

Web-based Instruction on the Fundamentals and Design of Micro- and Nanoelectronic Processes: Innovations, Challenges and Benefits*

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The focus is a web-based course on the fundamentals and design of micro- and nanoelectronics processing developed two years ago and offered once a year. To our knowledge, this is the first chemical engineering course on micro- and nanoelectronic materials and processing ever to be offered on the Web. Through this graduate/advanced undergraduate web-based course, we present and discuss related innovations, challenges and experiences on the impact the Internet is having in the field of engineering education, new technologies in engineering education, and preparing students for the challenges of nanoengineering in the 21st century.

INTRODUCTION

INCREASINGLY, more chemical engineers are entering the field of electronic materials and processing, in part because basic knowledge of this fast growing field lies in chemical engineering (ChE). Some representative example systems include [1–7]:

- novel nanometer-length scale dielectric materials;
- passivation of silicon and silicon germanium;
- surface and gas phase reaction chemistry in micro- and nano-fabrication;
- impurity diffusion through the films;
- process-structure-function relationships in the processing of micro- and nanometer-length scale electronic materials.

Chemical, electrical and material engineering principles in the fundamental understanding and design of microelectronics processing are bringing about great changes in integrated circuits, micro-electromechanical systems (MEMS), and other fields in which data acquisition, computation, or controls are necessary. Several engineering departments have been either offering courses in micro- and nanoelectronic materials and processing or incorporating several examples and case studies in core curriculum engineering courses (e.g. [8]).

We started a dual-level class (offered to graduate and advanced undergraduate students) entitled 'Fundamentals and Design of Microelectronics Processing' in Spring 1997. The objective of this

course was to provide participants and students the basic principles and practical aspects of the most advanced state of micro- and nanoelectronic materials processing as well as MEMS processing. The principles and philosophy underlying the selection of topics and their ordering focused mainly on fundamental notions of transport, reaction kinetics, thermodynamics, and reactor design along with process-structure relationships in electronic materials and nano/microfabrication.

In 1998, the scope and effectiveness of this course was substantially enhanced and augmented with the introduction and implementation of two web-based semiconductor simulation tools [9]: *ThermoEMP* and *TSuprem-4*. In Spring 2000, it became a web-based course, the effectiveness and innovations of which were further enhanced and expanded. At the present time, this course is also a part of the UIC Master of Engineering (M.Eng.) Degree Program, which is offered online.

The brief outline of the web-based course on nano- and microelectronic materials processing which consists of 43 lectures and extensive external links:

- Introduction (3 lectures)
- Crystal growth (4 lectures)
- Thin film deposition (14 lectures)
- *ThermoEMP* as a simulation tool (1 lecture)
- Passivation of Electronic Materials (4 lectures)
- *TSUPREM-4* as a simulation tool (1 lecture)
- Ion implantation (3 lectures)
- Advanced lithography (5 lectures)
- Dry etching (4 lectures)

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- Wet etching (2 lectures)
- Design of experiments (2 lectures)

INNOVATIONS OF WEB-BASED COURSE INSTRUCTION

In order to design effective class material for all students, we needed to take into account different ways of learning that included visual, audio, reading and writing, and interactive modes. Therefore, material had to be prepared with the different learning styles in mind. Various components were incorporated into the ChE class materials so as to mimic and enhance the real live experience of a classroom. Audio segments of the professor lecturing, for example, discussed specific issues and topics in depth. On the web, there were several effective ways to communicate and interact with the professor, teaching assistant, and classmates. By means of 'asynchronous and synchronous' communication tools such as e-mail, bulletin boards and chat rooms, the students in the class could substantially interact with the instructor and fellow classmates in Spring 2000 and 2001.

Text on a computer could be easily improved by taking advantage, for example, of HyperText Markup Language (HTML) and hyperlinks. It could be prepared to look like a book or a set of slides. In our course, an electronic set of extensive

written notes were included as the core reference material. Several references and relevant journal articles as well as other reading assignments were utilized every 3–5 lectures. HTML also helped us to incorporate rich media such as photos, drawings, audio, interaction and, more importantly, hyperlinks. Electronic sets of written notes can be updated and published on the website immediately. This is a significant benefit since current research and development would require material to be updated and enhanced frequently. Yet, the overall preparation of the first electronic set of written notes coupled with photos, audio, interaction, hyperlinks and drawings turned out to be a substantial commitment of time, effort and resources. It was estimated that our course took about three times more time and effort for its initial preparation on the website compared to the preparation for a well-run traditional course. Figure 1 shows an actual web page of our class that contains lecture material prepared using text with audio, hyperlinks, and additional explanations.

