ABSTRACT. Technology Computer Aided Design (TCAD) being an important component of modern semiconductor manufacturing, a new framework is needed for microelectronics education. In this paper, we describe our approach and methodology and address the issues arising in combining virtual device fabrication, remote electrical measurements, and modeling and TCAD simulations of basic semiconductor process and devices. An integrated measurement-based online microelectronics laboratory with simulation-based technology CAD laboratory is described. Proposed TCAD laboratory is unique as a student can perform both measurements (device characterization) and simulations (modeling of devices) and extract SPICE parameters and compare the results. We believe that the integrated online hardware-based remote laboratory and simulation-based TCAD laboratory will be a valuable resource in microelectronics education. The main idea of the work is to disseminate and popularize e-learning techniques as well as developing remote laboratories in the field of microelectronic education. The hardware-based measurement laboratory project envisions a global network of remote laboratories to which institutions can contribute their existing laboratory experiments in order to share them with other institutions. This research not only verifies the feasibility of designing and implementing a remote laboratory in the specialized field of micro- and nanoelectronics (semiconductor devices and circuits), but also measures its effectiveness as a teaching tool. Experiences from this research may be useful in setting up future remote laboratories in other areas of engineering education.

KEYWORDS/INDEX TERMS: Technology CAD, TCAD laboratory, microelectronics education, SPICE.
1 INTRODUCTION

The field of microelectronics technology is recognized as a driving force for the information age. The last six decades have seen steady advancements in the field of microelectronics and training of electronic/electrical engineers in microelectronics area has become imperative. Semiconductor science and technology is also a very dynamic field. The aim of microelectronics education is to produce high-quality graduates who are well prepared to make immediate contributions and to help shape the rapid change that characterizes semiconductor industry. However, conventional courses in microelectronic device physics often do not include a laboratory component due to very high cost in developing microelectronics laboratory. In microelectronics education, major concerns now are the limited resources of laboratory hardware due to the high start-up costs, high equipment cost and regular maintenance of such equipment. Due to the high cost of microelectronic fabrication laboratory, teaching microelectronic circuit fabrication is very much driven by the availability of resources at the institution providing such courses. Very few institutions can even afford an undergraduate microelectronics laboratory.

As the semiconductor measurement and characterization equipment are generally very expensive, creation of semiconductor devices laboratory has been very limited. The world of education is facing rapid changes today and will probably face even greater changes in the near future. With the emerging information and communication technologies, such as the Internet, online courses with associated laboratories are becoming a reality not only in remote areas but across the world. We proposed for the first time an internet-based online course on microelectronics technology integrated with TCAD laboratory (MAITI, 2012). Meeting the goal requires a “hands-on” experience, in which students have the opportunity to become familiar with industry-standard design tools, processing equipment, clean room infrastructures, metrology and testing techniques. Semiconductor device theory and IC processing courses are now common in electrical engineering curricula (ARMSTRONG; MAITI, 2008, KENROW, 2004) due to the fast changing semiconductor technologies and challenges faced by the semiconductor industry. Over the past few years, several universities have started research on technology and offering courses on integrated circuit manufacturing to meet the demand of the microelectronics industry. However, running semiconductor fabrication laboratories requires significant resources from the institution and is time consuming for the students. Therefore, it is a current trend in engineering education to transfer these laboratories into remote controlled laboratories that can coexist with the vast developments of online learning offerings (MAITI, 2010).

Microelectronics has virtually penetrated in all consumer goods which is a true technological revolution happened in a short span of time. The 2005 International Technology Roadmap for Semiconductors (ITRS) predicted that the use of technology computer aided design will provide as much as a 40 percent reduction in technology development costs by reducing the number of experimental lots and shortening development time for the semiconductor industry. In highly competitive manufacturing environment, one needs to take the full advantage of the predictive power of TCAD to reduce cost and time for product development. Currently, process and device simulation has established itself as an indispensable tool for developing and optimizing device and semiconductor process technologies in the R&D phase. With the device compact model parameter extraction for circuit analysis, TCAD can be extended into manufacturing for advanced process control and parametric yield analysis.

