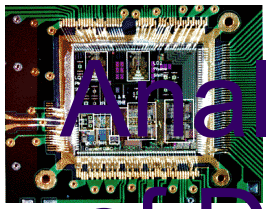

Analytical Modeling and Reduction of Direct Tunneling Current during Behavioral Synthesis of Nanometer CMOS Circuits

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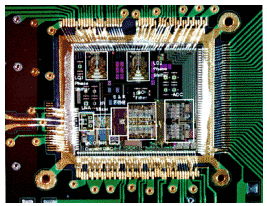
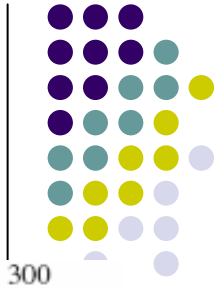
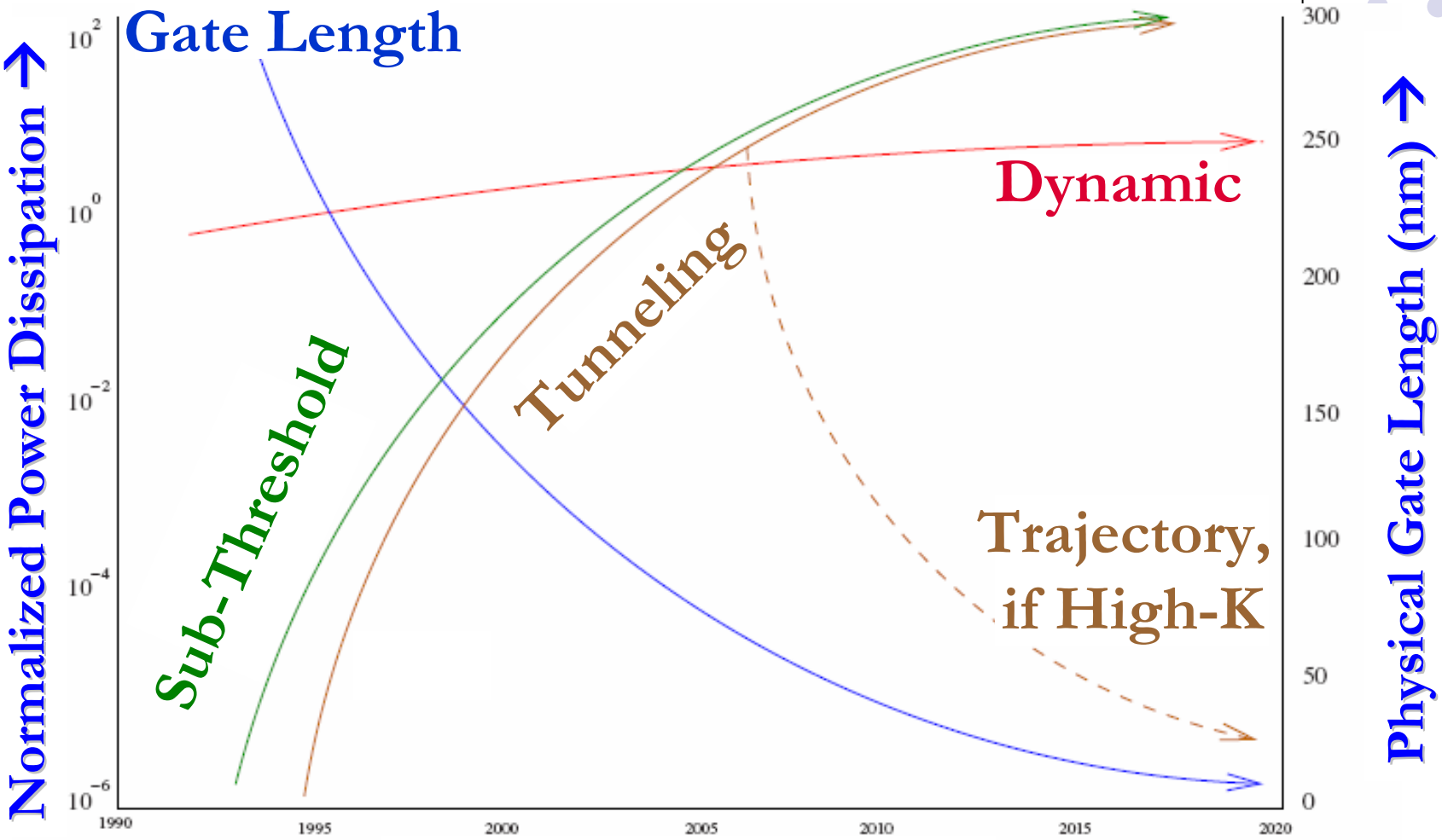
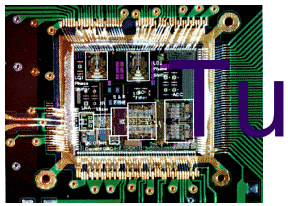


