EDUCATIONAL EXPERIMENTS WITH AN ONLINE MICROELECTRONICS CHARACTERIZATION LABORATORY

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Abstract ¾ We have developed and deployed an online microelectronics characterization laboratory that allows the characterization of transistors and other microelectronic devices in real time through the internet. The architecture of this system was devised to accomplish two goals: 1) the delivery of a rich educational experience in microelectronic device characterization to remote computers, and 2) the ability to scale to a large number of students as well as multiple courses. This system has allowed the introduction of device characterization projects and other laboratory exercise in microelectronics subjects that did not have a laboratory component in the past. We have demonstrated the scaling potential of this system through multiple educational experiments. At any one time, as many as 170 graduate and undergraduate students used the systems from locations in the U.S. and in Singapore. Since this project was launched in 1998, over 600 students have used the system in 9 different subjects.

Index Terms ¾ microelectronics, remote laboratory, WebLab,

INTRODUCTION

In the teaching of microelectronic device physics, hands-on characterization of transistors and other devices substantially enhances the educational experience. However, conventional courses in microelectronic device physics often do not include a laboratory component. This is because of equipment, space, user training, safety and staffing constraints that become nearly insurmountable for medium and large size classes. A remote laboratory that allows the characterization of microelectronic devices without the need for the user to be in front of the experimental set up solves many of these logistics concerns while largely preserving the educational experience. The use of web technology, in particular, allows the creation of such a laboratory while imposing minimum requirements on the remote user. Many institutions in different fields have explored this concept of a web-enabled remote laboratory [1-8].

There are several advantages to an online microelectronics device characterization lab:

- The experimental setup can be made available at any time of the day and night. This allows students to conduct their measurements whenever they wish.
- There are no special staffing requirements. Once the device is in place, no further staffing of the lab is required.
- The system is nearly as flexible as the instrumentation itself. This means that no new programming is necessary whenever a different device or measurement routine is required.
- There are no safety concerns. Students work from the safety of their homes or institutional computer clusters. No safety training is required to use the system.
- Scarce instrumentation and lab space can be effectively shared by many students. The system queues requests and executes them in real time. Under most circumstances, students have the feeling of “owning” the entire measurement setup. Furthermore, spreading the cost of the equipment among many users allows the use of the very same state-of-the-art equipment that students will face in industry after graduation.
- Training is manageable since students need only learn those instrument functions that have been programmed in the software interface. This cuts down the size of the manual from many pages to just a few. The manual can be made available on line.

Over the last few years, we have built a system at MIT that makes microelectronics device characterization over the Internet possible [1]. We call it the MIT Microelectronics WebLab, or WebLab for short. Through WebLab, students can take current-voltage measurements on transistors and other devices in real time from anywhere and at anytime. This paper summarizes the WebLab system and the lessons we have learned from its deployment in educational experiments. It is organized as follows. Section 2 briefly describes the architecture of the WebLab system. Section 3 discusses the educational use of WebLab to date and the lessons learned. Section 4 summarizes our major findings and charts out the future of the WebLab project at MIT.

WEBLAB SYSTEM ARCHITECTURE

At its essence, WebLab consists of instruments to characterize microelectronic devices and a group of computer hardware and software components that bring the laboratory experience onto the World Wide Web. This section presents a brief description of the system architecture. A more detailed description of WebLab’s

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architecture as well as its user interface has been published elsewhere [1].

Fig. 1 sketches the system architecture of the latest version of WebLab, v. 4.2 (deployed in September 2001). This core architecture has not changed since the beginning of the project in 1998. This architecture was devised with two key goals in mind: 1) the delivery of a rich educational experience in microelectronic device characterization to remote computers, and 2) the ability to scale to a large number of students as well as multiple courses. The first goal was achieved through the use of a Java applet that runs on a conventional web browser. This Java applet mimics the front panel of the Agilent 4155B Semiconductor Parameter Analyzer, the instrument that performs the WebLab measurements. The applet grants the remote user a high degree of freedom in programming the instrument and in graphing the measured data. It also enables downloading of the measured data to the local hard drive.

