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# THE USE OF TCAD SIMULATIONS IN SEMICONDUCTOR DEVICES TEACHING

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**Abstract**—Semiconductor devices have come a long way since the invention of the point contact transistor in 1947. These tiny devices transform and shape our lives and will continue to do so in ways we have yet to discover. Skills and knowledge in semiconductor devices are therefore essential for the development of a more sustainable world. Nevertheless, the ways we teach semiconductor devices are still rooted in 20th century textbooks and methods. Learning methods and materials therefore need to be updated so that students learn in ways that are appropriate for the global, dynamic and transnational environments in which they will work. Our methodology relied on using modern Technology CAD (TCAD) device simulations to revolutionize the teaching of semiconductor devices. Based on student responses, we believe that our methodology will enhance student employability and encourage student understanding of advanced semiconductor concepts, which are required for managing the global sustainability challenges. We demonstrate how the application of state-of-the-art simulation and visualization CAD tools can be used to teach undergraduate students how to understand the basic principles of key electronic devices. We provide examples of teaching materials and assessment exercises that were used to assist student learning of semiconductor devices within a transnational education (TNE) programme. Moreover, we believe that exposing students to modern industry software tools will help embed skills development and employability.

**Keywords**—TCAD, simulations, Sentaurus, teaching

## I. INTRODUCTION

To ensure that graduates have the necessary skills to cope with the continuously shifting careers landscape, which is driven in part by technological advancements, semiconductor engineers need to solve rapidly evolving and interdisciplinary problems. Embedding the development of digital literacy skills with soft skills such as critical thinking, creativity, and problem-solving within the curriculum is therefore a step on the journey for developing a truly competitive graduate workforce. Consequently, we believe that the effective use of Technology Computer Aided Design (TCAD) can improve students' digital literacy skills, as well as their understanding of key concepts in semiconductor device design.

Moreover, future semiconductor engineers are required to be competent in the use of existing process and device simulation tools. Consequently, the basic concepts of process and device simulations are now an integral part of the undergraduate teaching material [1]. To this end, we have introduced process and device simulations in a third year

Electronic Devices course, which can be taught to both on-campus and transnational students. This is now possible using Synopsys' Sentaurus Workbench framework, which provides an intuitive and user-friendly interface to different tools for process or device simulations and visualisation.

With the evolution of Technology Computer-Aided Design (TCAD) over the years, process and device modelling simulators have reached a high level of precision. The use of simulation modelling has been used widely, for manufacturing and many more areas [2], with the main reason being the progressively increasing cost of the manufacturing systems, [3]. The biggest TCAD framework currently in the industry is Synopsys Sentaurus Workbench, which is fuelling the ever-growing role of such tools. Semiconductor devices have transformed our lives during the past fifty years. These tiny devices are the basic building blocks of key electronic components found in biomedical circuits and systems. Hence the requirements on process development, manufacturing control and device or circuit optimisation, as well as business aspects such as time towards market distribution are increasing.

In this paper, we describe our motivation, methodology, as well as our approach in handling the challenges in developing the teaching material and laboratory for a third-year course on "Electronic Devices". The course provides important background studies in semiconductor physics, as well as the characteristics and operation principles of basic semiconductor devices such as diodes, bipolar junction transistors, MOS capacitors and MOSFETs.

## II. THE NEED FOR VISUALISATION

As part of our Transnational Education (TNE) programme between the University of Glasgow and the University of Electronic Science and Technology of China (UESTC), third year Electronic Engineering students were invited to take part in an open online survey. This was used to help us develop and customise the training materials according to the needs of our transnational students. The surveys were distributed among 214 transnational students in a third-year course on Electronic Devices. A total of 28 students took part in our surveys (13% response rate). This response rate is deemed sufficient for a class size of 200 for a 10% sampling error and 80% confidence level [4].

Students were asked to rate their experience with the current laboratory material, especially in terms of reinforcing and complementing their understanding of the lecture

material. The survey questions were formatted with a range of choices from 1 to 5 as Strongly Disagree and Strongly Agree respectively. According to the results shown in Figure 1, it is clear that students were dissatisfied with current laboratory materials and that a greater mix of practical material was required.