The basic components of the Web teaching approach used in the course were the following:

- Announcements, Course Information, Staff Information, Course Documents, Assignments, Bibliography, Communication, Student Tools, Resources, and Course Map links;

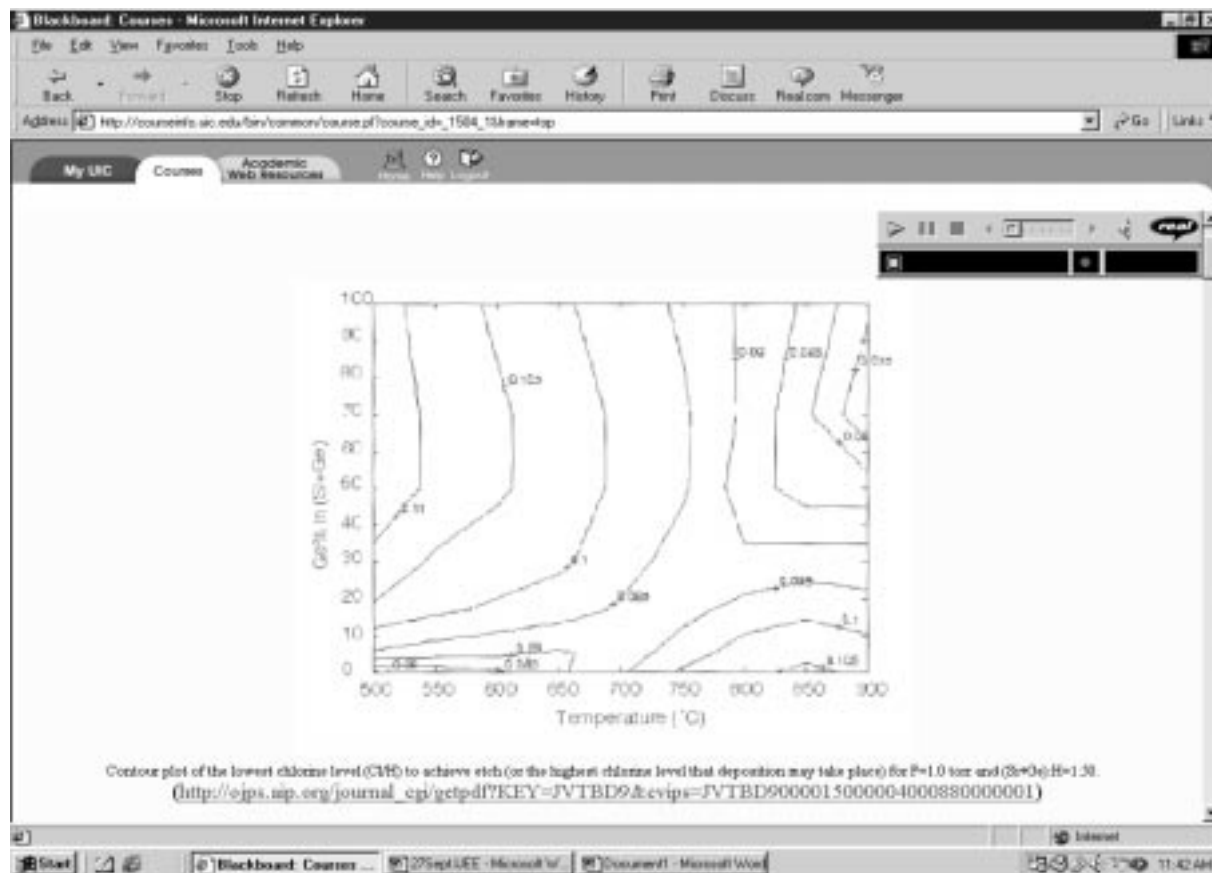


Fig. 1. Example of an actual web page of the class material; it demonstrates the use of different media.

- The Course Information Link has four items: Course Introduction, External Links, *ThermoEMP*—A Step-by-Step Manual, and *Tsuprem-4*—A Step-by-Step Manual;
- The Course Documents link includes References, Semiconductor Glossary, the Lectures, *ThermoEMP* and *Tsuprem-4* Examples, Material for the Help Sessions, and the Midsemester Exams (after they are taken);
- Each lecture includes an electronic set of written notes, 6–7 audio segments, each about four-minutes long, photos, drawings, and hyperlinks as needed.
- The Assignments link includes Quizzes, Homework Assignments, Reading Assignments, and Solutions to the Homework Assignments as needed;
- The Communication link includes: Send E-mail, Discussion Board, Virtual Classroom, Roster, and Group Pages; and
- The Student Tools comprise of Digital Drop Box, Personal Information, Calendar, Check Grade, Manual, Tasks, Electric Blackboard, and Address Book.

Web-based learning was beneficial for those who could not attend classrooms because of their personal or professional commitments, limited financial resources, or physical limitations. For example, people working in industry could now take the course, while they stayed at their work place. Also, professionals, who wished to pursue the UIC M.Eng. (a degree based on online courses at UIC), they would have the opportunity to do it, given that this course on micro- and nanoelectronic processes is part of the UIC M.Eng. Degree Program. Indeed, these were some of the important factors of teaching this course in a web-based format.