WebLab's scalability was accomplished through several architectural features that minimize the use of the server and the test equipment during client sessions. Communication between the Java applet and the WebLab server is carried out through the HTTP protocol. A queing system on the WebLab server queues and executes requests in the order in which they are received. A switching matrix allows the remote selection of one device out of eight possible devices that are connected to the system. Additionally, a remote management system combined with a database permits the flexible and efficient management of large numbers of users.

In a WebLab session, the user prepares test vectors that describe measurements on the Agilent 4155B, executes them, views the obtained data, and downloads the data to the local machine. Under the WebLab architecture, test vector preparation is done through the WebLab Java applet that is downloaded onto the client computer. The test vectors are also validated on the applet, so invalid inputs are never submitted to the server, thereby reducing server traffic and increasing the availability of the lab equipment. Only when a valid measurement is submitted, does the client establish connection with the instruments in the lab. The WebLab server queues the incoming requests until the instruments become available. The Agilent 4155B executes a measurement in a few seconds (the exact length of time depends on the details of the measurement), so the queue is rarely long.

After measurement execution, the instruments return numerical results to the user through the server, and the server terminates the connection with the client, instantly making the lab available again to a different user. The display and processing of the results are carried out on the client machine. This design fully realizes the sharing potential of Web-controlled labs that leads to high responsiveness, great access flexibility, and extremely low per-user costs.

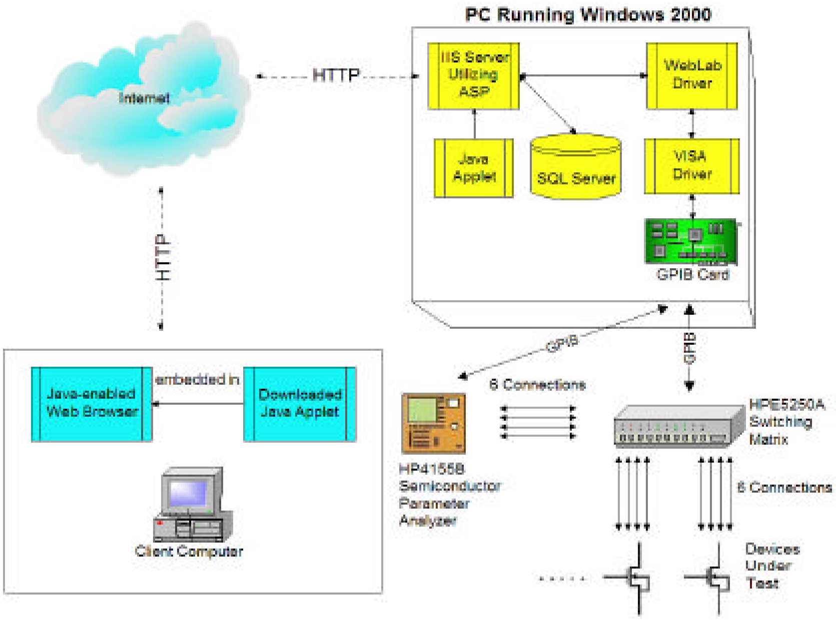

FIGURE 1: ARCHITECTURE OF WEBLAB (VERSIONS 4.0-4.2).

EDUCATIONAL USE OF WEBLAB

WebLab was first deployed for education at MIT in the Fall of 1998. Since then, WebLab has been used in remote laboratory assignments by over 600 students. Figure 2 graphs the use of Weblab per calendar year. Just in the Fall 2001 semester, over 170 students used Weblab in three different subjects simultaneously.

The majority of WebLab usage has been by MIT students enrolled in MIT courses. We have also carried out educational experiments in cooperation with National Singapore University, in the context of the Singapore-MIT Alliance (SMA), and Compaq Corporation. Figure 3 summarizes the locations of a particular set of experiments carried out in the Fall of 2000. These and other experiments will be described in this section, but before that, we will discuss the educational content of the WebLab exercises.

