SILICON EARTH

Introduction to the Microelectronics and Nanotechnology Revolution

We are in the swirling center of the most life-changing technological revolution the Earth has ever known. In only 60 years, a blink of the eye in human history, a single technological invention has launched the mythical thousand ships, producing the most sweeping and pervasive set of changes ever to wash over humankind; changes that are reshaping the very core of human existence, on a global scale, and at a relentlessly accelerating pace. And we are just at the very beginning. *Silicon Earth* introduces readers with little or no technical background to the many marvels of microelectronics and nanotechnology, using easy, nonintimidating language and an intuitive approach with minimal math. The general scientific and engineering underpinnings of microelectronics and nanotechnology are addressed, as well as how this new technological revolution is transforming a broad array of interdisciplinary fields, and civilization as a whole. Special "widget deconstruction" chapters address the inner workings of ubiquitous micro- or nano-enabled pieces of technology such as cell phones, flash drives, GPS, DVDs, and digital cameras.

John D. Cressler is the Ken Byers Professor of Electrical and Computer Engineering at The Georgia Institute of Technology. He received his Ph.D. in applied physics from Columbia University in 1990. After working on the research staff at the IBM Thomas J. Watson Research Center for eight years, he began his academic career at Auburn University in 1992 and then joined the faculty at Georgia Tech in 2002. His research interests center on developing blindingly fast, next-generation electronic components using silicon-based heterostructure devices and circuits. He and his research team have published more than 450 scientific papers in this area. He has served as associate editor for three IEEE journals and on numerous conference program committees. He is a Fellow of the IEEE and was awarded the C. Holmes MacDonald National Outstanding Teacher Award (Eta Kappa Nu, 1996), the IEEE Third Millennium Medal (2000), the Office of Naval Research Young Investigator Award (1994), the Birdsong Merit Teaching Award (1998), and the Outstanding Faculty Leadership for the Development of Graduate Research Assistants Award (2007). His previous books include *Silicon-Germanium Heterojunction Bipolar Transistors* (2003), *Reinventing Teenagers: The Gentle Art of Instilling Character in Our Young People* (2004), and *Silicon Heterostructure Handbook: Materials, Fabrication, Devices, Circuits, and Applications of SiGe and Si Strained-Layer Epitaxy* (2006). He is an avid hiker, gardener, and wine collector.

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John D. Cressler
Georgia Institute of Technology

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Description of the Cover Art

Curious about the slick cover art? Starting from NASA's famous "Earth at Night" image, we played some games with Adobe Photoshop to introduce curvature and atmosphere to the Earth and then added silicon integrated circuit oceans (read: Silicon Earth). The original concept of showing the Earth with an integrated circuit overlay was mine, but Peter Gordon led me to NASA's night view, and Poornima Ozarkar, the artistic wife of one of my Ph.D. students, executed a large number of design iterations to get it right. Final result? Pretty slick!

The "Earth at Night" (courtesy of NASA, 2000) is actually a composite of images created from data gathered by satellites that are a part of the U.S. Air Force's Defense Meteorological Satellite Program (DMSP), and that reside at about 800 km above the Earth's surface, in Sun-synchronous, near-polar orbits (99 degree inclination). The night view of the Earth clearly shows evidence of human civilization, speaking volumes about our reliance on electricity, and also suggests why it's awfully tough to get a great view of the Milky Way when you live in big cities! The brightest areas are obviously not the most populated, but rather the most urbanized (read: light pollution?!). The integrated circuit spanning the oceans of the Silicon Earth is actually a SiGe radar chip designed by my Georgia Tech research team.

To the many aspiring students
of microlectronics and nanotechnology:
May your imaginings be bold, your vision keen,
And your re-creation of a new world full of hope and promise.

And . . .

For Maria:
My beautiful wife, best friend, and soul mate for these 26 years.
For Matthew John, Christina Elizabeth, and Joanna Marie:
God's awesome creations, and our precious gifts.
May your journey of discovery never end.

The most beautiful thing
We can experience
Is the mysterious.
It is the source
Of all true art and science.
He to whom this emotion
Is a stranger,
Who can no longer pause
To wonder
And stand rapt in awe,
Is as good as dead:
His eyes are closed.

– Albert Einstein

Contents

Preface

We are in the swirling center of the most life-changing technological revolution the Earth has ever known. In only 60 years, a blink of the eye in human history, a single technological discovery has launched the mythical thousand ships, producing the most sweeping and pervasive set of changes ever to wash over humankind; changes that are reshaping the very core of human existence, on a global scale, and at a relentlessly accelerating pace. More important, these changes are only in their infancy! *Silicon Earth: Introduction to the Microelectronics and Nanotechnology Revolution* introduces readers with little or no technical background to the marvels of microelectronics and nanotechnology, using friendly, nonintimidating language and an intuitive approach with minimal math. This book introduces the general scientific and engineering underpinnings of microelectronics and nanotechnology and explores how this new technological revolution is transforming the very essence of civilization. To round things out for the technologically curious, special "widget deconstruction" chapters address the inner workings of ubiquitous micro or nano-enabled pieces of technology such as cell phones, flash drives, GPSs, DVDs, and digital cameras. Want to know how that i-Phone works? Here's your chance!

