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TCAD Based Power Semiconductor Device e-Learning Tool

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Abstract

An interactive web-based teaching tool for a power semiconductor course at the University of Central Florida is presented in this paper. A novel approach is introduced using Technology Aided Design Tools (TCAD) to generate time-lapsed 2D semiconductor device cross-section embedded in a webpage using Adobe® Flash (web design tool) platform to create interactive movies that demonstrate complex device physical phenomenon. Students can step through the interactive movies forward, backward, pausing, or looping. Each step represents a giving bias condition. Current-voltage plots are represented along with the semiconductor device and a visual point is placed on the IV curve to indicate the current bias conditions. The changes are then reflected in the 2D cross-section movie area and the IV plot. This tool was implemented in a classroom setting to augment the lectures or for discovery learning.

Key Words: e-learning, Flash, Technology Computer Aided Design, Web-based

I. INTRODUCTION

Learning semiconductor device physics is no easy task; there are many physical mechanisms to take into account, all of which are hard to visualize. Physics such as the electric field distribution or the potential distribution in a complicated structure can seem overwhelming. Once device learning passes the simple p/n diode structure understanding and visualizing the physics become more complex. Thus, for the University of Central Florida (UCF) Power Semiconductor Graduate course a supplement web-based educational tool was developed. Several devices were modeled using TCAD software. Then a Flash movie was extracted from 2D semiconductor device cross-section TCAD results. The clips are implemented to convey selected internal physics of power semiconductor devices.

Web-based learning has increased in popularity and effectiveness over the years. There has been a lot of research into the eLearing/web-based learning field [1],[2].

Most device physics text books lack the visual imagery needed for students to completely understand the material. If students pursue device engineering they will lack a comprehensive understanding of the internal physics intuition that comes with many years experience.

One solution is exposing students to TCAD simulations early through a class or as a project-based component. Some propose introducing TCAD early as a lab section. The proposed idea in [3] does not require the expensive lab setup or training time for students. However, some schools may not have the partnerships needed to obtain a large enough site license to provide TCAD tools to all students. Also, some courses lack the time and resources for students to use TCAD software in tandem with a given course.

This paper displays a novel web based tool which utilizes TCAD results and could be implemented with only one license; saving the cost of acquiring a larger site license. And removing the need for the student to learn the software on their own. Even though most TCAD software developers give a generous discount to Universities, not every budget is flush with cash.

TCAD tools have made designing semiconductor devices and circuits easier. Semiconductor device questions that once took weeks of round table discussion can now be a predictive finite element analysis (FEA) problem with results in mere hours. A TCAD based learning tool for students would have a twofold benefit. First, for students in a semiconductor course the visual learning will add in understanding the semiconductor devices. Second, students will learn to analyze TCAD device simulation results.

Therefore the authors in this paper present a Flash web-based TCAD generated tool for students. The courseware tool gives students a visual representation of semiconductor device physics along with a figure showing the devices IV waveform. The application of the tool developed is focused on power semiconductor device physics, but is readily scalable to any class where semiconductor device physics are of importance.

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II. Course Description

EEE 6317 Power Semiconductor Devices and ICs is a one-semester, three credit hour class for graduate students. The course objective is to provide fundamental understanding on modern power semiconductor devices and ICs in relation to their applications in power electronics systems. The topics include:

- Introduction: Basic power electronics applications, ideal power switching devices, various types of power semiconductor devices and their application ranges.
- Semiconductor device basics: Energy bands, electrons and holes, drift and diffusion currents, recombination and generation, basic semiconductor equations, ambipolar transport.
- PN junction theory: Forward conduction, avalanche breakdown, edge termination structures.
- Power diodes: High-voltage P-i-N diode, off-state blocking characteristics, forward conduction characteristics, reverse recovery characteristics, Schottky barrier diode, MPS rectifier.
- Power Bipolar Transistor and Thyristor: Power BJT, thyristor, GTO.
- Power MOSFET: Basic MOS device theory, device structure and operation, DC characteristics, switching behavior, integral diode, device fabrication, gate drive circuits, energy capability and SOA, applications.
- Insulated Gate Bipolar Transistor (IGBT): Device structure and operation, DC characteristics, switching behavior, device fabrication, gate drive circuits, ruggedness, SOA, and IGBT modules.
- Emerging power devices: MCT, IGCT, super-junction devices, SiC and GaN devices.
- Power Integrated Circuit: need for integration, RESURF principle, BCDMOS technology.

To support the device physics topics, the interactive web-based tool was used. It was introduced in class with an instructor walk through and then the students were encouraged to further explore the interactive tool at home. Not every device mentioned in class is available online. Core power semiconductor devices are chosen to convey the most important physical device physics in relation to power electronics applications. Selections included PiN diode, bipolar transistor, MOSFET, Vertical Double-Diffused Power MOSFET (VDMOS), Lateral Double-Diffused Power MOSFET (LDMOS), and an Insulated Gate Bipolar Transistor (IGBT).

