

Contents

Preface

Part I Overview 1

- 1.1 Low Power Microelectronics: Retrospect and Prospect 3
J. Meindl (*Proceedings of the IEEE*, April 1995).
- 1.2 Micropower IC 20
E. Vittoz (*Proceedings of the IEEE European Solid State Circuits Conference*, Grenoble, September 1980).
- 1.3 Low-Power CMOS Digital Design 36
A. P. Chandrakasan, S. Sheng, and R. W. Brodersen (*IEEE Journal of Solid State Circuits*, April 1992).
- 1.4 CMOS Scaling for High Performance and Low-Power—The Next Ten Years 47
B. Davari, R. Dennard, and G. Shahidi (*Proceedings of the IEEE*, April 1995).

Part II Low Voltage Technologies and Circuits 59

- 2.1 Low-Voltage Technologies and Circuits 61
T. Kuroda and T. Sakurai (INVITED PAPER).

SECTION 2.1 Threshold Voltage Scaling and Control 66

- 2.2 Ion-Implanted Complementary MOS Transistors in Low-Voltage Circuits 66
R. M. Swanson and J. D. Meindl (*IEEE Journal of Solid-State Circuits*, April 1972).
- 2.3 Trading Speed for Low Power by Choice of Supply and Threshold Voltages 74
D. Liu and C. Svensson (*IEEE Journal of Solid-State Circuits*, January 1993).
- 2.4 Limitation of CMOS Supply-Voltage Scaling by MOSFET Threshold-Voltage Variation 82
S. Sun and P. Tsui (*IEEE Custom Integrated Circuits Conference*, May 1994).

SECTION 2.2 Multiple Threshold CMOS (MTCMOS) 86

- 2.5 1-V Power Supply High-Speed Digital Circuit Technology with Multithreshold Voltage CMOS 86
S. Mutoh, T. Douskei, Y. Matsuya, T. Aoki, S. Shigematsu, and J. Yamada (*IEEE Journal of Solid-State Circuits*, August 1995).
- 2.6 A 1-V Multi-Threshold Voltage CMOS DSP with an Efficient Power Management Technique for Mobile Phone Application 93
S. Mutoh, S. Shigematsu, Y. Matsuya, H. Fukuda, and J. Yamada (*IEEE International Solid-State Circuits Conference*, February 1996).

SECTION 2.3 Substrate Bias Controlled Variable Threshold CMOS 95

- 2.7 50% Active-Power Saving Without Speed Degradation Using Standby Power Reduction (SPR) Circuit 95
K. Seta, H. Hara, T. Kuroda, M. Kakumu, and T. Sakurai (*IEEE International Solid-State Circuits Conference*, February 1995).
- 2.8 A 0.9V, 150MHz 10mW 4mm², 2-D Discrete Cosine Transform Core Processor with Variable Threshold-Voltage (VT) Scheme 97
T. Kuroda, T. Fujita, S. Mita, T. Nagamatsu, S. Yoshioka, K. Suzuki, F. Sano, M. Norishima, M. Murota, M. Kako, M. Kinugawa, M. Kakumu, and T. Sakurai (*IEEE Journal of Solid-State Circuits*, November 1996).

SECTION 2.4 Silicon-on-Insulator Based Technologies 105

- 2.9 SOI CMOS for Low Power Systems 105
D. Antoniadis (INVITED PAPER).
- 2.10 Back Gated CMOS on SOIAS for Dynamic Threshold Voltage Control 111
I. Yang, C. Vieri, A. P. Chandrakasan, and D. Antoniadis (*IEEE International Electron Devices Meeting (IEDM)*, December 1995).
- 2.11 Design of Low Power CMOS/SOI Devices and Circuits for Memory and Signal Processing Applications 115
L. Thon and G. Shahidi (INVITED PAPER).

