25.7 Adaptive Body Bias for Reducing Impacts of Die-to-Die and Within-Die Parameter Variations on Microprocessor Frequency and Leakage

James Tschanz, James Kao[1], Siva Narendra, Raj Nair, Dimitri Antoniadis[1], Anantha Chandrakasan[1], Vivek De

Microprocessor Research Labs, Intel Corporation, Hillsboro, OR, [1]Massachusetts Institute of Technology, Cambridge, MA

J. Tschanz

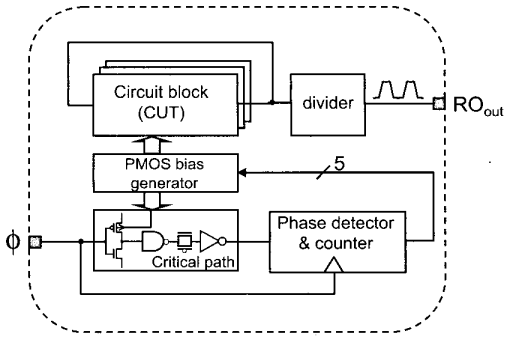
Measurements on a 150nm CMOS test chip show that on-chip bidirectional adaptive body biasing compensates effectively for die-to-die parameter variation to meet both frequency and leakage requirements. An enhancement of this technique to correct for within-die variations triples the accepted die count in the highest frequency bin.

See Digest page 422

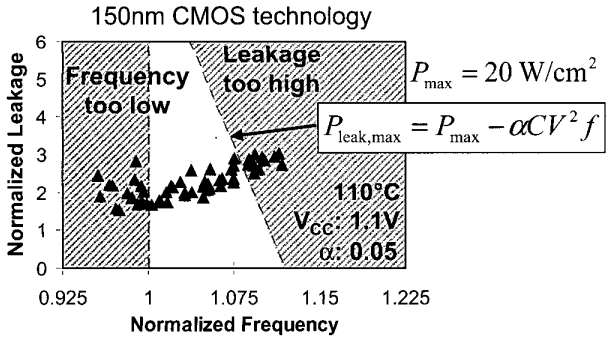
Outline

- **Process parameter variations**
  - **Die-to-die (D2D)**
  - **Within-die (WID)**
- **Adaptive body bias (ABB) test chip**
- **Effectiveness of ABB**
- **Impact of within-die variations**
- **Compensation of WID variations (WID-ABB)**
- **Conclusion**

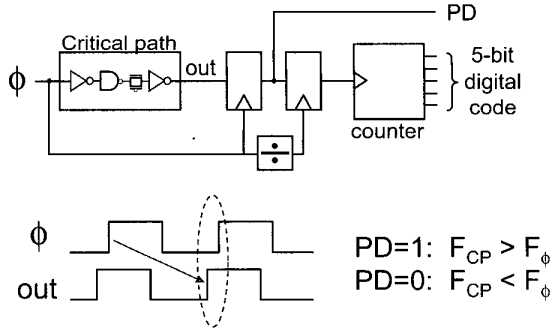
Block Diagram



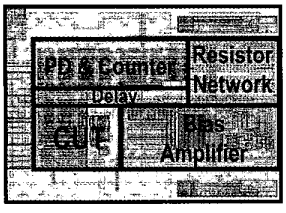
Parameter Variation



Phase Detector and Counter

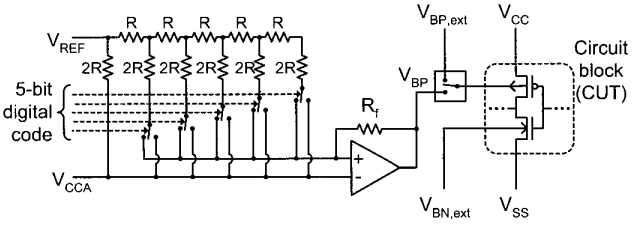


Adaptive Body Bias Test Chip



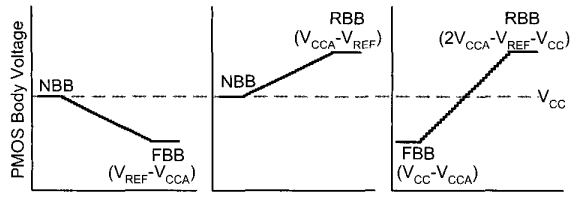
Technology	150nm CMOS
Dimensions (one subsite)	1.6X0.2 mm^2
Dimensions (all subsites)	4.5X6.7 mm^2
Subsites per die	21
V_{CC}	1.1V
Bias range	-0.5V to 0.5V
Body bias resolution	32mV

