or 0->1, the wire tends to switch too.
 - Called capacitive *coupling* or *crosstalk*.
- ❑ Crosstalk effects
 - Noise on nonswitching wires
 - Increased delay on switching wires



Crosstalk Delay

- Assume layers above and below on average are quiet
 - Second terminal of capacitor can be ignored
 - Model as $C_{\text{gnd}} = C_{\text{top}} + C_{\text{bot}}$
- Effective C_{adj} depends on behavior of neighbors
 - *Miller effect*

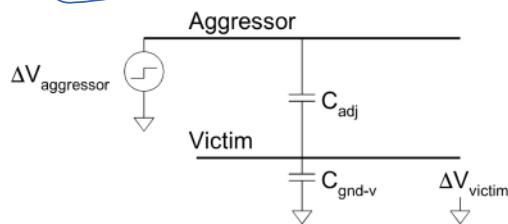


B	ΔV	$C_{\text{eff(A)}}$	MCF
Constant	V_{DD}	$C_{\text{gnd}} + C_{\text{adj}}$	1
Switching with A	0	C_{gnd}	0
Switching opposite A	$2V_{\text{DD}}$	$C_{\text{gnd}} + 2 C_{\text{adj}}$	2

Crosstalk Noise

- Crosstalk causes noise on nonswitching wires
- If victim is floating:
 - model as capacitive voltage divider

$$\Delta V_{victim} = \frac{C_{adj}}{C_{gnd-v} + C_{adj}} \Delta V_{aggressor}$$

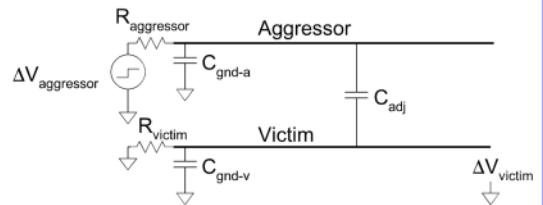


Driven Victims

- Usually victim is driven by a gate that fights noise
 - Noise depends on relative resistances
 - Victim driver is in linear region, agg. in saturation
 - If sizes are same, $R_{\text{aggressor}} = 2-4 \times R_{\text{victim}}$

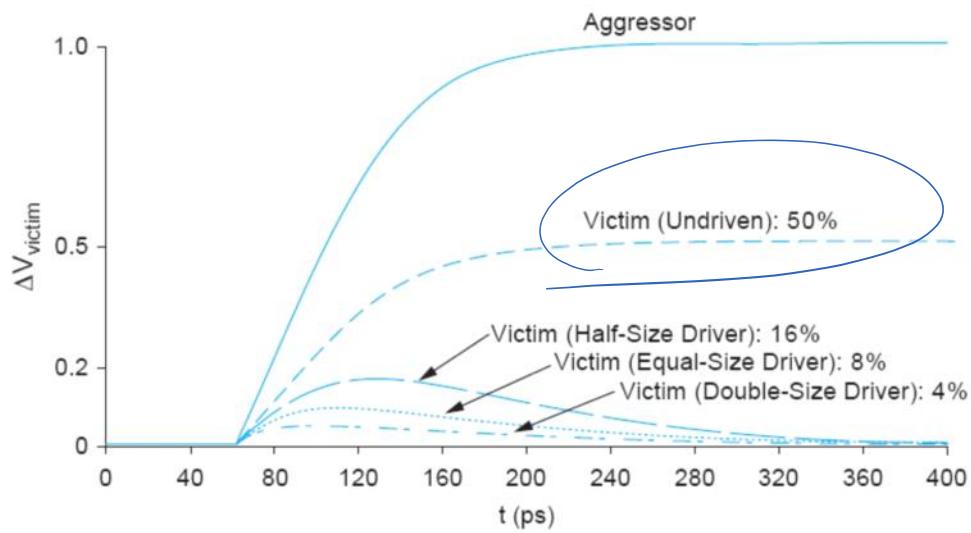
$$\Delta V_{\text{victim}} = \frac{C_{\text{adj}}}{C_{\text{gnd-v}} + C_{\text{adj}}} \frac{1}{1+k} \Delta V_{\text{aggressor}}$$

$$k = \frac{\tau_{\text{aggressor}}}{\tau_{\text{victim}}} = \frac{R_{\text{aggressor}} (C_{\text{gnd-a}} + C_{\text{adj}})}{R_{\text{victim}} (C_{\text{gnd-v}} + C_{\text{adj}})}$$



