AC 2010-89: A NEW APPROACH TO MICROELECTRONICS AND NANOTECHNOLOGY EDUCATION FOR UNDERGRADUATES OF ALL DISCIPLINES

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A New Approach to Microelectronics and Nanotechnology Education for Undergraduates of All Disciplines

Abstract

A new undergraduate course in microelectronics and nanotechnology is described. Importantly, this course does not assume any electrical and computer engineering background or substantive college pre-requisites, and is designed to be accessible for all undergraduate majors at all educational levels. The course focuses on developing the general scientific and engineering underpinnings of microelectronics and nanotechnology, but importantly, also examines how this new technological revolution is influencing a broad array of diverse fields and civilization as a whole.

Introduction

College undergraduate students are generally exposed to the disciplines of microelectronics and nanotechnology [1-3] only if they major in electrical and computer engineering (ECE) or associated majors, often only in advanced ECE classes (typically senior year), and in many cases perhaps not until graduate school. Counter examples to this classical model do exist [4-11], but they are recent and clearly in the overwhelming minority. In addition, such micro/nanotechnology courses remain largely for specialists with a well-defined skill set coming into the class (e.g., advanced undergraduate engineering or science students). Given the pervasive changes being thrust upon our global society by the remarkable cross-disciplinary innovations which are being fueled by microelectronics and nanotechnology, this classical course model is deficient, and must change if the future educational needs of our students are to be best satisfied, and our global community best served. Of particular interest in this context is the exposure of non-engineering majors (e.g., management students) to micro/nanotechnology, something they would generally never encounter in a "normal" college undergraduate curriculum. We offer here an example of a solution to this dilemma by describing a new course introduced at Georgia Tech which deals squarely with micro/nanotechnology at the undergraduate level, and importantly is intended to serve undergraduate students of all majors (e.g., management, engineering, sciences, etc.) and all educational levels (freshman through senior).

At Georgia Tech, we have introduced a new undergraduate elective course [12], which does not assume any ECE background or substantive college pre-requisites (only advanced high-school level math and science that most, if not all, incoming freshman, regardless of major, would possess). The course focuses on developing the general scientific and engineering underpinnings of microelectronics and nanotechnology; but importantly, the course also examines how this new technological revolution is influencing a broad array of diverse fields (engineering, biology, manufacturing, biomedical engineering, material science and engineering, chemistry, chemical engineering, renewable energy, physics, medicine, law, etc.), and civilization as a whole (art, business, film, gaming/entertainment, ecology, politics, etc.). Across campuses, the traditional science, engineering, business, and liberal arts disciplines are becoming increasingly blurred and inter-related, and this trend will surely accelerate. This new course embraces the changing interdisciplinary and globally-aware landscape emerging at universities and also examines the global impact of micro/nanotechnology (for both good and bad ends), a social concern of increasing interest to many students.

Course Details

The salient features of this new course are described here, including the course syllabus, the textbook used, and several creative types of student activities that augment the appeal and instructional effectiveness of the course. The new course has been introduced into the curriculum at Georgia Tech (beginning Fall 2008, and subsequently taught yearly), and is open to ALL Georgia Tech students (regardless of major or year). The course is listed under the College of Engineering (CoE) general curricula as CoE 3002 and is entitled "Introduction to the Microelectronics and Nanotechnology Revolution." CoE 3002 was originally intended for freshman through seniors of all majors in the Georgia Tech Honors' Program [13] and for juniors in Georgia Tech's joint College of Management and College of Engineering's joint new "Technology and Management (T&M) Program" [14] (CoE 3002 is required for the T&M management students, and an elective for the T&M engineering majors). The students taking this course come from many disciplines (engineering, management, the sciences, social science, technology policy, etc.), at varying educational levels, and importantly, with no real pre-requisites traditionally assumed for electrical and computer engineering courses. The 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 surrounding micro/nanotechnology [9]. The course syllabus is given below.

CoE 3002 Course Syllabus

Chapter 1 The Communications Revolution
- 1.1 The Big Picture
- 1.2 Evolutionary Trends: Moore's Law and Silicon ICs
- 1.3 The Micro/Nanoelectronics Distance, Time, Frequency, and Energy Scales
- 1.4 An Historical Perspective

Chapter 2 Widget Deconstruction #1: Cell Phone
- 2.1 With a Broad Brush
- 2.2 Nuts and Bolts
- 2.3 Where are the Integrated Circuits and What Do They Do?

