

Hierarchical Modeling & Simulation Curriculum Systematism Promotes the Development of Interactive Inquiry Teaching of Semiconductor-related Courses

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ABSTRACT

Implementing the interactive inquiry teaching (IIT) method in higher education could substantially promote the process to construct the first-class disciplines as well as universities. In this paper, the hierarchical modeling & simulation (M&S) curriculum systematism is creatively proposed, by merging and unifying several softwares for semiconductor materials and devices at different levels. It is demonstrated that such stage-by-stage curriculum construction would boost the feasibility to realize IIT in semiconductor-related courses. Particularly, author emphatically expounds what important role the above-mentioned hierarchical M&S curriculum play in five typical links of IIT, as well as the summary of classroom teaching effects. The step-by-step analysis on three common stages of semiconductor simulation implemented during teaching processes has been provided, covering basic design concepts as well as the corresponding well-directed software packages adopted in each stage. The above curriculum systematism can gradually stimulate students' learning enthusiasm and participation in semiconductor-related courses, which is the research achievement of IIT method, and also meets the requirements of the teaching reform oriented by national "double first-class" initiative in China.

Keywords: *Interactive inquiry teaching, Modeling, Simulation, Hierarchical, Semiconductor.*

1. INTRODUCTION

At present it is a critical stage for the development of the semiconductor field. The industry development route driven by Moore's law has almost terminated [1]. Currently, novel device structures, materials and technologies are constantly emerging, and it is necessary to break the energy consumption boundary of CMOS devices and the silicon-based speed limit in the future. In this case, up-to-date teaching for semiconductor-related courses must not only ensure that students are able to master the traditional semiconductor theory, but also comprehensively merge together the effect of interdisciplinary development [2, 3]. The ultimate goal is to lay a good foundation for the undergraduates who either work on the design of semiconductor devices or pursue advanced studies in microelectronic field.

The semiconductor-related courses usually include "semiconductor physics" and "semiconductor materials and devices", which are not only the professional basic courses for undergraduates majoring in

microelectronics, but also one of important professional elective courses for undergraduates majoring in science and engineering. The reform of teaching methods associating to such courses has always been explored until now [4-7]. It is necessary to concentrate on how to make students get rid of rote memorization for the dull concepts and formulas, as well as to stimulate their initiative to explore. In this case, it is reported in this paper that by constructing a stage-by-stage semiconducting M&S curriculum systematism we try to raise the educational quality and expand the teaching contents; IIT method has been focalized in order to improve students' capacities of problem solving when practically using semiconductor materials and devices. Thus the process of inquiry-based teaching reform for semiconductor-related courses can be fully promoted.

2. THE VALUES OF IIT AND M&S

The traditional classroom teaching is usually predominated by teachers. Since a large amount of knowledge has been imparted within a limited lesson

period, there is always a gap between theoretical learning and practical applications for most students. IIT requires teachers to introduce "independence, inquiry and cooperation" as the learning pattern into the teaching process, which includes five parts [8], i.e. (i) situation establishment, (ii) enlightenment of thinking, (iii) group investigation, (iv) cooperative communication and (v) summary and improvement. IIT aims to get rid of the traditional indoctrination in higher education, meanwhile to solve the intractable problems students often encountered such as low participation and poor learning effects.

M&S is one of the most important research methods in semiconductor industry and plays an important role in the development of semiconducting materials and devices. For undergraduates the study of M&S and involved professional software could enable them to have more thorough understanding of physical concepts and build a bridge for the introduction and expansion of new theories. More and more universities are carrying out the teaching reform, trying to combine the computer simulation with the inquiry learning method for undergraduates. For instance, University of Hartford has offered an undergraduate course "fluid mechanics and heat transfer" with learning of multi-physical field analysis software and M&S technique as required content [9]. Other universities have also begun to focus on training students to build mathematical models for practical problems solving with the help of computer calculation [10].

3. PRACTICALLY IMPLEMENTING IIT

3.1. Hierarchical M&S Curriculum Systematism

3.1.1. 1st Stage: Lay the Groundwork

Initially, teachers have instruct beginners in a simple one-dimensional model, which will couple several equations (i.e. Poisson equation and continuity equation of electrons and holes) together to describe the properties and distribution of carriers in semiconductor materials. Poisson equation correlates the carrier concentration distribution to the variation of the electrostatic field in semiconductor; continuity equation describes the effect of carrier generation and recombination rate on the spatial variation of electron and hole current density.

