The MIT Microelectronics WebLab: a Web-Enabled Remote Laboratory for Microelectronic Device Characterization

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Abstract

We have developed a web-enabled remote laboratory (WebLab) for microelectronic device characterization. This system allows remote clients to communicate with a server and carry out real-time measurements on transistors and other microelectronics devices. On the client side, a standard Java-enabled web browser and an Internet connection is all is required to access the instrumentation. A queuing system allows multiple clients to perform experiments in nearly simultaneous basis. The system incorporates a state-of-the-art semiconductor parameter analyzer and a switching matrix. This allows remote users to select one device to be studied out of eight that are available at any one time. This feature permits the deployment of the system in several subjects simultaneously. We have used WebLab in undergraduate and graduate microelectronics device and circuit subjects at MIT. The system, which resides at MIT, has also been used by students from Singapore in a graduate subject in electronics materials. A copy of the system was also installed at an industrial partner's site and used by graduate students at MIT to characterize state-of-the-art 0.18 μm CMOS devices without triggering any intellectual property concerns on the side of the industrial partner.

1. Introduction

In the teaching of microelectronic device physics, hands-on characterization of transistors and other devices substantially enhances the educational experience. Through a properly constructed laboratory experience, students can characterize real devices and compare their operation with the theoretical models presented at lecture. In this way, they can extract parameters and reflect on non-idealities of the devices and shortcomings of the models. Through experimentation, students also gain an appreciation for device characterization techniques and develop data manipulation skills. Additionally, an open-ended laboratory experience allows students to independently explore device behavior following their curiosity. Close contact with the real world is always a powerful motivator and students learn better. The same can be said of many other domains of engineering where hands-on laboratory experimentation plays a critical role in high-level education.

Yet, in spite of these advantages, 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 versatile experimental set-up to obtain the current-voltage characteristics of microelectronic devices consists of a semiconductor parameter analyzer (such as an HP4155B) to which the device under test is connected. A semiconductor-parameter analyzer is a costly state-of-the-art tool that is widely used by device engineers in industry. In addition to its cost, the complexity of this tool represents a significant barrier to its deployment in a class. A typical manual spans hundreds of pages covering the many modes of operation that the instrument supports. Its front panel is covered with many keys and many more soft keys appear in the display in its various modes of operation. In addition to this, the logistics of student training and scheduling of exercises, particularly working with limited space, laboratory staff, equipment and large numbers of students, are daunting. If less expensive equipment is used, more test stations can be established, but at the cost of more space and staffing costs as well as a diminished educational experience.

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 integrity of 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. In fact, many instruments, including semiconductor parameter analyzers, allow for a certain degree of computer control. Hence, it is conceivable to “transfer” that control to a remote user through, for example, Java client-server technology. In this approach, clients equipped with a simple Java-enabled web browser can communicate with the instruments from anywhere at anytime.

There are several advantages to this approach:

- The experimental setup can be made available over extended periods of time 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 used 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 hundreds of pages to just a few. The manual can be made available online.

Over the last few years, we have built a system at MIT that makes this possible. We call it the MIT Microelectronics WebLab. We have deployed this system in a number of educational experiments in different course settings. Section 2 of this article describes the system. Section 3 describes some of the most significant educational experiments that have been carried out. Section 4 summarizes some of our future plans for this system. Several groups around the world are also investigating remote online laboratories similar to ours [1-5].

2. System Description

The basic architecture of the MIT Microelectronics WebLab [6] is shown in Fig. 1. It consists of three main components: 1) the testing hardware and the devices under test, 2) a server that doubles as instrument controller, and 3) one or more remote clients.

At the heart of the WebLab system is a HP4155B Semiconductor Parameter Analyzer. This is a state-of-the-art instrument that allows the measurement of current-voltage characteristics of microelectronics devices and small circuits with up to eight terminals. The testing hardware also includes an HPE5250A Switching Matrix [7]. This is an instrument that has been configured to multiplex up to eight different devices into the HP4155B. The use of a switching matrix provides redundancy against device blowup and allows the system to be used in different subjects at the same time. The devices under test are mounted in a packaged form onto standard test fixtures that are connected to the switching matrix. Control of both instruments, as well as data transfer out of the HP4155B is carried out through the GP-IB interface, a standard instrument control language.