Chapter 3 Semiconductors
- 3.1 What Makes Semiconductors So Special?
- 3.2 Crystal Structure and Energy Bands
- 3.3 Electrons and Holes
- 3.4 Moving Charge Around in Semiconductors

Chapter 4 Widget Deconstruction #2: USB Flash Drive
- 4.1 With a Broad Brush
- 4.2 Nuts and Bolts
- 4.3 Where are the Integrated Circuits and What Do They Do?

Chapter 5 Micro/Nanoelectronics Fabrication
5.1 The In's and Out's of Micro/Nano Fabrication
5.2 Building Mr. Transistor and Packaging Him

Chapter 6 Transistors
6.1 Why Are Transistors So Darn Useful?
6.2 The pn Junction
6.3 The BJT
6.4 The MOSFET

Chapter 7 Widget Deconstruction #3: GPS
7.1 With a Broad Brush
7.2 Nuts and Bolts
7.3 Where are the Integrated Circuits and What Do They Do?

Chapter 8 Microtools and Toys: MEMS, NEMS, and BioMEMS
8.1 Micro-Intuition and the Science of Miniaturization
8.2 Micromachining Silicon and MEMS
8.3 Cool App #1 -- MEMS Accelerometers

Chapter 9 Photonics
9.1 The Interaction of Light With Semiconductors
9.2 Photodetectors and Solar Cells
9.3 CCD's , LEDs, Laser Diodes, and Fiber Optics

Chapter 10 The Nanoscale World
10.1 Nanotech, Nanobots, and Grey Goo
10.2 Darwinian Evolution in Microelectronics: The End of the Silicon Road
10.3 Buckyballs, Nanotubes, Graphene, and Nanoapps

A rather unconventional book has been written for use with the course [15], which assumes no technical background, making it readily accessible to undergraduates of all disciplines (and offered in paperback, at an intentionally moderate student-friendly price-point compared to traditional textbooks). *Silicon Earth: Introduction to the Microelectronics and Nanotechnology Revolution,* Cambridge University Press, 2009 (Fig. 1), contains a number of unique features. For instance, in the author's experience most people (even most bright university students) have virtually no clue as to how common pieces of technology do what they do (e.g., cell phone, thumb drive, digital camera, GPS). The book's "widget deconstruction" chapters address this need from a perspective of "how does the widget actually work," "how does micro/nanotechnology play in that functionality," and "where is the technology going and how will it change civilization." Additional topical cover of the book parallels the course table of contents shown above, seeking to first motivate the micro/nanotechnology field, provide an historical perspective, cover the engineering and scientific foundations of micro/nanotechnology, and then leveraging that foundational understanding explore the societal implications of the field.

In CoE 3002, weekly round-table "discussion threads" on items of topical interest, as well as monthly "team debates" aimed squarely at having students assess/critique the nuanced ethical issues and societal impact associated with the micro/nanotechnology revolution are used to move the class beyond a traditional lecture style. Each are addressed below in more detail.