TCAD being an important component of modern semiconductor manufacturing, innovation in microelectronics education has become essential now, and new teaching framework is needed for microelectronics education.
The Virtual Wafer Fabrication (VWF) has become an integral part of semiconductor fabrication. For manpower training (both via lectures and simulation laboratory), it is important to introduce courses on Technology CAD in the curricula. With the introduction of TCAD for microelectronic fabrication, it is imperative that the teaching institutions introduce a new course/laboratory on Technology CAD. Currently, no educational institution offers TCAD course and associated laboratory due to non-availability of such laboratory. In this work, an integrated measurement-based microelectronics laboratory with simulation-based technology CAD laboratory is described. The students perform real measurements on a wide variety of devices. The measured experimental data (from the device characteristics) can then be passed on to the simulation-based TCAD laboratory for the extraction of SPICE parameters.

2 ROLE OF TECHNOLOGY CAD

Shrinking device dimensions approaching atomic dimensions and new device designs utilizing band-gap engineering give rise to many new and previously unknown effects in the electrical, mechanical and thermal behavior of semiconductor devices. It is also now well known that silicon technology is facing its fundamental limits and one needs new materials for advanced microelectronic applications. Currently, most of the semiconductor industry is struggling with extending the chip performance. Both the innovative device structures and new materials are needed to continue with the Si CMOS roadmap, both in transistor performance and density. To maintain rapid advancement, device and process designers have increasingly turned to computer simulations of the process; design of electronic devices and circuits for solutions such as, TCAD.

TCAD is the field of engineering that simulates the fabrication processes of integration circuits. It uses process recipe and layout information to simulate the several fabrication process steps (e.g., lithography, deposition, etc.). TCAD is used to design, analyze and optimize semiconductor technologies and devices with fundamental and accurate models.

Before the 1980s, numerical simulation was not considered seriously for electronic device development. Instead, the device structures and fabrication steps were modified following a set of simple guidelines (scaling laws). Availability of increasingly powerful computers and TCAD software had made possible accurate multidimensional simulation of realistic device structures and physics. TCAD replaced scaling laws in the central role of guiding electronics development in the 1990s. Figure 1 shows a high level block diagram of the TCAD system, showing how the individual tool set fits into the overall TCAD process. In TCAD, a broad range of modelling and analysis activities such as simulation of IC processes, device electrical characterization and extraction of device parameters for equivalent circuit models are involved. The objective of the laboratory component of any semiconductor manufacturing course is to teach the students the unit processes involved in microelectronic fabrication and to introduce the practice of process development.

Introducing TCAD tools to students is considered important for the following reasons; proficiency with the use of TCAD tools has become a necessity in modern manufacturing environments and the use of TCAD tools allows students to learn the fundamentals of device processing in a virtual environment. However, teaching TCAD tools is a difficult task. This is due mainly to the complicated user interaction with most of the available process and device simulators; usually the input information is prepared in the form of files written in a specific input language for each simulator. Professional technology CAD simulation tools are in general difficult to use and are considerably more complex. The users need dedicated training sessions to successfully use the tools and the instructors need to be highly competent in the specific TCAD tools used in class. In addition, the institutions need to provide the required learning environment, which includes well-maintained computer resources to run the TCAD tools.
The main use of TCAD (ARMSTRONG; MAITI, 2008) in semiconductor manufacturing is two-fold; viz., process and device simulation. Process simulation models the complex flow of semiconductor fabrication steps and ends up with detailed information on geometric shape (structure) and doping profile distribution of a semiconductor device. Device simulation uses the information of the process simulation to calculate the characteristics of semiconductor devices. Numerical simulation of semiconductor device/circuit fabrication and operation is also important to the design and manufacture of integrated circuits because it provides insights into complex phenomena that cannot be obtained through experimentation. An important role of the predictive modelling using TCAD is to utilize detailed process and device simulation to facilitate the interaction between the circuit designer and process technologist, until the product data is incorporated into the design kit. TCAD represents our physical understanding of processes and devices in terms of computer models of semiconductor physics. The conventional process and device simulation flow is shown in Figure 2.

Historically, all the TCAD tools developed were available on various UNIX-based platforms. Central computer servers often with multiple CPUs and UNIX- or Linux-based operating system and large amounts of RAM are used, as such servers are ideal for large-scale computing tasks such as TCAD. Attempts have also been made for Windows versions of TCAD tools, but the use of Windows versions are very limited, as the software packages are distributed and supported by third-party vendors. Also, as laptops are typically optimized for mobility and long battery life instead of large-scale computation, laptops are generally not used for running TCAD applications. However, the use of commonly available remote access software tools conveniently transforms a Windows-based laptop into a graphic terminal for a central UNIX- or Linux-based computer server.