The server hosting WebLab is currently an Athlon-class personal computer running Windows 2000 Server operating system. This computer carries the double function of instrument controller of the testing hardware and web server that communicates with the clients.

Communication between the server and the remote clients takes place through the HTTP protocol. For the remote user, this only requires the use of a computer equipped with a Java-enabled web browser and access to the Internet. When a user wants to initiate a session, it points its browser to an ASP (Active Server Page) on the server (weblab.mit.edu). After authenticating the user, the server downloads a Java applet to the client. Through this applet the remote user selects the device to test and specifies a test vector to be carried out.

When the user has completed the specifications of the test vector and requests its execution, the client opens a socket connection with the server and sends the user inputs to an ASP on the server. The ASP converts the inputs into a format understood by the GP-IB instrument driver. It passes the commands to the driver, which is a DLL object. Through a GP-IB card, the GP-IB commands are passed to the instruments which execute them: the switching matrix switches first to the selected device, and then the HP4155B executes the test vector. When the measurements are done, the HP4155B sends the data back to the ASP which forwards it to the client's applet. The socket connection is subsequently closed.

Upon receiving the data, the applet processes the results and displays them graphically on a new frame. There is a lot of flexibility in how the data can be graphed. In a separate function on the server side, the ASP logs appropriate information onto a database.

The Java applet provides the core of the user experience. We have constructed this applet to mimic the front panel of the HP4155B. This was based on our judgment that the designers of the HP4155B had already thought a great deal about an optimal user interface for their instrument. When designing the applet, we did not attempt to capture the entire functionality of the HP4155B but just those elements that were deemed useful to accomplish our educational goals. More functions can be added at later stages. This is a powerful feature of the remote laboratory concept: its ability to offer the use of professional engineering instruments in an educational environment while drastically reducing the complexity that is presented to the users.

The Java applet that is downloaded to the user has several frames. Fig. 2 (left) shows the *measurement specification* frame through which the test vector is specified. This frame is divided into three panels: a *channel definition* panel to specify the device connections, a *variable set up* panel to specify the range of voltages or currents to be applied to the device, and a *user-defined function setup* panel to compute simple algebraic functions "on the fly" (this is a feature of the HP4155B). The measurement specification frame additionally contains four menus that allow the user to control the frame. A *file* menu to save and retrieve test vectors, a *measurement* menu, to specify the variables to be measured and to launch the measurement, a *device* menu to select the device under test, and a *help* menu with an online manual. This Java applet has been constructed to recognize common mistakes in the test vector prior to its submission. In this way, traffic through the server is minimized and the instrument is only presented with testing requests that have a good chance of being executed correctly.

A second frame of the Java applet, called *measurement results,* graphs the obtained data. A sample of it is shown in Fig. 2 (right). The graphics in this frame can be manipulated with great flexibility. Through this frame, the data can be downloaded in a standard format to the client's local hard-drive for offline processing using common spreadsheet or mathematics software.

3. Educational experiments

There are three aspects to the educational experience associated with WebLab exercises. The first one is in the construction of the test vector. The second one is in the data display. And the third one is the offline data manipulation.

There is a great deal of educational value in the preparation of the test vector. It forces the students to pay detailed attention to the precise requirements of the exercise. Of the many test vectors that one could prepare, only a few respond to the specifications of the exercise. Configuring the test vector also brings to the fore issues of measurement range, data point distribution, measurement speed, and device compliance. Finally, the students are made aware of how the instrument actually carries out the measurements. The *measurement specification* frame of WebLab has been constructed to preserve a substantial portion of the experience associated with hands-on operation of the instrumentation.

The second component of the WebLab educational experience concerns the data display. The graphics frame of WebLab 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 (an Autoscale function helps the identification of suitable ranges to display the acquired data). This graphing flexibility forces students to think about the optimal way to display the data and to study in detail the standard formats followed in the microelectronics world.

The third educational aspect of the WebLab experience is offline data manipulation. A download button allows exporting the obtained data to a file of in a format that makes them 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.