Two innovations in this ChE course are also the web-based simulation tools *ThermoEMP* and *Tsuprem-4* [9]. *ThermoEMP* is a computer simulation program that calculates the chemical equilibrium compositions of microelectronic materials processing; results are generated through a methodology that minimizes the Gibbs free energy of the system via a rigorous thermodynamic analysis [10]. The minimum temperature above which oxide-free silicon growth (a very important requirement in the electronics industry) or silicon carbide growth or gallium nitride growth can take place, or the effects of dichlorosilane flow rate and temperature on the selective epitaxial growth of silicon or silicon germanium ($\text{Si}_{1-x}\text{Ge}_x$) can, for example, be effectively studied *a priori* and very quickly.

Figure 2 shows this basic three-step web-based simulation tool. Figure 2a illustrates the commands associated with the ‘input file,’ while Fig. 2b shows the execution step of the simulation. With a database of more than 2000 species, several thousand simulations per second (computer time) can typically be done. Hence, vast regions of the

parameter space may be explored over a short period of time. Figure 2c includes the basic layout of the output files. A remarkable aspect of such studies is that students experience key issues in real life problems and they have the opportunity to see that solutions may be obtained, in some cases at least, within a very short period of time without doing *any* experiments, i.e. from fundamental knowledge-driven simulation tools [9]. For example, Fig. 1 demonstrates the contour plots of the lowest chlorine level (e.g. Cl/H) required to achieve etching (or the highest chlorine level that deposition may take place at) for a total system pressure of 1 torr and the initial ratio of $(\text{Si} + \text{Ge}) : \text{H} = 1 : 50$; these results have been obtained through *ThermoEMP* and have been essential in the selective growth of $\text{Si}_{1-x}\text{Ge}_x$ in low-pressure deposition reactor systems that included dichlorosilane and germane as the source feed gases for Si and Ge, respectively [11, 12].

Tsuprem-4 (licensed from Technology Modeling Associates (TMA), Inc.) is a computer program simulating the processing steps involved in the manufacture of silicon integrated circuits, discrete devices and MEMS [13]. This program can simulate a highly wide range of processing steps. Examples are ion implantation, inert ambient drive-in, silicon and polysilicon oxidation and silicidation, epitaxial growth, low temperature deposition and etching of various materials. For each such process, plots can be easily obtained for many variables (e.g. dopant concentration profiles). Figure 3 illustrates the three basic stages of the web-based use of *Tsuprem-4*: the web pages for the ‘input file’ (Fig. 3a), the execution and program status stages of the simulation (Fig. 3b), and the layout of the output files as well as the output of a specific case study included in the input file (Fig. 3c).

Another example, based on *Tsuprem-4*, is presented below. This was part of assignments given to the students after the topic of ‘ion implantation’ had been taught in the class. It includes multiple ion implantation processes coupled with an annealing step; such realistic situations require numerical calculations that a sophisticated simulation tool, like *Tsuprem-4* in this case, should be able to take care of. After this stage, students were asked to investigate and explore the effects of varying system parameters along with possible additional processing steps through the use of *Tsuprem-4*. At this point, the simulation tools’ ease of usage and ability to give fast results were found to be very helpful.

Example case study based on *tsuprem-4*

Use *Tsuprem-4* to simulate the process run which had the implantations and oxidations as listed below (show your ‘program’ output):