Body Bias Generator



$$V_{BP} = \frac{R_f}{R} \bullet \frac{(0,1,2,...,31)}{32} \bullet (V_{CCA} - V_{REF}) + V_{CCA}$$

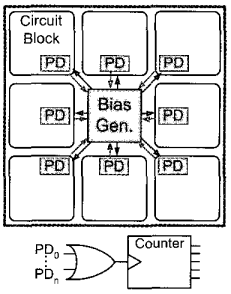
Body Bias Modes



NBB → FBB	NBB → RBB	FBB → RBB
$V_{CCA} = V_{CC}$	$V_{CCA} = V_{CC}$	$V_{CCA} < V_{CC}$
$V_{REF} > V_{CCA}$	$V_{REF} < V_{CCA}$	$V_{REF} < V_{CCA}$
Count: PD=0	Count: PD=1	Count: PD=1

Adaptive Body Bias (ABB)

Accounts for WID variation



Area overhead: ~2-3%

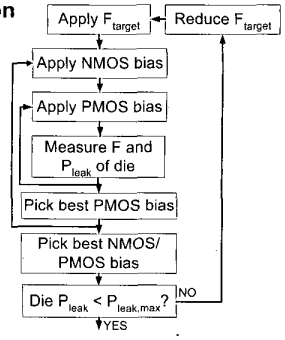
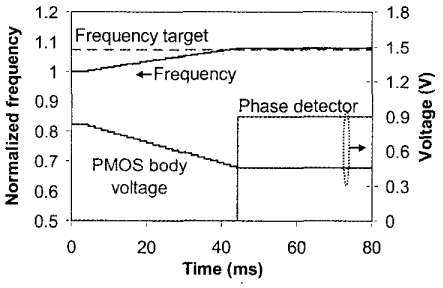
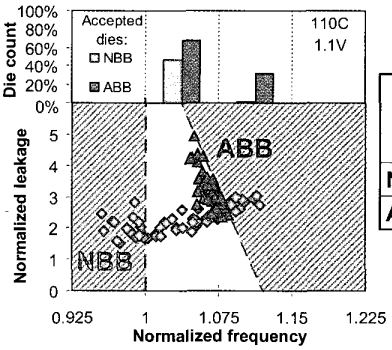


ABB Test Chip Operation



Body bias adapts to meet frequency target with minimum leakage

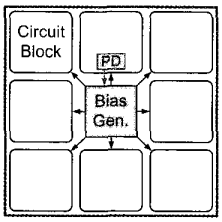
Effectiveness of ABB



	Frequency Variation σ/μ
NBB	4.1%
ABB	0.69%

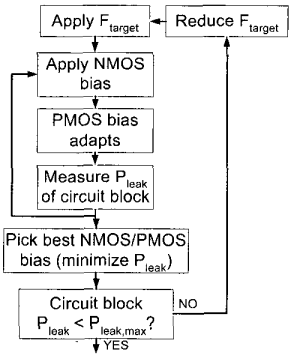
Simple Adaptive Body Bias (S-ABB)

Neglects WID variation

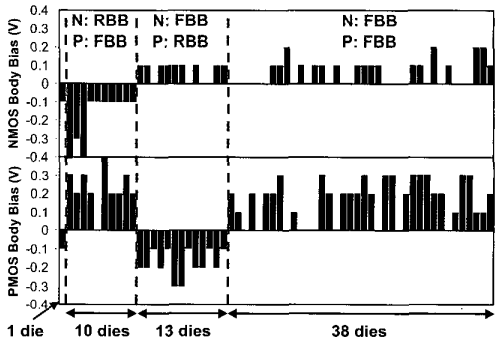


PD = Phase detector and critical path

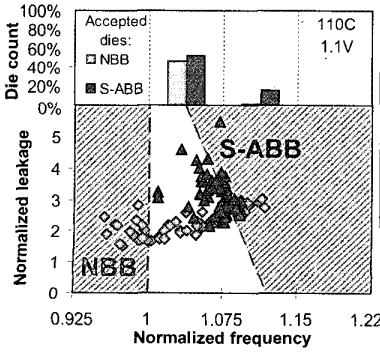
Area overhead: ~2% [paper 16.4]



