2006-1739: DEVELOPMENT AND ASSESSMENT OF INTERACTIVE SPREADSHEET SOFTWARE FOR THE TEACHING OF SEMICONDUCTOR DEVICE THEORY

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Development and Assessment of Interactive Spreadsheet Software
for the Teaching of Semiconductor Device Theory

Abstract

Previously, we reported on the initial development of specialized interactive spreadsheets and supporting exercises to aid in the teaching of semiconductor device concepts. Here, we discuss the continued development, implementation, and optimization of these tools using feedback based on instructor observation, course surveys, student focus groups, and various measures of student performance. The software is designed to serve as a "virtual laboratory" in which students can gain experience and use visualization to observe the inner workings of semiconductor devices, which are not normally directly observable. Quantities such as energy band diagrams, electron and hole concentrations, electric fields and potentials, recombination rates, and current densities are plotted for various devices, whose structural and doping parameters and applied biases can be varied interactively using dialog boxes. The resulting real-time graphical feedback can help to develop intuition and appeal to a variety of learning styles. Statistical analysis has been performed to assess the impact of assigning interactive exercises involving these spreadsheets on student learning. Students have expressed high levels of satisfaction with the quality and value of using this software and the related exercises. The interactive approach used in this software, with ActiveX-based controls over real-time plots, should be extendable to various other subject areas in engineering and physics instruction as well.

Introduction

The tremendous growth of the semiconductor industry has created an increasing demand for engineers who are well trained in the subject of semiconductor device theory. Yet courses in this subject are often very difficult for students, because of the abstract nature of the material and our inability to provide a genuine laboratory experience involving the inner workings of those devices.[1,2] To address this problem, we began development of a set of interactive Excel spreadsheets to provide a "virtual laboratory" experience for the students and thereby facilitate active learning processes.[2] Here, we discuss the continued development, implementation, and optimization of these tools using feedback based on instructor observation, course surveys, student focus groups, and various measures of student performance.

Typically, students tend to fail to master two major concepts in this subject, the behavior of excess minority carriers in quasi-neutral regions, and the energy band diagram of metal-oxide-semiconductor (MOS) capacitors. They often fail to grasp the relationships between slopes and magnitudes of excess carrier density plots at depletion region boundaries, and between the diffusion currents and instantaneous voltage across a junction, respectively. Students also fail to appreciate the connection between electric fields and band bending in the MOS-C, and the change in field across the oxide-semiconductor interface. They also make typical mistakes relating charge density, electric field, and electrostatic potential. They also have difficulty inferring carrier concentrations from band diagrams. We believe these difficulties can be traced to the use of passive lecture delivery.

The importance of active learning and interactive engagement strategies when tackling such a difficult subject cannot be overemphasized, as has been extensively documented in the educational literature.[3-10] Techniques such as peer instruction[4] and other types of interactive engagement improve student learning and retention, overcome shortened attention spans, improve student attitudes and peer interactions, reduce drop-out rates, and create long-lasting bonds between students and instructors. Yet to date there have been few studies of student learning; typically limited, if any, use of active learning strategies; and no standardized assessment tools developed for upper-division solid-state electronics classes. Some useful software already exists to aid the teaching of this subject,[1,11-13] but more in-depth, comprehensive, and interactive software is needed to support fully interactive learning.

Spreadsheet software tools have been used to stimulate student interest and to teach subjects interactively since as early as 1984.[14-16] They have been used to teach diverse technical subjects like mathematics,[17-20] physics,[21,22] chemistry,[23,24] and computer science.[25,26] There is even an electronic journal entitled Spreadsheets in Education (www.sie.bond.edu.au). Spreadsheets have been used in electrical engineering to teach concepts in circuits,[27] linear systems theory,[28,29] and electromagnetics.[30-33] They have been used a few times in the solid state area,[13,34,35] most notably by their inclusion in the on-line textbook of Van Zeghbroeck.[13] However, none of these applications have been extensive or comprehensive, and most lack graphical user interfaces (GUIs) such as we have introduced. In our approach, spreadsheets with GUIs become ideal tools for learner-centered inductive learning processes, which are typically more effective for most engineering undergraduates,[36] yielding better understanding and longer retention.