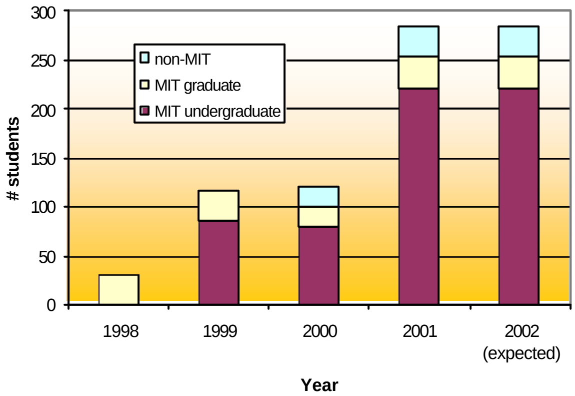

FIGURE 2: WEBLAB USAGE SINCE 1998.

In our educational experiments, we have found that there are three aspects to the educational experience associated with WebLab exercises. These are the construction of the test vector, management of the data display, and offline data manipulation.

There is a great deal of educational value in the preparation of the WebLab test vector. Of the many test vectors that one could prepare, only a few respond to the specifications of the exercise, so the students are forced to pay attention to the precise requirements of the exercise. Configuring the test vector also brings to the fore issues of measurement range, data point distribution, measurement speed, and device compliance. Additionally, the students are made aware of how the instrument actually carries out the measurements. The measurement specification portion of the WebLab Java applet user interface has been constructed to preserve a substantial portion of the experience associated with hands-on operation of the instrumentation; Weblab users are not spared from opportunities to prepare erroneous test vectors that do not respond to the assignment or that are not executable. Substantial learning takes place in the debugging of the test vector that results from these errors. Additionally, the flexible nature of the user interface allows students to follow their curiosity and explore other modes of operation of the DUT's that go beyond the specified assignment.

The second component of the WebLab educational experience concerns the data display. The results graphing portion of the WebLab user interface allows the user to easily select which variables to graph in three different axes (one abcissa and two ordinate axes), whether the scales are linear or logarithmic, and the range of all the scales. This graphing flexibility forces students to think about the optimal way to display the data and to study in detail the standard graphing formats followed in the microelectronics world.

The third educational aspect of the WebLab experience is offline data manipulation. A download button on the user interface allows the exporting of the obtained data to a file in a format that is easily portable to many standard data analysis software tools. The student uses his or her favorite software package to further process the data, extract parameters, build simple models and compare their predictions with the acquired data. One of our most significant findings is the clumsiness of most students in data manipulation. We discuss this below.