Choosing a remote access tool requires several important considerations, as they are available from various vendors and differ in several respects:

- Bandwidth requirements
- Support for encrypted data exchange
- Possibility to disconnect from and reconnect to a terminal session
- Possibility to use local Windows applications
- Ease-of-use and initial setup

3 CONVENTIONAL MICROELECTRONICS TEACHING

Due to the rapid development time needed for the semiconductor industry, it is challenging for universities to teach modern Integrated Circuit (IC) design. In the following, we discuss the current trends in micro- and nanoelectronics teaching.
In classical microelectronic teaching, students acquire skills in device physics as well as in analog and digital IC design. Each subject is taught using dedicated CAD tools which leads to a compartmentalizing of the teaching by putting conceptual barrier in the student's mind. Galliere et al. (GALLIERE, 2009) have proposed a laboratory in which students can mix TCAD electrical and SPICE simulation which highlight the possible interdependence between these tools.

As the access to state-of-the-art designs is usually not available in the university environment and the process detail, being normally proprietary, universities lack access to the necessary semiconductor technology data required to implement educational projects. Under University Program, several vendors (like Synopsys) have started developing educational design kit for teaching IC design courses based on their tools (GOLDMAN, 2014). Hong et al. (HONG, 2013) have presented a hands-on experience-based microelectronics manufacturing engineering education course for a four-year university degree program in the area of microelectronics. Authors have proposed a methodology for undergraduate students to acquire hands-on experience through integrated circuits design, wafer fabrication and microelectronic packaging. From the student’s survey, it has been shown that the inclusion of hand-on experience-based courses are beneficial to enhance students' motivation of learning. Using multi-university collaboration, attempts have been made to enhance the potential of microelectronics in the Philippines (CHUA, 2013).

Barzdenas et al. (BARZDENAS, 2013) have presented a detailed overview of the Micro- and Nano-electronics curriculum for undergraduate and postgraduate programs in Vilnius Gediminas Technical University in Lithuania. These programs focus on designing integrated circuits using advanced EDA Tools. The programs cover various aspects of the IC design process: from the understanding of IC manufacturing processes and technologies to IC verification, physical design implementation and testing.

Under the computer aided design of integrated circuits within the European project “Remote-labs Access in Internet-based Performance-Centered Learning Environment for Curriculum Support”, the Technical University of Sofia has implemented a remote access to the professional software (very expensive and running only on workstations) laboratory which is being used by the students from the MSc degree for working on their projects (RADONOVIĆ, 2013). One of the greatest challenges to attracting and retaining early engineering students is the lack of "hands-on" experiences early in the university curriculum. Vijay Kumar et al. (VIJAYKUMAR, 2002) reported a project aimed at introducing early university students to the high-tech field of microelectronics through the use of web-based "virtual experiments". The website allows for exploration of microelectronics at levels ranging from underlying science, device physics, processes and processing tools. New pages even recreate the layout and operation of an actual microelectronics factory site. Virtual reality is also used to support a real university lab in which a student can fabricate actual devices in a few short lab sessions. The web material is presented in an intuitive and highly visual 3D form that is accessible to a diverse group of students. It has already been tested with high school science students, engineering students, and graduate business students.

Khaliq et al. (KHALIQ, 2001) have that through laboratory experiments, students gain further understanding of the theory of processing parameters, manufacturing issues, and the final electrical testing of the chip, helping them to appreciate the impact of processing parameters on IC chips. To improve the quality of microelectronics education, the European network for integrated circuit testing has been extended microelectronics students in Europe (BERTRAND, 2002).
French experience on engineering test education also allows distant student to have a remote access to resource center equipped with up-to-date and high-tech testers.

To provide graduates with the required qualifications to make them ready for employment immediately upon graduation, several universities are developing new educational models based on close collaboration between industry and academic institutions. Synopsys' cooperation (GOLDMAN, 2012) with leading technical universities in Armenia and the surrounding region have resulted in new and more effective forms of delivering microelectronics education. In fact, Student Working Groups (SWGs) that are in essence a prototype design team within an educational environment have been created for professional skill development.

