

Spreadsheets to Promote Interactive Engagement in Semiconductor Device Courses

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Abstract

The development and initial implementation of a prototype “virtual laboratory” based on Microsoft[®] Excel spreadsheets with associated Visual Basic[®] for Applications modules is described for use in semiconductor device courses for engineering undergraduates. The spreadsheets use graphical methods to illustrate quantities such as charge densities, electric field profiles, electrostatic potentials, energy band diagrams, carrier concentrations, current density plots, and related quantities for various semiconductor devices, including *pn* junctions, bipolar junction transistors, MOS capacitors (including both electrostatics and capacitance-voltage characteristics), MOSFETs, and also for semiconductor statistics. The students can use scrollbars and other ActiveX[®] controls interactively to adjust device parameters such as doping levels, applied bias voltages, layer widths, and temperature, and immediately visualize the effects of those changes on the device behavior. Interactive exercises using these spreadsheets have also been developed. The initial use and assessment of these tools using student examination and homework scores, student teaching evaluations, focus groups, and a special web-based Device Concept Inventory developed in this project are described.

Introduction

Traditional passive, lecture-based instruction in semiconductor device theory, even when it is of excellent quality, has only limited success in promoting conceptual understanding and student achievement. The importance of interactive engagement in technical courses has been well documented in the literature.¹⁻³ Yet there is a critical national need for engineers who are well trained in device theory to support the semiconductor industry, which has become the largest manufacturing industry in the United States. The inherently difficult nature of the subject matter, which places exceptional demands on students’ skills with elementary mathematics, calculus, and differential equations, and on their background in electrostatics, statistical mechanics, and quantum mechanics, contributes to the lack of success.⁴ A particular problem is the lack of student intuition in this area, because students are unable to see, hear, feel, or touch electrons and holes, energy band diagrams, electrostatic field or potential distributions, and other facets of semiconductor devices. Laboratory experiments can familiarize students with some basic semiconductor properties, and with terminal characteristics of devices, but it is virtually impossible to construct ones that allow students to observe the internal operation of a device directly. There is an urgent need for a “virtual laboratory” based on simulation, in which students can easily visualize and interact with these quantities, and learn by experience how they

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behave. This laboratory can then serve as a basis for more active learning strategies involving interactive engagement of the students.

Some software for this purpose currently exists, in the form of Java™ applets,^{4,5} MATLAB® scripts,⁶ and relatively simple Excel spreadsheets.⁷ While the existing items are certainly useful, more in-depth, interactive, comprehensive, and detailed software is needed to support a fully interactive learning approach involving both qualitative and quantitative reasoning. A full set of exercises using the material is also needed. In this pilot project, we are developing such software to serve as the basis for a fully interactive virtual laboratory. The level of physics includes both simple analytical textbook models and more realistic ones including partially numerical calculations. Interactive exercises requiring discussion of both what happens and why have been written to ensure that students actually use and benefit from the spreadsheets. Assessment is being performed using student examination scores, student teaching evaluations and surveys, focus groups, and a special web-based Device Concept Inventory developed in this project. Comparisons are being made between a control section who did not use these tools and experimental sections that do. In the following, we outline the development of the spreadsheets and exercises, give examples of their outputs, and summarize the results of our assessment efforts to date.

Interactive Spreadsheet Development

Microsoft Excel was chosen as the platform for these instructional materials, based on its plotting and scientific function capabilities, its widespread availability, the ease of development, and the nearly universal familiarity with this software on the part of students and instructors alike (unlike more specialized software). Moreover, it allows users to examine the formulas and methods underlying the computations and even to alter or extend them at will, unlike compiled software. To provide a fully interactive interface, dialog boxes and other controls are implemented using Visual Basic for Applications (VBA). These enable students to use scrollbars, arrow keys, and other ActiveX controls to adjust device parameters such as doping levels, applied bias voltages, layer widths, and temperature, and immediately visualize the effects of those changes on the device behavior. Both graphical and tabular outputs are provided for qualitative and quantitative analysis. A few computations not readily performed in spreadsheet cells, such as the solution of nonlinear equations, are implemented in VBA subroutines that function as “black boxes,” although these routines can also be examined by students.