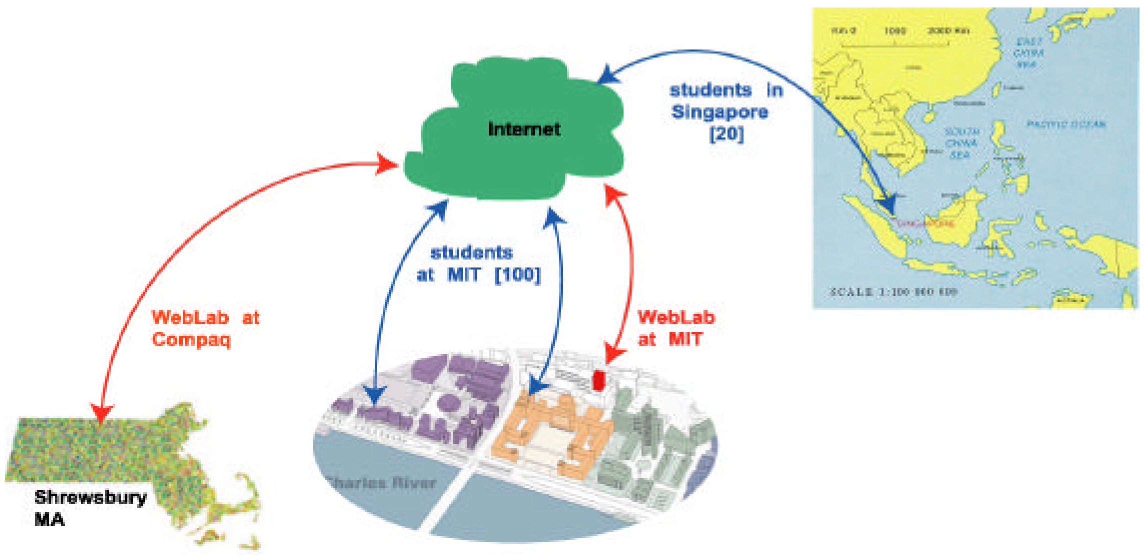

FIGURE 3
SUMMARY OF OUR EDUCATIONAL EXPERIMENTS WITH WEBLAB IN THE FALL OF 2000.

Over the last four years, WebLab has been used in three different courses: a junior-level subject on microelectronics devices and circuits at MIT (“6.012”), a graduate subject on microelectronics device physics at MIT (“6.720”), and a graduate level subject on electronic materials taken by students in Singapore as part of the Singapore-MIT Alliance (“SMA5104”). None of these subjects included a lab component previously. The next subsections summarize the educational experiments that we have performed and what we have learned from them.

Use of WebLab in Graduate and Undergraduate Subjects at MIT

Since its first deployment, WebLab has been used most effectively in device characterization projects. These are assignments that typically take 10 or 15 hours and include several elements:

- measurement of several types of device characteristics on a given device (for a MOSFET in a graduate class, they would be output, transfer, backgate, and subthreshold characteristics);
- graphing of the obtained characteristics in prescribed ways (using the applet or after data download);
- downloading the data onto the student’s local machine;
- extraction of multiple device parameters from the data set (for a MOSFET, examples are threshold voltage, body parameter, surface potential at threshold, k-factor, channel length modulation parameter, subthreshold slope, and off-current, among others);
- programming a model based on the equations that describe the device operation as presented in lecture (in the case of a MOSFET, the model will involve a set of equations that smoothly describe the I-V characteristics of the device in the linear and saturation regimes and involve finite output conductance);
- “playing back” of the model using the extracted parameters as inputs against the obtained data;
- measurement of other device characteristics of the student’s choice.

The last item in the list above, open-ended exploration, embodies the engineering laboratory experience at its best and is made possible by the flexibility of WebLab’s measurement specification frame. In response to a request of this kind, students typically study other device characteristics that are mentioned in class or that they have seen in other books. Some examples for a MOSFET are the diode characteristics of the source-body and drain-body pn junctions and observation of mobility degradation due to vertical electric field.

Device characterization projects constructed around WebLab have now become the norm in MIT’s graduate subject on microelectronics device physics, 6.720. In this class, three assignments are given every year (on diode, MOSFET and bipolar transistor). Simpler device characterization projects involving more elementary models are now also common in MIT’s undergraduate subject in microelectronics devices and circuits, 6.012. Since the Spring of 2001, all offerings of 6.012 have included WebLab exercises.

Use of WebLab from Singapore

In the Fall of 2000, WebLab was deployed for the first time in SMA5104, a subject offered by the Singapore-MIT Alliance (SMA). The Singapore-MIT Alliance was established in 1998 between the National University of Singapore (NUS), Nanyang Technological University

(NTU), and the Massachusetts Institute of Technology (MIT) to promote global engineering research and education. SMA offers several graduate degrees among which there is one in advanced materials. It is in SMA5104 “Fundamentals of Semiconductor Device Physics”, a course in this program, where WebLab was deployed to about 20 students in the Fall of 2000 and to about 30 students in the Fall of 2001. An interesting feature of this experiment is that not only the lab, but the instructor and the teaching assistant were also located at MIT, while the students were located in Singapore. As in 6.720, the SMA5104 WebLab assignments required extensive characterization of an n-channel MOSFET, device parameter extraction, and device model generation and playback.