- N-type (100) wafer, phosphorous doped $N_D = 6 \times 10^{14}/\text{cm}^3$

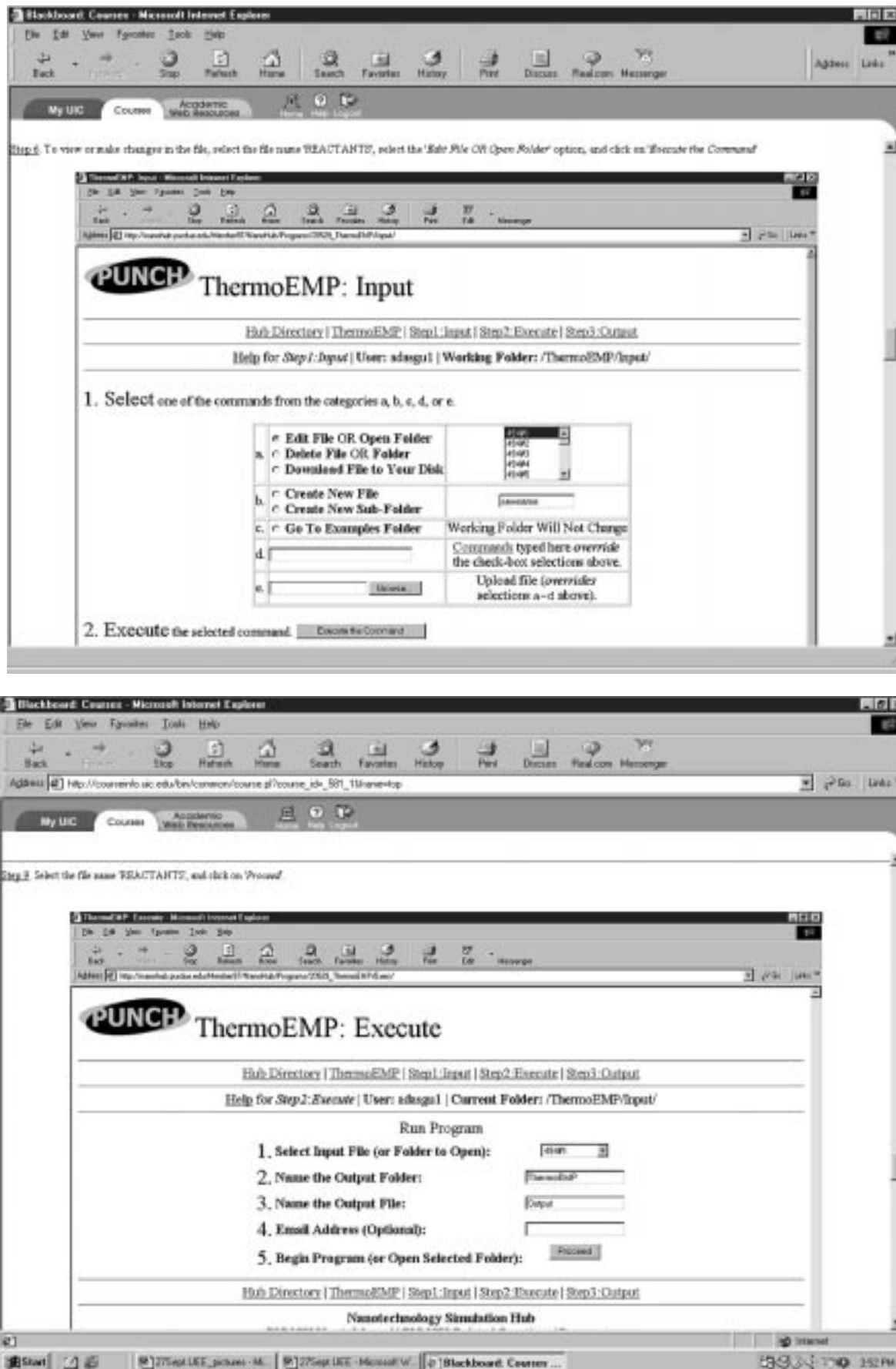


Fig. 2. The three steps of the web-based simulation tool *ThermoEMP*: (a) preparation of the input file; (b) execution of the simulations; (c) acquiring of the output files.