4 INTEGRATED TCAD LABORATORY

Measurements are fundamental to understanding of semiconductor device. Towards teaching device design and developing concepts, an online remote hardware-based laboratory for characterizing microelectronic devices has been developed (HARWARD, 2008 MAITI, 2010). Conventional laboratories have become increasingly costly for educational institutions. The increased costs of equipment, materials, and support personnel, coupled with time, space, and enrolment constraints, have made the addition of remote laboratory components essential. Through a Java-enabled web browser, users all over the world can run experiments on real transistors, diodes, and other devices by means of a semiconductor parameter analyzer Agilent 4145B or 4156C. By using LabVIEW program, both virtual instruments has been designed and the equipment are controlled via GPIB, RS232 or VXI interface and web based applications that users can access via internet can be performed. This remote laboratory allows the experimental testing of several semiconductors devices, such as diodes, BJT, JFET and MOSFET in real time in order to obtain the output characteristics of each one and to study their behavior in different experimental conditions.

The success of a VLSI circuit design depends on the device models used to describe the device behavior. As semiconductor devices shrink, the need for accurate circuit simulation using SPICE model becomes acute. The most important component in an IC manufacturing process is the devices themselves. It is thus imperative that these devices are accurately characterized so that accurate model parameter set for the device can be extracted. The device models usually consist of a set of model equations that are either empirical or derived from device physics or a combination of both. Therefore, the design of integrated circuits is heavily dependent on circuit simulation, which needs compact device models.

From the measured device characteristics, SPICE parameters are extracted. Parameter extraction is also an integral part of compact modelling. The goal of parameter extraction is to determine the values of device model parameters that minimize the total differences between a set of measured characteristics and results obtained by evaluation of the device model. It is thus important to develop remote device characterization integrated with simulation-based TCAD laboratory.

![Figure 3: Typical components in a TCAD laboratory module.](image)

When integrated with a measurement-based online microelectronics and VLSI engineering laboratory, a new degree of flexibility in teaching is obtained as the student can perform real measurements on a wide variety of devices and extract the SPICE parameters. With online TCAD laboratory, the students can perform simulation experiments and explore the impact of process flow modifications virtually at no cost (see Figure 3).
Major steps for remote online laboratory development are: (a) the design of the experiment, (b) remote control and operation of the instruments (for example, via LabVIEW, IC/CVlite, EasyExpert, VEE etc.), (c) conversion to web applications and (d) launching the experiments on the internet. A modular online remote laboratory typically consists of 10-15 hardware-based experiments which need to be made available always to students. The Laboratory-on-Demand is an initiative to develop an online measurement based integrated Microelectronics Laboratory with simulation-based Technology CAD laboratory. The Home page for the laboratory is shown in Figures 4 and 5. Online TCAD laboratory gives the student, even at the undergraduate level, a chance to learn about realistic silicon wafer processing via hands-on simulation experiments. Recent advances in computer hardware now make even a standard laptop suitable to run TCAD simulations in a matter of minutes. In measurement-based Microelectronics Laboratory, the students perform real measurements on a wide variety of devices. The measured experimental data are then passed on to the simulation-based TCAD laboratory for the extraction of SPICE parameters. TCAD Laboratory Module currently consists of the following experiments:

- Process Simulation using SUPREM
- Device Simulation using BIPOLE
- Bipolar Device Characterization and SPICE Parameter Extraction
- MOSFET Characterization and SPICE Parameter Extraction

The developed Technology CAD laboratory has been designed for developing two levels of knowledge: the definition/implementation of the simulation script (input file) and the analysis/understanding of the results. The current version of the laboratory module has the following sessions:

Session 1: The process simulator SUPREM is introduced. The student simulate step-by-step a bipolar transistor. During this session, the doping profiles are investigated after each process step.

Session 2: The device simulator BIPOLE is introduced. In this session the students compute the output characteristics of the bipolar transistor for several process parameters.

Session 3: The student uses the SUPREM to design a process flow for a MOS transistor. The students test the process flow by simulating it and extracting the doping profiles.

Session 4: With the device simulator BIPOLE, the students compute the output and Gummel characteristics of the BJT for several process parameters. The electrical characteristics are used to obtain the compact model of the transistor. The student extracts Gummel-Poon model parameters from TCAD device simulations.

Figure 4: Home page for integrated measurement-based microelectronics and Technology CAD laboratory.