Since most undergraduates are freshmen for semiconductor M&S learning, teachers should introduce the basic modeling ideology, targeting the idealized devices. Specifically, a basic framework has to be built in the first step, in which the direct-bandgap recombination model is used while the influence of trapping/detrapping is ignored. Then, other non-ideal factors are gradually considered, and the description of

carrier generation, recombination and trap distribution is refined according to the characteristics of simulated devices. Finally, by taking into account the electrode connection characteristics, the differential equations are numerically solved by using the appropriate boundary conditions.

3.1.2. 2nd Stage: Get Achievability from Easy-to-digest

Lack of ability in mathematical calculation and computer programming always occurs to most of the undergraduates; therefore the teaching at this stage should aim to make them getting a sense of achievement. Aggressive teaching should be not used in order to avoid induced fear of difficulties and even discouraged enthusiasm for subsequent inquiry learning. The knowledge involved in the above-mentioned one-dimensional model introduced at the first stage belongs to the course foundation of "semiconductor physics", which students should be familiar with. Therefore, how to "make the first move" from theoretical knowledge to modeling implementation is the crux of the matter.

Several kinds of software are suitable for M&S teaching at present stage. For example, AFORS-HET, the one for analyzing the photoelectric properties of microelectronic and semiconductor devices, is developed by the Helmholtz-Zentrum Berlin Research Center and is currently available free of charge. AFORS-HET can analyze the influence of semiconductor materials and device structure on device performance, and simulate the response of semiconductor devices to applied light, bias voltage and external temperature. AMPS-1D, another cost-free one-dimensional device simulation program developed by Pennsylvania State University, is applicable to any two-terminal devices such as diode, sensor, photo-diode and solar cells for the analysis of microelectronic and photonic structures. The advantage of these softwares is that as long as the material and structural parameters are set through the program interface, the built-in calculation engine will automatically solve the partial differential equations of the model numerically, output the calculation results and do the data visualization in real time. Therefore, it is especially suitable for undergraduates who are not good at doing numerical calculation. Although there is a certain gap between the results obtained in above-mentioned way and the actual device model, the practice has proven that most students can learn the basic operation of those softwares, run the program and analyze the calculation results within a short time, which greatly stimulates the interest of students in learning M&S, so the classroom teaching effect is usually satisfactory.

3.1.3. 3rd Stage: Experience Accumulation for Meeting Higher Requirements

With the accumulation of students' modeling experience, teachers should appropriately improve requirements, e.g. to extend the device structure from basic two-terminal devices to three-terminal devices (bipolar transistors) or even four-terminal devices (field effect tubes), and to extend the dimensions of the model from the basic one-dimensional to the two- or three-dimensional structure, gradually approximating to the real semiconductor devices.

COMSOL Multiphysics, advanced commercial numerical simulation software based on finite element algorithm, is suitable for M&S teaching at this stage. COMSOL can realize to establish the two- or three-dimensional model, which is closer to the actual devices. For example, when doing the simulation of semiconductor power devices, except for the common electrical characteristics, the spatial distribution and influence of thermal effect can also be calculated by coupling the interface of heat transfer physical field, which is obviously unable to be achieved by the one-dimensional simulation program.

Based on the daily teaching process, students have a strong interest in learning COMSOL. The main reason is that the interface design of COMSOL is user-friendly, which makes beginners do not need to directly deal with the complex simulation process of multi-module coupling such as light, electricity and heat. Besides, COMSOL can visualize the simulation results and show the influence of critical parameters on the physical field. The vivid and beautiful calculation results can also enhance students' confidence and further improve their enthusiasm in learning and using M&S.

3.1.4 4th Stage: Potentiality Inspiration and Encouragement of Innovation

Matlab, a commercial mathematics software, is a good choice for modeling teaching at this stage. It provides a large number of functions and toolkits for numerical algorithms that are easy to call directly, compared with the modeling software used in last two stages, the prominent features of Matlab are higher flexibility, which means that theoretically any kinds of devices can be simulated. It is especially important for emerging new optoelectronic devices nowadays. For example, Nano materials have frequently adopted in many semiconducting devices, so it calls for advanced M&S technique that Matlab can be competent to flexibly adjust the boundary conditions without being constrained by the basic semiconductor PN junction or heterojunction structure model. The practice shows that some students of higher learning ability can benefit from the teaching at this stage. They can not only master a new programming language, but also have a

preliminary understanding of the basic algorithms involved in numerical calculation. The flexibility of MATLAB modeling can better stimulate its potential and gradually develop innovative thinking mode in the relatively free exploration process.