The PiN diode was selected as an example of conductivity modulation. A very important phenomenon that reduces a semiconductor devices on-state resistance by using two carriers to conduct current instead of one; also know as bipolar conduction. A MOSFET example helps convey minority carrier transport in an inversion layer. The IGBT demonstrates how conductivity modulation can be combined with a MOSFET-like operation to create a device that has the characteristics of two discrete devices. These examples give students a comprehensive view at core power semiconductor operating principles.

III. Device PHYSICS

Semiconductor device physics is ruled by physical equations like the possion equation, and electron and hole current continuity equations. The equation below is the possion's equation for 1D case.

$$\frac{dE}{dx}=\frac{\mathrm{q}}{\varepsilon}(\mathrm{p(x)}-\mathrm{n(x)}+\mathrm{N}_d^+(\mathrm{x})-\mathrm{N}_\mathrm{a}^-\ (\mathrm{x})). \tag{1}$$

Where the gradient of E the electric field is related to the electron and hole concentrations given by p and n, q is the elementary charge, ε is the permittivity of the material, $N_d^+ and N_a^-$ are the positive and negative ionization concentrations of the impurities. In the 1D case this equation appears simple, however, for advanced device structures with complicated device profiles such as RESURF [4] or 3D super junction semiconductor devices. The equation gets much more complicated as shown for the 2D and 3D equations are more complicated.

$$\text{(2D)} \qquad \nabla \mathrm{E}=\frac{dE}{dx}+\frac{dE}{dy} \tag{2}$$

$$\nabla \mathrm{E}=\frac{q}{\epsilon}\left(p(x)-n(x)+N_d^+(x)-N_a^-(x)\right)+\frac{q}{\epsilon}\left(p(y)-n(y)+N_d^+(y)-N_a^-(y)\right) \tag{3}$$

$$\text{(3D)} \qquad \nabla \mathrm{E}=\frac{\mathrm{dE_x}}{\mathrm{dx}}+\frac{\mathrm{dE_y}}{\mathrm{dy}}+\frac{\mathrm{dE_z}}{\mathrm{dz}} \tag{4}$$

$$\nabla \varepsilon=\frac{q}{\epsilon}\left(p(x)-n(x)+N_d^+(x)-N_a^-(x)\right)+\frac{q}{\epsilon}\left(p(y)-n(y)+N_d^+(y)-N_a^-(y)\right)+\frac{q}{\epsilon}\left(p(z)-n(z)+N_d^+(z)-N_a^-(z)\right). \tag{5}$$

In equations (1-5) the more dimensions added the more complicated possion's equation. Accurately visualizing these kinds of equations becomes nearly impossible. Countless hours can be spent expanding and solving such equations by hand. However, the development of TCAD software has enabled researchers such ability. If the continuity equations for electron and holes were displayed in this format it would have taken up almost one whole page. This is the challenge that the education tool discussed in this study is meeting. The software calculated these equations and can display 2D device cross-section per chosen time step. Thus 2D cross-sections can then be brought into the classroom so students do not have to struggle with grasping how the electric field is distributed or how the current flows, etc. Visualizing the physical changes in a device reduces learning time for when a new device structure is introduced.

IV. Power electronics Learning DISCUSSION

For power electronics engineering students learning the basics of power semiconductors can be a useful skill. It is easy to expand the tool to cover extracting power semiconductor parameters of interest to power electronics engineers like on-resistance, breakdown voltage, and threshold voltage.

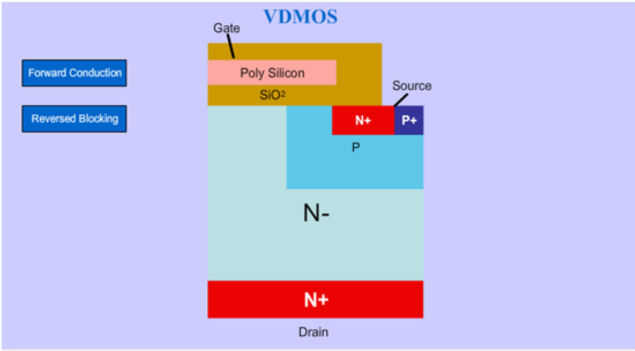

Fig. 1. Example of the VDMOS interactive main menu.

Synopsys TCAD is capable of mixed mode simulations so a semiconductor device can be simulated in a power electronics circuit. This can provide power insight into how the circuit topology affects the power semiconductor device and which limits of the device you might be approaching.

V. Interactive Web Tool

Adobe® Creative Suite 3 was used to develop the web-based interactive movies. Flash CS3 from the suite was the main development tool used in this paper. The learning curve of the software is high, but the ease of generating movies once a template is created is fast and efficient. The background coding uses an Adobe® Flash Actionscript 3.0 coding language to implement the interactive components.

