Statistical Modeling of Leakage in Nano-CMOS Circuits
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Acknowledgments

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Outline

- Motivation
- Variability and leakage
- Statistical simulation: the standard approach
- Problems of statistical simulation
- Statistical simulation: virtual manufacturing
- Examples
- Conclusions
The power crisis

- Power density in high performance VLSI chips is already at the same level as in a nuclear reactor
- Cooling is a big problem and is becoming expensive
- Increasing amount of energy is consumed by electronic devices (Amsterdam: 20% for telecom; USA: 9% for internet,...*)
- Battery maximum power and capacity increase by 10-15% per year, but chip power requirements increase much faster: 35-40% per year.

*Source: 2000 CO² conference, Amsterdam, NL
Leakage: a major contributor...

Leakage in nanometer scale CMOS: % of total power budget

5-10%  20-25%  35-50%  40-60%  45-70%

180 nm  130 nm  90 nm  65 nm  45 nm

The main advantage of static CMOS logic - negligible static power consumption - is lost!
How variability affects leakage

The problem: **highly nonlinear** dependences of some leakage currents on parameters that are subject to process variability.

Examples:
- subthreshold current as a function of the threshold voltage
- gate tunneling current as a function of gate oxide thickness

Subthreshold “off” current:

\[
I_{\text{subth}} = \mu_n C \frac{W_N}{L_N} V_t^2 \exp \left( -\frac{V_{\text{TH}}}{nV_t} \right)
\]

If \( V_{\text{TH}} \) is a random variable distributed normally with mean value \( V_{\text{TH0}} \) and standard deviation \( \Delta V_{\text{TH}} \), the distribution of the “off” current \( I_{\text{subth}} \) is log-normal with mean value

\[
\overline{I}_{\text{subth}} = I_{\text{subth0}} \exp \left[ \frac{1}{2} \left( \frac{\Delta V_{\text{TH}}}{nV_t} \right)^2 \right]
\]

\((I_{\text{subth0}} = I_{\text{subth}} \text{ for } V_{\text{TH}} = V_{\text{TH0}})\)
For $V_{TH}$ variability of the order of $nkT/q$ ($n\times26$ mV; $n$ between 1 and 2) the mean value of the “off” current increases by about 65%.

If this is local (intra-die) variability, the sum of “off” currents of all devices increases accordingly.

The mean value and the total subthreshold “off” current increases with increasing variability.
Variability is large and unavoidable

Threshold voltage $V_{TH}$ is a function of doping in the channel, and subthreshold leakage depends on $V_{TH}$ exponentially

However, doping in the channel means single atoms in nanometer CMOS: the average number of boron atoms in the channel of a 32 nm device is 3.5.

$\rightarrow$ 3 atoms in one device and 4 atoms in another means 25% difference of the doping dose.

Variability is large and unavoidable

Lithography and variability

Year

Micron

Size

365nm

248nm

193nm

157nm

Wavelength

0.01

0.1

1

0.001


Statistical Modeling of Leakage... MOS-AK Meeting, Eindhoven, April 4, 2008
Variability is large and unavoidable

Litography related variations of subthreshold leakage:

90 nm: 20% variations of channel dimensions -> 2x $I_{\text{off}}$ variations

Compact model based methodology (the standard approach): statistical Monte Carlo simulation in a circuit simulator

- Foundry design kit
- Monte Carlo loop
- Random Number Generator
- Randomly varied device model parameters
- Circuit simulator
- SPICE circuit netlist
- Statistics of device parameters
- Device model parameters
Compact model based methodology: statistical Monte Carlo simulation in a circuit simulator

**Advantages:**
- Well established
- Only standard EDA tools needed
- Limited computational complexity

**Disadvantages**
- It is difficult to include correlations (between model parameters in a single device and between parameters of various devices in the circuit)
- No direct link to physical design and to manufacturing
- Expensive and time consuming experimental characterization of test devices needed
Variability affects leakage in a complex way

Litography: variability of channel dimensions
- directly affects $I_{on}$, $I_{off}$
- indirectly affects $I_{on}$, $I_{off}$ via $V_{TH}$ variations (short channel effect)

Variability of gate oxide thickness
- directly affects $I_{on}$, $I_{off}$ via $C_{ox}$
- indirectly affects $I_{on}$, $I_{off}$ via $V_{TH}$ variations ($V_{TH}$ depends on $C_{ox}$)

Variability of doping concentrations and profiles
- indirectly affects $I_{on}$, $I_{off}$ via:
  - $V_{TH}$ variations
  - variations of actual channel length
  - variations of body effect factor
Variability affects leakage in a complex way

**Intra-device correlations**

**Intra-device correlations**: e.g. threshold voltage is correlated with gate oxide thickness and channel length

These correlations are not accounted for in compact model based Monte Carlo simulation. The mathematical technique is known (K. S. Eshbaugh, IEEE Trans. on CAD, vol. 11, no. 10, 1992, pp. 1198-1206) but computationally infeasible in most cases.
Variability affects leakage in a complex way

The loading effect

Unlike other leakage components, gate leakage changes the way CMOS static gates work: DC current flows from gate output nodes to input nodes of other gates (the "loading effect").