Power Dissipation Trend



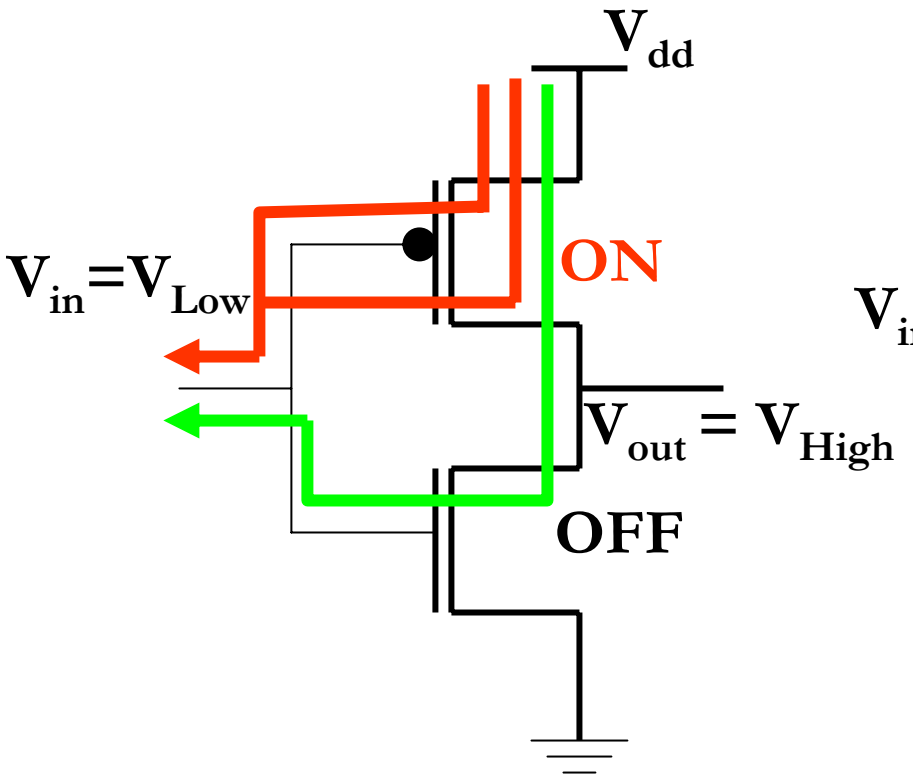


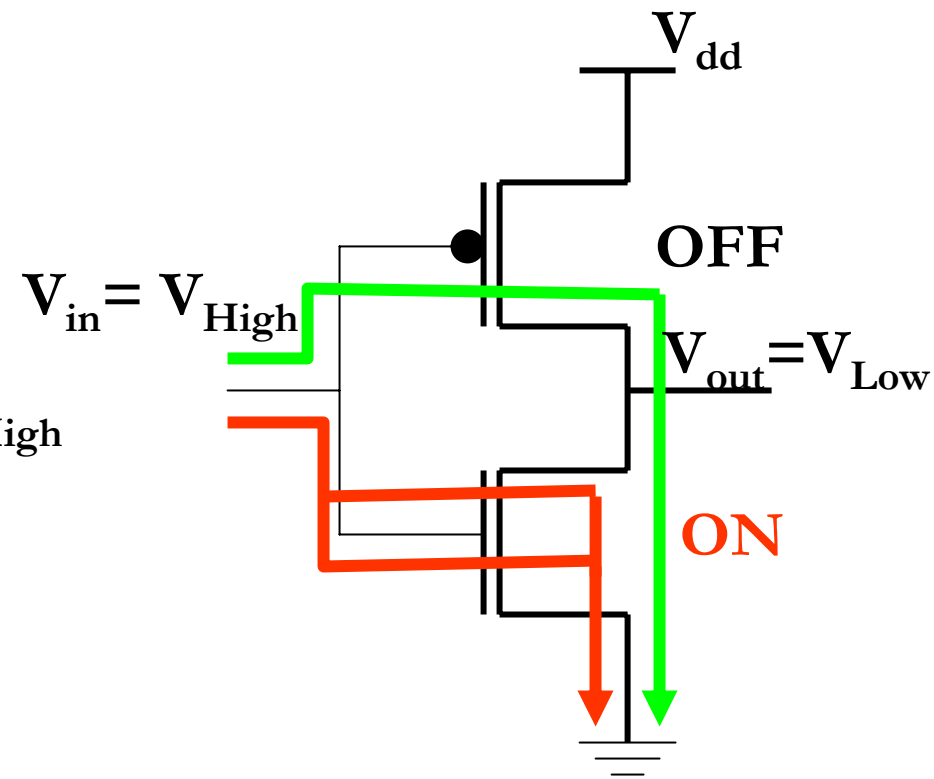
Source: Hansen 2004

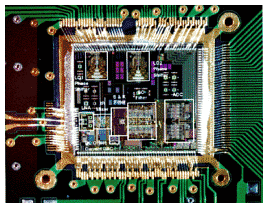


Tunneling Paths in an Inverter

- **Low Input :** Input supply feeds tunneling current.
- **High Input :** Gate supply feeds tunneling current.