Figure 5: Homepage for the TCAD simulation laboratory.
The home page for the current version of the TCAD laboratory showing various available simulation experiments is shown in Figure 5. In this section, we describe the outcomes for some of the above tasks:

**Process Simulation: SUPREM**

Process and device simulations are commonly used for the design of new VLSI technologies. Simulation programs serve as exploratory tools in order to gain better understanding of process and device physics. Proposed TCAD course and laboratory will impart “hands-on” training on all aspects of silicon and other semiconductor technology, development of new technologies and the prediction of the behavior of new device structures. SUPREM is an advanced 2D process simulator originally developed for submicron silicon structures. It provides cross-sections of arbitrary device structures based on physical models for ion implantation, diffusion, and oxidation and annealing. It is designed to interface with other programs that accurately simulate etching and deposition of thin films on the semiconductor surface, although it includes basic models for these processes as well. Process simulator SUPREM generates both printed and graphical outputs that describe the simulation results. The SUPREM simulation page is shown in Figure 6.

**Device Simulation: BIPOLE**

In the field of microelectronics, a device simulator is an important engineering tool with tremendous educational value. With a device simulator, a student can examine the characteristics of a microelectronic device described by a particular model. This makes it easier to develop an intuition for the general behavior of that device and examine the impact of particular device parameters on device characteristics. A device simulator lets students explore device behavior in regimes that would otherwise be infeasible or unsafe to examine. Device simulation is used to obtain simulated electrical measurements of a device, largely for technology characterization.

BIPOLE is a quasi-two-dimensional device simulator, developed at the University of Waterloo, Canada, which specifically focuses on rapid prediction of terminal electrical characteristics of bipolar transistors. Program input comprises fabrication data such as mask dimensions, impurity profiles and physical parameters such as carrier lifetime. The calculation is based on the variable boundary regional approach using one-dimensional transport equations. Two-dimensional and quasi-cylindrical edge effects are handled by combining the vertical one-dimensional analysis with a coupled one-dimensional horizontal analysis of the transport equations in the base region. It is then used to solve the transport equations for diffusion and drift in the presence of arbitrary recombination in quasi-neutral regions. This scheme is extremely fast in terms of computing time. BIPOLE can also be used for accurate avalanche multiplication and breakdown studies in high-speed transistors with shallow collector regions and heterojunction structures, including graded base Ge fraction in SiGe devices, and emission across the thin interfacial oxide layer in a poly-Si emitter and offers a facility for automatic parameter extraction for SPICE models. The BIPOLE simulation page is shown in figure 7.
Measurement is the final arbiter for any semiconductor simulation module. The developed Technology CAD laboratory includes several types of measurement systems. Figure 8 shows the device characterization (output characteristics) page for a bipolar transistor measured using Agilent 4145B device parameter analyzer. The measured experimental data is then passed on to the simulation-based Technology CAD laboratory for extraction of SPICE parameters. In the present version used in our laboratory, only the dc simulation is implemented. The complete set of semiconductor dc parameters can be quickly and accurately evaluated with Agilent 4145B/4156C stand-alone semiconductor device parameter analyzer. As an example, the measured Gummel plot of an NPN transistor is shown in Figure 8. The measured data can be graphically analyzed to obtain saturation current, current gain, and current gain vs. collector current characteristics, along with base resistance and recombination current characteristics.

The highest level in the proposed technology CAD laboratory module is the SPICE parameter extraction. The main link between circuit level simulation and lower level TCAD tasks is through the compact models used in circuit simulators to characterize the behavior of individual circuit components. Simulators have tremendous educational value. With a device simulator, a student can examine how the device described by a particular model behaves when presented with various inputs. Although this exploration can be done with a real device, the appropriate equipment is often prohibitively expensive. These models are fitted to the data produced from process and device simulation, providing circuit designers with a CAD environment that accurately characterizes the manufacturing lines that will make the circuits.

**SPICE Parameter Extraction**

Circuit simulation is essential in integrated circuit design, and the accuracy of circuit simulation depends on the accuracy of the transistor model. The success of a VLSI circuit design depends on the device models used to describe the device behavior. It is thus imperative that these devices are accurately characterized so that the most accurate model parameter set for the device under test can be extracted.
The device models usually consist of a set of model equations that are either empirical or derived from device physics or a combination of both. Therefore, the design of integrated circuits is heavily dependent on circuit simulation which needs compact device models. Several programs for parameter extraction are available on a commercial basis. Industry standard compact models such as, SGP, VBIC and HiCUM can be used for bipolar device parameter extraction for the design of complex analog/RF circuits and to verify analog mixed-signal designs.