- 2.12 A Dynamic Threshold Voltage MOSFET (DTMOS) for Very Low Voltage Operation **121**
F. Assaderaghi, S. Parke, D. Sinitsky, J. Bokor, P. K. Ko, and C. Hu (*IEEE Electron Device Letters*, December 1994).
- 2.13 A 0.5V SIMOX-MTCMOS Circuit with 200ps Logic Gate **124**
T. Douseki, S. Shigematsu, Y. Tanabe, M. Harada, H. Inokawa, and T. Tsuchiya (*IEEE International Solid-State Circuits Conference*, February 1996).

Part III Efficient DC-DC Conversion and Adaptive Power Supply Systems 127

SECTION 3.1 Efficient Low Voltage DC-DC Converter Design 129

- 3.1 A Low-Voltage CMOS DC-DC Converter for a Portable Battery-Operated System **129**
A. Stratakos, S. Sanders, and R. Brodersen (*IEEE Power Electronics Specialists Conference*, 1994).
- 3.2 Ultra Low-Power Control Circuits for PWM Converters **137**
A. Dancy and A. Chandrakasan (CONTRIBUTED PAPER).

SECTION 3.2 Adaptive Power Supply Systems 143

- 3.3 A Voltage Reduction Technique for Battery Operated Systems **143**
V. von Kaenel, P. Macken, and M. Degrauwe (*IEEE Journal of Solid-State Circuits*, October 1990).
- 3.4 Automatic Adjustment of Threshold and Supply Voltage for Minimum Power Consumption in CMOS Digital Circuits **148**
V. von Kaenel, M. Pardoen, E. Dijkstra, and E. Vittoz (*IEEE Symposium on Low-Power Electronics*, October 1994).
- 3.5 Low-Power Operation Using Self-Timed Circuits and Adaptive Scaling of the Supply Voltage **150**
L. Nielsen, C. Niessen, J. Sparso, and K. van Berkel (*IEEE Transactions on VLSI Systems*, December 1994).
- 3.6 A Low-Power Switching Power Supply for Self-Clocked Systems **157**
G. Wei and M. Horowitz (INVITED PAPER).
- 3.7 Variable-Voltage Digital-Signal Processing **166**
V. Gutnik and A. Chandrakasan (CONTRIBUTED PAPER).
- 3.8 Scheduling for Reduced CPU Energy **177**
M. Weiser, B. Welch, A. Demers, and S. Shenker (*First Symposium on Operating Systems Design and Implementation (OSDI)*, Usenix Association, 1994).

Part IV Circuit and Logic Styles 189

SECTION 4.1 Conventional Circuit and Logic Styles 191

- 4.1 Silicon-Gate CMOS Frequency Divider for the Electronic Wrist Watch **191**
E. Vittoz, B. Gerber, and F. Leuenberger (*IEEE Journal of Solid-State Circuits*, April 1972).
- 4.2 CODYMOS Frequency Dividers Achieve Low Power Consumption and High Frequency **196**
H. Oguey and E. Vittoz (*Electronics Letters*, July 1973).
- 4.3 Short-Circuit Dissipation of Static CMOS Circuitry and Its Impact on the Design of Buffer Circuits **198**
H. J. M. Veendrick (*IEEE Journal of Solid-State Circuits*, August 1984).
- 4.4 A 3.8ns CMOS 16×16 Multiplier Using Complementary Pass Transistor Logic **204**
K. Yano, T. Yamanaka, T. Nishida, M. Saitoh, K. Shimohigashi, and A. Shimizu. (*IEEE Custom Integrated Circuits Conference*, 1989).
- 4.5 A High-Speed, Low-Power, Swing Restored Pass-Transistor Logic Based Multiply and Accumulate Circuit for Multimedia Applications **208**
A. Parameswar, H. Hara, and T. Sakurai (*Proceedings of Custom Integrated Circuits Conference*, May 1994).
- 4.6 Static Power Driven Voltage Scaling and Delay Driven Buffer Sizing in Mixed Swing QuadRail for Sub-1V I/O Swings **212**
R. Krishnamurthy, I. Lys, and L. R. Carley (*International Symposium on Low-Power Electronics and Design*, August 1996).
- 4.7 The Power Consumption of CMOS Adders and Multipliers **218**
T. Callaway and E. Swartzlander, Jr. (INVITED PAPER).
- 4.8 Delay Balanced Multipliers for Low Power/Low Voltage DSP Core **225**
T. Sakuta, W. Lee, and P. T. Balsara (*IEEE Symposium on Low-Power Electronics: Digest of Technical Papers*, October 1995).
- 4.9 Asynchronous Does Not Imply Low Power, But, . . . **227**
K. Van Berkel, H. van Gageldonk, J. Kessels, C. Niessen, A. Peeters, M. Roncken, and R. van de Wiel (INVITED PAPER).
- 4.10 Latches and Flip-Flops for Low-Power Systems **233**
C. Svensson and J. Yuan (INVITED PAPER).

