

The background of the cover is a composite image. The upper portion shows a view of Earth from space, with a bright horizon line and a starry sky. The lower portion is a detailed, high-contrast image of a microchip or silicon wafer, showing intricate circuit patterns. The two images are blended together, with the chip pattern appearing to be on the surface of the Earth.

Second Edition

Silicon Earth

**Introduction to Microelectronics
and Nanotechnology**

John D. Cressler



CRC Press
Taylor & Francis Group

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and Nanotechnology

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Description of the Cover Art

Curious about the slick cover art? Starting from NASA's famous "Earth at Night" image (Figure 15.42), we played some games with Adobe 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 of Cambridge University Press led me to NASA's night view, and Poornima Ozarkar, the artistic wife of one of my PhD students, executed a large number of design iterations to get it right. For the second edition, John Gandour of CRC Press massaged the original colors and added in the background of stars and interstellar gas. Final result? Pretty slick!

The "Earth at Night" (courtesy of NASA, 2000) is actually a composite of images created from data gathered by satellites which are a part of the U.S. Air Force's Defense Meteorological Satellite Program (DMSP), and which 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 this Silicon Earth is actually a SiGe radar chip designed by my Georgia Tech research team.

*To the many aspiring students
of microelectronics and nanotechnology:
May your imaginings be bold, your vision keen,
and may your re-creation of our new world
blossom with hope and promise.*

And ...

*For my Maria:
My beautiful wife, my best friend, and my soul mate for these 33 years.
For Matthew John (and Mary Ellen, and now Elena and Moira),
Christina Elizabeth (and Michael, and now Owen and Amelia),
and Joanna Marie (and Eric):
God's awesome creations, and our precious gifts.
May your journeys of discovery endure forever.*

*People Like You And Me,
Though Mortal, Of Course, Like Everyone Else,
Do Not Grow Old No Matter How Long We Live.
What I Mean Is That We Never Cease
To Stand Like Curious Children
Before The Great Mystery Into Which We Were Born.
This Interposes A Distance Between Us
And All That Is Unsatisfactory In The Human Sphere.*

Albert Einstein

Preface to the Second Edition

Remarkably enough, *Silicon Earth* came out in 2009, seven years ago! Time flies. I have used the book in my CoE 3002 course, “Introduction to the Microelectronics and Nanotechnology Revolution” (aka “Micro/Nano” or simply “Silicon Earth”), taught yearly since 2008, and it has been a fantastically joyful class to teach. Great fun! To my intense pleasure, students love the book. Hip! Hip! Hooray! Still, in our rapidly evolving technological world, things age quickly, and thus, I have been thinking for a while now about a second edition, and the tickle just wouldn’t go away. I was delighted when I got a greenlight from CRC Press to take *Silicon Earth* over from Cambridge University Press and do a new edition, and we were off to the races. AND, CRC Press offered me color pics to boot. Fantastic!

Since *Silicon Earth* came out, I have been engaged in my new gig—fiction writing! Historical novels. Yup! Love stories set in medieval Muslim Spain, a magical era marked by the harmonious coexistence of Islam, Judaism, and Christianity, and with an implicit message for our globally conflicted twenty-first century. What fun creative writing is! Fiction writing is a dream come true, so breaking away from that siren’s call to work on *Silicon Earth* gave me some pause for thought. But then it happened; those pesky deadlines began to loom, and I put novel three on hold and picked up my baby again after so many years, kicked my feet up, lifted my cup of trusted coffee for a sip, and began to peruse what I crafted so many years back. What a joyful rediscovery it was! I’ll just lay it out there. I LOVE this book!

Can it be better still? Yes, it can! I have undated everything, turned the old B&W pics back to color, put lots more pics in, and added quite a bit of new material, mostly in response to student feedback and thoughts from professors at other universities that teach a similar course using *Silicon Earth*. There is a new chapter called “From Transistors to Circuits to Systems” (Chapter 9), which details how electronic systems are birthed from transistors and how software fits in with all that. I split the nanotechnology chapter off as a separate chapter (Chapter 14), and added a substantive new chapter on the “The Future of Electronics” (Chapter 13). Lots to talk about there. I added some new stuff to the widget deconstructions, including a GPS-enabled smart watch. I also revised and added quite a bit of new material to the chapter on “Societal Impact” (Chapter 15). So many issues to discuss! Tons of new topics and tons of new questions. Yep, *Silicon Earth* just got better. Much better!

I am grateful to several folks for helping bring this together. First, to Peter Gordon, for arranging the transfer from Cambridge to CRC Press. To Nora Konopka at CRC for embracing my vision, and Jessica Vakili, Cynthia Klivecka, Christine Selvan, and John Gandour for all the hard work getting my baby into production. I wholeheartedly thank my many CoE 3002 students over the years for finding all the typos (hundreds!) and making lots of suggestions on how to improve the book. My favorite comment by my students? “Dr. Cressler, we can hear you in our heads when we read the book!” I LOVE IT! I would also like to thank Dr. Sherra Kerns of Olin College, who uses *Silicon Earth* in a course like mine. It has been fun, Sherra, swapping micro/nano stories and being wowed by our oh-so-bright-and-fun students!

