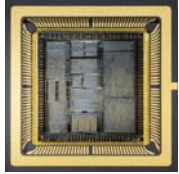


Lecture 5 : Power Dissipation

CSCE 6651 Advanced VLSI Systems

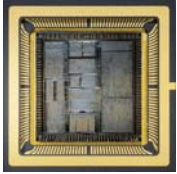
Instructor: Saraju P. Mohanty, Ph. D.

NOTE: The figures, text etc included in slides are borrowed from various books, websites, authors pages, and other sources for academic purpose only. The instructor does not claim any originality.



Outline

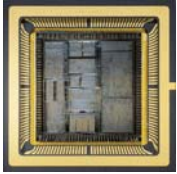
- Power and Energy
- Dynamic Power
- Static Power
- Low Power Design



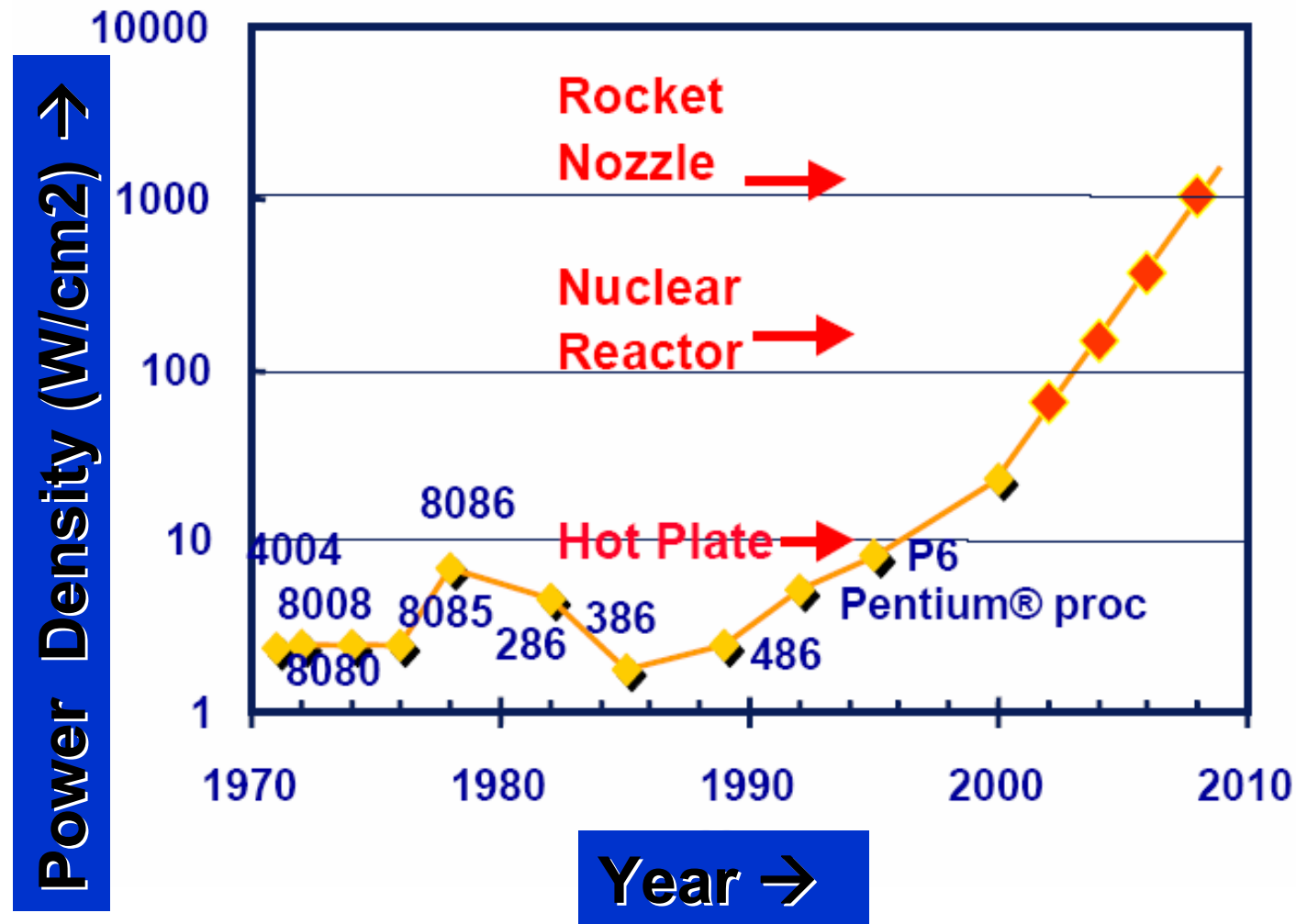
Power Consumption Trend



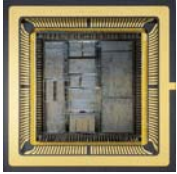
Source: Intel



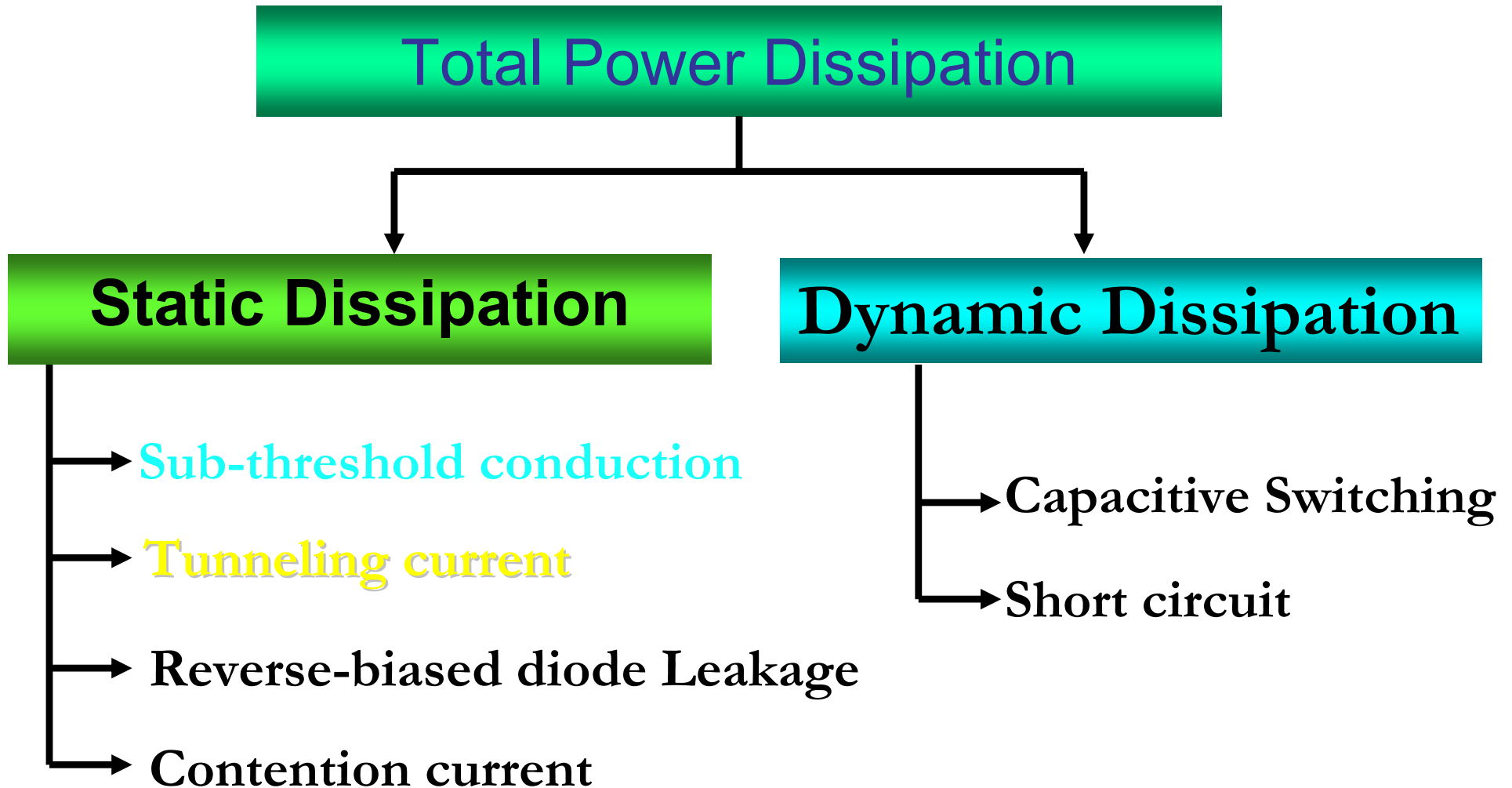
Power Consumption Trend

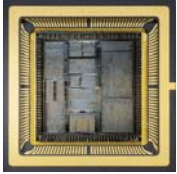


Source: Intel

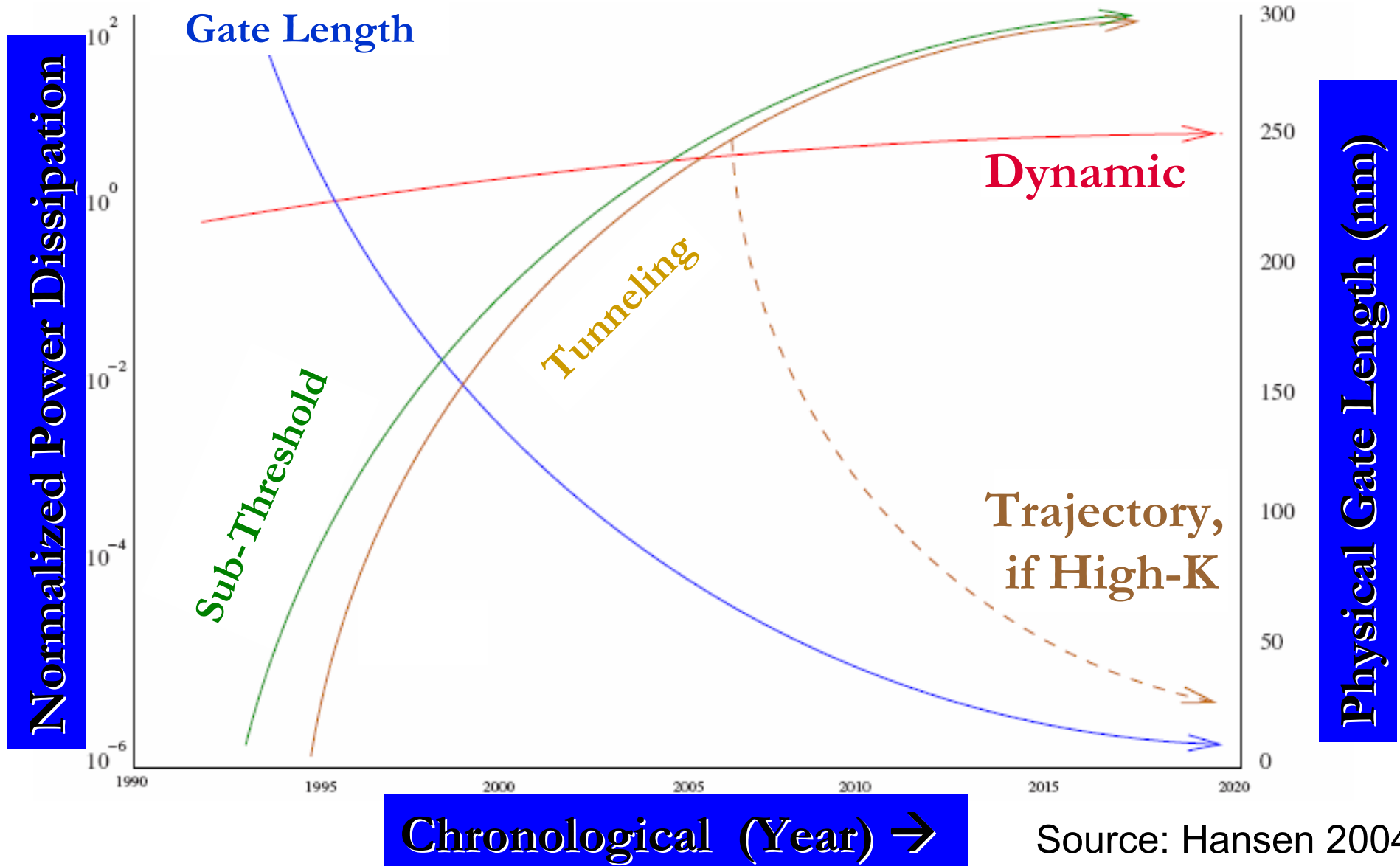


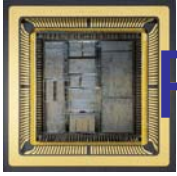
Power Dissipation in CMOS





Power Dissipation Trend

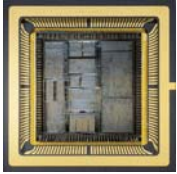




Power Dissipation in CMOS : Dynamic