Is this really such a big deal that it warrants plunking down some hard-won bucks and allocating some quiet reading time? You bet it is! The microelectronics and nanotechnology revolution is profoundly reshaping planet Earth as we speak, changing forever the ways we humans communicate, socialize, shop, play games, create art, elect our leaders, practice medicine, teach, conduct business, and, yes, even think. A big deal. Should you care? You'd better, else you're going to be steamrolled by the relentless advance of micro/nanotechnology sweeping across the globe. Think of this cute little book as an investment in your future, a chance for you to be in the know and ahead of the curve. One up on your friends. So, yes, go ahead, use that ATM card to send a few electrons to your checking account . . . and let's get learning!

1. THROWING DOWN THE GAUNTLET

I am throwing down the gauntlet![1] I would like to issue my challenge to the legions of you bright young people of our world, you students on a learning curve to become the next set of technology practitioners, the future movers and shakers of our world. To win the challenge, you must understand what microelectronics and nanotechnology are really all about and then gleefully revel in all the glamor and excitement, appreciating the incredible myriad of future applications awaiting your inventive minds. Don't let it end there! It mustn't end there! I challenge you to take up the gauntlet. Knowing what you soon will discover in these pages, I invite you to then step back, reflect, muse a bit, and take a stand regarding HOW the development of these remarkable microelectronics and nanotechnology inventions you will conceive can best be put to use in serving our global community for the greater good. The final chapter in this book examines the many evolving societal transformations and the numerous issues swirling around the ensuing microelectronics and nanotechnology revolution and is offered for your serious consideration. First things first, though – let's learn some micro/nano stuff!

2. USING THIS BOOK

This book is intended to be used by two very different audiences: (1) As a textbook for an interdisciplinary, introductory course in microelectronics and nanotechnology and (2) as a pick-up-and-read-cover-to-cover book for those curious about what all this micro/nanobabble is all about. More important, this book assumes no special technical background in the subject matter, and thus should be accessible to your typical university freshman from virtually any discipline. Have you been out of school for a while? No worries, you should do just fine. Some basic physics and electrical engineering refresher appendices are included for those that might need them.

This book serves as the textbook for a course (CoE 3002) I have introduced into the curriculum at Georgia Tech (Fall 2008), titled "Introduction to the Microelectronics and Nanotechnology Revolution." It is intended for freshmen and sophomores in the Georgia Tech Honors' Program and for juniors in Georgia Tech's joint College of Management and College of Engineering's new Technology and Management Program. The students taking this course come from many disciplines (engineering, management, science, social science, etc.), at varying educational levels, and, important for the reluctant among you, with no real background in electrical engineering. That's the intent, so the book is pitched to the level of this audience. My course consists of a mixture of lecture, several tours to real micro/nanotechnology research labs on campus, and roundtable discussions based on the philosophical and social topics addressed in the last chapter of the

[1] You know, the Middle Ages, armored knights, swordplay, chain mail, chivalry, duels! A gauntlet is a type of glove with an extended cuff protecting part of the forearm against a sword blow. To throw down the gauntlet is to issue a formal challenge. A gauntlet-wearing knight would challenge a fellow knight to a duel by throwing one of his gauntlets on the ground. His opponent would then pick up the gauntlet to formally accept the challenge. Let the games begin!

book. For these discussions, I form different "debate teams" who first research and then adopt pro–con positions (by draw of the card) on the topic in question to heighten the energy level of the experience. Students also engage in a collaborative capstone research experience in which five-person teams do their own widget deconstructions and present those findings to the class. I make it a competition. Works very well. For those who are interested, my course Web site (*http://users.ece.gatech.edu/~cressler/courses/courses.html*) contains more information on debate topics and class deconstruction projects.

My sincere hope is that this type of come-one-come-all cross-disciplinary university entry-level micro/nano course becomes a groundswell across campuses (hopefully globally). Encouraging signs can already be gleaned at U.S. universities. I believe this material, if placed in the right hands, could also be effectively introduced to select seniors at the high school level.

3. SOME SPECIAL THANKS

I am truly grateful to my editor, Peter Gordon, of Cambridge University Press, for his unwavering support throughout this project. Peter came highly recommended to me by Dave Irwin, a trusted mentor. True, it took a little time for Peter to embrace what has evolved into a decidedly nontraditional approach to authoring a textbook, especially with regard to my intentionally, shall we say, "free-spirited" writing style. From minute one I wanted this book to be fun, not stuffy; a new take on what an engaging textbook could and should be – and something that could simultaneously be embraced by students as well as a general readership. Peter bought into my vision; helped me hone my book into a feasible, cost-effective package; and even agreed not to unleash the English-usage police on me! If the final product gives you any pause for thought, for any reason, please blame me, not Peter!