Consequences:
- logic levels and noise margins may be affected,
- gate fanout is limited by the DC load,
- total leakage in a digital circuit can no longer be calculated as a sum of leakages of all gates treated independently.
Variability affects leakage in a complex way

The loading effect may either increase or reduce the total leakage of the gate.

R. Mendoza, R. Ferre, L. Balado and J. Figueras, in Proc. IEEE Int. Conf. on Design and Test of Integrated Systems in Nanoscale Technology, Tunis, Sept. 2006:
1% error in estimated total leakage of a logic block ($t_{ox}=1.85$ nm)

5% to 8% error for a single gate ($t_{ox}=1.0$ nm) but lower for bigger logic blocks

from 1.9% up to 17.2% error for various ISCAS benchmark blocks
Variability affects leakage in a complex way

Two MOS transistors connected in series

Pre-layout simulation:

MN1 1 2 3 0 Nchan W=325E-9 L=65E-9
+PD=1040E-9 AD=6.34E-14

MN2 3 4 5 0 Nchan W=325E-9 L=65E-9
+PD=1040E-9 AD=6.34E-14

OK for layout 1

WRONG for layout 2: actual area and perimeter of D1 and S2 much lower than the sum for individual drain/source junctions

The same schematic, the same W and L, but different S1 and D2 areas and perimeters -> different leakage
Variability affects leakage in a complex way

Two MOS transistors connected in series:
1,2: separate devices; 3,4: shared source/drain

Post-layout simulation (after extraction): to avoid ambiguities and either missing or duplicated S/D areas, transistors and S/D diodes should be extracted separately -> PSP and JUNCAP2 models
Process variability: modeling methods

“Virtual manufacturing” methodology: statistical (Monte Carlo) process, device and circuit simulation

- Statistical description of litography process
  - Layout (CIF, GDSII)
  - Technology file

- Statistical circuit extractor
  - Set of netlists extracted from statistically disturbed layout

- Statistical process/device simulator
  - Statistical process data
  - Process schedule and parameters

- Set of SPICE circuit netlists with individual model for each device

- Circuit simulator

First Monte Carlo loop (extraction repeated for all given chip locations on wafer)
Second Monte Carlo loop (netlist driven: process simulation and device modeling repeated for every device on every netlist)
Third Monte Carlo loop (simulation repeated for every netlist)
Virtual manufacturing methodology: statistical (Monte Carlo) process, device and circuit simulation

- **Advantages:**
  - Based on statistical process and device simulations, with process variabilities accounted for
  - All correlations taken into account
  - Actual device layout taken into account
  - Allows “what if” experiments with processing parameters, may show directions to process and device design optimization

- **Disadvantages**
  - Special software needed
  - Process must be known or at least reasonable assumptions must be made; fitting to nominal characteristics of real devices needed
  - Significant computational resources needed for large statistical samples
Process variability: variation types

Process variations

Local value of a parameter $p$: $p = p_{\text{nom}} + \delta p_g + \delta p_d(x, y) + \delta p_r$

- Actual value at $(x,y) = \text{nominal value}$
- + Global variation $\delta p_g$
- + Local deterministic variation $\delta p_d$
- + Local random variation $\delta p_r$

(spatial dependence of local deterministic variation is not necessarily radial)
Virtual manufacturing

Virtual technology fitted to an industrial 65 nm technology: 65 nm NMOS device

- target (real) device
- virtually manufactured device

- $-I(V_{ds})$
Example: a small digital block (c17 ISCAS benchmark)
Variability of "off" drain current vs. doping variability

A single nMOSFET, L=65 nm

"Off" drain current vs. variability of channel implant dose
Virtual manufacturing

Total leakage power vs. **local** variability of the channel doping

C17 benchmark version 1
The standard approach

Total leakage power vs. variability of the gate oxide thickness

C17 benchmark version 2
Virtual manufacturing

Total leakage power vs. variability of the gate oxide thickness

C17 benchmark version 2
Conclusions

- Large process variability leads to increased total static power consumption
- Standard approach (compact model based Monte Carlo simulation inside a circuit simulator) may lead to inaccurate or even misleading results due to:
  - Complex intra-device correlations
  - No direct link to layout
  - No direct link to manufacturing process