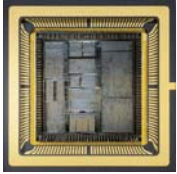
Capacitance Switching Current: This flows to charge and discharge capacitance loads during logic changes.

Short-Circuit Current: This is the current due to the DC path between the supply and ground during output transition.



Power Dissipation in CMOS : Static

- **Subthreshold Current:** Sub-threshold current that arises from the inversion charges that exists at the gate voltages below the threshold voltage.
- **Tunneling Current:** There is a finite probability for carrier being pass through the gate oxide. This results in tunneling current thorough the gate oxide.
- **Reverse-biased Diode Leakage:** Reverse bias current in the parasitic diodes.
- **Contention Current in Ratioed Circuits:** Ratioed circuits burn power in fight between ON transistors



Leakages in Nanometer CMOS

I_1 : reverse bias pn junction (both ON & OFF)

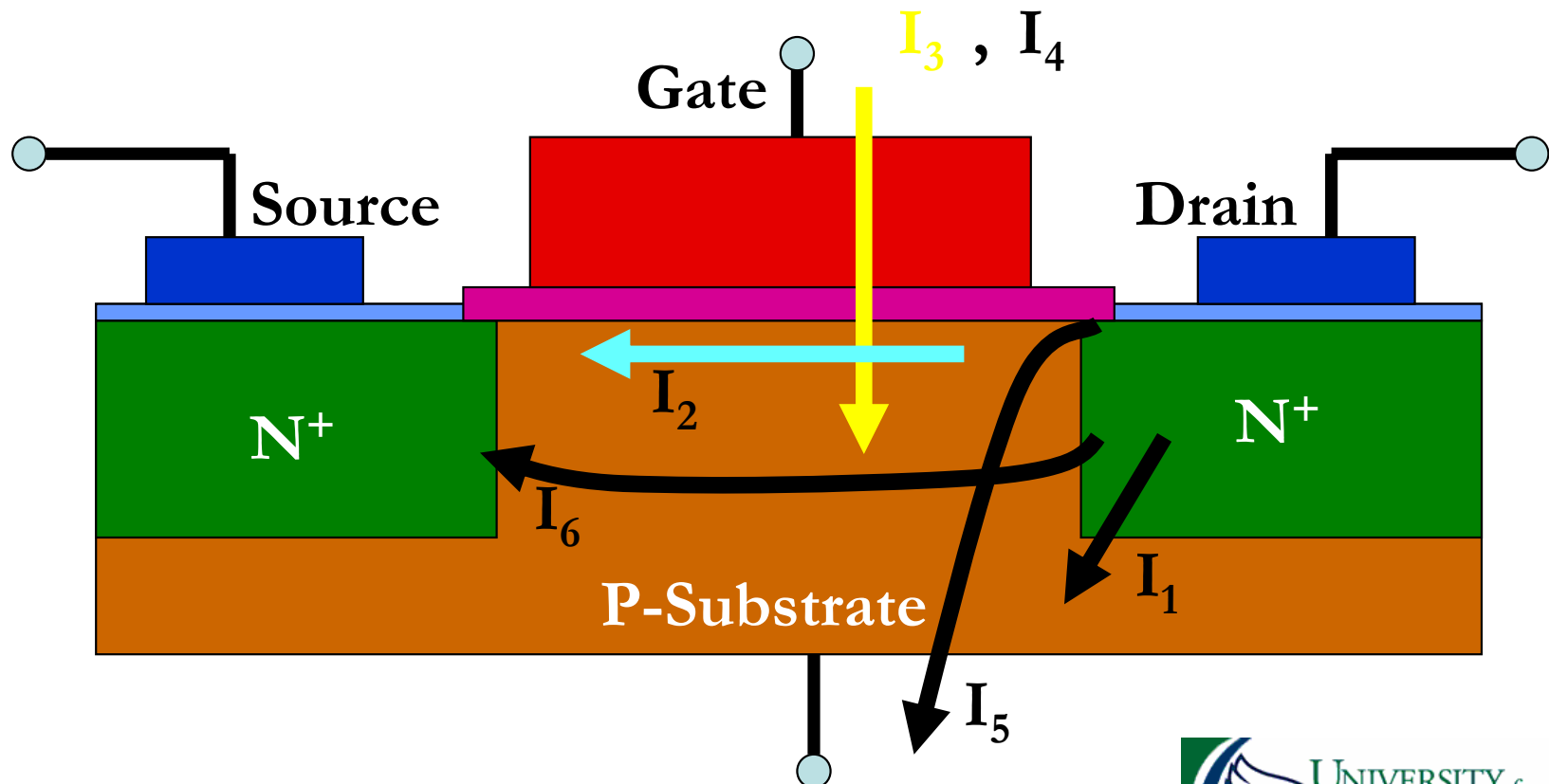
I_2 : subthreshold leakage (OFF)