Do take the time to read the original preface, which details the conception and intended usage of the book. It is all still very relevant. AND, for you students especially, please

revisit my challenge to “take up the gauntlet.” Yep, I am hereby officially throwing down my gauntlet! And please, please, please, write me and tell me what you think of the new book. We authors need some feedback.

Now, dear friends, I gently lay my labor of love once more at your feet. A new and improved *Silicon Earth*. Enjoy!

John D. Cressler

*Schlumberger Chair Professor of Electronics
School of Electrical and Computer Engineering
Georgia Tech
Atlanta, Georgia*

Preface to the First Edition

We are in the swirling center of the most life-changing technological revolution the Earth has ever known. In only 60 years, the blink of an 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/nano-enabled pieces of technology such as cell phones, flash drives, GPSs, DVDs, and digital cameras. Want to know how that iPhone 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 for 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!* 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. 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

* You know, the Middle Ages, armored knights, sword play, 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!

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 be put to best 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 with 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 this micro/nano babble 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 Business 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 round-table discussions based on the philosophical and social topics addressed in the last chapter of the book. For these discussions, I form different "debate teams," who first research and then adopt pro/con positions (luck of the draw) 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 website (<http://users.ece.gatech.edu/cressler/courses/courses.html>) contains more information on debate topics and class deconstruction projects. There is also substantial material available on my book website for professors interested in teaching such a course: overheads for lecture, example homeworks, a deconstruction project, example discussion threads, etc. Please email me or visit: <http://johndcressler.com/non-fiction/silicon-earth/>.

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.

I 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 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, 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 you think my discussion could be improved here and there with a little tweaking or, heaven forbid, if you really did enjoy my approach ... please, please, please 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

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Author



John D. Cressler received his BS in physics from the Georgia Institute of Technology in 1984 and his PhD in applied physics from Columbia University in 1990. From 1984 to 1992, he was on the research staff at the IBM Thomas J. Watson Research Center, and from 1992 to 2002 he served on the faculty at Auburn University. In 2002, he joined the faculty at Georgia Tech, and is currently Schlumberger Chair Professor of Electronics in the School of Electrical and Computer Engineering.

The basic thrust of Dr. Cressler's research is to develop novel micro/nanoelectronic devices, circuits, and systems for next-generation applications within the global electronics infrastructure. He and his team attempt to break the business-as-usual mold in this field and reimagine the way electronics in the twenty-first century can and should be practiced. He and his students have published more than 700 scientific papers in this field and during his academic career he has graduated 47 PhD students (and counting). He was elected Fellow of the Institute of Electrical and Electronics Engineers (IEEE) in 2001 for his research contributions, and was awarded the 2010 Class of 1940 W. Howard Ector Outstanding Teacher Award (Georgia Tech's top teaching award), the 2011 IEEE Leon Kirchmayer Graduate Teaching Award (the IEEE's top graduate teaching award), and the Class of 1934 Distinguished Professor Award (the highest honor Georgia Tech bestows on its faculty).

Dr. Cressler's nonfiction books include *Silicon-Germanium Heterojunction Bipolar Transistors* (2003), *Reinventing Teenagers: The Gentle Art of Instilling Character in Our Young People* (2004), *Silicon Heterostructure Handbook: Materials, Fabrication, Devices, Circuits, and Applications of SiGe and Si Strained-Layer Epitaxy* (2006), *Silicon Earth: Introduction to the Microelectronics and Nanotechnology Revolution* (2009), and *Extreme Environment Electronics* (2012).

One of Dr. Cressler's passions is speaking on technical topics to nontechnical audiences, and this began in earnest with the publication of *Silicon Earth* in 2009, which introduces microelectronics and nanotechnology and their societal impact to general audiences (and is also used in an undergraduate course open to all majors at Georgia Tech).

Recently, Dr. Cressler has become enamored with writing fiction, with a goal of reawakening an important and largely unappreciated period of medieval history, a time when Christians, Jews, and Muslims lived together in relative harmony. His debut historical novel, *Emeralds of the Alhambra*, a love story set in the Alhambra Palace in fourteenth-century Granada, Spain, was released in June 2013 by Sunbury Press, and is the first book in the Anthems of al-Andalus series, which is intended to break open medieval Moorish Spain for modern audiences. Book two in the series, *Shadows in the Shining City*, a prequel to *Emeralds* and set in late tenth-century Córdoba during the Golden Age of Moorish Spain, was released in July 2014. He is presently working on book three in the series, *Fortune's Lament*, with a targeted release of 2016.

Beyond his academic duties, Dr. Cressler has been active in service to the local community throughout his career. He served in youth ministry to high school students (nine years), in prison ministry (six years), and for the past five years in JustFaith Ministries, which serves Atlanta's homeless community.

He and his wife Maria have been married for 33 years and are the proud parents of three exceptional young people: Matthew John (and his wife, Mary Ellen), Christina Elizabeth (and her husband, Michael), and Joanna Marie and her soon-to-be husband, Eric. They are the doting grandparents of four wee-ones: Elena and Owen, and now Moira and Amelia. Dr. Cressler's hobbies include hiking, gardening, all things Italian, collecting (and drinking!) fine wines, bonsai, reading, cooking, history, writing, and carving walking sticks, not necessarily in that order. He considers teaching and mentoring of young people to be his life's work, with his writing a close second.

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