Interactive Spreadsheet Development and Related Exercises

The initial development of seven workbooks treating semiconductor statistics, the abrupt *pn* junction diode, the uniformly-doped bipolar junction transistor (BJT), the electrostatic and capacitance-voltage properties of the MOS-C, and the MOS field-effect transistor (MOSFET) was described elsewhere.[2] We have since developed four additional workbooks covering an alternative approach to semiconductor statistics using Shockley diagrams of concentrations as a function of Fermi level,[37] the turn-on transient of a *pn* junction, the ac response of excess carrier concentrations in a *pn* junction, and the current-voltage (*I-V*) characteristics of a BJT using the Ebers-Moll model. The ac response of the *pn* junction is illustrated using animation, where the excess carrier concentration is rapidly re-plotted at successive instants of time to illustrate both the temporal and spatial variations. The iteration capabilities of Excel are used to accomplish the "sweeping" of the time variable. The frequency can be adjusted to see its effect on the ac behavior, although the time taken to plot a single time period is kept fixed so that the behavior can be observed clearly.

We also carried out major revisions and enhancements of the other workbooks, particularly with regard to the GUI design. Previously, we frequently used scrollbars to adjust quantities such as doping, voltage, region widths, temperature, etc. This approach suffers from the disadvantage that the allowable range of parameter values must be preset, limiting the range that can be used. It can also be difficult to achieve adequate resolution. A more serious problem is that certain combinations of different parameters can lead to error conditions, such as

degeneracy, punch-through, high-level injection, or other conditions that are not compatible with the analytical theories being used. Formerly, we had to display warnings that the results were not valid in these cases. In our new approach, we generally use arrow keys to set these parameters, with larger keys for coarse adjustment and smaller keys for fine adjustment. An example of the revised GUI for the *pn* junction band diagram is shown in Fig. 1. With this approach, preset ranges of parameters are unnecessary, and each parameter can be limited to values that do not cause any errors based on the values already set for all other parameters. If the user tries to reach a value outside of the currently permissible range, the Visual Basic code used to implement the ActiveX controls causes a beep to be sounded and an appropriate error message to be displayed to explain the problem. This method avoids faulty plot displays and other problems.

Based on student suggestions, we added drawings of the device as additional plot sheets in each device spreadsheet, shown on the same scale as the various plots. This feature helps students to understand the geometry of the devices and the relationships between the device structure and the plots.

Other major enhancements in the *pn* junction spreadsheet include the computation of the exact electrostatic solution using numerical integration (whose display can be turned on or off), as illustrated for the charge density plot in Fig. 2; addition of depletion capacitance-voltage characteristics and reverse *I-V* characteristics (including the effects of generation in the depletion region); addition of a pop-up box to display various junction parameters (see Fig. 2); and the
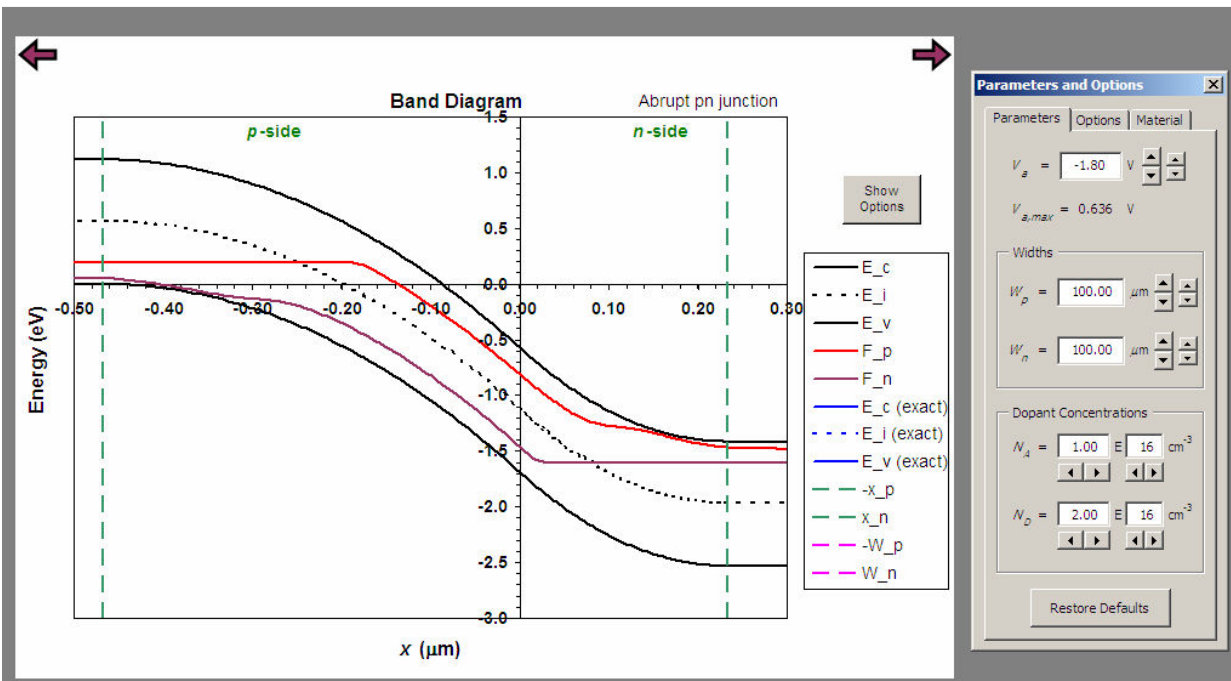