Coupling Waveforms

- Simulated coupling for $C_{adj} = C_{victim}$

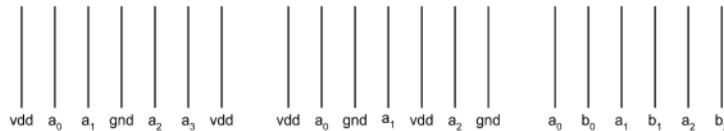
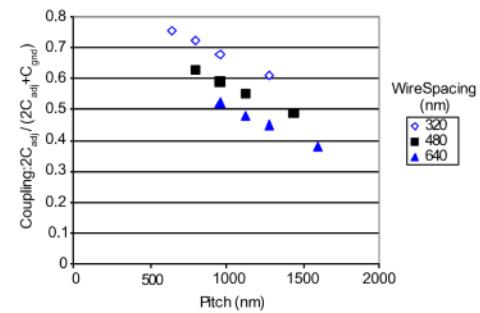
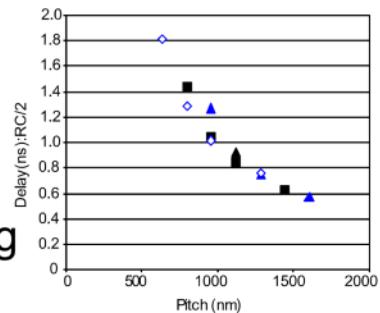


Noise Implications

- So what if we have noise?
- If the noise is less than the noise margin, nothing happens
- Static CMOS logic will eventually settle to correct output even if disturbed by large noise spikes
 - But glitches cause extra delay
 - Also cause extra power from false transitions
- Dynamic logic never recovers from glitches
- Memories and other sensitive circuits also can produce the wrong answer

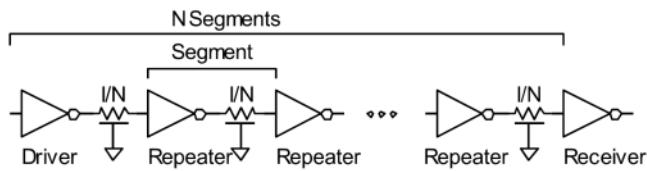
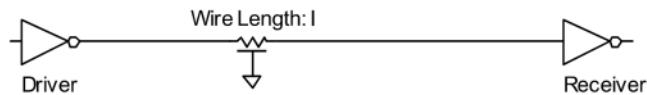
Wire Engineering

- Goal: achieve delay, area, power goals with acceptable noise
- Degrees of freedom:
 - Width
 - Spacing
 - Layer
 - Shielding



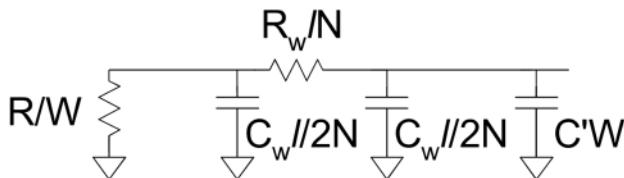
Repeaters

- R and C are proportional to l
- RC delay is proportional to l^2
 - Unacceptably great for long wires
- Break long wires into N shorter segments
 - Drive each one with an inverter or buffer



Repeater Design

- How many repeaters should we use?
- How large should each one be?
- Equivalent Circuit
 - Wire length I/N
 - Wire Capacitance $C_w * I/N$, Resistance $R_w * I/N$
 - Inverter width W ($n\text{MOS} = W$, $p\text{MOS} = 2W$)
 - Gate Capacitance $C' * W$, Resistance R/W



Repeater Results

- Write equation for Elmore Delay
 - Differentiate with respect to W and N
 - Set equal to 0, solve

$$\frac{l}{N} = \sqrt{\frac{2RC'}{R_w C_w}}$$

$$\frac{t_{pd}}{l} = \left(2 + \sqrt{2}\right) \sqrt{RC'R_w C_w}$$

~40 ps/mm
in 65 nm process

$$W = \sqrt{\frac{RC_w}{R_w C'}}$$

Repeater Energy

- Energy / length $\approx 1.87C_wV_{DD}^2$
 - 87% premium over unrepeated wires
 - The extra power is consumed in the large repeaters
- If the repeaters are downsized for minimum EDP:
 - Energy premium is only 30%
 - Delay increases by 14% from min delay