SECTION 4.2 Adiabatic Logic Circuits 239

- 4.11 Zig-Zag Path to Understanding 239
R. Landauer (*IEEE PhysComp '94*).
- 4.12 A Low-Power Multiphase Circuit Technique 245
B. Watkins (*IEEE Journal of Solid-State Circuits*, December 1967).
- 4.13 Asymptotically Zero Energy Split-Level Charge Recovery Logic 253
S. Younis and T. Knight (*International Workshop on Low Power Design*, 1994).
- 4.14 Low Power Digital Systems Based on Adiabatic Switching Principles 259
W. C. Athas, L. Svensson, J. G. Koller, N. Tzartzanis, and E. Y. Chou (*IEEE Trans. on VLSI Systems*, December 1994).
- 4.15 Adiabatic Dynamic Logic 268
A. Dickinson and J. Denker (*IEEE Journal of Solid-State Circuits*, March 1995).

Part V Driving Interconnect 273

- 5.1 Sub-1-V Swing Internal Bus Architecture for Future Low-Power ULSIs 275
Y. Nakagome, K. Itoh, M. Isoda, K. Takeuchi, and M. Aoki (*IEEE Journal of Solid-State Circuits*, April 1993).
- 5.2 Data-Dependent Logic Swing Internal Bus Architecture for Ultra Low-Power LSIs 281
M. Hiraki, H. Kojima, H. Misawa, T. Akazawa, and Y. Hatano (*IEEE Journal of Solid-State Circuits*, April 1995).
- 5.3 An Asymptotically Zero Power Charge-Recycling Bus Architecture for Battery-Operated Ultra-High Data Rate ULSIs 287
H. Yamauchi, H. Akamatsu, and T. Fujita (*IEEE Journal of Solid-State Circuits*, April 1995).
- 5.4 Bus-Invert Coding for Low Power I/O 296
M. Stan and W. Burleson (*IEEE Trans. on VLSI Systems*, March 1995).
- 5.5 A Sub-CV² Pad Driver with 10 ns Transition Time 306
L. J. Svensson, W. C. Athas, and R. S-C. Wen (*IEEE International Symposium on Low-Power Electronics and Design*, August 1996).

Part VI Memory Circuits 311

- 6.1 Reviews and Prospects of Low-Power Memory Circuits
K. Itoh (INVITED PAPER). 313

SECTION 6.1 DRAM 318

- 6.2 Trends in Low-Power RAM Circuit Technologies 318
K. Itoh, K. Sasaki, Y. Nakagome (*Proceedings of the IEEE*, April 1995).
- 6.3 Standby/Active Mode Logic for Sub-1V Operating ULSI Memory 338
D. Takashima, S. Watanabe, H. Nakano, Y. Oowaki, K. Ohuchi, and H. Tango (*IEEE Journal of Solid-State Circuits*, April 1994).
- 6.4 A Charge Recycle Refresh for Gb-scale DRAM's in File Application 344
T. Kawahara, Y. Kawajiri, M. Horiguchi, T. Akiba, G. Kitsukawa, T. Kure, and M. Aoki (*IEEE Journal of Solid-State Circuits*, June 1994).