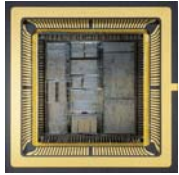
I_3 : oxide tunneling current (both ON & OFF)

I_4 : gate current due to hot carrier injection (both ON & OFF)

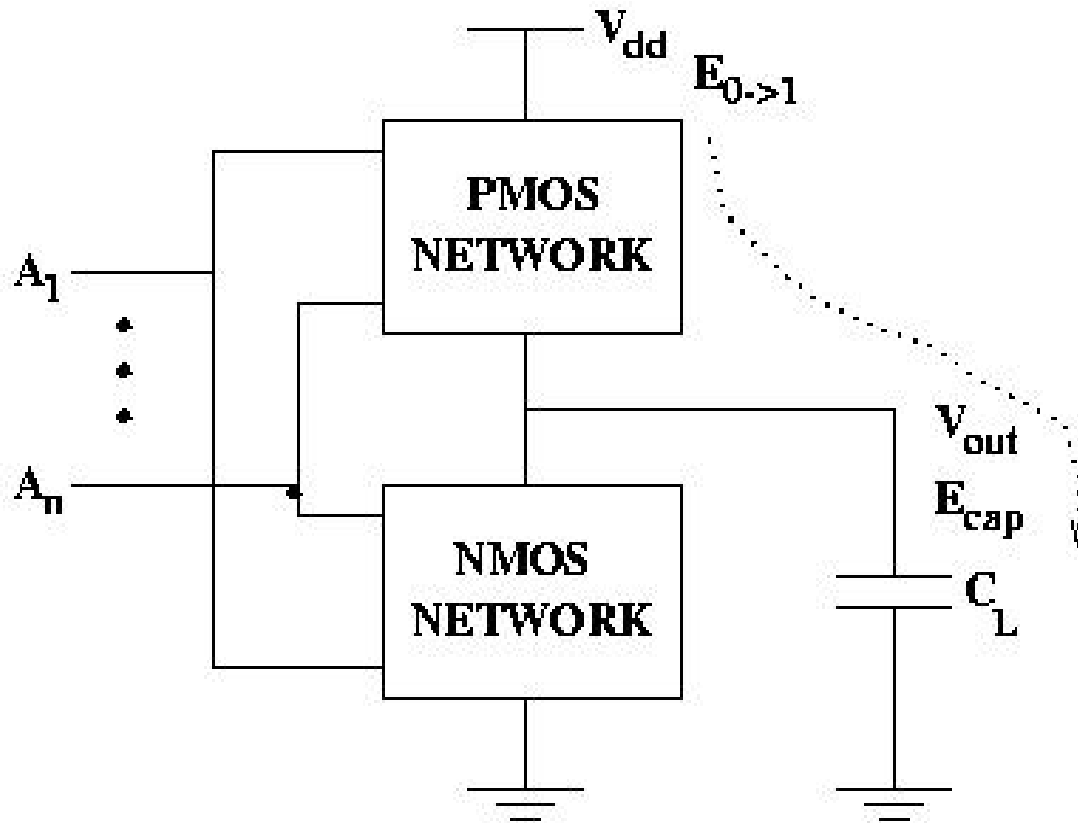
I_5 : gate induced drain leakage (OFF)

I_6 : channel punch through current (OFF)



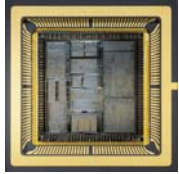


Power Dissipation in CMOS : Dynamic



A general CMOS transistor circuit

- Dynamic power is required to charge and discharge load capacitances when transistors switch.
- One cycle involves a rising and falling output.
- On rising output, charge $Q = CLVDD$ is required.
- On falling output, charge is dumped to GND.