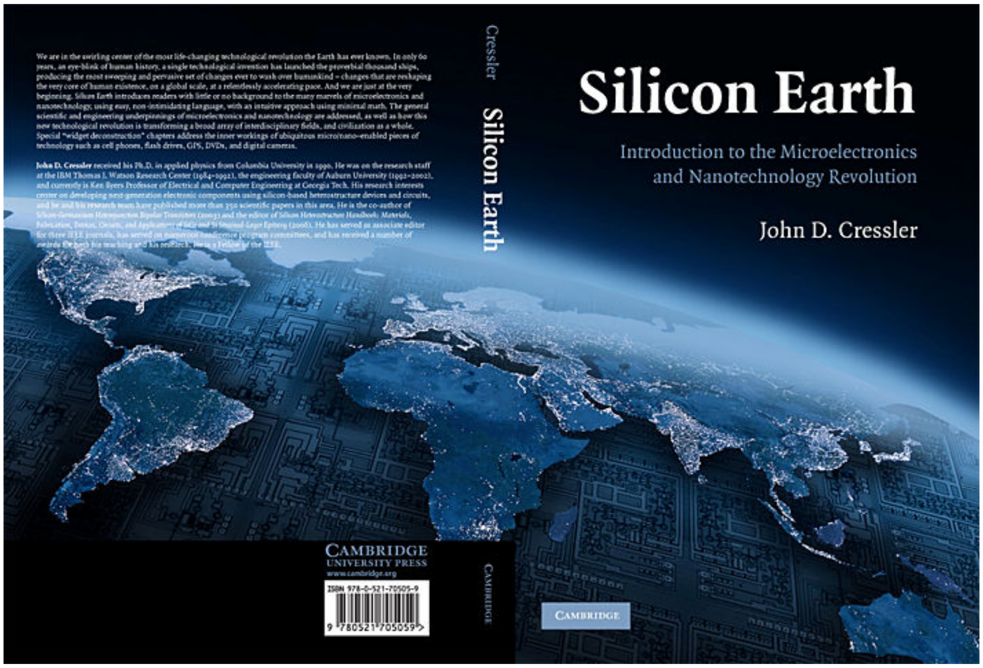

Figure 1. Dust cover of *Silicon Earth*, Cambridge University Press, 2009.

Discussion Threads

To break up the pace of lecture, brief weekly "discussion threads" are used to engage students on non-technical, societal impact issues associated with micro/nanotechnology. Using current event material (e.g., a newspaper clipping) on various aspects of how micro/nanotechnology intersects daily life, we have a short informal discussion. The intent is to choose topics that require the students to form an opinion and share that with the class. The mechanics of the discussion thread are given below, as well as an example.

Mechanics:
During lecture, typically at least once per week, the instructor will pause, and the class will collectively engage in a brief (no more than 15-20 minutes), informal discussion on a relevant topic. The goal is for students to muse a bit and formulate some thoughts in advance, and be ready to add something meaningful to the class conversation. The intent is to identify these topics and hand them out during the preceding lecture (with the appropriate reference material), so that students can give some prior thought to them. Students are also free to suggest topics they would like to collectively probe.

Example Discussion Thread Topic:
"It has been recently argued that the use of digital technology, Information Age gadgets, and other pieces of transistor-enabled toys, are physically re-wiring the brains of "digital natives" – ummm, you guys. Agree? Disagree? What are the pros and cons associated with the heavy use of digital media, and its potential impact on thinking, analysis, social interaction, reading

comprehension, etc.? Time to weigh in." I copied in this case a newspaper clipping highlighting the results of a recent study.

Team Debates

In addition to the in-class discussion threads, two student "debate teams" first research and then adopt pro vs. con positions on the debate topic in question to heighten the energy level of the classroom experience. Teams of 4 students on each side of the issue debate the topic at hand, with the rest of the class as the audience. This type of team debate experience forces students to probe complex, no-easy-answer societal impact issues associated with micro/nanotechnology, and hone their opinions, that they then must articulate to the class. It can be quite instructive for a student to have to forcefully argue a point that they may not necessarily agree with. An example "Team Debate" and the mechanics of the debate are given below.

Background:
The microelectronics and nanotechnology revolution is changing civilization in profound ways; some good, some bad. The team debate experiences probe the nuances of some high-profile topics via a debate format, with one team arguing "pro" and the other arguing "con" (assigned by luck of the draw). The debate topics are intentionally chosen to be contentious and have no easily agreed upon answer.

Example Topic:
"Should the Internet be regulated to address the burgeoning problem of child exploitation and the exploitation of other at-risk individuals? If so, how could this be done? If not, how do we then deal with these emerging problems?"

- Team-Pro (student 1, student 2, student 3, etc.) – "Yes, it should be regulated"
- Team-Con (student 1, student 2, student 3, etc.) – "No, it shouldn't be regulated"

Debate Mechanics:
Each team turns in a one page "position statement." A minimum of three primary references must be included in the position statement. A hardcopy and a softcopy are due at the beginning of the class prior to the debate (e.g., Tuesday, for a Thursday debate). The instructor then sends this out to the entire class (e.g., via email) so that the entire class is prepared for discussion in advance.

The debate occurs during the last 45 minutes of lecture. Each team is given 10 minutes to argue their case (the time limit is strictly enforced). The starting team is decided by coin toss. All team members must take part in the presentation, and each team may use any means at their disposal to make their points more forcefully (e.g., with creative A/V, etc.). After both sides are finished with their arguments, the topic is then "broken open" for comments and opinions from the entire class, for a more general round-table discussion. Each person in class may then adopt any position they feel strongly about, regardless of their team's official position.

Each team receives a team grade, based upon a combination of: a) the written position statement, b) the instructor's judgment of the team's approach to their presentation and the strength of their arguments, and c) the audience's opinion of each team's effort (a debate evaluation is filled out by the class to provide critical feedback to each team).

