Variability is More than Statistics: What’s Needed in Compact Models

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IC Factions

Analog
- Live and die by yield and performance
- Schematic cowboys
- DFM “Did you Factor in Mismatch?”
- Know digital is easy

Digital
- Live and die by speed and density
- Code jockeys
- DFM “Did you Fudge the Masks?”
- Know analog doesn’t pay the bills
Sources of Variability

• Global statistical variation
• Local statistical variation (mismatch)
• Process gradients

• Mask and other optical variations
  • systematic and local components

• Proximity effects
  • STI stress
  • well proximity
  • contact stress relief

Modeling Device Variations

• Limits
• Distributions
• Correlation
Statistical Modeling

- Easiest if done via uncorrelated “process parameters”
  - $V_{FB}$, $T_{OX}$, $N_{SUB}$, $\mu_0$, …
  - not via $V_{TH}$, $\gamma$, $k_p$, …
- This always explains anomalous geometry and bias dependence
- Automatically gives correlations between model “parameters” and between device performances
- Two sources of variation in $P_j$
  - global variation
  - local variation (mismatch)
- Global variation commonly modeled via geometry independent mean $P_{j0}$ and standard deviation $\sigma_{Pj}$
- Local variation modeled as correlation coefficient $\rho_{Pj1,2}$

V_{TH} Variation
Slide 7

V_{TH} Variation, Wide/Long

Slide 8

V_{TH} Variation, Narrow/Short
Better Statistical Model Basis

- Physically, mismatch is atomistic differences between devices
  - statistically independent
- Model variations as combination of global and local variation

\[ P_j = P_{j0} + \delta P_{jG} + \delta P_{jL}(g) \]

- Total statistical variance is then

\[ \sigma^2_{P_j} = \sigma^2_{PjG} + \sigma^2_{PjL}(g) \]
  - has correct geometry dependence

Local Variation Dominates

- Total variation is geometry dependent
  - not captured by correlation approach
- Local > global as geometry shrinks
Benefits

• Can do mismatch-only analysis (Monte Carlo like)
  ▪ have to include global variations for correlated approach
• Can do mismatch for parameters with zero global variation
• Physically correct, easily handles different geometries and more than two devices
  ▪ mismatch is not just a phenomena between identical pairs
    > e.g. important for N:1 ratioed devices and R2-R ladders
• Independent sampling is easy
• Allows analytic mismatch evaluation
  ▪ correlated approach does not
• Captures the geometry dependence of total variation
• Does not require ~$N^2$ correlation coefficients

Issues

• When local variation dominates, devices vary independently, the whole concept of case simulation become inapplicable
  ▪ still works, but gives over-design by a factor of $\sqrt{N}$
  ▪ really better than this in practice as not all devices contribute to extreme circuit performance
• In implementation
  \[ p = p_0 + n_{sig} \cdot sig + n_{smm} \cdot smm(L,W) \]
  so for devices not included in mismatch analysis the effective global sigma needs to be mapped to \[ \sqrt{sig^2 + smm(L,W)^2} \]
  ▪ need a flag for this
• Needs physical analysis for each type of device
  ▪ not good for “generic” capability from tool vendors
  ▪ good for job security for IDMs 😊
Proximity Effects: Empirical Paradigm

• Make some measurements
  ▪ note that $V_{TH}$ varies with effect
  ▪ panic
  ▪ ask UCB to add to BSIM

• Make some more measurements
  ▪ note that $g_m$ ($\mu_0$) varies with effect
  ▪ panic
  ▪ ask UCB to add to BSIM

• Make even more measurements
  ▪ note that $\gamma$ ($k_2$) varies with effect
  ▪ panic
  ▪ ask UCB to add to BSIM

Observations and Comments

• You can always do better by sitting back and understanding what is going on physically
  ▪ interesting and fun to do
  ▪ captures first order correlations
  ▪ enables statistical modeling

• These sources of variation in device electrical performance are dependent on layout
  ▪ models cannot just be defined by modeling people
  ▪ have to engage with layout extraction (LPE) folks

• Same paradigm often followed for mismatch
Two Ways to Implement PEs in Models

• As a relative difference w.r.t. a reference layout
  ▪ this is done in BSIM for STI modeling
  ▪ cannot remove STI from intrinsic device
  ▪ very convenient for parameter extraction
  ▪ means that “intrinsic” model parameters implicitly include effects of stress for the reference layout
  > potential issue for statistical modeling

• As an absolute difference w.r.t. an isolated device
  ▪ this is done in BSIM for WPE modeling
  ▪ can remove WPE from intrinsic device
  ▪ need to take care of in test structure layouts

WPE

• Extensive set of data will be presented at CICC 2006
  ▪ “Implications of Proximity Effects for Analog Design” by P. G. Drennan, M. L. Kniffin, and D. R. Locascio

• Some results presented here with permission
Well Implant Scattering

- Increased concentration

Well Profile

- Doping higher near well edge
- Can give big differences in device performance
- Significant effect on matched devices
  - especially small devices
  - especially ratioed/multi-fingered devices
Saturated $I_d$ Variation with Well Spacing

• See CICC 2006 Proceedings for plot

Source-Drain Asymmetry

• See CICC 2006 Proceedings for plot
PE Modeling Challenges

- Mismatch
- Asymmetry (noted by P. Drennan)
  - makes devices LDMOS-like (graded/out-diffused channel)
  - peaky $g_m$ characteristic
  - peaky $C_{gd}$ characteristic
    > Miller effect for near threshold operation
  - these are not encompassed by existing models
  - ...
- Asymmetry is **not** included in existing LPE methodology
  - source and drain pin assignment?
- “Averaging” may not be sufficiently accurate for multi-finger devices (RF, ratioed devices)
- Effects on analog circuits will be covered at CICC 2006

Additional Observations

- Test structures for characterization and measurement are in a different layout environment than circuits
  - big pads, minimal interconnect, isolated devices
  - is tiling sufficient to make them electrically close to devices in a dense, highly interconnected layout?
- LPE experts are engaged at the Compact Model Council
  - this is very positive
- STI and WPE layout extraction established
  - needs to be further developed
Conclusions

- Historically “variability” has meant statistics of devices
  - corner cases for digital
  - mismatch/global distributions for analog
- Proximity effects are now also critical
  - “variability” is then in the layout
- Needs to be factored into
  - schematic based design
  - cell based design
- Could be rule or simulation-based
- Either way, need statistics and layout dependence in models
  - and LPE consistent with models