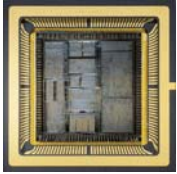
Power Dissipation in CMOS : Dynamic

$$E_{0 \rightarrow 1} = \int_0^T P(t) dt = V_{dd} \int_0^T i_{\text{supply}}(t) dt = V_{dd} \int_0^{V_{dd}} C_L dV_{\text{out}} = C_L V_{dd}^2$$

$$E_{\text{out}} = \int_0^T P_{\text{out}}(t) dt = \int_0^T V_{\text{out}} i_{\text{out}}(t) dt = \int_0^{V_{dd}} C_L V_{\text{out}} dV_{\text{out}} = \frac{1}{2} C_L V_{dd}^2$$

Note:

1. the difference between the two is the loss
2. Energy doesn't depend on frequency



Power Dissipation in CMOS : Dynamic

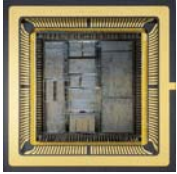
For N_c clock cycles energy loss :

$$E_{N_c} = C_L V_{dd}^2 n(N_c)$$

$n(N_c)$: is the number of 0->1 transitions in N_c clock cycles

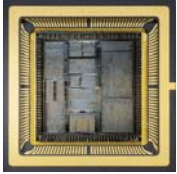
$$P_{avg} = \lim_{N \rightarrow \infty} \left[\frac{E_{N_c}}{N_c} \right] f = \left[\lim_{N \rightarrow \infty} \frac{n(N_c)}{N_c} \right] C_L V_{dd}^2 f$$
$$= \alpha_{0 \rightarrow 1} C_L V_{dd}^2 f$$

Note: Power depends on frequency



Short Circuit Current

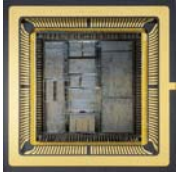
- When transistors switch, both nMOS and pMOS networks may be momentarily ON at once.
- Leads to a blip of “short circuit” current.
- $< 10\%$ of dynamic power if rise/fall times are comparable for input and output.



Static Power : Subthreshold Current

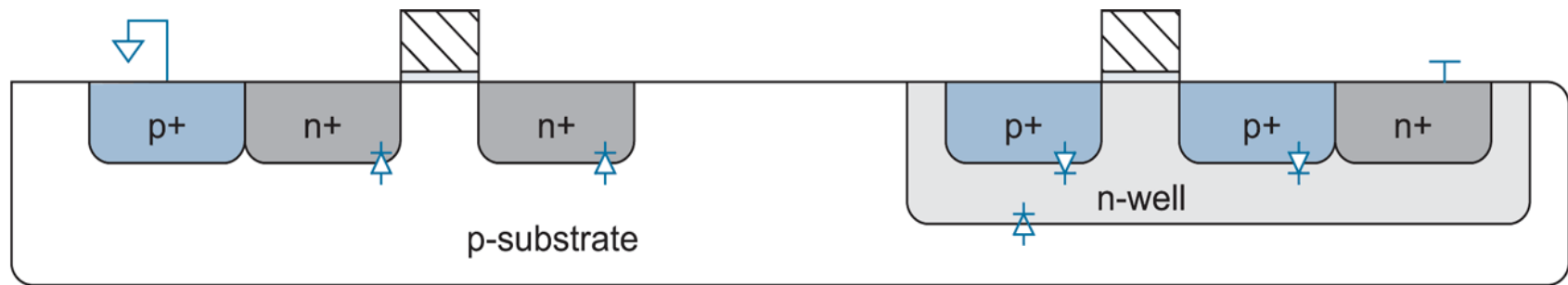
- In OFF state, undesired leakage current flow.
- It contributes to power dissipation of idle circuits.
- Drain-Induced-Barrier-Lowering (DIBL) an prominent effect for short channel transistors also impacts subthreshold conduction by lowering V_T .
- This current increases as the V_T increases.
- It also increases as the temperature increases.
- If v_t is the thermal voltage and I_0 is the current at V_T then the subthreshold current is :

$$I_{ds} = I_0 \left[1 - \exp\left(-\frac{V_{ds}}{v_t}\right) \right] \cdot \exp\left(\frac{V_{gs} - V_{th} - V_{off}'}{nv_t}\right)$$