Since its first experimental deployment in a graduate subject at MIT in the Fall of 1998, WebLab has been used in several undergraduate and graduate microelectronics device and circuit subjects, none of which included a lab component previously. The experiments performed in the Fall of 2000, involving the simultaneous use of WebLab in three different subjects, illustrated the range and capabilities of the system. A total of about 120 students were involved. A sketch of the experiments is shown in Fig. 3. In the Fall 2000 academic term, two MIT courses used WebLab: a junior level subject in the Department of Electrical Engineering and Computer Science with about 80 undergraduate students (6.012 "Microelectronics Devices and Circuits") and a joint EECS/Material Science graduate-level subject with about 20 students (6.720J/3.43J "Integrated Microelectronics Devices"). In addition to this, a graduate subject in the Singapore-MIT Alliance (SMA5104 "Fundamentals of Semiconductor Device Physics") also added 20 graduate students from Singapore. The use of WebLab by students from Singapore was interesting in itself as the laboratory, the instructor and the teaching assistant were located at MIT while the students ran experiments from Singapore. Each of these subjects used different devices at different times throughout the semester. The device redundancy was effective in preventing even a single device blackout event.

The use of WebLab by these many students allowed us to estimate the capacity of the system. At its busiest hour, WebLab handled 13 users running 99 different jobs. This extrapolates to a capacity of over 2000 users per week and over 15,000 experiments per week. During its busiest hour, the average total execution time for each test vector was still less than 15 seconds. 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.

Concurrent to this, in the Fall of 2000 we installed a copy of WebLab at Compaq's Alpha Development Group center in Shrewsbury, MA. Through this system, 6.720J/3.43J students accessed the latest 0.18 μm CMOS hardware with which Compaq's designers were working at the time. MIT's graduate students were able to take remote measurements in real time and download the data. They were also able to compare the performance of the 0.18 μm technology with 10-year old 1.5 μm hardware that was made available through the on-campus WebLab system. At that time, Si wafers belonging to the 0.18 μm technology generation were closely guarded. Having a wafer on campus connected to WebLab was clearly out of question due to IP concerns. A local copy of WebLab at our industrial partner's site eliminated these concerns while preserving a great deal of the educational experience associated with the characterization of modern deep-submicron CMOS.

4. Future Plans

Our future plans span three fronts: further development of the MIT Microelectronics WebLab, the exploration of a richer educational platform created around remote online laboratories, and the investigation of the extendibility of the WebLab concept to other engineering disciplines.

On the first front, we are considering many possible enhancements to our Microelectronics WebLab. Our plans include enabling remote and simultaneous measurement of the temperature of the laboratory, introducing a remote-controlled hot-chuck to vary device temperature, implementing a more intuitive graphical interface for test vector definition, and adding a new capacitance-voltage test capability.

We view remote online laboratories as the core of an educational platform with enormous educational value. This is what we call the I-Lab concept – a rich educational experience associated with a web-enabled laboratory. Our second front of action focuses on pursuing that concept. Simulations tools can be integrated onto the WebLab platform so that one or several simulations can be launched simultaneously with the measurements. The results of simulations and measurements can be reported jointly through the same interface. We are also developing a collaboration/tutoring tool that will enable several remote users in separate locations to share the input and output frames of WebLab while "chatting" about the experience [8]. Finally, "smart" semiautomatic feedback and evaluation systems can be added to assist users with common mistakes or to evaluate the degree to which a certain result complies with the assignment.

On the third front, together with a group of faculty at MIT, we are exploring the portability of the WebLab concept to other engineering disciplines [9]. Several remote online laboratories are currently being developed at MIT. In the Department of Aeronautics and Astronautics, a mechanical structures laboratory is being constructed to study beam deformation in response to various stresses. In the Department of Chemical Engineering, a chemical reactor, a heat exchanger, and a microscope-based polymer recrystallization experiment are being designed and assembled. Finally, in the Department of Civil and Environmental Engineering, remote monitoring systems for a flagpole and model building structures mounted on a shake table are under development. These laboratory experiments have been chosen to explore the WebLab concept across regimes where the physical variables of interest are of diverse natures and with time-scale and length scales that span several orders of magnitude.

5. Conclusions

Remote online laboratories have great potential in science and engineering education. Our experience with a web-enabled microelectronics test station designed and assembled at MIT reveals that remote online laboratories enjoy enormous economies of scale. This will enable the introduction of new laboratory experiences to places where they did not exist. It will allow different academic and research institutions to share laboratories. Most importantly, Universities and centers of learning in the developed world will be able to support science and engineering education in the developing world at small marginal cost.