Fig. 1. Energy band diagram displayed by the *pn* junction spreadsheet under reverse bias. The modified GUI dialog box used to control device parameters, scales, and options in real time is shown at the right (two of the tabs are not visible). Input parameter definitions are: Va = applied bias; Na = acceptor doping on *p*-side; Nd = donor doping on *n*-side; Wp = total width of *p*-side; Wn = total width of *n*-side.
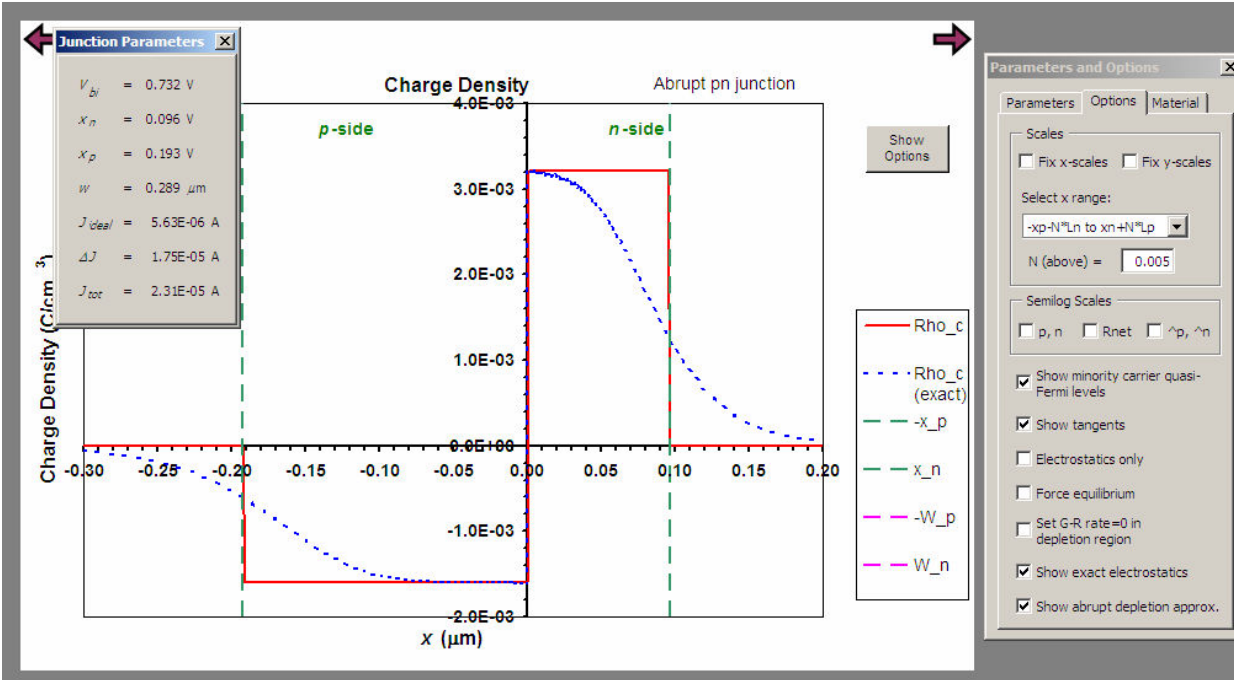
Fig. 2. Charge density profile in a *pn* junction under forward bias, shown both in the abrupt depletion approximation (solid, red curve) and in the exact electrostatic solution (dashed, blue curve). The Options tab of the dialog box is shown here, as is a pop-up box that shows various junction parameters.

inclusion of an iterative calculation of the quasi-Fermi levels to display them more accurately, especially in reverse bias.