The feedback received from the students in Singapore was similar to that obtained from the MIT students that used WebLab in 6.012 and 6.720: mostly excitement with the novelty of the remote laboratory experience combined with expressions of minor frustration with a few aspects of the system. Some suggestions for improvement were given by the students. Most of the suggestions were related to the user interface, and some reported bugs that we had not identified previously. No specific issues associated with the 9000 miles that separated MIT and Singapore were identified.

Use of WebLab from Compaq

In a third experiment, carried out in the Fall of 2000, we installed a copy of WebLab at Compaq’s Alpha Development Group center in Shrewsbury, MA. The purpose of this was to allow students in MIT’s microelectronics graduate subject 6.720 to have access to the then state-of-the-art 0.18 µm CMOS device technology that Compaq’s engineers were using to design leading-edge microprocessor products. In the Fall of 2000, Si wafers belonging to the 0.18 µm technology generation were closely guarded by microelectronics companies. Having a wafer on campus for our students to characterize was out of question due to intellectual property concerns. These concerns were eliminated by installing a copy of the WebLab system at Compaq’s site and having the students characterize the wafers remotely through WebLab.

Through this system, MIT’s graduate students were able to take remote measurements of 0.18 µm CMOS hardware, download the data, and compare the performance of modern deep-submicron CMOS technology with 10-year old 1.5 µm hardware that was made available through the on-campus WebLab system.

SUMMARY OF LESSONS LEARNED

In the four years that we have been using WebLab in education, we have learned a number of lessons. The most important ones are summarized here.

The first lesson is that students are intrigued and motivated by the novelty of WebLab and as a consequence, they pay considerable attention to WebLab assignments. Presumably, this results in more effective learning. To formalize this observation, we studied the homework assignments of 120 (mainly undergraduate) students enrolled in 6.012 at MIT in the Spring of 2001. In that semester, there were seven regular problem-based homework assignments and three device characterization projects using WebLab. We found that the average score in the WebLab exercises was 83, while the average score in the problem set homeworks was 72. Also, 96% of the 6.012 students turned in solutions to the WebLab exercises, while only 92% did the same for the traditional homework. These statistics show that the nature of the WebLab experiences catches the student’s interests. This can be exploited to further the educational goals of the subject in which WebLab is inserted.

The second conclusion is that students dread real laboratories and appreciate the convenience of the remote laboratory experience. Engineering students at MIT, as in other engineering programs, have to take a number of laboratory-based courses. Students know what real hands-on laboratory experiences feel like, and they generally dislike them because of the inconvenient locations and unpleasant environments of most laboratories. In contrast, WebLab offers a new level of convenience that students really value, and according to them, this allows them to focus on the educational issues.

The third significant finding from our WebLab experiments is that students, particularly in the undergraduate programs, have a great deal of trouble handling “real-world data.” In retrospect, this is not surprising since there are very few experiences in the traditional engineering curriculum that exposes students to this. We have learned that students often cannot distinguish “good” data from “bad”. They also have great difficulty manipulating measured data, such as graphing the data in another program or extracting parameters that describe a real device. We have also learned that students have very little intuition about what it takes to compare measured data with the theoretical models presented in class. Students often find themselves at a loss when they realize that the data do not fit the model perfectly.

The fourth lesson we have learned is that it is difficult to integrate the WebLab device characterization projects with the rest of a subject. This is probably the case because none of the subjects in which we have deployed WebLab had ever had a lab component in the past. In order to take advantage of WebLab, we have found that a certain degree of subject redesign must be carried out.

Analysis of accessibility and scalability

During the fall term of year 2000, we analyzed WebLab’s scalability during a week in which 75 students in an undergraduate subject on microelectronics devices and circuits at MIT had to carry out a WebLab assignment. For this assignment, a total of 1,237 measurements were submitted. Since the applet catches most of the errors on the client side, 92% of the requests received by the Agilent 4155B were valid test vectors and were executed. In other words, only 8% of the requests occupied instrument time with unproductive tasks.