Acknowledgments

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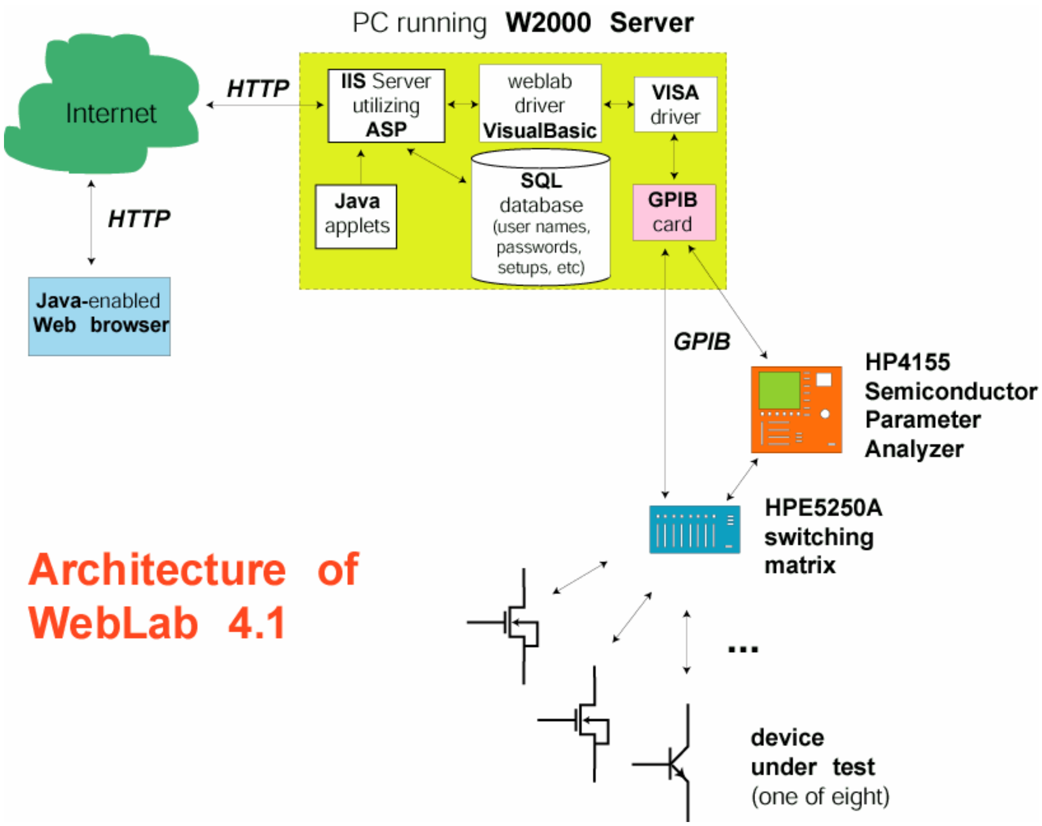

Fig. 1: Architecture of MIT Microelectronics WebLab (version 4.1).