In the integrated online TCAD laboratory described above, simulation program, Tool for Electronic Model Automation (TEMA) is used for the extraction of SPICE parameters (TEMA, 2010). The software is an EDA tool for automated SPICE modeling of advanced semiconductor devices for development of an Analog/RF circuit design kit. The tool is suitable for modeling of dc, ac, RF, 1/f noise and high-frequency noise for on wafer or packaged semiconductor devices. From the measured device characteristics SPICE parameters are extracted. One of the most important steps in evaluating bipolar transistor parameters is measuring collector current and base current as a function of base-emitter voltage (Gummel plot). SPICE parameter extraction from BJT Gummel data is shown in Figure 9.

**Evaluation of Online Laboratories**

Our experience on internet learning systems has shown that the great benefits come from automating at least part of the unit assessment so staff can spend more time with students while they are doing the exercises. One of the critical factors impacting upon the difficulty in evaluating the success or otherwise of remote laboratories is the lack of clear objectives for laboratory experiments.

*Figure 9: SPICE parameter extraction from BJT Gummel data.*

From the first month of operation, the TCAD laboratory module has been used for teaching in which students could remotely test and characterize semiconductor devices in web-enabled experiments and extract the SPICE parameters. In the context of online laboratory education, quality assurance seeks to balance experiment design, pedagogy, and technology with the needs of learners. Teaching in an online laboratory class is different from teaching in a traditional laboratory class room, and faculty who often lack the skills to adapt the online laboratory courses to teach must learn new skills in order to be effective. The acceptance of distance learning technology is not automatic; much skepticism still remains in spite of its effectiveness. In fact, the technological innovations in internet technology and communications have reduced the problems of teacher-student interaction. It is apparent that the emergence of online laboratory education in traditional higher education system will alter teaching and learning contexts. However, there is little research on the effects of these changes. Studying various approaches for integrating communication and web technology for student’s performance evaluation is a very important issue which will address the role of online laboratory education. For proper functioning of the online laboratory, the student’s role is also very important. Typically a student using the laboratory management system (LaMS) need to interact in the following way:

a) Selection of laboratory experiment by student,
b) System opens laboratory environment,
c) Student joins the laboratory session,
d) System allows the full control of the equipment to the student,
e) Student perform the experiment,
f) Student passes the control to partner to conduct the experiment (in case collaborative learning),
g) Student complete laboratory activities, such as saves data etc.
h) Student appear for viva-voce examination, submit laboratory report etc. and logs out,
i) LaMS closes the laboratory session, and
j) Student completes the learning objectives

Keeping track of each learner’s activities and progress in the laboratory sessions is essential for the instructor. The process of students’ performance evaluation (for each experiment) is generally done at several stages in our laboratory modules, for example,

- Pre-laboratory online quiz (after which a student is allowed to book time and perform experiment),
- Submission of the laboratory report after the successful completion of the experiment, and
- Appearing in the online Viva-Voce examination for the experiment.

The main motivation of online hardware-based laboratory experiment is to provide the facility to as many students as possible and thus the number of users per instrument is large. It is thus necessary that a user really engages the equipment only when he/she performs the experiment. This is why a preliminary quiz is proposed and conducted before the learner can get access to the actual experiment webpage and the equipment and/or the experimental setup. This is done primarily to optimize the use of the instruments by making sure that the user is familiar with the instruments and knows about the experiment. The quiz consists of several random True/False type questions about the instrument, setup, experiment and fundamentals (see Figure 10). The user goes through the learning materials, videos, detail of setup available for each experiment. When the user is ready to use the instrument, the student appears for the quiz. Only after the learner obtains a certain marks (set by the instructor for each experiment), the student is allowed to book the experiment time slot. The student gets the access of the experimental setup during this time slot.

![Figure 10: Preliminary Quiz screen shot.](image)

**Viva-Voce Examination**

After successful submission of the laboratory report, the student can take part in the viva-voce examination. Both the – viva-voce performance and the laboratory report are checked for each experiment performed successfully by a student. Finally, the learner has to take part in the viva-voce which consists of several true/false or multiple choice questions as asked in a conventional oral examination (see Figure 11). The students need to answer them in a certain period of time. The data is matched for correctness and the number of correct answers is determined. The performance is graded accordingly. This value is then added to the laboratory report marks to get the final marks for the experiment for a student.