I'd like to thank Dustin Schisler, Glendaliz Camacho, and their colleagues at Cambridge University Press for their expert handling of the figures and layout. Thanks also to Larry Fox of Aptara for his expertise in production, and Vicki Danahy for her interest and skillful copyediting. I am also grateful to Poornima Ozarkar for her help with the book cover and, expertly exercising the minimiracles of Adobe Photoshop.

I'd like to thank Mark Ferguson, Linda Oldham, Monica Halka, Greg Nobles, Gary May, Joe Hughes, Doug Williams, and Larry Jacobs of Georgia Tech, for their support in getting my new micro/nano course off the ground.

My fundamental approach to writing this book originates from my deeply held belief that ANY subject can be effectively taught to ANY audience if you work hard enough as a teacher–writer. Call me naive! This can be challenging, to be sure, but it has worked here. Does it take audacity to teach a subject so deeply technical as microelectronics and nanotechnology to folks with no real electrical engineering background? You bet! Can it work well? It can. I've had some help along the way, clearly. I'd like to thank my many students, both undergraduate and graduate, over the years for helping me hone my teaching skills.

Yea verily, I am shameless when it comes to subjecting my friends, my colleagues, my graduate students, my nieces and nephews, my brothers- and sisters-in-law, and even my wife and kids to preliminary drafts of several of the chapters in this book for their feedback and a sanity check. Does it make sense? Can you understand it? Am I out in left field? Thanks to all for their indulgence.

In the spirit of the burgeoning social media landscape enabled by the Internet, I have frequently drawn inspiration from various Wikipedia entries on a number of subjects contained in this book. My apologies to any of my fellow professors who may find a wiki citation bloodcurdling! In the present case, given my target (nonexpert) audience, who are all VERY familiar with Wikipedia, it seemed to me silly to not employ the extensive information out on the Web. However, let me amplify what students frequently hear from us professors: Wikipedia should be used as a starting point, not as an end in itself. And, as with all things Web-based, a healthy nonzero level of skepticism regarding the accuracy of what you find on the Web is always warranted. Let me issue a special thanks to all you wiki authors out there who devote your time and energy to improving our global knowledge base.

My earliest draft of the table of Contents for this book dates to January of 2005 – sigh . . . over four years back. Yes, it has been a long road, and a TON of work, but I have to admit, I really enjoyed writing this book! If my treatment remains too technical for you, or if it seems overly obtuse in certain areas, or if I've managed to botch some facts along the way, or if you think my discussion could be improved here and there with a little tweaking, or if heaven forbid, if you really did enjoy my approach . . . please, by all means let me know; I'd love to hear from you!

I now gently lay my labor of love at your feet. I hope my efforts please you, and maybe even make you smile here and there! Enjoy.

John D. Cressler
School of Electrical and Computer Engineering
Georgia Tech
July 2009

About the Author

John D. Cressler is Ken Byers Professor of Electrical and Computer Engineering at The Georgia Institute of Technology (Georgia Tech), Atlanta, GA. He received his Ph.D. from Columbia University, New York, NY, in 1990; was on the research staff of the IBM Thomas J. Watson Research Center, Yorktown Heights, NY, from 1984 to 1992; and was on the engineering faculty of Auburn University, Auburn, AL, from 1992 to 2002, when he left to join Georgia Tech. His research focuses on developing next-generation, high-speed electronic systems and is currently centered on the fundamental understanding, technological development, and clever new uses of nanoscale-engineered, silicon-based, heterostructure transistors and circuits (admittedly a mouthful!). He and his research team have published more than 450 scientific papers in this field. He is the co-author of *Silicon-Germanium Heterojunction Bipolar Transistors* (Artech House, 2003); the editor of *Silicon Heterostructure Handbook: Materials, Fabrication, Devices, Circuits, and Applications of SiGe and Si Strained-Layer Epitaxy* (CRC Press, 2006); and the author of *Reinventing Teenagers: The Gentle Art of Instilling Character in Our Young People* (Xlibris, 2004). He has served as editor for three scientific journals, has played various roles on numerous technical conference committees, and has received a number of awards for both his teaching and his research. To date, he has graduated 27 Ph.D. students and 25 M.S. students during his 17-year academic career. He was elected Fellow of the Institute of Electrical and Electronics Engineers (IEEE) in 2001. On a personal note, John's hobbies include hiking, gardening, bonsai, all things Italian, collecting (and drinking!) fine wines, cooking, history, and carving walking sticks, not necessarily in that order. He considers teaching to be his primary vocation. John has been married to Maria, his best friend and soul mate,

for 26 years, and is the proud father of three: Matt (24), Christina (22), and Jo-Jo (19).

Dr. Cressler can be reached at:
School of Electrical and Computer Engineering
777 Atlantic Drive, N.W.
Georgia Institute of Technology
Atlanta, GA 30332-0250 U.S.A.
or
cressler@ece.gatech.edu
http://users.ece.gatech.edu/~cressler/