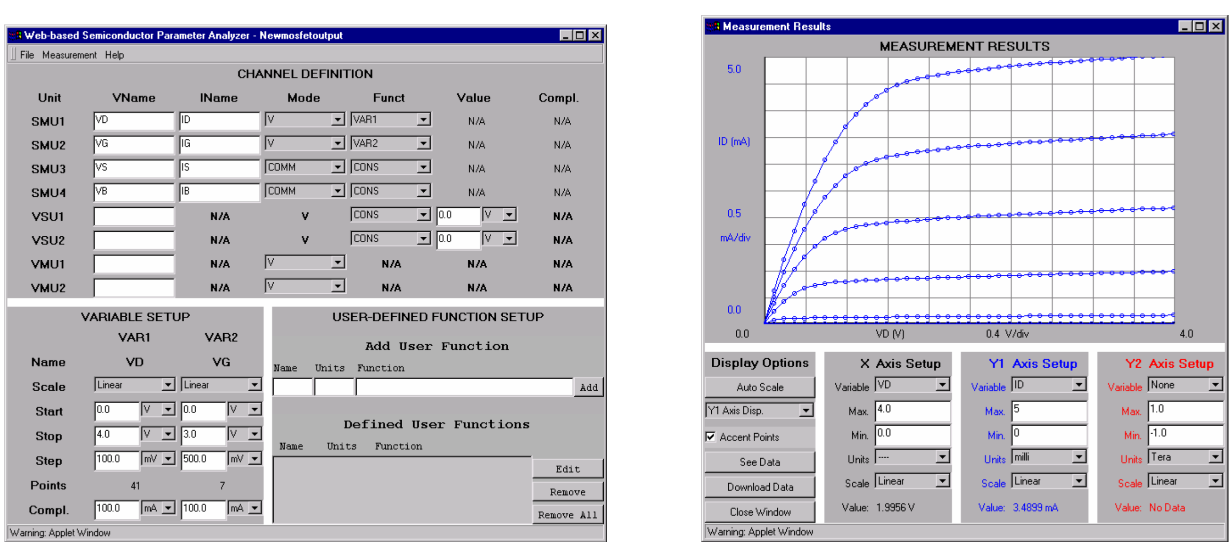

Fig. 2: Input (left) and output (right) frames of Java applet of MIT Microelectronics WebLab.

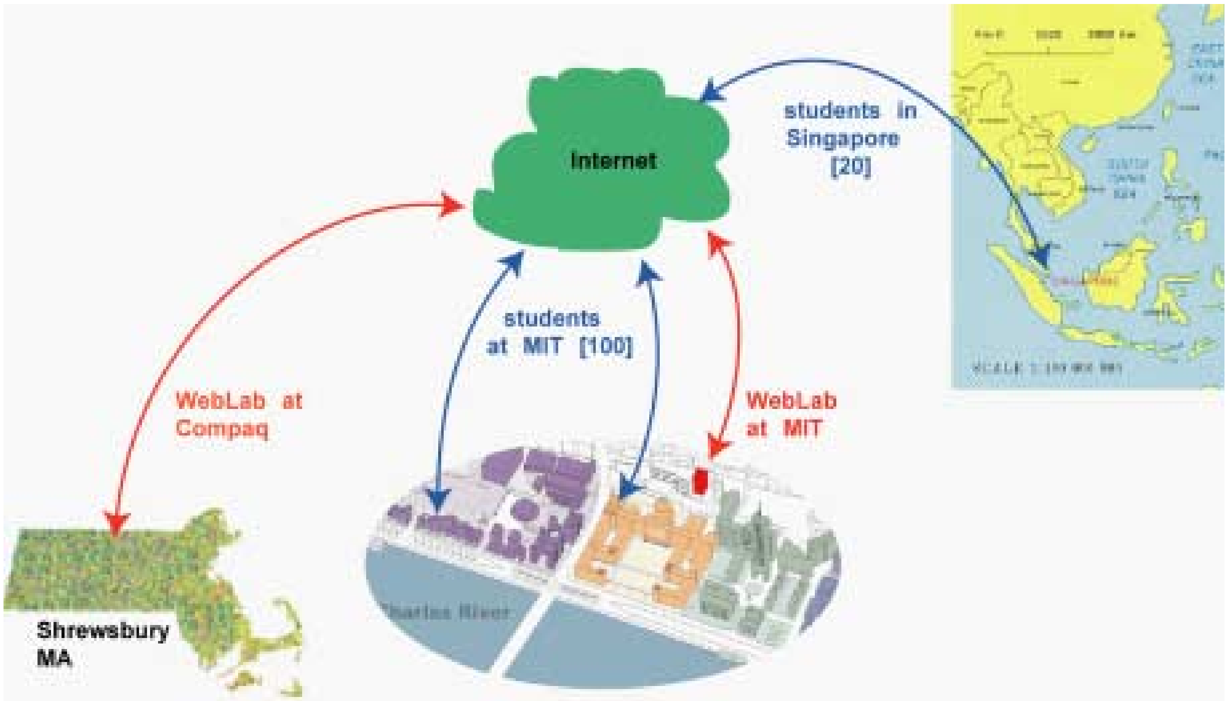

Fig. 3: Fall 2000 educational experiments involving MIT Microelectronics WebLab.