The overall effectiveness of the online lessons was assessed based on the following criteria:
Student survey responses after performing remote experiments are very positive. Over 90% of all responses indicated that the experiments and demonstration were either “Effective” or “Very Effective.” Additionally, the students expressed the unanimous desire for more remote laboratories. The remote experiments and the use of integrated measurement, characterization of devices and SPICE parameter extraction have enriched the students understanding of concepts presented in lectures. Through remotely performed laboratory experiments, students were able to link the device principles taught in class without having to enter a traditional laboratory. Figure 12 shows the pattern of students’ use of the remote laboratories. Majority of the students preferred to conduct the experiments during weekends.

Briefly, we can say that the development of remote TCAD laboratory has provided opportunities to explore new teaching methodologies that make use of the internet technology in real contexts. We consider that the remote laboratory helps students develop abilities in:

- observation, interpretation and analysis of results in a way that is similar to what researchers do,
- stand-alone tasks put the students in practice of reflexive and proactive attitudes, the planning and the self-control of students’ learning activities,
- interpretation of the behavior of electronic devices under different experimental conditions from a scientific perspective, and
generation of SPICE parameters, the analysis and construction of device models help students for the microelectronics industry.

However, some problems are there for the remote laboratories, such as:

- Cost of maintaining the system to keep up with hardware, operating system, and internet service provider and browser technology changes,
- Complexity of technological components and of integrating in a working system,
- Need to deal with unreliable internet connections, and
- Need for collaborating users to be able to work together.

5 CONCLUSION

The world of education is facing rapid changes today and will probably face even greater changes in the future. With the emerging communication technologies, such as the internet, online laboratories are becoming a reality not only in remote areas but across the world. The possibility of teaching semiconductor manufacturing in university environment in a highly cost-effective manner by taking the advantages of high speed internet and available TCAD tools has been explored. Technology CAD is shown to be an excellent resource for teaching microelectronics. When used in conjunction with conventional modes for teaching design and fabrication of semiconductor devices and circuits, the process simulation tools, combined with the device simulation can be a very powerful tool for greater understanding of electronic devices and their operations. Device modeling and parameter extraction can help students understand the principles of electronic device operations and their applications in electronic circuits. With online TCAD laboratory, the students are able to perform simulation experiments and explore the impact of process flow modifications virtually at no cost.

A new conceptual framework for teaching technology and device/process design has been presented. Various aspects of semiconductor technology cross-sections can be illustrated by using the TCAD in process/device analysis and design. The importance is the fact that these simulations are immediately available to the teacher and student to re-run and hence explore the multi-dimensional space of physics and device design. Given a reasonable junior level device/process course, this new methodology will provide the opportunity to initiate a strong interactive simulation environment for both experimenting with physics and technology. This is a unique opportunity for students to embark on real device/technology design and as an independent study. In short, the proposed TCAD simulation laboratory will serve for Virtual Wafer Fabrication to circuit design in one platform. Thus the proposed online TCAD teaching methodology will provide an opportunity for expanding microelectronics education. This methodology will provide the foundation for research in both advanced device design and manufacturing science and technology.

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Dr. C. K. Maiti received his B.Sc. (Phys. Hons.), B. Tech. (Appl. Phys.), M. Tech. in Radiophysics and Electronics all from the University of Calcutta and MSc (by research) from the University of Technology, Loughborough and PhD degree from Indian Institute of Technology - Kharagpur in 1969, 1972, 1974, 1976 and 1984, respectively. He joined the Electronics and Electrical Communication Engineering Department of Indian Institute of Technology in 1984 as an Assistant Professor and was appointed as a Professor in 1999. He currently leads the semiconductor device/process (TCAD) simulation research group in the Department. He has contributed significantly in the area of low temperature dielectric formation on Si and Group IV alloy layer films. He has co-authored five books on Silicon-Germanium and strained-Si materials and devices. He has authored/co-authored more than 250 technical articles and conference publications. His current research interests cover various aspects of semiconductor process and device simulation on heterojunction transistors involving strained layers.

In the area of microelectronics education, he has been instrumental in the development of hardware-based remote microelectronics laboratory (Microelectronics and VLSI Engineering Laboratory) for device characterization and parameter extraction, remote hybrid Semiconductor Devices and Circuit Characterization Laboratory and simulation-based technology CAD (TCAD) remote laboratory.