**Electronics from the ‘Bottom Up’:
An Intel-NCN@Purdue initiative in nanoelectronics education**

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1. Background and Rationale

In the 1960’s, a group of leaders from industry and academia, the Semiconductor Electronics Education Committee (SEEC), recognized that the age of vacuum tubes was ending, and that engineers would have to be educated differently if they were to realize the opportunities that the new field of microelectronics presented. SEEC eventually produced seven undergraduate textbooks and four films and reshaped the teaching of electronics. Today, channel lengths have shrunk by a factor of 100, microelectronics has become nanoelectronics, but we still teach students very much as they were taught 30 years ago. Today, research on mesoscopic physics and molecular electronics has given us a new understanding of nanoscale devices. New methods to treat stochastic effects for problems in reliability, random dopant fluctuations, etc. are being developed. The new knowledge emerging from research is still largely absent from the semiconductor engineering curriculum. Is it time for a new SEEC initiative?

Fig. 1. The SEEC Notes, a series of seven paperback books produced by the Semiconductor Electronics Education Committee (from http://www.mit.edu:8001/people/klund/books/seec.html).

“In the fall of 1960 Richard B. Adler and Campbell L. Searle organized the Semiconductor Electronics Education Committee (SEEC). By 1966, 31 people from nine universities and six companies produced seven coordinated textbooks and related curricular material, aimed at third-year and fourth-year electrical engineering students. … SEEC was a triumph of engineering science, with a substantial, lasting impact. The basic ideas influenced many textbooks written in subsequent years.” (From “The Electron and the Bit” by Paul Penfield, http://www-mtl.mit.edu/~penfield/pubs/eb-03.html)

One argument for a new approach to education in semiconductor electronics is that to push

CMOS technology to its limits, engineers will need to think about materials, devices, circuits, and systems in a new way; they will need to be comfortable working at the atomistic scale, at treating stochastic effects, and at relating atomistic structure and disorder to the continuum level of the macro-world. We should learn to think of effects at the nanoscale as opportunities to be exploited – not just as problems to be managed. Research is giving us a new understanding of electronics at the nanoscale – one that is more suitable for nanoelectronics than conventional methods and that is often simpler that conventional approaches. This kind of 'bottom-up' thinking should help us push CMOS to its limits, but it could also lead to a new era in technology with fundamentally new devices and new ways to assemble them into systems.

A second reason to teach electronics as nanoelectronics is that the way we teach engineers to think about electronic devices is outdated and, in some cases, simply wrong. Concepts like mobility, velocity saturation, and even bandstructure are deeply imbedded in our thinking, but they are less and less valid with each technology generation. Just as a hydrogen atom is easier to understand than is a complex molecule or macroscopic material, nanoscale devices should be easier to understand than large devices. They only appear to be more complicated because we try to think about small devices using the traditional perspective of semiconductor electronics. Textbook writers (typically senior faculty) are steeped in the traditional approaches of semiconductor electronics and may find the bottom-up perspective difficult, but students don't. We do our students as disservice if we train them to think about devices as we learned to think about them 30 years ago.

A third reason to teach electronics from the bottom up is that the possibilities of nanoscience and technology have captured the imagination of young people. We have an opportunity to educate students on the fundamentals of physics, chemistry, materials, and engineering in the context of some of the most exciting science and technology today. We can use this opportunity to engage the best and brightest students and prepare them to contribute fresh ideas to the next stage of the evolution of electronics. This is an opportunity that we should not miss.

The SEEC texts that were innovative 40 years ago were the model for present-day textbooks today, but we now need to complement the traditional approach to electronics with a new perspective. At Purdue, we are developing a new approach. Supriyo Datta's graduate course, "Quantum Transport: Atom to Transistor," teaches students how to think about semiconductor electronics in a new way. It begins with a discussion current flow through a molecule and, then builds step-by-step to bandstucture and, by the end of the course, to MOSFETs. An undergraduate course, "Fundamentals of Nanoelectronics" takes the same approach. Mark Lundstrom's course on nanoscale transistors discusses device physics and circuits using the approaches and concepts that have been developed to understand molecular and carbon nanotube electronics. Ashraf Alam's course on reliability teaches students to treat stochastic effects, which occur more and more often as the importance of atomistic disorder increases. These courses teach students solid fundamentals and a new way to think about devices, but they do it in the context of some of the most important technological challenges and exciting nanoscience. They are also extremely popular with students. Through Purdue's leadership in the Network for Computational Nanotechnology and its science gateway, the nanoHUB (www.nanoHUB.org), these courses and related tutorials and educational simulations are being disseminated to students worldwide.

We believe that the time has come to introduce a new approach to electronic devices and that the most effective way to disseminate this new approach is via a set of innovative course modules.

2. Course Modules

A. Definition: In our view, the best approach is not to develop a comprehensive set of semester-long courses (which are difficult for others to insert into their curricula) but, rather, to follow the SEEC example. A series of well-defined topics will be produced as a set of related, but individual modules. Each module will be a self-contained treatment of a topic from an original perspective that derives from recent research and brings a new approach to the field. Each module will be an intellectual contribution to the field, but readily accessible to students. The SEEC chose low cost paperback books as a means of broad dissemination. Electronics from the Bottom Up modules will be disseminated online. Each module will consist of lectures, live simulation exercises, and be accompanied by a set of course notes. These modules (each one two to four weeks in length) will be suitable for self-paced study by students and professionals. They will also serve as course components that others can readily incorporate in existing courses.