The initial set of seven workbooks that was developed in this pilot project was designed to illustrate the most important principles related to those key devices that are covered in virtually every semiconductor device course: the abrupt pn junction diode, the uniformly-doped bipolar transistor, the MOS capacitor (MOS-C), and the MOSFET. Two of the workbooks deal with the important physics topic of semiconductor statistics. The scope of the project limited us to addressing the most basic, static characteristics of the devices (although MOS capacitance is computed at both high and low frequencies and in deep depletion). We hope to treat the dynamic (AC and switching) characteristics of each device; various topics in semiconductor physics (other than semiconductor statistics); the electrostatics and carrier concentration profiles of arbitrary, user-defined layered structures at equilibrium; and additional devices such as Schottky diodes, junction FETs, metal-semiconductor FETs, nonuniformly doped pn junctions and bipolar

transistors, heterojunctions, thyristors, and possibly some optoelectronic devices in a more comprehensive project at a later time.

The pn junction workbook has the following structure, which is typical of many of the others. A Materials spreadsheet is used to select the semiconductor material from a drop-down list (currently limited to Si, Ge, or GaAs, but more can be added later) and the temperature, and then displays many material properties and fundamental constants automatically. It also contains cells to enter the doping and total width of each side, and displays a number of derived parameters. (Most of the input parameters can alternatively be entered or changed in the Options dialog box while using the charts; see below.) Definitions of each symbol and quantity appear whenever the user positions the cursor over that quantity, using the comment feature of Excel. A second Data spreadsheet is used to enter the applied bias voltage and device area (the former can also be entered from the Options dialog box), and displays numerical values of various bias-dependent parameters. It also contains the large tables of data used for all of the plots.

Nine other sheets each display a plot of various quantities as a function of position across the diode, such as the energy band diagram (including quasi-Fermi levels); the charge density distribution; the electric field profile; the electrostatic potential; the total electron and hole concentrations; the excess electron and hole concentrations; the electron, hole, and total current densities (J_n , J_p , and J); the net (Shockley-Read-Hall, SRH) recombination rate (R_{net}) as a function of position; and the separate drift and diffusion components of the electron and hole current densities. Another sheet shows miniature, side-by-side versions of all these plots, so that the interrelationships among the various quantities can be more easily visualized. The abrupt depletion approximation is currently used for the electrostatic quantities, although we plan to incorporate the exact electrostatic solution as well in a later version. The currents and excess carrier densities in the bulk regions of arbitrary lengths (terminated by ideal ohmic contacts) are calculated from the minority carrier diffusion equation, using the quasi-equilibrium approximation in the depletion region, and the allowable bias is automatically limited to avoid high level injection. We calculate the actual SRH recombination rate everywhere and integrate it across the depletion region to find the actual variations in J_n and J_p across that region, without assuming that they are constant there as done in the ideal textbook Shockley model. There is however an option to artificially set $R_{net} = 0$ inside the depletion region, to facilitate comparison with textbook figures. The quasi-Fermi levels are computed from the excess carrier densities in the bulk regions (assuming nondegenerate statistics), and are assumed to be constant across the depletion regions (quasi-equilibrium). The calculations are therefore all based on standard analytical formulas, with the exception of one-dimensional integrations performed with the trapezoid rule.

Sample plots of the band diagram and net recombination rate from this workbook are shown in Figs. 1 and 2, respectively. One tab of the interactive dialog box that controls the device parameters, plot scales, and options for real-time interaction is also shown in each case (it is activated by clicking on the “Show Options” button on the spreadsheet). The applied bias, doping levels, and total widths of each side can be adjusted using scroll bars, resulting in almost instantaneously visible changes to the plots. In addition to changing device parameters on the dialog box, the students can set the horizontal range of the plots to display different portions of the device, can elect semilogarithmic or linear plots in several cases, can select the