SECTION 6.2 SRAM 352

- 6.5 A 1-V 1-Mb SRAM for Portable Equipment 352
H. Morimura and N. Shibata (*International Symposium on Low-Power Electronics and Design*, August 1996).
- 6.6 A Single Bitline Cross-Point Cell Activation (SCPA) Architecture for Ultra-Low-Power SRAMs 358
M. Ukita, S. Murakami, T. Yamagata, H. Kuriyama, Y. Nishimura, and K. Anami (*IEEE International Solid-State Circuits Conference*, February 1994).
- 6.7 Techniques to Reduce Power in Fast Wide Memories 360
B. Amrutur and M. Horowitz (*Proceedings of the IEEE Symposium on Low Power Electronics*, 1994).
- 6.8 A 2-ns, 5-mW, Synchronous-Powered Static-Circuit Fully Associative TLB 362
H. Higuchi, S. Tachibana, M. Minami, and T. Nagano (*IEEE Symposium on VLSI Circuits*, June 1995).
- 6.9 Driving Source-Line (DSL) Cell Architecture for Sub-1-V High Speed Low Power Applications 364
H. Mizuno and T. Nagano (*IEEE Symposium of VLSI Circuits*, June 1995).

Part VII Portable Terminal Electronics 367**SECTION 7.1 General Purpose Processor Design 369**

- 7.1 Energy Dissipation in General Purpose Microprocessors 369
R. Gonzalez and M. Horowitz (*IEEE Journal of Solid-State Circuits*, September 1996).

- 7.2 Energy Efficient CMOS Microprocessor Design **376**
T. Burd and R. Brodersen (*Proceedings of the 28th Annual HICSS Conference*, January 1995).
- 7.3 A 160MHz 32b 0.5W CMOS RISC Microprocessor **386**
J. Montanaro, R. Witek, K. Anne, A. Black, E. Cooper, D. Dobberpuhl, P. Donahue, J. Eno, G. Hoepfner, D. Kruckemyer, T. Lee, P. Lin, L. Madden, D. Murray, M. Pearce, S. Santhanam, K. Snyder, R. Stephany, and S. Thierauf (*IEEE Journal of Solid-State Circuits*, November 1996).
- 7.4 A 320Mhz, 1.5mW @ 1.35V CMOS PLL for Microprocessor Clock Generation **396**
V. Von Kaenel, D. Aebischer, C. Piguat, and E. Dijkstra (*IEEE Journal of Solid-State Circuits*, November 1996).

SECTION 7.2 Dedicated and Programmable Digital Signal Processors 404

- 7.5 A Low-Power Chipset for a Portable Multimedia I/O Terminal **404**
A. P. Chandrakasan, A. Burstein, and R. W. Brodersen (*IEEE Journal of Solid-State Circuits*, December 1994).
- 7.6 A Portable Real-Time Video Decoder for Wireless Communication **418**
T. Meng, B. Gordon, and E. Tsern (INVITED PAPER).
- 7.7 Low Power Design of Memory Intensive Functions **433**
D. Lidsky and J. Rabaey (*IEEE Symposium on Low-Power Electronics*, 1994).
- 7.8 A 16b Low-Power Digital Signal Processor **435**
K. Ueda, T. Sugimura, M. Okamoto, S. Marui, T. Ishikawa, M. Sakakihara (*IEEE International Solid-State Circuits Conference*, February 1993).
- 7.9 A 1.8V 36mW DSP for the Half-Rate Speech CODEC **437**
T. Shiraishi, K. Kawamoto, K. Ishikawa, H. Sato, F. Asai, E. Teraoka, T. Kengaku, H. Takata, T. Tokuda, K. Nishida, and K. Saitoh (*Proceedings of the IEEE Custom Integrated Circuits Conference*, May 1996).
- 7.10 Design of a 1-V Programmable DSP for Wireless Communication **441**
P. Landman, W. Lee, B. Barton, S. Abiko, H. Takahashi, H. Mizuno, S. Muramatsu, K. Tashiro, M. Fusumada, L. Pham, F. Boutaud, E. Ego, G. Gallo, H. Tran, C. Lemonds, A. Shih, M. Nandakumar, B. Eklund, and I-C. Chen (INVITED PAPER).
- 7.11 Stage-Skip Pipeline: A Low Power Processor Architecture Using a Decoded Instruction Buffer **450**
M. Hiraki, R. Bajwa, H. Kojima, D. Gorny, K. Nitta, A. Shridhar, K. Sasaki, and K. Seki (*International Symposium on Low Power Electronics and Design*, August 1996).