In those experiments, we also found that the average execution time of a measurement (i.e. the amount of time the execution occupies the WebLab instruments) was 16 seconds. Using that value, we estimate that, in steady state, WebLab can handle up to 225 requests of this kind per hour, or 37,800 requests per week. Figure 4 shows the hourly distribution of requests the system received during the studied week. In the peak hour of usage, the system received 99 requests, about 44% of its steady-state capacity. Of these 99 requests, over 70% of all requests were executed immediately after being received by the server, about 25% had to wait for one job to be finished, and 3% had two jobs ahead of them – the queue had hardly been used. Even at its busiest hour, WebLab still had plenty of capacity available.

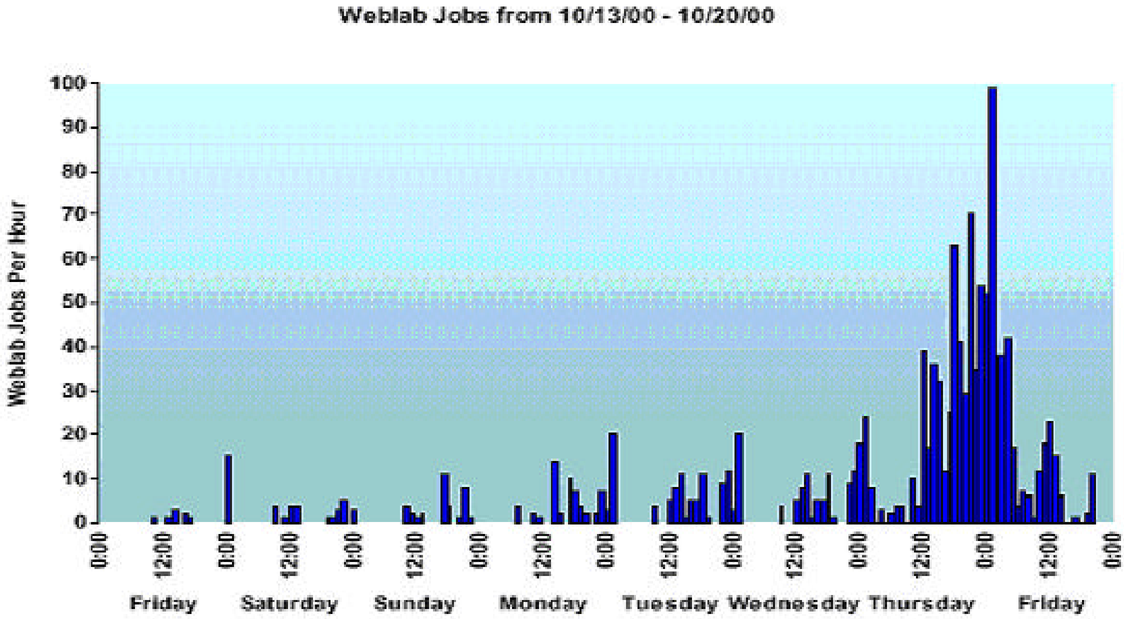

Figure 4: Hourly distribution of WebLab jobs received from 10/13/00 to 10/20/00 in an undergraduate MIT subject on microelectronics devices and circuits with 75 students.

CONCLUSIONS AND FUTURE PLANS

We have developed and deployed an online microelectronics laboratory to carry out real-time microelectronics device characterization through the Internet. The system was designed from the beginning to maximize accessibility and scalability. These features have been proven in a number of educational experiments that we have carried out. These experiments have also revealed that systems such as WebLab allow novel educational experiences with significant educational value.

Our future plans include the introduction of a remote-controlled hot-chuck to vary device temperature, the implementing a more intuitive graphical interface for test vector definition, and adding a new capacitance-voltage test capability. We are also working on integrating a simulation tool with WebLab. This would allow users to compare simulations with real-time measurements.

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