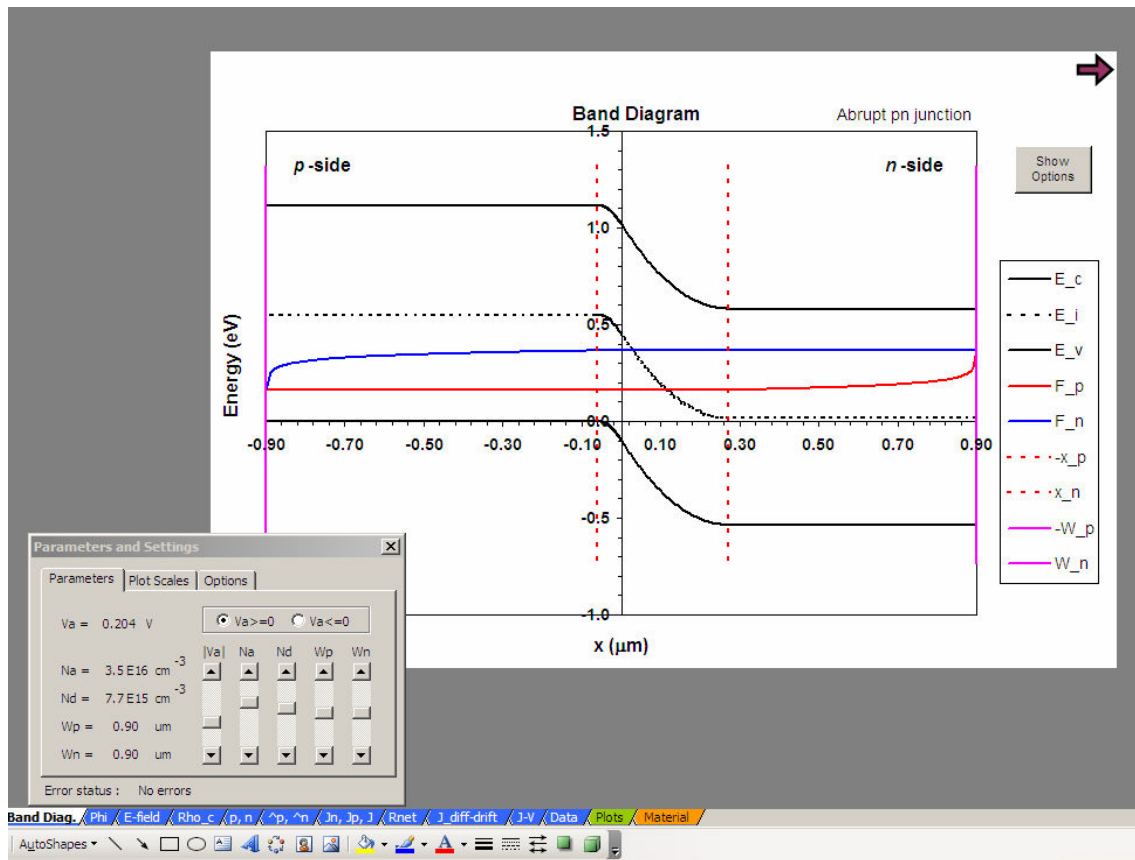


Fig. 1. Energy band diagram displayed by the pn junction spreadsheet. The dialog box used to control device parameters, scales, and options in real time is shown at bottom left (two of the tabs are not visible). Input parameter definitions are: V_a = applied bias; N_a = acceptor doping on p -side; N_d = donor doping on n -side; W_p = total width of p -side; W_n = total width of n -side.

semiconductor material, and can select various options to control what quantities are displayed and what physical effects are included.

Using the above controls, students can explore the effects of changing different parameters, and be guided through exercises in which they are required to explain these changes in terms of the device physics they have learned. It is important to emphasize that these spreadsheets are not intended to provide stand-alone instruction in device theory, but to serve as an aid with which to explore how devices behave, and thereby solidify understanding gained from conventional textbooks and lectures. They are flexible, however, in that they can be used in an exploratory way prior to covering the conceptual and analytical material in lecture, as a lecture demonstration tool, for in-class interactive exercises, as exercises to be performed after the lectures (e.g., as homework or recitation), or in any combination of these ways.