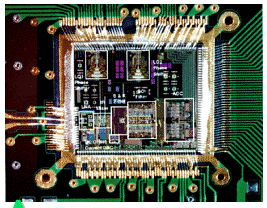


Dual-T_{OX} ?

- Gate oxide tunneling current I_{ox} [Kim2003, Chandrakasan2001] (α is an experimentally derived factor) :

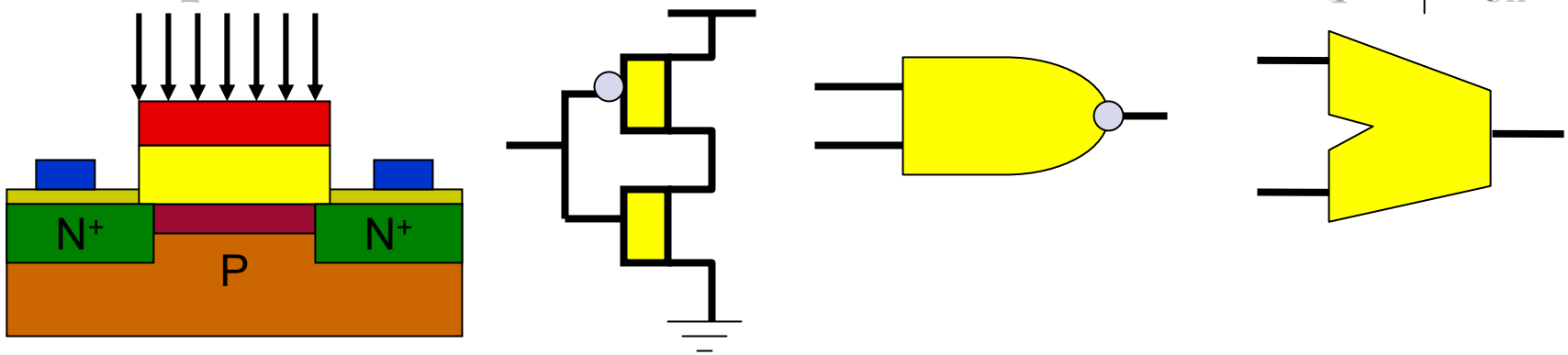
$$I_{ox} \propto (V_{dd} / T_{ox})^2 \exp(-\alpha T_{ox}/V_{dd})$$