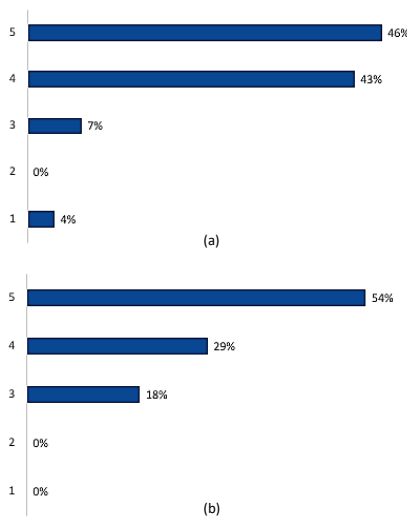


Figure 1. (a) Survey results for the effectiveness of the practical exercises in understanding the lectures and (b) appropriate mix of theoretical and practical material in the course (bottom).

Consequently, students were asked whether the use of simulations will help them improve their understanding of the teaching material. According to their responses, 64% of students strongly agreed that simulations will enhance their understanding, as shown in Figure 2(a). Moreover, 54% strongly agreed that animations and videos would also help with their understanding, as shown from the results in Figure 2(b). These results clearly agree with previously published data regarding the use of computer simulations to support scientific learning, [5].

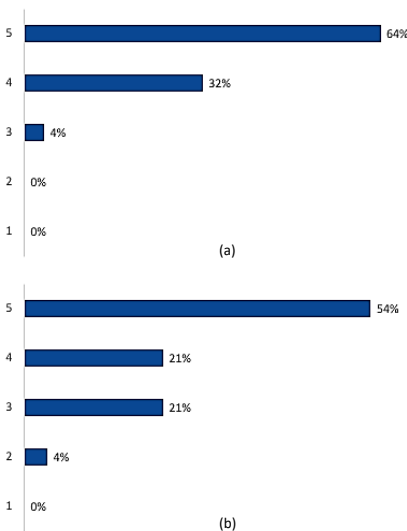


Figure 2. (a) Survey results for the opinion of the students on using simulations during the practical laboratory. (b) Survey results for the opinion of the students on using video and animation material during the practical laboratory

Lastly there was a positive response on the student’s support, on upgrading the material with simulations, with a 57% of students strongly agree that the simulations will assist and improve their understanding of the course materials, Figure 3. Therefore, the TCAD simulations material is more appealing to our students than the current laboratory material.

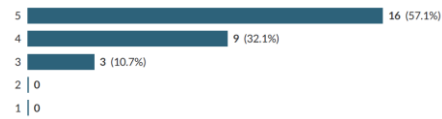


Figure 3. Survey results on simulations advantage on improving the students understanding of the material.

## METHODOLOGY

Process and device simulations takes the form of input information that is prepared in a specific input language for each simulator. This input language requires knowledge about grid generation, numerical methods, model parameters, as well as other modelling details. Consequently, this knowledge is often outside the scope of undergraduate teaching, which makes it difficult for instructors to use TCAD in undergraduate courses.

However, “Sentaurus Workbench is a complete graphical environment for creating, managing, executing and analysing TCAD simulations” [6]. It provides a modern, well-structured user interface, that allows the use of all the embedded simulation and visualisation tools with ease, which we find ideal for undergraduate teaching.

Consequently, to avoid these issues, project files for each laboratory session were created in advance, setting the starting point being to run the simulations. We organised Sentaurus tools with unique icons on the top of the project tree. For the laboratory projects, we included custom made icons alongside the original icons, indicating what device is simulated and what kind of simulation each tool executes. This allows students to know which tool to use for each analysis and to get them familiarized with the real environment of Sentaurus. An example of a loaded project is shown in Figure 4.

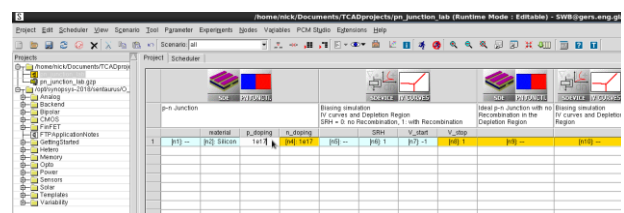


Figure 4. Pre-configure project loaded in Sentaurus Workbench. The tools used are two SDE and two SDEVICE, having the original icon on the left side and the custom icon on the right side.

To ensure that the new simulation materials agreed with student expectations, we developed exercises that met the following three criteria. Firstly, we designed pre-developed simulation projects. Secondly, we ensured that the laboratory sessions covered the main material taught during the lectures. Thirdly, we ensured that the instructions for using the TCAD software tools were clear and had plenty of figures.