The pn junction workbook also contains a plot of the current-voltage characteristic (on either a linear or semilog scale), which is computed using the one-dimensional data table feature in Excel. The table automatically plugs a series of values into the applied bias cell, and stores the resulting total current density computed by the spreadsheet in the table. Using this approach (as opposed to just placing simple ideal diode formula in each cell) allows us to optionally

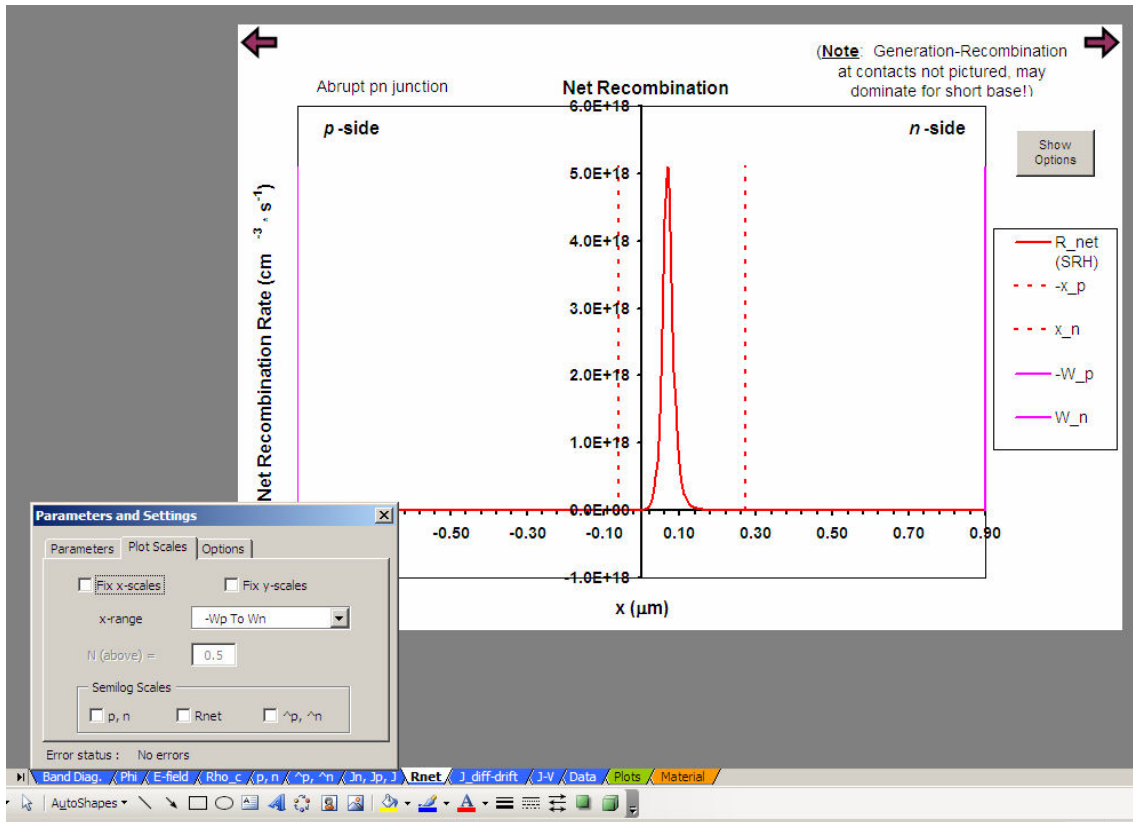


Fig. 2. Plot of net recombination rate as a function of position displayed by the *pn* junction spreadsheet. The dialog box used to control device parameters, scales, and options in real time is shown at bottom left (two of the tabs are not visible).

include the effects of generation-recombination in the depletion region (which is included by numerical integration at each bias voltage) and series resistance. This plot must be refreshed manually by clicking on a button when device parameters are changed, since the lengthy table computation would otherwise slow down the spreadsheet too much. (The computation mode is set to “Automatic except tables.”)