Part VIII Computer Aided Design Tools 457

SECTION 8.1 Power Analysis Techniques 459

- 8.1 Transition Density: A New Measure of Activity in Digital Circuits **459**
F. Najm (*IEEE Trans. on Computer Aided Design of Integrated Circuits and Systems*, February 1993).
- 8.2 Estimation of Average Switching Activity in Combinational and Sequential Circuits **473**
A. Ghosh, S. Devadas, K. Keutzer, and J. White (*IEEE/ACM Design Automation Conference*, June 1992).
- 8.3 Power Estimation for Sequential Logic Circuits **480**
C. Tsui, J. Monteiro, M. Pedram, S. Devadas, A. Despaigne, and B. Lin (*IEEE Trans. on VLSI Systems*, September 1995).
- 8.4 A Monte Carlo Approach for Power Estimation **492**
R. Burch, F. N. Najm, P. Yang, and T. Trick (*IEEE Transactions on VLSI Systems*, March 1993).
- 8.5 Stratified Random Sampling for Power Estimation **501**
C. -S. Ding, C. -T. Hsieh, Q. Wu, and M. Pedram (*IEEE/ACM International Conference on Computer-Aided Design*, November 1996).
- 8.6 A Survey of High-Level Power Estimation Techniques **508**
P. Landman (INVITED PAPER).
- 8.7 Activity-Sensitive Architectural Power Analysis **516**
P. Landman and J. Rabaey (*IEEE Transactions on CAD*, June 1996).
- 8.8 Power Analysis of Embedded Software: A First Step Towards Software Power Minimization **533**
V. Tiwari, S. Malik, and A. Wolfe (*IEEE Trans. on VLSI Systems*, December 1994).

SECTION 8.2 Power Optimization Techniques 542

- 8.9 Technology Mapping for Low Power **542**
V. Tiwari, P. Ashar, and S. Malik (*Proceedings of the IEEE/ACM 30th Design Automation Conference*, June 1993).
- 8.10 POSE: Power Optimization and Synthesis Environment **548**
S. Iman and M. Pedram (*IEEE/ACM 33rd Design Automation Conference*, June 1996).

- 8.11 Transformation and Synthesis of FSMs for Low-Power Gated-Clock Implementation **554**
L. Benini and G. De Micheli (*International Symposium of Low Power Design*, April 1995).
- 8.12 Precomputation-Based Sequential Logic Optimization for Low Power **560**
M. Alidina, J. Monteiro, S. Devadas, A. Ghosh, and M. Papaefthymiou (*Proceedings of the IEEE/ACM International Conference on Computer-Aided Design*, November 1994).
- 8.13 Glitch Analysis and Reduction in Register Transfer Level Power Optimization **568**
A. Raghunathan, S. Dey, and N. Jha (*IEEE/ACM 33rd Design Automation Conference*, June 1996).
- 8.14 Exploiting Locality for Low-Power Design **574**
R. Mehra, L. Guerra, and J. Rabaey (*Proceedings of the IEEE Custom Integrated Circuit Conference*, May 1996).
- 8.15 HYPER-LP: A System for Power Minimization Using Architectural Transformations **578**
A. P. Chandrakasan, M. Potkonjak, J. Rabaey, and R. W. Brodersen (*IEEE/ACM International Conference on Computer-Aided Design*, November 1992).
- 8.16 Variable Voltage Scheduling **582**
S. Raje and M. Sarrafzadeh (*International Symposium on Low Power Design*, April 1995).
- 8.17 System-Level Transformations for Low Power Data Transfer and Storage **609**
F. Catthoor, S. Wuytack, E. de Greef, F. Franssen, L. Nachtergaele, and H. Deman (INVITED PAPER).

Author Index **619**

Index **623**