- **Options for reduction of tunneling current** :
  - Decreasing of supply voltage V_{dd} (will play its role)
  - Increasing gate SiO_2 thickness T_{ox} (delay increases)
- We believe that combined use of high-T_{ox} resources and low-T_{ox} resources can reduce the gate oxide tunneling current of a datapath with little compromise in circuit performance.

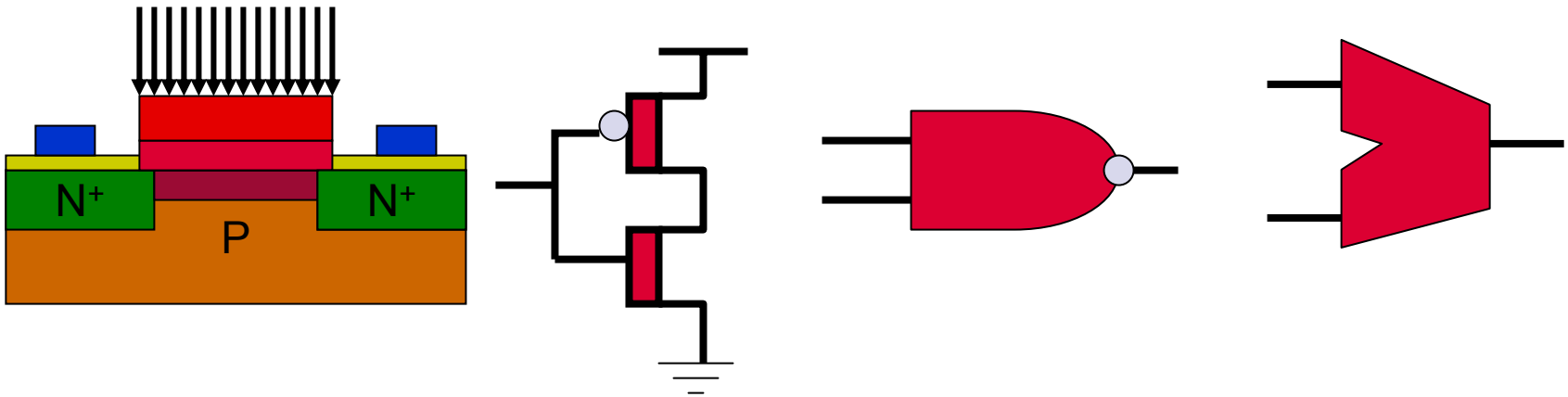


Dual-T_{OX} ?

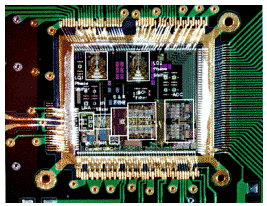
Assumption: All transistors of a resource are of equal T_{ox}.



High T_{ox} Resource : Smaller I_{ox}, but Larger delay



Low T_{ox} Resource : Larger I_{ox}, but Smaller delay



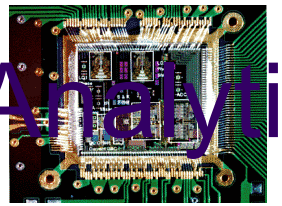
Related Works

Behavioral Level Subthreshold :

- **Khouri, TVLSI 2002 :** Algorithms for subthreshold leakage power analysis and reduction using dual threshold voltage.
- **Gopalakrishnan, ICCD2003 :** MTCMOS approach for reduction of subthreshold current

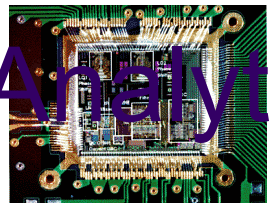
Logic / Transistor Level Tunneling :

- **Lee, TVLSI2004 :** Pin reordering to minimize gate leakage during standby positions of NOR and NAND gates.
- **Sultania, DAC2004 :** Heuristic for dual T_{ox} assignment for tunneling current and delay tradeoff.