Team Widget Deconstruction Project

Students also engage in a collaborative capstone research experience in which 5-person teams do their own widget deconstructions and present those findings to the class (this serves as the final exam for the course). Students are given a budget to purchase their widget from e-Bay, must perform a hands-on dissection (e.g., i-Phone, DVD player, laptop, camcorder), and then creatively present the widget (and its guts!) to the class, together with how it works. This type of comprehensive team project in indispensible for allowing students to digest and understand a complex technological object on their own that they would not see in lecture (or the book). Students must first research their widget, focusing specifically on how it is constructed and how it actually functions, and importantly where the micro/nanotechnology is in play within that functionality. The act of physically taking apart a complex piece of technology to see what is inside seems to be an increasingly rare encounter for most students, especially non-engineering students, and can be wonderfully instructive and engaging to them. Such team projects also help hone critical social and team-building skills, and importantly foster student creativity. Perhaps most importantly, they really seem to enjoy doing these widget deconstructions! An example "Widget Deconstruction Project" and the mechanics of the project are given below.

Set-up:
Each team must perform a "widget deconstruction," a technology dissection of sorts, on an example of a ubiquitous consumer electronics widget. Widgets are assigned by luck-of-the-draw. Teams must then address a number of questions, including:

1) Why is this widget so appealing and so successful?
2) What is its history and how did it come to be? Who were the players?
3) How does this widget actually work? Answering this is key.
4) How does microelectronics and nanotechnology (e.g., the integrated circuits; the transistors) play in that functionality? Answering this is also key.
5) Where is the technology underlying this widget going in the next decade and how will it impact the future form and function?
6) How will this widget change the way each of us live our lives?
7) How much does it cost and how is that price point evolving over time?
There are many other logical questions …

Examples of such widget deconstructions exist in the book but each team is free to decide their own path and what works best.

Mechanics:
Each team submits a written report detailing their widget deconstruction. This report includes a title page (clearly indicating which team member did what), no more than 10 pages (single spaced) of text body with embedded figures, appendices that might be relevant, and references. English usage, formatting, visual appeal, image quality, overall "slickness" of the effort all figure prominently in the grading. In addition to each team's project report, they must also deliver a 15

minute presentation on their widget deconstruction, with each team member taking part. Creativity and visual appeal are key metrics for this portion of the project. Each team member receives the team grade. It is up to the team to divide the work equitably, set up outside meeting times, etc. ALL are expected to share the load. In addition, to foster some sense of competition, each member of the winning team receives 2 extra credit points added to their course final homework average.

Example Killer Widget Deconstruction Topics:
Laser Printer
Laptop Computer
DVD Player
MP3 player
Digital Camcorder
Flat screen TV

Courtesy of the Georgia Tech's Technology and Management Program, each team is allocated a budget of up to (but not exceeding) $50 for their deconstruction project, to be spent in any way they deem appropriate (a receipt is required for reimbursement). For example, the team might decide to go on e-Bay and actually buy the object they intend to dissect, and then physically dissect it, documenting their work as they go. But that is each team's decision, and I have seen it done many different ways. Safety is clearly important and I insist that students should not do anything that might prove questionable with regard to their own safety during a hypothetical dissection ceremony.

Student Evaluations

Clearly, the success of any new course, especially one of this type, must ultimately rest with the students' opinions. Do they enjoy it? Is it useful? Can they understand the material? Would they recommend it to their peers? This is particularly true in the case of CoE 3002, given that students are being exposed to very new and challenging material for which they have no formal prerequisites. CoE 3002 has been taught for two semesters now (Fall 08, Fall 09), to a very diverse set of individuals (freshmen through senior students, management majors to engineering and science majors). Included below (Figs. 2 and 3) are the unedited student course evaluations (this student evaluation format is standard for all courses at Georgia Tech), and clearly offers a positive view of the student's experience and perception of this new course. Note that the evaluations are split into two sections for each course offering (Fall 2008 and Fall 2009P), one for the Honors' Program students, and one for the Technology and Management students. A typical breakdown for the overall class student make-up would be:

- Management majors (roughly 1/2 of the class) – typically juniors
- Engineering majors (roughly 1/4 of the class) – typically sophomores through seniors
- Science majors (roughly 1/4 of the class) – typically freshmen through seniors