The quasi-Fermi level calculation proceeds as follows. The quasi-Fermi levels are first assumed to be constant across the depletion region (quasi-equilibrium approximation) to calculate the current densities. The current densities are then used to re-calculate the quasi-Fermi levels within the depletion region, integrating point by point using the relation

$$
F_n\left(x_1\right) = F_n\left(x_o\right) + k_B T \ln \left[1 + \int_{x_o}^{x_1} \frac{J_n\left(x'\right) e^{\frac{E_c\left(x'\right) - F_n\left(x_o\right)}{k_B T}}}{q D_n N_c} dx' \right] \qquad -x_p \leq x < x_n
$$

for the electron quasi-Fermi level, F_n, for example. Here, x_o and x_1 are two successive points, k_B is Boltzmann's constant, T is absolute temperature, J_n is electron current density, E_c is the conduction band edge, q is the magnitude of the electronic charge, D_n is the diffusivity of the electrons, N_c is the effective density-of-states in the conduction band, and x_p and x_n are the widths of the depletion region on the *p*-side and *n*-side, respectively ($x=0$ denotes the metallurgical junction). The integration is performed only between each successive pair of points using the trapezoid rule, and not using the more obvious limits of x to x_n, in order to avoid numerical

overflows at large reverse biases. A similar formula is used for $F_p(x)$. The results are shown in Fig. 1. The quasi-Fermi levels are not at all constant in reverse bias, as some textbooks assume; a detailed discussion was given previously by Sah.[38] The artificial "humps" noted in F_p near the n-side of the depletion region and in F_n near the p-side are attributed to the failure of the abrupt depletion approximation in those regions, which causes errors in the value of $E_c(x)$ entering the above formula. We will attempt to fix this issue in a future version using the exact electrostatic results.

We have continued development of the interactive homework exercises to accompany the spreadsheets, which now number 14; all are accompanied by solutions. Based on student suggestions, the individual questions in the spreadsheets were broken out more clearly. Most of the exercises were classroom tested and were generally received favorably by the students.

Assessment Results

Many of the spreadsheets were first used in our senior-level semiconductor device course, EEE 436 (Fundamentals of Solid State Devices), in Fall 2004 as described previously.[2] The full set was then used in the same course in Spring 2005. The results were compared to those from a section taught in Spring 2004 which did not use these materials. All three sections were taught by the same instructor using the same textbook and lecture notes, and with very similar homework assignments and examinations. The homework did differ however in that the spreadsheet exercises were substituted in the experimental sections for some of the traditional problems requiring numerical computations that were assigned in the comparison section. Other homework problems involving derivations or other types of problems were used in all three sections. Some use of the spreadsheets was made in lecture in both semesters in a demonstration mode, but they were primarily used for the homework exercises.

The student performance in the course was assessed using various measures, including the scores on each exam (and on each problem of each exam), the homework scores, the total averaged course score, and the results of the Device Concept Inventory (DCI) described previously.[2] Some of the more important data is summarized in Table I. The overall course scores appear significantly higher in the comparison section, but that section also had a significantly lower prior grade point average (GPA). The results on the DCI post-test are not significantly different, which may be due to the absence of graphically-oriented questions on the present version of that assessment instrument. Graphical understanding is an area that should be particularly enhanced by use of the spreadsheets.

Table 1. Summary of student characteristics and measures of achievement.

Section	# of students	% graduate students	Prior GPA	DCI Pre-test*	DCI Post-test*	Total Course Score*
Comparison	15	60	3.04±0.61	--	68±17 (9)	66±23
Experimental (F'04)	19	26	3.43±0.49	35±10 (19)	64±13 (16)	77±10
Experimental (S'05)	24	38	3.47±0.52	30±11(11)	64±10(6)	79±9

* Values are given as mean ± standard deviation. Number in brackets indicates the number of students who took the test.