The distribution functions workbook plots the Fermi-Dirac and Maxwell-Boltzmann distribution functions and the relative error in the latter approximation as a function of energy, using linear or semilog axes and absolute or normalized energy units. The temperature is controlled interactively by a scroll bar. Another plot shows the energy density-of-states in the valence and conduction bands and the electron and hole concentrations per unit energy on various scales selected by the user. The position of the Fermi level and the temperature can both be varied interactively to view their effects on the electron and hole populations.

The semiconductor statistics workbook plots the carrier concentrations, degree of dopant ionization, and band diagram as a function of temperature. The computations are based on solution of the quartic charge neutrality equation for the Fermi level at each temperature, which is performed by a quartic equation solver implemented in Visual Basic. All three regimes (freeze-out, extrinsic, and intrinsic) are therefore included for both *n*- and *p*-type material. The dopant concentration and impurity ionization energy can be controlled interactively from the

dialog box, and the temperature range to plot can be selected. Carrier concentrations can be plotted on linear or semilogarithmic axes or as an Arrhenius plot. The temperature dependence of the band gap is optionally included. A second, very similar set of plots is given as a function of impurity concentration at a user-specified temperature, which can be interactively varied.

A workbook devoted to the electrostatics of the ideal MOS capacitor (with an added source region contact for optional back-biasing) plots the energy band diagram, charge densities, electric field profile, and electrostatic potential as a function of position throughout the structure. The computations are based on the exact electrostatic solution (using numerical integration to find the position corresponding to each value of the potential), but a simplified “block charge diagram” similar to that in some textbooks is also provided. Parameters including the gate voltage, back bias, and substrate doping concentration can be varied interactively while observing any of these plots, and the scaling can also be adjusted. The substrate doping can be chosen as either *n*-type or *p*-type. Automatically-generated labels on all plots indicate the regime of operation.

Another workbook for MOS capacitors focuses on the capacitance-voltage (*C-V*) characteristics in the low frequency, high frequency and deep depletion cases. The characteristics are plotted using the exact theory as well as using the “delta depletion approximation” often discussed in textbooks. A dialog box interactively controls the back bias voltage, oxide thickness, and substrate doping type and concentration. Any or all of the three characteristics can be plotted on one graph. Other, more advanced plots in this workbook show the total semiconductor charge per unit area as a function of either gate bias or normalized surface potential, and the normalized capacitance as a function of normalized surface potential.

A workbook to illustrate the physics of the MOSFET was also developed. It permits a family of current-voltage (*I-V*) output characteristics to be plotted in a curve-tracer mode using both the square-law model and the bulk-charge model (future versions may include the charge-sheet model as well). Interactive controls to vary the source-to-body back bias and the substrate doping are provided. The spreadsheet also plots various quantities at the surface as a function of distance along the channel between the source and drain, including the energy band diagram; the electrostatic potential; the inversion, depletion, and total charge densities; the depletion width; and the surface quasi-Fermi level splitting. These quantities can be plotted for either or both of the two models. The plots are at present performed only in the triode regime. A future version will also plot electrostatic quantities along lines perpendicular to the surface at user-specified locations between the source and drain.

The bipolar junction transistor workbook is done for a *pn*p transistor and is very similar to the *pn* junction workbook discussed above. Constant doping is assumed in each region, as well as nondegeneracy and low level injection. All three doping levels and region widths can be adjusted interactively, as well as the two applied bias voltages. Recombination in the base can be either included or neglected. In addition to the various currents under given bias conditions, the transistor performance parameters such as current gains and leakage currents are computed. The plotted parameters are the same as in the *pn* junction workbook. Another spreadsheet is in development to plot the input and output characteristics using the Ebers-Moll model.

Interactive Exercises

The structure of the above spreadsheets lends itself to a learner-centered inductive learning process, which is generally more effective than purely lecture-based methods.⁸ The use of numerous graphs and diagrams, free from the requirement to study the underlying equations in the initial explorations, should aid students who are visual, rather than verbal learners.⁸ The concrete information and observable behavior of the graphs when changing parameters should be of help to the many students who are sensors rather than intuitors,⁸ as will the computer-aided instructional approach.⁹ The interactive engagement should aid both active and reflective learners.⁸ However, actual use of these materials by busy students can be ensured only by assigning specific exercises based on them.