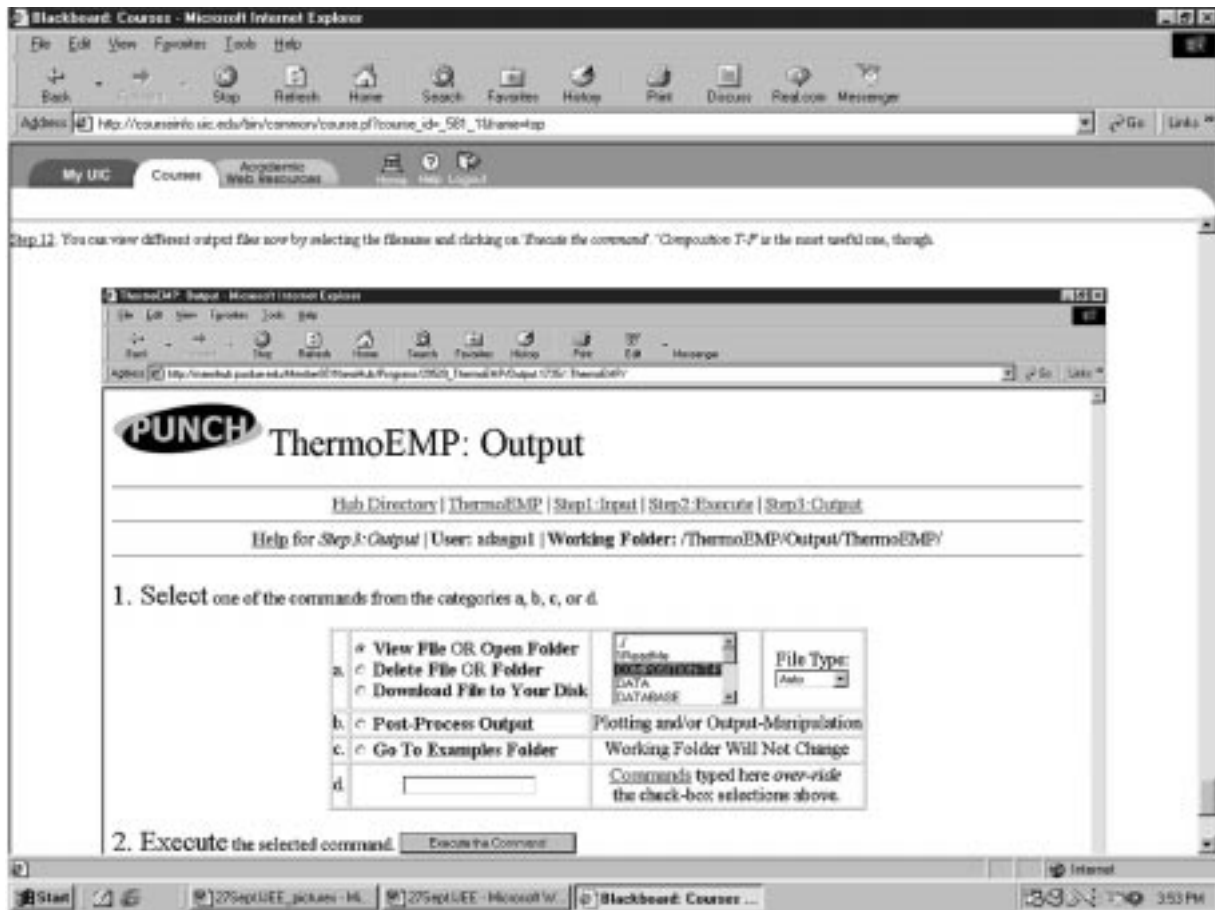


Fig. 2. Continued.

- Boron ion implantation at 90 KeV and a dose of $9 \times 10^{12}/\text{cm}^2$. Plot the LOG_{10} of $/\text{cm}^3$ vs distance into the substrate. What is the junction depth?
- 1050°C anneal for 20 min in N_2 . Plot the LOG_{10} of $/\text{cm}^3$ vs distance into the substrate, before and after annealing, on the same plot as above. (i) What is the junction depth? (ii) What is the approximate peak doping concentration?
- After above two stages, an additional arsenic ion implantation at 70 KeV with a dose of $7 \times 10^{14}/\text{cm}^2$ is applied and then annealed at 1000°C for 15 min in N_2 . Plot the LOG_{10} of boron, phosphorus, and arsenic as well as the net doping $/\text{cm}^3$ vs distance into the substrate on the same set of axis. Are there any p-n junction(s)? If yes, how far are they from the surface?

The tandem and organized use of both semiconductor simulation tools has been developed and introduced for the first time to advanced level courses in micro- and nanoelectronic materials and their processing for better understanding of the basic principles and practical aspects of the most advanced state of the processes and design of micro- and nanofabrication techniques.

BENEFITS OF THE WEB-BASED COURSE AND ASSESSMENT OF STUDENTS' PROGRESS

The instructors and students received immediate feedback. It was particularly useful for those students, who perhaps were shy and afraid to ask questions in public, as indicated by the students' instructor and course evaluations at the end of the course. Another advantage was accessibility. Instructional material was available 24 hours a day. Because the instructional material was always available, learning was self-paced. One characteristic example was the case of three students, who expressed the wish to start taking the course a full month before the beginning of Spring 2002, because of their upcoming course-load and the full-time work-load for one of them. Thus, the material for the first 15 lectures became available to them ahead of time; this kind of flexibility is indeed unique for web-based courses.

From the instructor's point of view, the preparation, editing and publishing of all material on the website for the first time was a huge undertaking. Once the class material was in electronic format, it was easier to modify/update it. Students substantially benefited from the web-based simulation tools, which could indeed prepare them and enable them to meet the challenges of fundamental