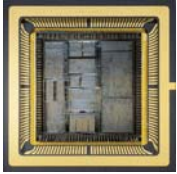


Static Power : Junction Leakage

- The pn junctions between diffusion, substrate and well are all junction diodes.
- These are reversed biased as substrate is connected to GND and well connected to V_{dd} .
- However, reversed biased diode also conduct small amount of current.



Reverse-biased diodes in CMOS circuits

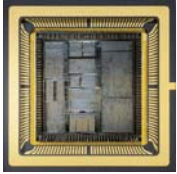


Static Power : Junction Leakage

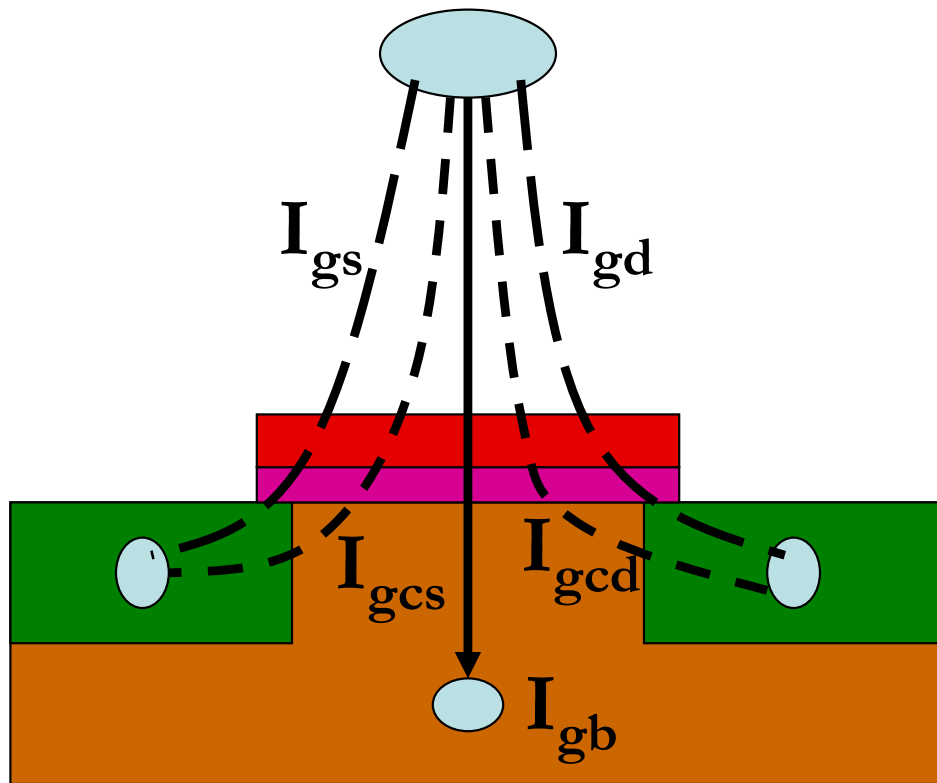
- The reverse-biased junction current is expressed as follows: (D is not for drain, S is not for source)

$$I_D = I_S [\exp (V_D/v_T) - 1]$$

- I_S depends on the doping level, the area, and perimeter of the diffusion region.
- V_D is the diode voltage e.g. V_{sb} or V_{db} .

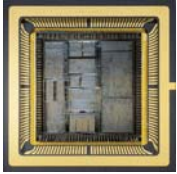


Static Power : Tunneling



BSIM4 Model

- There is a finite probability for carrier being pass through the gate oxide.
- This results in tunneling current thorough the gate oxide.
- The effect is predominate for lower oxide thickness.