Thus, we divided the Electronic Devices course materials into three main sessions covering PN Junctions, MOS Capacitors and finally MOSFETs. All sessions can be

completed using standard workstations, with a 8/16-core CPU, 16 GB of RAM and a CUDA-enabled Nvidia GPU, with access to Sentaurus. Before drafting the exercise sheets, a text document was developed for each session independently, with thorough instructions for using Sentaurus to simulate and analyse the devices.

Through the development of the session manuals, multiple projects were created in Sentaurus to explore the possibilities of the analysis tools. The most important tool used in the lab exercises was SVISUAL, which is the visualization extension for both structure and electrical properties of the device. SVISUAL provides all the necessary tools with a user friendly interface to analyse and export plots of the given device.

The instructions manuals were used as the basis for drafting the student laboratory sheets. Moreover, a unified template for the laboratory sheets was developed. These templates had specific sections for background reading, figures, as well as separate sections for the ideal and non-ideal structure analysis. These features were implemented to ensure that all labs were aligned with the course's learning outcomes.

Finally to address feedback from the survey, the instructions were structured to simplify the use of Sentaurus to let the students focus on the analysis. This was achieved by having the instructions follow the pattern of an experiment, as it was shown that students achieve greater results when following an experiment, rather than a traditional instructional content [7].

### III. RESULTS & DISCUSSIONS

To evaluate the effectiveness of the laboratory sheets, the final draft was distributed to members of the Device Modelling Group of University of Glasgow, which included at the time, 4 postdocs, 1 senior lecturer and 2 postgrad students. The background of the students were Chemistry and Electrical engineering. A questionnaire was produced to accompany the laboratory sheets, designed to maximise the response rate and undertake appropriate data analysis, [8].

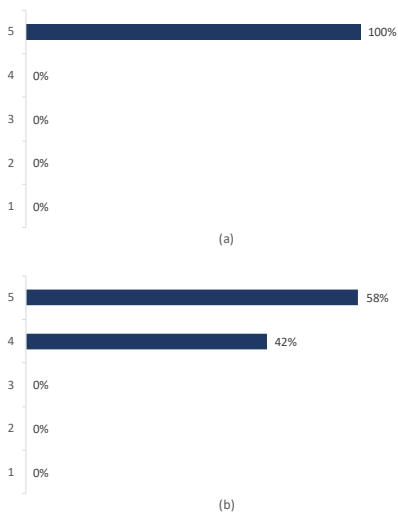


Figure 5. (a) Questionnaire results on the clarity of the instructions in the laboratory sheet. (b) Questionnaire feedback on the ease of use of the TCAD software in the exercises.

The response was greatly positive, as can be seen from Figure 5(a), all 7 of the participants that responded found the instructions clear and thorough with 3 of them had minor

difficulties undertaking the exercises, Figure 5(b). Figure 6 shows a snapshot from the first exercise, where there is a short introduction with an illustration of the expected state of the workbench, and the following steps are in bullet points, again accompanied with illustrations. The participants were asked to provide feedback at the end of the laboratory and some of the positive testimonials include: “The laboratory gives you a practical idea of the semiconductor devices and their physic parameters behind them while you are studying them”, “It gave me the ability to visualize the relatively abstract quantities and hence improve my understanding of the semiconductor device physics”. Another positive feedback was “The laboratory is well organized and a great ‘Getting Started’ example”.

**1. Exercises**

**1. Symmetric p-n junction**

In this section you will simulate an ideal symmetric p-n junction, with dimensions of 500x500 nm for each side and will extract the key properties of the device by visualising the exported simulation data. Your workspace should look like Figure 10.

Figure 10. Simulated nodes. Light blue means it's a virtual node and yellow means it's done. See bottom right of workbench for colour code

If you cannot see the numbering for the nodes press F9 to toggle the numbering on. Before starting to plot the graphs, you should calculate the depletion region width to compare your results with the simulated ones in your report.

**1.1. Simulations**

**1.1.1. P-n junction in equilibrium**

- Select node 8 and click on the icon from the second menu bar from the drop-down menu select Sentaurus Visual (Select File...), Figure 11.

Figure 11. Screenshot of the Sentaurus Visual menu.

Figure 6. Snapshot of the first page in the laboratory sheet exercises section. On the top is the introduction of the exercise with an illustration of the workbench, on the bottom is the first step for visualizing the data.

The following figures show some of the expected results of the simulations exercises included in the exercises, from the 2D structures to the current-voltage (I-V) curves and Band Diagrams.