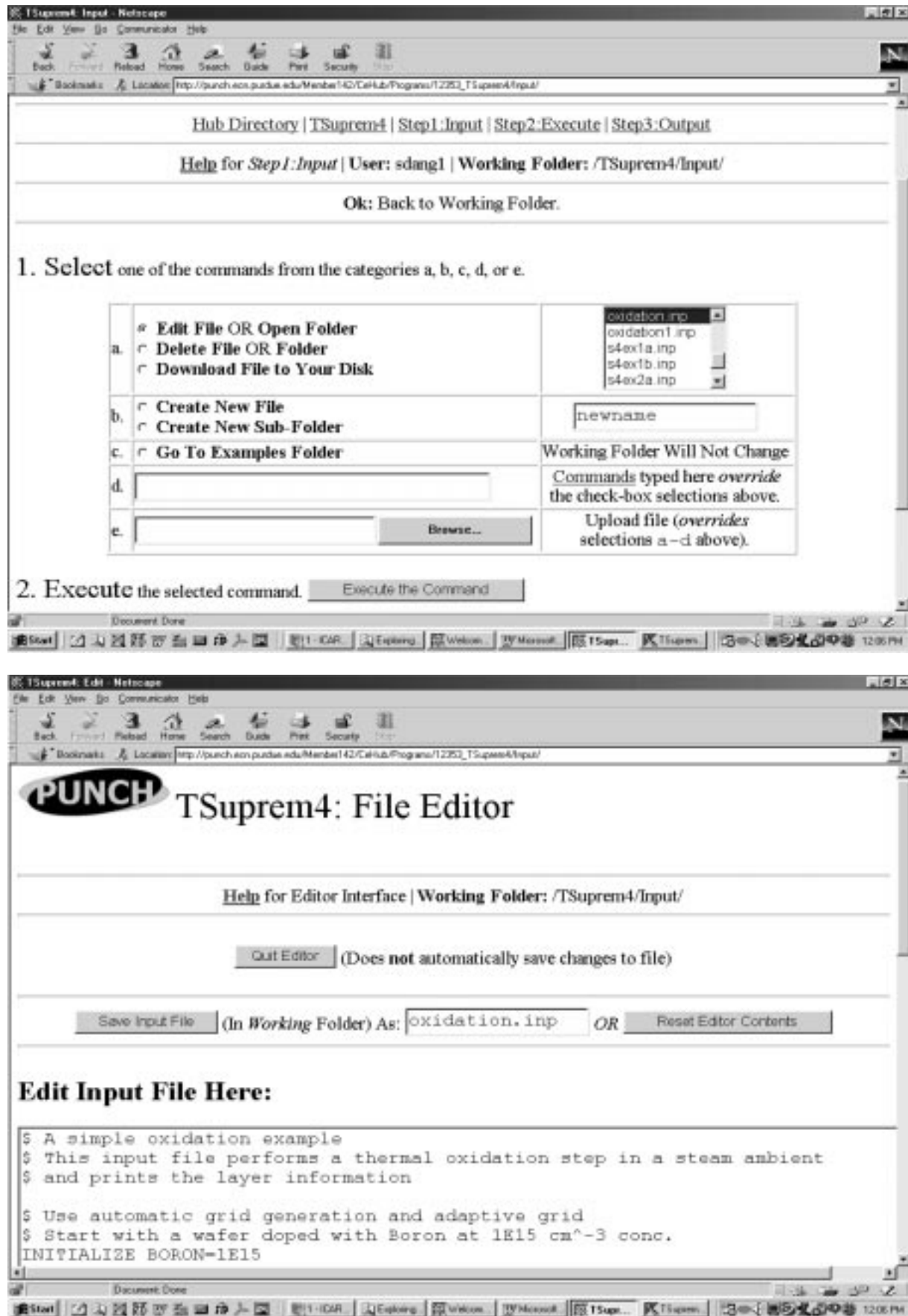


Fig. 3. The three steps of the web-based simulation tool *TSuprem-4*: (a) web-based commands for and an example of the input file; (b) execution and program status stages of the simulations; (c) layout of the output files along with an example output file.

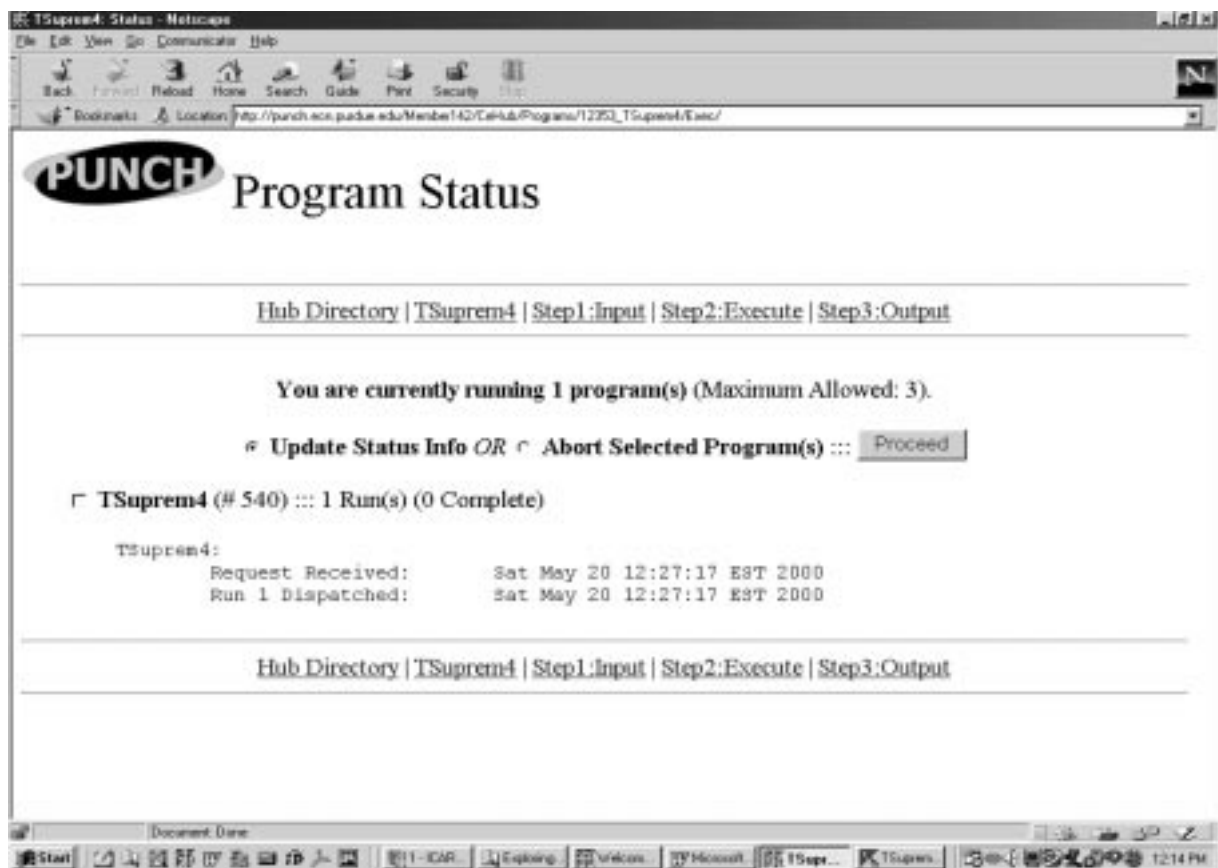


Fig. 3. Continued.