Adaptive Bias Distribution

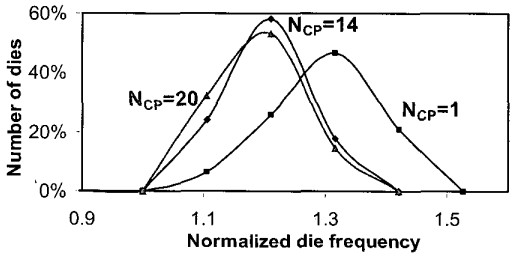


Effectiveness of S-ABB



	Frequency Variation σ/μ
NBB	4.1%
S-ABB	1.0%

Frequency vs. Critical Path Count (N_{CP})

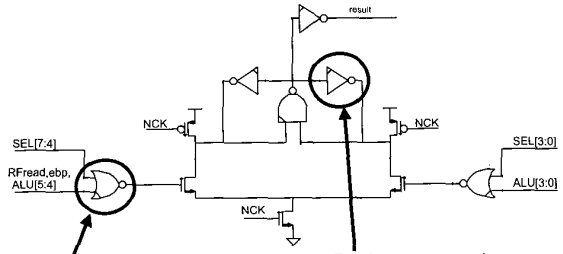


- **Frequency μ and σ reduce as N_{CP} increases**
- **Frequency distribution unchanged for N_{CP} > 14**

Continued on Page 538

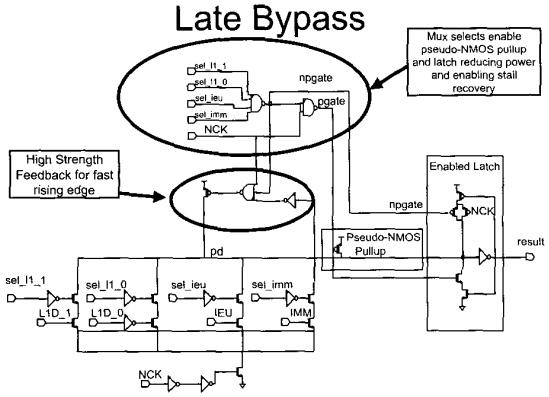
Continued from page 343

Middle Bypass

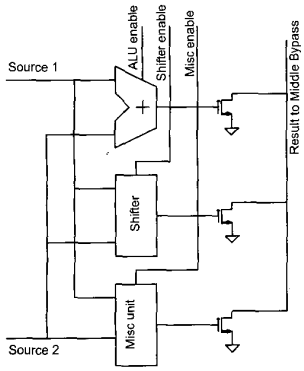


- Active low inputs and static receivers reduce impact of noise
- Full keepers used on dynamic nodes to allow phase 1 (CK) inputs to be "caught" removing the need for a latch

Late Bypass



Results Datapath



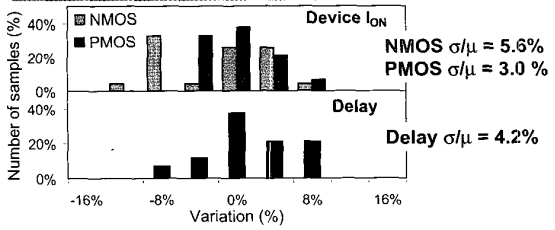
- Functional units (FU) are pre-enabled saving power and removing the need for a result mux
- *FU outputs flow* transparently through the middle and late bypasses stopping only for the CK clock boundry at the input to the FU
- Antimillers are used to enable long precharge pulldown results busses