3.2. Instance analysis of merging M&S and IIT

Combining with the flowchart shown by Figure 1, we present here an instance analysis on how to merge M&S to IIT together based on teaching process of "PN junction" section in the course "semiconductor devices". In this section, the influence of interface defects on bipolar devices has always been a sticking point. It is difficult for students to make clear the influence of interface defects on the electrical properties of devices just by teaching the abstractive theory and formulas. Therefore, by making IIT as the guiding-thought, teacher sets the learning task, i.e. to simulate the crystalline silicon PN junction device and calculate its electrical characteristics, and meanwhile proposes the detailed inspiring problems furthermore (e.g. how to insert a thin layer between p- and n-type semiconductor materials as an equivalent interface layer of PN junction?).

Next, the teacher guides the students to spontaneously form a study group and adopt the cooperative mode for learning. Each group of students chose different simulation calculation objects according to their understanding and emphasis of the problem. For example, they could simply explore the influence of interface layer on device impedance, or they could further increase the difficulty of simulation calculation and simulate the influence of state density distribution of defect layer.

Then the teacher should guide students to spontaneously form study groups and do the teamwork. Each group can choose different objects to simulate according to their understanding on the problem. For example, they could either simply explore the influence of interface layer on device impedance or further increase the difficulty to investigate the influence of state density distribution of interfacial layer.

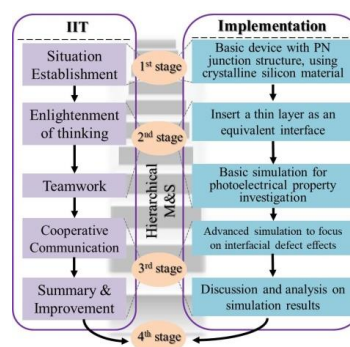


Figure 1. Flowchart showing implementation of merging M&S with IIT.

In short, what should be simulated and how to calculate is never decided by the teacher; it depends on each group of students after doing discussion and collaboration. Finally, teachers should guide students to analyze the simulation results, focusing on generalization and summary, and ultimately return to the theoretical teaching.

4. TEACHING VALIDITY AND ENLIGHTENMENT

With the assistance of M&S, students can conduct virtual experiments and visualize the output, which concretizes the abstract theories and formulas. IIT-based learning in small groups is usually accompanied by close collaboration and communication among team members. Students often carry out "brainstorming" spontaneously, which makes teaching full of vitality and thus breaks away from the dull classroom atmosphere in traditional teaching which is mainly taught by teachers. In the process of IIT, some students are not satisfied with the basic knowledge, so they try to use the model as a tool to do the deeper investigation. For example, some of them changed the external electrical signal input into the optical signal, and extended the simulation object to the PN-junction photovoltaic device. In this case, it was found that the interface layer has a particularly significant impact on the two parameters of the device's photoelectric conversion characteristics, i.e. the filling factor and open circuit voltage. This process is conducive to tapping the potential of students and laying a foundation for cultivating top talents. Most students can analyze and summarize the modeling results. Compared with the traditional teaching method which pays too much attention to concept memory and exercise calculation, IIT makes students more flexible in mastering knowledge points and own divergent thinking.

It is worth noting that M&S-IIT teaching should be more down-to-earth and start from the actual demand in order to ensure the rationality and correctness of the model built up by students. Teachers can guide students to begin with some conventional semiconductor materials/devices, in order to easily validate preliminary simulation results. The experimental data of such conventional materials/devices can usually be collected from the literature. Thus we try to make students always try to get to the root of the matter, i.e. simulation results, and thus to lay a solid foundation for students to design new materials/devices with the aid of M&S.

5. CONCLUSION

We innovatively propose the hierarchical M&S curriculum systematization, that it to merge various softwares for teaching of semiconductor materials and devices in different levels. We have demonstrated that

such stage-by-stage curriculum construction can realize IIT in semiconductor-related courses. We have clarified in detail that how the above-mentioned hierarchical M&S curriculum play the significant roles in five links of IIT and summarized the corresponding classroom teaching effects. In conclusion, we have confirmed that the proposed curriculum systematization can not only stimulate the learning enthusiasm of students, but also meet the requirements of construction of first-class university and disciplines.

AUTHORS' CONTRIBUTIONS

Dr. S. Ma and Prof. G. Guo conceived and designed the study. Dr. F. Xia and Dr. S. Ma implemented the IIT method during daily teaching of course Semiconductor physics and devices. Dr. S. Ma wrote the manuscript. Dr. F. Xia reviewed and edited the manuscript. All authors read and approved the manuscript.

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