Analytical Model for Tunneling Current

- We assumed that resources such as adders, subtractors, multipliers, dividers, are constructed using 2-input NAND.
- There are total n_{total} NAND gates in the network of NAND gates constituting a *n*-bit functional unit.
- n_{cp} number of NAND gates are in the critical path.



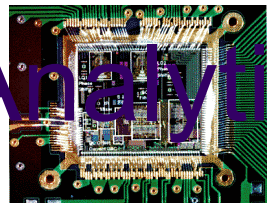
Analytical Model for Tunneling Current

- The tunneling current of a *n*-bit functional unit :

$$I_{DT\text{FU}} = \sum_{j=(1 \rightarrow ntotal)} Pr_j \sum_{\text{MOSi } \varepsilon \text{ NAND}j} Pr_i I_{DTi}$$

Pr_j is the probability that input of the NAND gate is at logic “0”, and Pr_i is the probability that inputs of the transistors that are connected in the parallel i.e. PMOS are at logic “0”.

- The average tunneling current for a NAND is calculated as $I_{DT\text{NAND}} = \sum_{\text{MOS}i \ \varepsilon \text{ NAND}} Pr_i I_{DTi}$



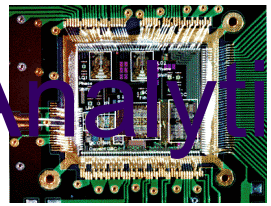
Analytical Model for Tunneling Current

- The direct tunneling current of a MOS :

$$I_{DT} = \frac{WLq^3V_{ox}^2}{16\pi^2\phi_B T_{ox}^2}\exp\left[-\frac{4\sqrt{2m_{eff}}\phi_B^{1.5}T_{ox}}{3\hbar qV_{ox}}\left\{1-\left(1-\frac{V_{ox}}{\phi_B}\right)^{1.5}\right\}\right]$$

- The voltage across the MOSFET gate dielectric V_{ox} is expressed as follows:

$$V_{ox} = V_{gs} - V_{fb} - \Psi_S - V_{poly}$$

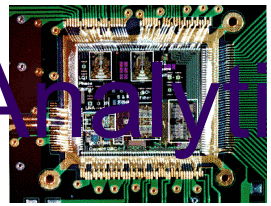


Analytical Model for Tunneling Current

- By solving a quadratic equation we obtain an expression for V_{ox}.

$$V_{OX} = \frac{\sqrt{1 - 2(V_{fb} + \psi_S - V_{gs})\left(\frac{\varepsilon_{OX}^2}{q\varepsilon_{Si} N_{poly} T_{OX}^2}\right)} - 1}{\left(\frac{\varepsilon_{OX}^2}{q\varepsilon_{Si} N_{poly} T_{OX}^2}\right)}$$

- The flat-band voltage V_{fb} can be obtained using the expression $(qN_{channel}T^2_{ox} / 2\varepsilon_{Si})$.
- Ψ_S = 2 * Fermi-Level, for strong inversion.