Once the template was generated a semiconductor device was chosen and then added e-Learning tool. Then a Finite-Element-Analysis simulation was run with Synopsys TCAD Suite [4]. The graphical viewing program TECPLOT, included in the Synopsys Suite, is used to generate device captures from electrical simulations that are taken at equal intervals throughout each simulation for forward conduction and reverse bias conditions. The captures were then outputted as flash movies (an option available in Tecplot part of the Synopsys TCAD suite). Finally, the TCAD Flash movies were applied to the web-based template.

A screenshot of the template is shown in Fig. 1 and Fig. 2. On the main screen there is an outline of the device that shows an exaggerated doping profile and appropriate contact labels. Also on the main screen are two buttons. The buttons can switch the screen into an interactive mode depending on the button chosen. Typically the buttons are “forward conduction” state or “reverse blocking” state.

On each subsequent screen from the main menu a device schematic is displayed with three images of the TCAD device generated movies. Each movie displays a physical representation of electric field, electron current, hole current, etc. The exact physical phenomenon (impact ionization, current density etc.) is limited to three due to limited screen size. As a result of the limited screen size the important physical events were added to the web tool for a given device.

Shown with the three physical pictures are an IV plot and a biasing schematic. The schematic had a box that displayed the current biasing conditions and two interactive buttons to control whether you added voltage or subtracted voltage. For power devices this control was over the drain bias. With the gate voltage fixed to ensure the device was sufficiently on. And the source kept at a constant reference, in the test cases ground. The graph on the upper right displayed the current of the device VS drain voltage. A red dot indicates the device biasing conditions on the curve.

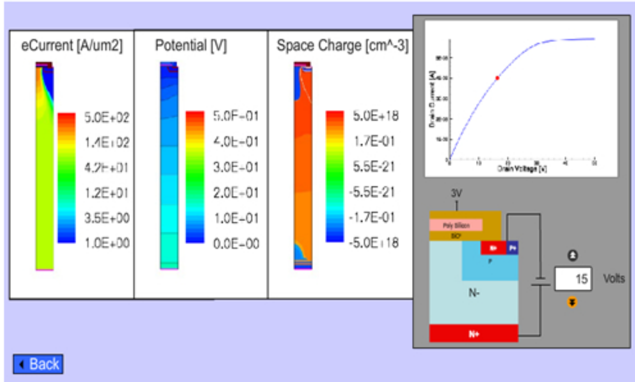

Fig. 2. Example of interactive portion of the web-based tool.

TABLE I
SURVEY RESULTS CONDUCTED AT END OF SEMESTER

Survey Question	- -	-	-+	+	++
I used it outside class	0	2	1	8	4
I found it helpful	0	0	0	6	10
The interface is friendly	0	0	2	5	9
I learned more about device physics with the courseware	0	1	3	7	5
I had a hard time finding the courseware	8	6	3	0	0

The courseware was published to the University’s web-courses web portal. This is used as a website that class instructors can post lectures, assignments, grades, etc.

VI. Results and Discussion

At the end of the Spring 2009 semester a survey was conducted to gather information on the effectiveness of using the courseware in the classroom; as perceived by the students taking the course. The class size for the Spring 2009 semester was 16 students. Results of the survey conducted are in Table I. The questions were given to asked to determine the extent the students used the tool and how they felt it affected their learning.

At least 75% of the students used the courseware outside of class. 100% of the students found it helpful. The survey results convey that using the universities webcourse portal is a good location to have the e-Learning tool. Most likely because all the students have used it before and know how to navigate it with ease. Students also had the opportunity to give feedback on the courseware a few of the comments the students wrote:

“Picture representations always help to understand difficult concepts. I love the videos!”

“The TCAD simulator is very helpful, and very convenient to go back and forth with sections that require more repetitive reviews.”

“It is very good. It would be nice to see some of the small semiconductor features more clearly. It would be nice if they were a little bigger."

"I feel it was very useful and I wish I had used it a bit more."

"Improvements in GUI, but besides that I would use it more."

"Very useful."

"Would it be possible to download the courseware too? It is only available online right now."

The consensus reveals the courseware was a helpful in understanding power semiconductor device physics. Research has shown that most students are visual learners and would benefit from such a e-Learning tool [5],[6]. Therefore the unique approach this paper presents using TCAD generated 2D simulation results, will enable more visual learning and enhance comprehension.

VII. Conclusion

A new interactive web-based tool using TCAD 2D device cross-section movies has been developed to assist students in understanding semiconductor devices physics. It has been implemented in a power semiconductor course for Spring 2009. Results from a survey at the end of the semester showed that students found this tool helpful and used it often to gain a better understanding of semiconductor device physics. The methodology for creating courseware for semiconductor classes can easily be applied to other fields that use TCAD software. In addition mixed mode simulations can provide a unique ability for power electronics students see the impact of circuit topologies on the semiconductor components. Costs to do so are minimal if a single license is obtained, other than a site license, given if costs are a concern. There is no need to have or maintain a TCAD lab reducing the overall cost of implementing this plan even more.

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