Core Questions								
Item	**Strongly Agree**	**Agree**	**Partially Agree and Partially Disagree**	**Disagree**	**Strongly Disagree**	**N/A**	**No.of Resp.**	**Interpolated Median**
1. Course Seemed Well Planned And Organized	10	4	1	0	0	0	15	4.8
2. Good Job Covering Course Objectives/Content	9	5	1	0	0	0	15	4.7
3. Explained Complex Material Clearly	5	8	2	0	0	0	15	4.2
4. Was Approachable And Willing To Assist	13	2	0	0	0	0	15	4.9
5. Encouraged Students To Consult With Him/Her	9	5	0	0	0	0	14	4.7
6. Class Attendance Important In Promoting Learning Of Material	9	5	0	0	0	0	14	4.7
7. Number Of Course Assignments Was Appropriate.	4	9	2	0	0	0	15	4.1
8. Exams Covered Course Content/Objectives	6	8	1	0	0	0	15	4.3
9. Exams And Quizzes Were Of Appropriate Difficulty.	4	9	2	0	0	0	15	4.1
10. The Instructor Was An Effective Teacher	11	4	0	0	0	0	15	4.8

Core Questions								
Item	**Strongly Agree**	**Agree**	**Partially Agree and Partially Disagree**	**Disagree**	**Strongly Disagree**	**N/A**	**No.of Resp.**	**Interpolated Median**
1. Course Seemed Well Planned And Organized	9	2	0	0	0	0	11	4.9
2. Good Job Covering Course Objectives/Content	8	3	0	0	0	0	11	4.8
3. Explained Complex Material Clearly	5	5	1	0	0	0	11	4.4
4. Was Approachable And Willing To Assist	9	1	0	0	0	0	10	4.9
5. Encouraged Students To Consult With Him/Her	10	1	0	0	0	0	11	5.0
6. Class Attendance Important In Promoting Learning Of Material	8	3	0	0	0	0	11	4.8
7. Number Of Course Assignments Was Appropriate.	8	3	0	0	0	0	11	4.8
8. Exams Covered Course Content/Objectives	8	2	1	0	0	0	11	4.8
9. Exams And Quizzes Were Of Appropriate Difficulty.	7	3	0	0	0	0	10	4.8
10. The Instructor Was An Effective Teacher	8	3	0	0	0	0	11	4.8

Figure 2. Student evaluations of CoE 3002 for Fall 2008 (total course enrollment was 26). Honors' Program students are on top and Technology and Management students are on the bottom. A 5 point scale is used.

Core Questions								
Item	Strongly Agree	Agree	Partially Agree and Partially Disagree	Disagree	Strongly Disagree	N/A	No.of Resp.	Interpolated Median
1. Course Seemed Well Planned And Organized	6	2	1	0	0	0	9	4.8
2. Good Job Covering Course Objectives/Content	5	4	0	0	0	0	9	4.6
3. Explained Complex Material Clearly	4	3	2	0	0	0	9	4.3
4. Was Approachable And Willing To Assist	6	3	0	0	0	0	9	4.8
5. Encouraged Students To Consult With Him/Her	8	1	0	0	0	0	9	4.9
6. Class Attendance Important In Promoting Learning Of Material	6	2	0	0	1	0	9	4.8
7. Number Of Course Assignments Was Appropriate.	5	4	0	0	0	0	9	4.6
8. Exams Covered Course Content/Objectives	4	5	0	0	0	0	9	4.4
9. Exams And Quizzes Were Of Appropriate Difficulty.	4	4	1	0	0	0	9	4.4
10. The Instructor Was An Effective Teacher	6	2	1	0	0	0	9	4.8

Core Questions								
Item	Strongly Agree	Agree	Partially Agree and Partially Disagree	Disagree	Strongly Disagree	N/A	No.of Resp.	Interpolated Median
1. Course Seemed Well Planned And Organized	16	1	1	0	0	0	18	4.9
2. Good Job Covering Course Objectives/Content	15	3	0	0	0	0	18	4.9
3. Explained Complex Material Clearly	11	5	2	0	0	0	18	4.7
4. Was Approachable And Willing To Assist	15	3	0	0	0	0	18	4.9
5. Encouraged Students To Consult With Him/Her	15	3	0	0	0	0	18	4.9
6. Class Attendance Important In Promoting Learning Of Material	17	0	0	0	0	0	17	5.0
7. Number Of Course Assignments Was Appropriate.	14	4	0	0	0	0	18	4.9
8. Exams Covered Course Content/Objectives	13	4	0	0	0	0	17	4.9
9. Exams And Quizzes Were Of Appropriate Difficulty.	14	3	1	0	0	0	18	4.9
10. The Instructor Was An Effective Teacher	16	1	1	0	0	0	18	4.9

Figure 3. Student evaluations of CoE 3002 for Fall 2009 (total course enrollment was 27). Honors' Program students are on top and Technology and Management students are on the bottom. A 5 point scale is used.