We have therefore developed a total of nine fairly detailed multi-part exercises (and corresponding solutions) to date for use with the above workbooks, to have at least one exercise for each workbook. Typically these exercises begin by specifying a set of parameter values to be used in the spreadsheet, and then guide the student through an examination of the various plots while systematically changing different parameters. The student is required to answer a series of questions about observed behaviors, including both what happens and, very importantly, why. Hints are given as to the relevant physical principles and equations. Specific numerical values and/or printouts of some of the plots are requested to ensure actual use of the spreadsheets (as opposed to answers based on the behaviors students *expect* to see). The exercises were tested as assigned homework problems during one semester, and generally worked well. In the focus group at the end of the semester, all six student participants agreed with the statements that “the assigned exercises using the spreadsheets were well constructed,” and that “they encouraged sufficient exploration of the spreadsheets by the students.”

Device Concept Inventory

To help provide an objective, standardized evaluation of student learning of this subject, we developed a 50-question multiple-choice and multiple-answer quiz called a Device Concept Inventory (DCI). The questions cover the full range of basic semiconductor physics and the theory and operating principles of the major devices, including the *pn* junction, the MOS-C, the MOSFET, the bipolar transistor, and one question on Schottky diodes. A 90 minute time limit was set, but 60 minutes was generally found to be sufficient. The problems are all conceptual or factual in nature and do not require computations. Plausible distracters were designed based on the experience of the author with student misconceptions. The level of difficulty ranges from fairly easy to moderately difficult. The order of the questions and the order of the answers are both randomly shuffled each time the quiz is taken. The present version does not incorporate any questions involving the interpretation of graphs, although such questions would be highly desirable for this subject material and may be incorporated into future versions. Questions requiring the students to sketch graphs, while also desirable, would unfortunately be difficult to incorporate in a web-based implementation (especially one that can be automatically graded). The multiple-answer questions are assigned full or partial credit (2 pts. or 1 pt., respectively) according to a defined system for each question. The quiz has been set up as a web site where students can log in and take it at their convenience (they are instructed not to use any aids). The results are downloaded into an Excel spreadsheet for analysis. The questions have been ranked

by the difficulty students had with them, which is yielding useful insights into areas that require greater emphasis.

The DCI has been administered to two sections of an introductory device theory class (as described below), and also to a small number of experienced M.S. and Ph.D. students in solid state who had prepared to take it. The graduate students had scores from 79 to 90 out of 100. The total scores of the students in the device classes correlated reasonably well with their scores on the DCI post-test, with a correlation coefficient around 0.75. More extensive validation of this assessment will however be needed. The authors intend to make the DCI available to instructors in other institutions who wish to use it (via the web), and may be contacted directly for this purpose.

Initial Usage and Preliminary Assessment Results

Preliminary assessment of the effectiveness of these spreadsheets has been carried out using one section of our standard undergraduate semiconductor device theory class who did not use these materials (the control section) and a subsequent section that did (the experimental section). Both sections were taught by the author using mostly the same approach in lecture, the same textbook, and very similar examinations. In the experimental section, the interactive exercises were assigned in place of some of the conventional homework problems that were assigned in the control section. The instructor made some use of a couple of the spreadsheets for demonstration in lecture, but did not do so in most cases due to time constraints and due to delays in completing some of the spreadsheets. As the spreadsheet development was completed in parallel with the course, the MOS *I-V* workbook was ready to use only for an extra-credit exercise after the normal homework was completed (although 84% of the students elected to do the exercise), and the bipolar workbook was not finished in time to use during the experimental semester. More effective use of the materials will therefore be possible in a future section, which would provide a better gauge of their impact.

A summary of the student characteristics and measures of achievement in each section is given in Table 1. The DCI was administered at the end of the semester in the control section, and at both the beginning (pre-test) and end (post-test) of the semester in the experimental section. No significant difference was noted in the DCI post-test results for the experimental and control sections. However, the total course scores (based 80% on exams and 20% on homework) did increase significantly by 11 points in the experimental section. Unfortunately, it is difficult to determine how much of this improvement may be due to the higher average incoming GPA of that section. The DCI results may be largely attributable to the current absence of graphically-oriented questions on that instrument, since the spreadsheets are expected to help most in

Table 1. Comparative measures of student characteristics and achievement.