Summary

- A 7.48mm² integer datapath is constructed with 128 general registers,6 fully bypassed ALUs and 4 cache address ports
  - Double-pumped decoders/wordlines in register file delivered high performance/bandwidth in a small foot print
    - 96 GB/s read bandwidth, 64 GB/s write bandwidth in 2mm²
  - Antimiller circuits reduce area by allowing long minimally spaced precharge-pulldown nets
  - Register file write bitlines are reused to accomplish first stage of bypass
  - Pre-enabled functional units reduce power consumption 15% while removing logic stages from bypass network

Continued from page 345

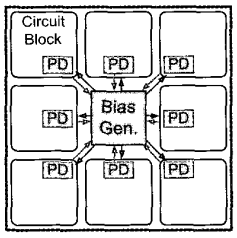
WID Delay Variation vs. Logic Depth



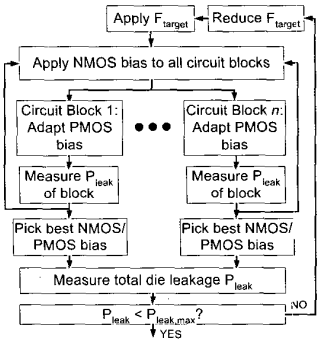
	[2]	This work
Path Depth	49	16
Device σ/μ	2.4%	4.27%
Frequency σ/μ	0.55%	4.17%

Within-Die Adaptive Body Bias (WID-ABB)

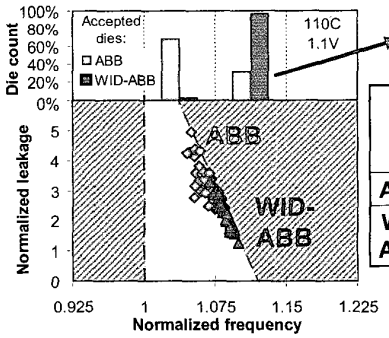
Compensates for WID variation



Area overhead: Similar to ABB

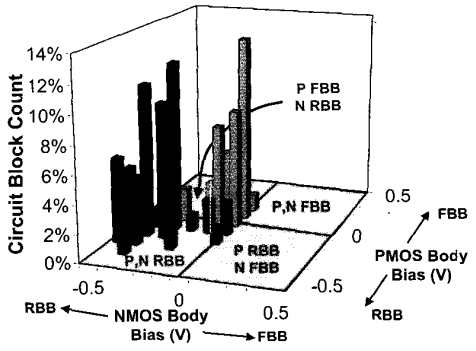


Effectiveness of WID-ABB



	Frequency Variation σ/μ
ABB	0.69%
WID ABB	0.21%

Within-Die Bias Distributions



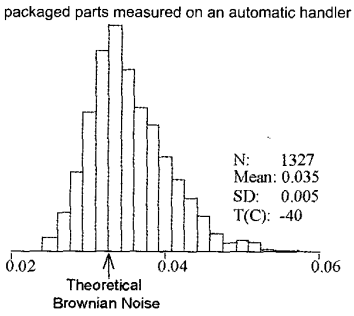
Continued from page 347

Bias Resolution

Bias resolution	ABB		WID-ABB	
	dies, F > 1	σ/μ	dies, F > 1.075	σ/μ
500mV	79 %	2.87 %	2 %	1.89 %
300mV	100 %	1.47 %	66 %	0.50 %
100mV	100 %	0.69 %	97 %	0.21 %

- **300mV bias resolution sufficient for ABB**
- **WID-ABB requires 100mV bias resolution**

Distribution of White Noise (°/√s)



Conclusion

- **D2D and WID variations impact microprocessor frequency and leakage**
- **ABB improves die acceptance rate from 50% to 100%**
- **ABB is most effective when WID variations are considered**
- **Compensating for WID variations by WID-ABB increases number of high frequency dies from 32% to 97%**

Conclusion

- The measured angular rate white noise is 0.05 deg/rt.s with an ultimate resolution of 50 deg/h.
- The gyros operate accurately -40C to +85C during applied shocks over 1000 gees and survive shocks of 30,000 gees unimpaired.
- Complete angular rate to voltage transducer in 7mm x 7mm x 3mm package weighing 0.35 grams.