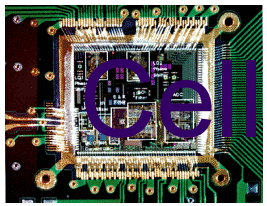
Analytical Model for Propagation Delay

- The critical path delay of a *n* bit functional unit using the NAND gates as building blocks :

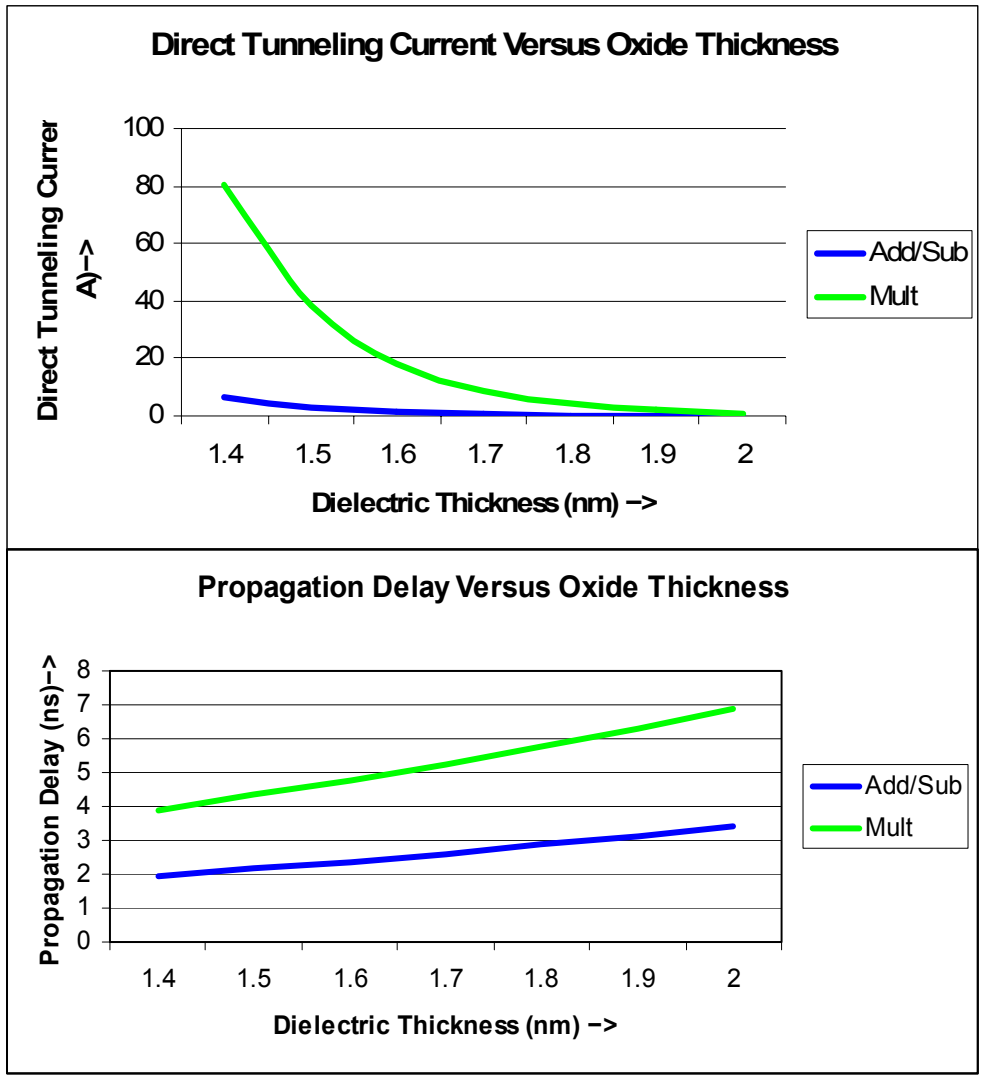
$$Tpd_{FU} = \sum_{I=(1 \rightarrow ncp)} 0.5(n_{fan\text{-}in} Tpd_{NMOS} + Tpd_{PMOS})$$

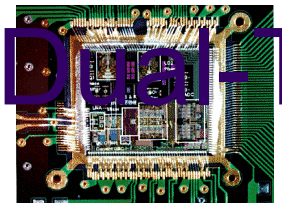
- $n_{fan\text{-}in}$ is the effective fan-in factor.
- Using physical-alpha-power model the delay of a MOS, where I_{DSat0} is the saturation drain current of the MOS for $V_{gs} = V_{dd}$.