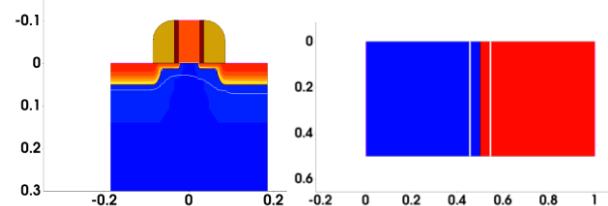


Figure 7. (left) Schematic of a simple MOSFET structure, simulated in Sentaurus. The white line represents the potential. (right) Schematic of a simple PN-Junction structure, simulated in Sentaurus. Red in n-type material and blue is a p-type.

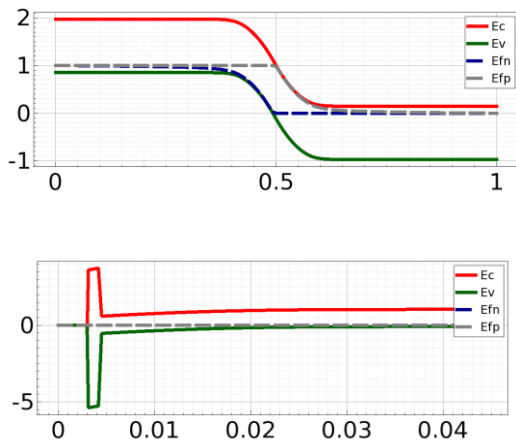


Figure 8. (a) Band Diagram of the PN Junction plotted in SVISUAL. (b) Band Diagram of the MOS Capacitor in Depletion regime, plotted in SVISUAL. Green is the valence band and red is the conduction band. The dash lines are the Fermi levels.

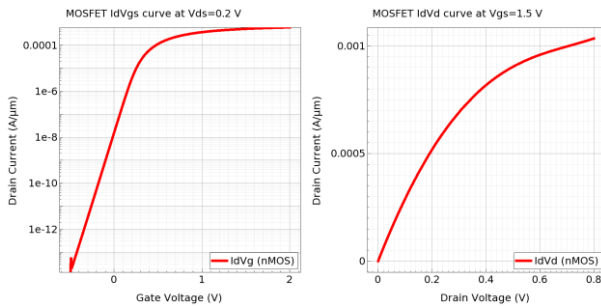


Figure 9. (left)  $I_{ds}$ - $V_{gs}$  curve of a MOSFET with a drain voltage of 0.2V plotted in SVISUAL. (right)  $I_{ds}$ - $V_{ds}$  curve of a MOSFET with gate voltage of 1.5V plotted in SVISUAL.

Device testing involved  $I_{ds}$ - $V_{gs}$  and  $I_{ds}$ - $V_{ds}$  measurements. The students were required to compare the simulated and calculated results from the analytical expressions. After the  $I_{ds}$ - $V_{ds}$  analysis, they will run a process simulation to observe the different stages of processing the MOSFET structure.

Although the structure of the lab instructions was satisfactory, there are areas for further consideration and improvement. For example, only 20% of the participants took more time to complete the exercises. This was perhaps due to the different processing speeds of the workstations, which meant that simulations were completed in different times. Consequently, we will ensure that our preconfigured projects are optimized for the minimum computer and system requirements to complete the labs in the designated timeslot. Finally, since the new laboratories are software based, they can be completed remotely without requiring a fabrication lab.

#### IV. CONCLUSION

In this manuscript, we presented our approach in enhancing third-year student experience taking the Electronic Devices course using advanced TCAD simulations. Our motivation was to improve student digitally literacy skills and to provide students an opportunity to use modern tools that are widely used in the semiconductor industry. These efforts were geared towards improving their employability in the constantly shifting job market. We have concluded that the

laboratory exercises improved student understanding of abstract or difficult engineering concepts. It helped them understand the underlying physical properties of key electronic devices such as MOSFETS and PN junction diodes. Using the more accurate and detailed device visualisation tools, students were able to understand these concepts better, as evidenced by the survey results and testimonials.

We also believe that this innovative intervention in using TCAD for teaching semiconductor devices is important to ensure that students continue to receive high quality education, even during the spread of the COVID-19 pandemic.

Nevertheless, our approach to laboratory design using TCAD is not restricted to third year electronic engineering students. Our approach can be replicated with other transnational or on-campus students. The Sentaurus tools can be used for further, more advanced courses. For example, laboratories can be designed to further show the effects of different device fabrication processes, as well as device variability.

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