In order to assess the impact of the spreadsheets more rigorously, we fit a Gaussian linear model to each outcome (total course score, scores on each exam, DCI scores, and even scores on individual exam questions) using prior GPA and a binary variable denoting spreadsheet use as covariates. This analysis was conducted under the supervision of the Center for Research on Education in Science, Mathematics, Engineering, and Technology (CRESMET) at Arizona State University to ensure objectivity. The regression coefficients were then tested for significance using a *t*-test, and 95% confidence intervals were calculated. A transformation was used on response variables whose distributions were non-normal. The results showed that the many of the outcomes were significantly correlated to prior GPA, including the total course score and the exam scores. A clear, statistically significant, benefit to the spreadsheet use could not be found, mainly due the strong influence of prior GPA and the relatively small samples sizes. Several exam questions did show improved performance when using spreadsheets, but larger sample sizes are needed to be certain of the effects. We plan to add additional control data and continue using the spreadsheets in other sections to obtain better statistics. In addition, we feel that more in-class use of the spreadsheets in an active learning mode could yield to a significantly greater impact on course performance.

Student satisfaction with the spreadsheets was generally very high. Several measures of satisfaction from the teaching evaluations are shown in Table 2. The rating of the "Textbook/supplementary material" increased in the experimental sections, even though the same textbook was used, as did that of "laboratory assignments/projects." There is no actual laboratory for the course, so the responses in the experimental section are believed to relate to the spreadsheet exercises. The homework and overall ratings were similar or somewhat higher. Results of a focus group of six students conducted at the end of Fall 2004 were discussed previously.[2] To obtain additional feedback in Spring 2005, we used an on-line survey open to all students in the course. The student feedback from this survey was quite positive. All students agreed that the spreadsheets were helpful, with 80% agreeing that they were "quite helpful" or "very helpful." All of them agreed that in-class usage of spreadsheets helped them use the spreadsheets on their own and that the spreadsheets worked well and were not too complex for the course. A total of 80% of the students said that they would "recommend or strongly recommend taking courses that used spreadsheets." Students commented on the survey that "I found the spreadsheets extremely helpful. After using them, I gained a much better understanding of key concepts from the course. It helped tremendously to 'see' things change right in front of you," "They were useful and worth developing more," and "The spreadsheet was very helpful for me to understand the lectures and concepts. It is very difficult for me to

Table 2. Student satisfaction with spreadsheets.

Section	Textbook/ Supplementary Material	Value of assigned homework	Value of lab assignments /projects	Overall quality of the course and instruction
Control	4.08	4.31	2.0*	4.23
Experimental Fall '04	4.65	4.58	4.80**	4.43
Experimental Spring '05	4.33	4.38	4.46†	4.22

* Rating by 1 student only; other 12 students rated as "not applicable"
** Rating by 5 students; other nine students rated as "not applicable"
† Rating by 13 students; other five students rated as "not applicable"

understand how it works. From the spreadsheet, I could figure out why and how the phenomena." Their requests for improvements centered mainly on providing a user manual and more explanation of the theory and equations underlying the computations in the spreadsheets. To address this issue, we plan to adapt a Master's thesis written about the spreadsheet construction for use as such a manual.[39] It contains detailed information about the underlying theory, equations, and computational methods as well as the spreadsheet construction.

Conclusions

Interactive Excel spreadsheets have been developed as a virtual laboratory for use in semiconductor device theory classes, along with accompanying structured exercises. Graphical user interfaces implemented with Visual Basic for Applications and ActiveX controls permit variation in device parameters with the results immediately visible on plots of the internal device variables. The interfaces have been optimized, including provisions to prevent various error conditions from occurring. The student response has been overwhelmingly positive, but further use of the spreadsheets with larger student populations and probably more in-class use in an active learning approach will be necessary to demonstrate a clear effect on student learning.

The approach developed here (spreadsheets with plots whose input parameters are controlled in real time by GUI's) can very likely be applied to topics in a wide variety of other engineering disciplines, whenever it is desired to allow students to explore the effects of varying parameters in "standard" problems. Possible example applications could include beam bending problems, tank filling and mixing problems in chemical engineering, the plotting of linear response functions and unit impulse and unit step responses as a function of pole-zero placement in linear systems theory, certain heat transfer problems, well and barrier problems in quantum mechanics, and many others. We believe that this method should be very useful in helping students develop intuition in difficult problems, especially where real laboratory experiments are either impractical, difficult, or overly time-consuming.

Acknowledgments

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