$$T_{pd} = \frac{0.5 C_L V_{dd}}{I_{DSat\ 0}} + T_T \left\{ \frac{0.5 - \left(\frac{V_{dd} - V_{Th}}{V_{dd}}\right)}{\alpha + 1} \right\}$$

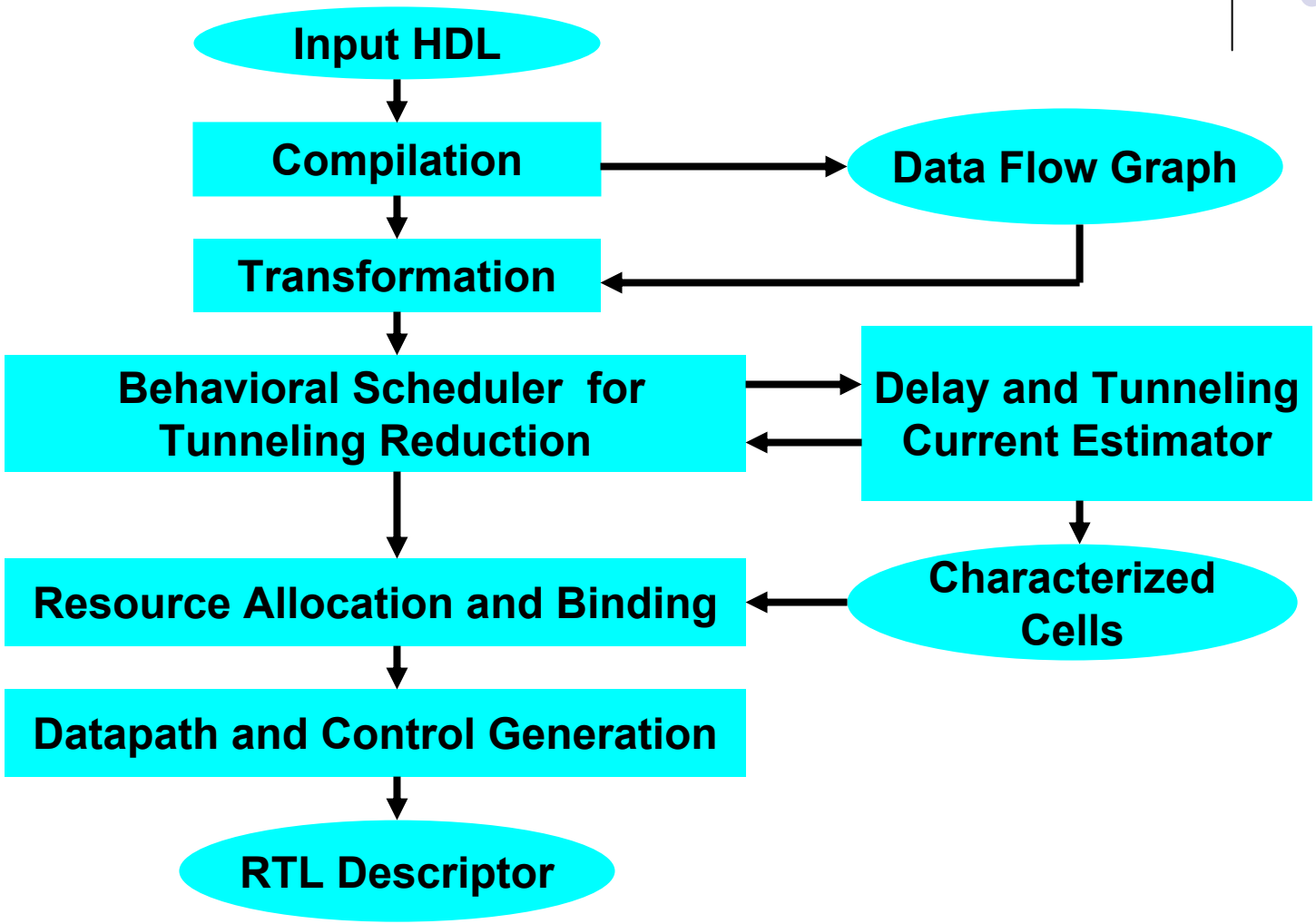


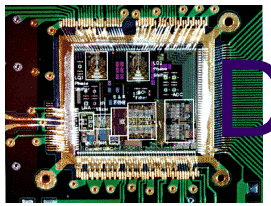
Characterization : 45nm Tech





Dual-T_{ox} Based Behavioral Synthesis

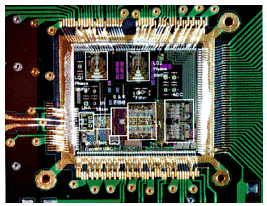




Dual-T_{OX} Assignment : Basis

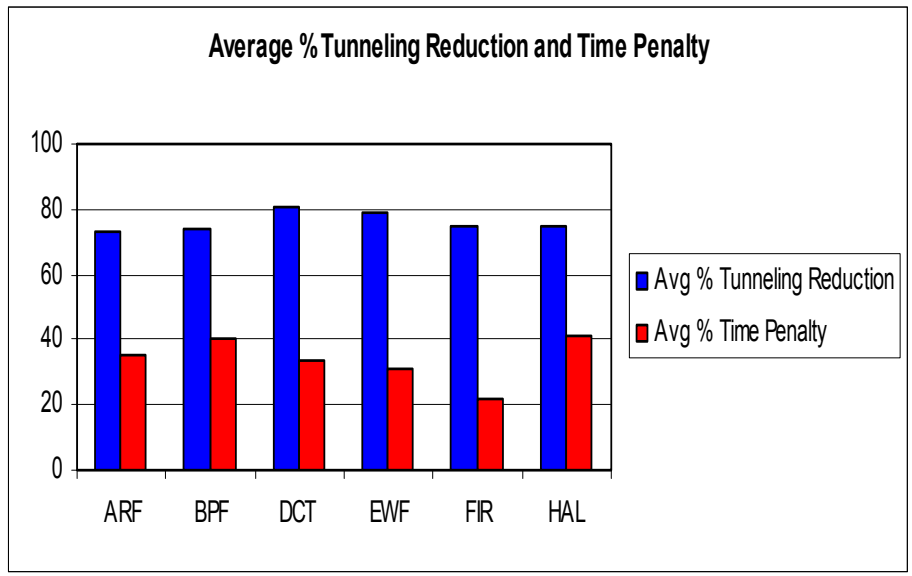
- **Observation**: Tunneling current of Functional Units increases and propagation delay decreases as oxide thickness deceases.

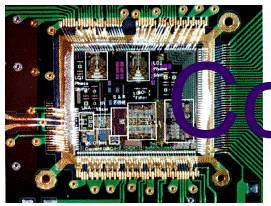
- **Strategy**: Maximize utilization of high-T_{OX} high leaky resources (e. g. multipliers) and low-T_{ox} low leaky resources (e.g. adder-subtractor) to improve chances of tunneling current reduction with minimal performance degradation.



Experimental Results

- The library consists of Multipliers and Adder-Subractor units, characterized for the 45 nm technology.
- We used T_1 = 1.4 nm, and T_2 = 1.7 nm to perform our experiments.
- The value of T_1 is chosen as the default value from the BSIM4.4.0 model card and value of T_2 is intuitively chosen.





Conclusions and Future Works

- Tunneling current is a major component of total power consumption of a low-end CMOS nanometer circuit.
- Dual-T_{OX} approach results significant reductions in tunneling current with minimal performance penalty.
- Development of optimal assignment algorithm is under progress.
- Tradeoff of tunneling, area and performance needs to be explored.
- Dual-T_{OX} based design may need more masks for the lithographic process during fabrication.