PUNCH TSuprem4: Output

[Hub Directory](#) | [TSuprem4](#) | [Step1:Input](#) | [Step2:Execute](#) | [Step3:Output](#)

[Help for Step3:Output](#) | User: sdang1 | Working Folder: /TSuprem4/Output/TSuprem4/

1. Select one of the commands from the categories a, b, c, or d.

| | | | |
|----|---|--|--------------------|
| a. | <input checked="" type="checkbox"/> View File OR Open Folder <input type="checkbox"/> Delete File OR Folder <input type="checkbox"/> Download File to Your Disk | TReadMe Output TIMELOG oxidation.out oxidation.ps | File Type: Auto |
| b. | <input type="checkbox"/> Post-Process Output | Plotting and/or Output-Manipulation | |
| c. | <input type="checkbox"/> Go To Examples Folder | Working Folder Will Not Change | |
| d. | <input type="text"/> | Commands typed here <i>override</i> the check-box selections above. | |

2. Execute the selected command.

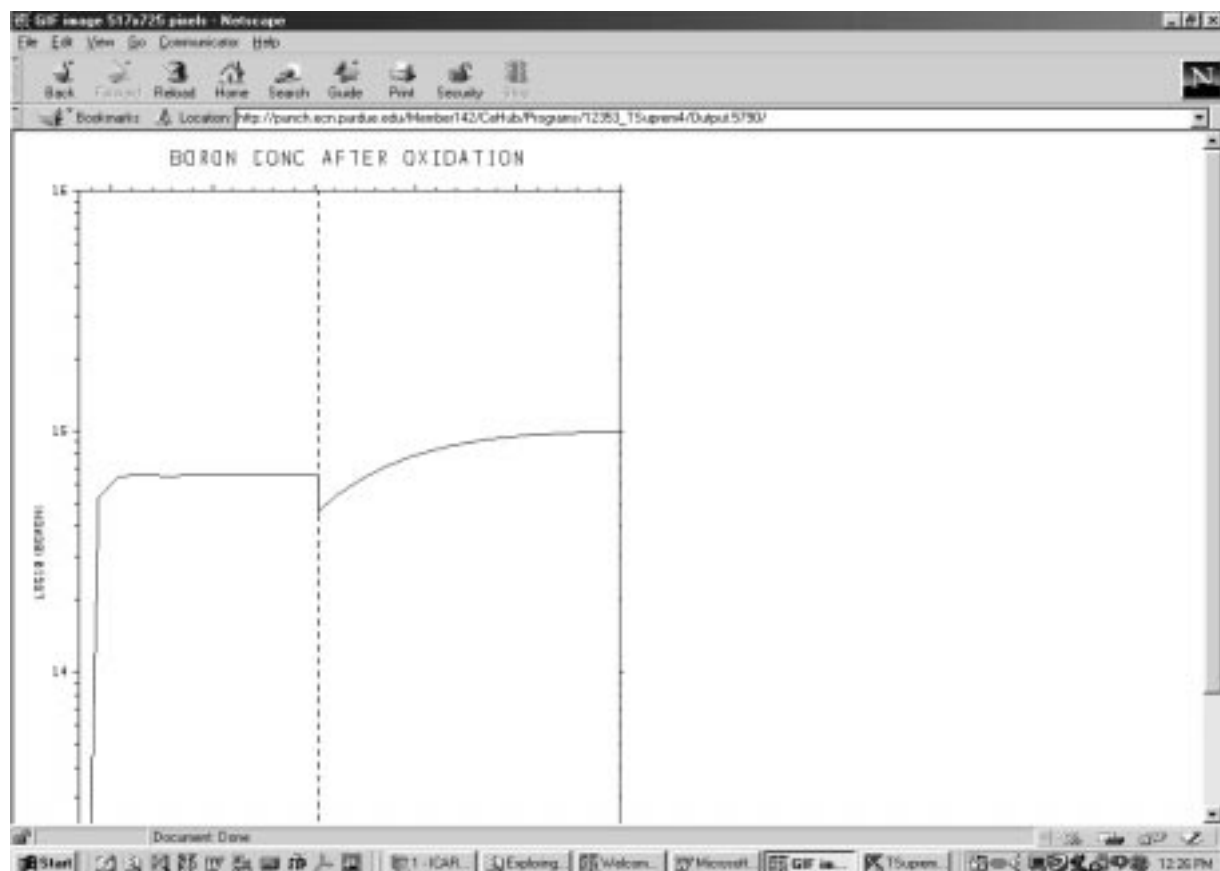


Fig. 3. Continued.

knowledge-driven engineering of micro- and nanometer length scale systems.