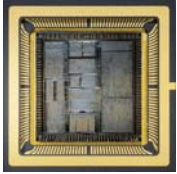


Static Power : Tunneling

- The gate oxide leakage current can be expressed as follows [Kim2003, Chandrakasan2001] (K and α are experimentally derived factors).

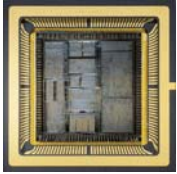
$$I_{\text{gate}} = K W_{\text{gate}} (V_{\text{dd}} / T_{\text{gate}})^2 \exp(-\alpha T_{\text{gate}} / V_{\text{dd}})$$

- **Options for reduction of gate leakage power :**
 - Decreasing of supply voltage V_{dd} (will play its role)
 - Increasing gate SiO_2 thickness T_{gate} (opposed to the technology trend !!)
 - Decreasing gate width W_{gate} (only linearly dependent)



Various Metrics of Power Profile of CMOS Circuits

- Average Power
- Total Energy
- Energy-Delay-Product (EDP)
- Power-Delay-Product (PDP)
- Power-Square-Delay-Product (PSDP)
- Peak Power
- Transient Power
- Cycle Difference Power
- Peak Power Differential
- Cycle-to-Cycle Power Gradient (Fluctuation)
- and many more



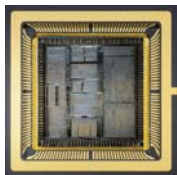
Why Low-Power ?

Motivation: Extending battery life



Chargers / Adapters

Source: Power Integrations Inc



Why Low-Power ?

Battery Lifetime



Cooling and Energy Costs

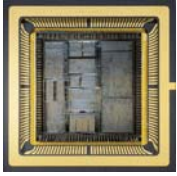


Environmental Concerns



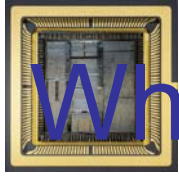
System Reliability





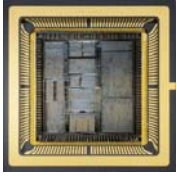
Why peak power reduction ?

- To maintain supply voltage levels
- To increase reliability
- To use smaller heat sinks
- To make packaging cheaper



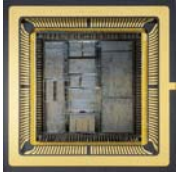
Why Average Power/ Energy reduction ?

- To increase battery life time
- To enhance noise margin
- To reduce energy costs
- To reduce use of natural resources
- To increase system reliability



Why Transience / Fluctuation Minimization ?

- To reduce power supply noise
- To reduce cross-talk and electromagnetic noise
- To increase battery efficiency
- To increase reliability



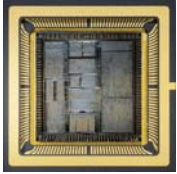
Low-power design: Key Principles

- using the lowest possible supply voltage
- using the smallest geometry, highest frequency devices, but operating them at lowest possible frequency
- using parallelism and pipelining to lower required frequency of operation
- power management by disconnecting the power source when the system is idle



Voltage, Frequency and Power Trade-offs

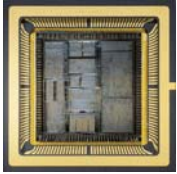
- **Reduce Supply Voltage (V_{dd}):** delay increases; performance degradation
- **Reduce Clock Frequency (f):** only power saving no energy
- **Reduce Switching Activity (N or $E(sw)$):** no switching no power loss !!! Not in fully under designers control. Switching activity depends on the logic function. Temporal/and spatial correlations difficult to handle.
- **Reduce Physical Capacitance:** done by reducing device size reduces the current drive of the transistor making the circuit slow



How much we save ?? Varying V_{dd} / f

Voltage (V_{dd})	Frequency (f)	Power (P_d)	Energy (E_d)
V_{dd}	f_{max}	P_d	E_d
$V_{dd} / 2$	f_{max}^*	$P_d / 4$	$E_d / 4$
$V_{dd} / 2$	$f_{max} / 2$	$P_d / 8$	$E_d / 4$
V_{dd}	$f_{max} / 2$	$P_d / 2$	E_d

* Note : $f_{max} \propto V_{dd}$



Low Power Design : Static Reduction

- Reduce static power
 - Selectively use ratioed circuits
 - Selectively use low V_t devices
 - Leakage reduction:
stacked devices, body bias, low temperature