Supplemental Materials for Professors

The CoE 3002 web site [16] includes a significant amount of material for professors contemplating introducing such a course (this process is already underway at several universities), and is located under the button labeled "Resources for Professors Using This Book" on the web site, and includes: 1) power point material for each chapter, and including all of the art from the book (e.g., see Fig. 4); 2) example homework sets with answers; 3) example Discussion Threads, 4) example Debate Topics; and 5) example Team Deconstruction Projects.

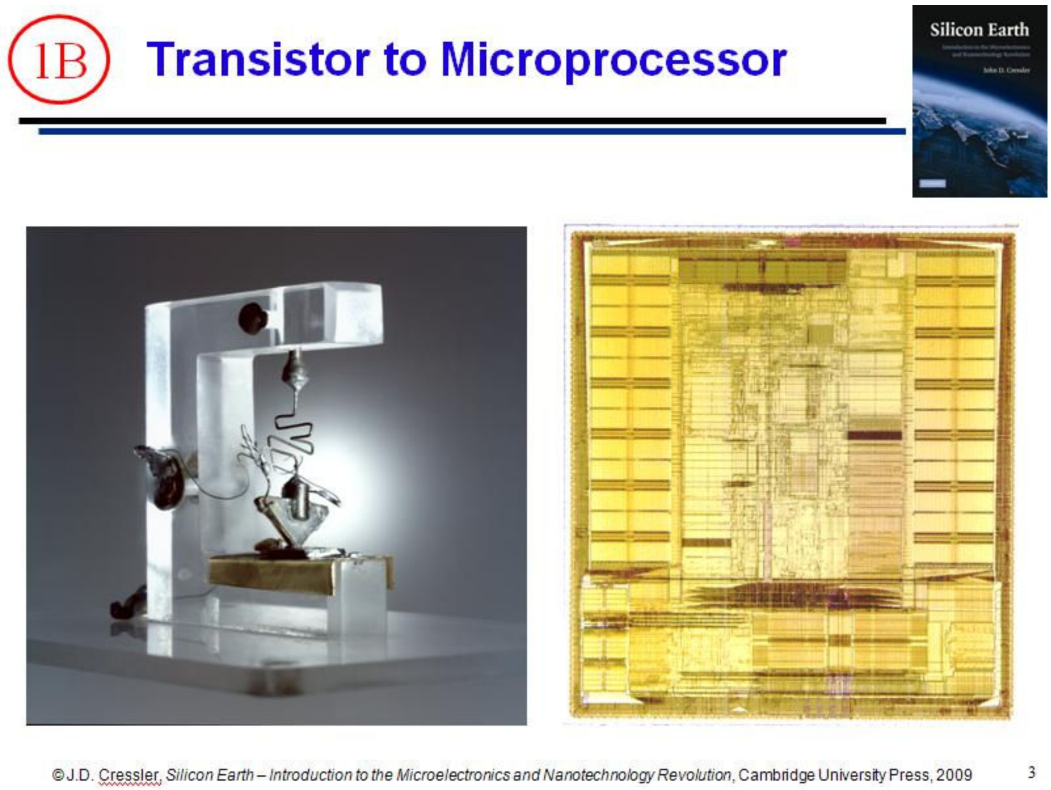

Figure 4. Example power point slide including all of the book's art, and which is made available to professors for use.

Summary

At Georgia Tech, a new undergraduate elective, CoE 3002, "Introduction to the Microelectronics and Nanotechnology Revolution," has been introduced and is described here. CoE 3002 does not assume any ECE background or substantive college pre-requisites, and focuses on developing the general scientific and engineering underpinnings of microelectronics and nanotechnology. Importantly, however, it also examines how this new technological revolution is influencing a broad array of diverse fields (engineering, biology, manufacturing, biomedical engineering, material science and engineering, chemistry, chemical engineering, renewable energy, physics, medicine, law, etc.), and civilization as a whole (art, business, film, gaming/entertainment, ecology, politics, etc.). The sincere hope is that this type of come-one/come-all cross-disciplinary university entry-level micro/nanotechnology course becomes a groundswell across campuses (hopefully globally). Encouraging signs can already be gleaned at U.S. universities. The author believes that this material, if placed in the right instructors' hands, could also be effectively introduced to select seniors at the high school level.

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