Section	# of students	% graduate students	Prior GPA*	DCI Pre-test*	DCI Post-test*	Total Course Score*
Control	15	60	3.04±0.61	--	68±17	66±23
Experimental	19	26	3.43±0.49	35±10	64±13	77±10

*Values are given as (mean ± one standard deviation).

developing graphically-oriented understanding. Such understanding is a very important component in learning device theory. The relatively small sample sizes and different characteristics of the two sections imply that larger studies will be needed to assess the impact of these materials accurately. More extensive use also needs to be made of the materials in lecture, as noted above.

Student satisfaction with the spreadsheets was evaluated from the usual instructor evaluations. The standardized questions on these surveys do not specifically address the Excel spreadsheets, but responses to related questions are shown in Table 2. A substantially improved rating of the “Textbook/supplementary material” was noted (the textbook itself was unchanged), as well as of “laboratory assignments/projects.” There is no actual laboratory for this course, so the responses in the experimental section probably relate to the spreadsheet exercises. The homework (which partially used the interactive exercises) was rated more highly, and the overall course rating improved as well.

A focus group was conducted at the end of the experimental section to obtain specific student reactions to the spreadsheets. An assessment specialist and another solid-state professor conducted the group to ensure objectivity, and the results were not communicated to the instructor until after final grades had been submitted. Ten students were randomly selected to participate but only six could attend due to conflicts; students were paid \$50 each to encourage participation. The students were generally unanimous in their opinions. All agreed in the structured interviews that “the Excel spreadsheets were helpful in learning the course material,” that “the spreadsheets were sufficiently ‘user-friendly’ and easy to understand,” and that they are not “too complex or detailed for this course.” All “would recommend to a friend to take a course that used spreadsheets like this.” All six agreed that “increased use of these spreadsheets during lecture by the instructor would be helpful to improve the instruction (in demonstration mode),” and that “such use would make it easier for students to use them on their own.” However, none of the students felt that “it would be beneficial to have students work interactive exercises on these spreadsheets during class, in place of some of the conventional lecture time.” It may be that students would be more appreciative of the value of this approach if they actually did such exercises, however, since this method is known to improve learning. A very encouraging result was that all students stated they had used the spreadsheets on their own several times, for some purpose other than to complete the assigned or extra credit spreadsheet exercises. This observation suggests that they genuinely found them useful.

Table 2. Comparative measures of student satisfaction from instructor evaluations.*

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	4.65	4.58	4.80***	4.43

*All values on a 1.00-5.00 scale (higher scores are better).

**Rating by 1 student only; other 12 students rated as “Not Applicable.”

***Rating by 5 students; other 9 rated as “Not Applicable.”

The focus group suggested breaking out the individual questions that the students are supposed to answer in the exercises more clearly. This change is being made in the second semester the exercises are used. They also suggested adding “pictures” of the device structures to the spreadsheets to make it clearer what is being plotted, and this enhancement is being added to the new versions. Future focus groups will be used to elicit additional suggestions for improvement.

Student comments on the instructor evaluations were uniformly supportive of the value of the spreadsheets. Students commented that “The spreadsheet exercises were also a wonderful tool to get a good ‘hands on’ understanding of the material without having to worry about difficult equations and having to generate all the plots ourselves. The supplied Matlab code in the book also helped as well, but I preferred the Excel spreadsheets personally.” Also, “I also really liked the Excel spreadsheet exercises. I found them to be a valuable tool in learning the material.”

Conclusions

A preliminary set of interactive Excel spreadsheets has been developed to help students visualize the various quantities related to semiconductor device operation, along with exercises that use these materials and a Device Concept Inventory for use in assessment. Student reaction to the use of these materials has been overwhelmingly positive, although more detailed assessments will be needed to accurately gauge their impact on student learning. Work in the immediate future will focus on refining the existing spreadsheets and on incorporating greater interactive use of these materials into the course delivery, with the expectation of further improvements in student learning.

Acknowledgments

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