Overall we have identified the following components for each learning module:

1. **High quality online voiced presentations**
After experimenting with technologies, we have identified Breeze as the best choice. Powerpoint files are converted to Flash animations and synched with audio. The resulting audio presentation works well with low bandwidth Internet connections and should be suitable for viewing almost anywhere. The production of a talk takes some thought and effort – to use animations that follow the audio. With this effort, the result can be quite good – some students say even better than a live lecture.

2. **Accompanying notes**
Each module should be accompanied by written notes that interested students and potential instructors can go to. We envision 150-200 pages per module and hope to identify a way to publish these at low cost.

3. **Homework exercises**
Homework exercises are essential if these modules are to be used in the classroom. Instructors need HW problems with worked out answers. This is especially true for these modules because the material is new to the intended instructors as well as the students. Modules should be accompanied by standard homework problems with solutions. When appropriate, we will include MATLAB exercises and/or interactive simulations provided through the nanoHUB.

4. **Simulation exercises**
The nanoHUB provides a unique capability to use live simulations in education. These may be HW exercises that use a simulation tool to reinforce concepts presented in the lecture. They may also be special simulations developed to illustrate specific concepts.

B. Choice of Topics: Topics will be carefully selected with the following criteria in mind:

(1) Uniqueness of content: The material should not be easily available elsewhere else. Indeed, each module will be an original contribution to the field and a model for subsequent textbook writers.

(2) Relevance and interest: Although we are aiming for a broad audience, our primary target

is students preparing for careers in the electronics industry and professional engineers already working in industry.

(3) Level: Although we hope to attract undergraduates, graduates and professionals, the level of presentation will be targeted at college seniors and beginning graduate students with an introduction to each module that is accessible to college freshmen. The material will be self-contained with a clear statement of the necessary prerequisites.

With these criteria in mind we have identified a preliminary list of four course modules.

1) ***Fundamentals of nanoelectronics (Datta)***
(An introduction to the bottom up way of thinking about small electronic devices. This module will begin by explaining how to compute the I-V characteristic of a molecule and then develop the intellectual framework that is the basis of this series.)

2) ***Nanoscale transistors (Lundstrom)***
(A treatment of nanoscale MOSFETs from the bottom-up perspective.)

3) ***Carrier Transport at the nanoscale (Alam and Lundsrom)***
(The drift-diffusion equation is the basic description of carrier transport for traditional electronic devices. This module will use a novel approach that begins with ballistic transport, then adds scattering and then treats stochastic (percolative) transport. The basic techniques students need to analyze modern, nanoscale electronic device will be developed.)

4) ***Reliability of nanoelectronic devices (POC: Alam)***
(Device reliability is rarely taught in academia, but device and circuit designers need to understand the physics of reliability at the nanoscale. At the microscale, reliability must be treated phenomenologically, but at the nanoscale, reliability can be directly related to physics.)

These four modules are a starting point. Several more could be envisioned, and as the project proceeds, we will consider adding additional modules.

C. Review and Assessment:

Peer review: We hope the engage our colleagues in educational institutions world wide in order to review the modules and related materials and to test them in a classroom setting. Our ultimate objective is to prepare faculty at universities worldwide to incorporate these new materials in their own curricula. (Potential academic partners should contact Mark Lundstrom.)

Statistics: The NCN will provide usage statistics so that we know how much these materials are being used, where they are being used, and by whom.

Assessment: Educational experts will conduct assessments of these materials to determine how effective they are in helping students learn. Based on the result of the peer review and online assessment, each learning module will be revised and re-deployed. Intel and the authors will work together to market the learning modules through a series of on-site workshops.

The overall process seeks to engage the entire NCN@Purdue team in the development of each module along with external advisors and experts at Intel and in academia. At any one time, one module will be in the process of being defined, another in the process of being produced, and a third in the process of being reviewed and revised. During the course of this work, we expect to have numerous opportunities to present these modules live at various tutorials and workshops. At the midpoint, and then again at the end of the overall project, several multi-day workshops will be conducted at locations worldwide to be determined by Intel. Intel support for travel and meeting expenses will be requested for this stage of the process.

D. Dissemination: Broadly we can classify our dissemination plans into two categories: on-line and on-site. Each of these is discussed below.

<u>Online through www.nanoHUB.org</u>

The NCN's nanoHUB, a resource for online simulation and more, is much more than a web page; it is a sophisticated science gateway that provides live simulation services and access to educational resources. The annual usage is over 20,000 and growing rapidly. The nanoHUB is a good forum to host our educational modules because it has gained significant visibility, momentum, and credibility in the nanotechnology community of scientists, educators, and most importantly with students. Well-established processes provide clear procedures for developing, deploying, revising, and assessing educational content.

<u>On-Site</u>

It is important to complement the online learning materials with workshops where the module developers will interact face-to-face with Intel engineers and the faculty who will teach these new materials to students. In addition to disseminating the modules online, we plan to present a set of live workshops at national and international locations. These workshops would be specifically directed at faculty, with the objective of facilitating the use of these new materials in engineering curricula worldwide.

6. Summary

Forty years ago, a committed group of individuals changed the way engineers were educated. The Electronics from the Bottom Up series will produce a set of educational modules that could have great impact on the way engineers are educated in the future. We have an opportunity to engage and energize a new generation of young people and prepare them to address the challenges of electronics in the 21st century.