Assessing the progress of students in the web-based ChE course was superior to that in the conventional classroom. Each lecture had an essay type quiz, which was graded electronically by the instructor/teaching assistant. This system of quizzes was found to be extremely effective, beneficial and challenging to the students. The implementation of one quiz per lecture is almost impossible for classroom courses, in part because of time considerations. Homework was posted on the website and had to be turned in electronically. Exam assessment might be done electronically, but with the present technology it was deemed 'safer' to do it the old fashioned way: in a classroom. Before each exam, there was a help session offered in both formats: on the website and in the classroom. The web-based help sessions were offered in the format of a virtual classroom.

During the last five times this course was offered, the number of students has typically been about fifteen. The first time this course was taught on the web, in Spring 2000, there was one off-campus student. The second time, there were five off-campus students. A direct comparison of the averages on the mid-semester and final exams in the website (Spring 2000, and 2001) and traditional formats (Spring 1997, 1998, and 1999) of the course showed that students in the website format scored about 15% higher than those in the traditional one.

Yet, in such comparisons, two apparent assumptions have to be considered:

1. The exams had comparable difficulties.
2. The average caliber and background of the students who took the course during the last five spring semesters were the same.

We believe that the former assumption was a good one. However, the latter assumption is very difficult to check.

CHALLENGES FOR THE STUDENTS AND THE INSTRUCTOR

One of the key challenges is the organization of the material and the teaching strategy of such instruction, since the course typically involves engineers and scientists from several different disciplines. The use of web-based multimedia appears to be particularly useful for classes involving participants with diverse scientific and technical backgrounds. Also, the feedback and written evaluations of the students on the scope and instruction effectiveness of the two web-based semiconductor simulation tools, *ThermoEMP* and *TSuprem-4*, have been overwhelmingly positive [9, 14]: it was easy to figure out how to use the simulation tools, the overall class experience was substantially enhanced by the use of the software,

and it was convenient to have universal access to programs via the web.

The feedback and written evaluations of the students on the scope and instruction effectiveness of their first ever web-based course included several useful points. The students were strongly positive about:

- the convenience of taking a lecture at any time, any place and pace they wished;
- the flexibility of getting started with the course material well before classroom courses were scheduled to start,
- the effectiveness of learning through the use of several multi-media approaches;
- the use of one quiz for each lecture;
- the availability of hyperlinks to several websites of interest and reference;
- the help session(s) before each exam;
- perhaps, above all the half an hour long optional weekly meetings we had in the classroom throughout the semester. These meetings turned out to be very important in the troubleshooting of many aspects of the implementation of this course on the website the first time.

The live help sessions in the classroom before each exam as well as the weekly classroom meetings were praised as 'extremely helpful'.

Further insight that was gained from our experience as to how to improve attempts at true 'distance' education and how to meet new challenges of web-based instruction on nano- and microelectronic materials and processing included: unavailability of effective means for proctoring tests and exams outside the classroom, substantial benefit from video-conferencing, need for more thinking about minimizing students' tardiness with the class material, and partial lack of ideas on how to handle students who may be willing to finish the course material (and possibly everything else) at a fast pace, say, in 8 weeks instead of 16 weeks.

SUMMARY AND FUTURE PLANS

The ability to instantly communicate and exchange information with anyone at anytime, anywhere in the world, i.e. the Internet, has eliminated distances that once kept people apart. Here, we have focused on a course on the fundamentals and design of micro- and nanoelectronics engineering that was offered for the first time on the Web in Spring 2000, and for a second time in Spring 2001. Through this web-based dual-level ChE course, we have presented related innovations, experiences and challenges on the impact the internet is having in engineering education, fundamental knowledge-driven technologies in engineering education, and effective preparations for the upcoming challenges of nanoengineering. We have also examined the Internet's potential benefits to learning in the context of teaching

a graduate/advanced undergraduate web-based engineering course on the fundamentals and design of micro- and nanoelectronics processes.

One of the interesting points that have come out from the students' feedback is their request for some lab experiments that could probably accompany this web-based course. Currently, participants and students, who have taken this web-based course, typically take next the course EECS 449, 'Microdevices and Micromachining Technology Laboratory,' which is offered by the Electrical Engineering Department at the UIC. The sequence of these two courses ChE 494 and EECS 449 appears to be very effective in providing the fundamentals and the hands-on experiences in micro- and nanofabrication. However, there are two plans for the immediate future, besides the continuous updating of the existing course material and its online form of presentation:

1. The addition of computational fluid dynamics software that is expected to significantly enhance the web-based educational experience in the fundamentals and design of nano- and microelectronic processes.
2. The enhancement of the possibilities of sharing the experience with other universities.

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