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An Engineering Physics Introduction to Electronics for ECE Sophomores

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Abstract

Electronic devices and circuits are fundamental parts of undergraduate curricula in electrical engineering and computer engineering (ECE). A sophomore-level course that gives a balanced treatment of semiconductor device physics and electronic circuit analysis is described. The course topics are semiconductor physics, diodes, transistors, operational amplifiers, and optoelectronics. The course is a prerequisite for upper-level electronics, semiconductor physics, and semiconductor circuit layout curricula. A stronger link between physical principles and device behavior and an improved sequence in electronics instruction are outcomes.

I. Introduction

Electronics is a particularly important area of electrical and computer engineering (ECE) and has been recognized by the National Academy of Engineering as one of the twenty "Greatest Engineering Achievements[1]." It gives instrumentation and processing support. It gives the hardware integral to systems and projects. It is a core area for assessment examinations such as the Fundamentals of Engineering (FE)[2] and for curricula guidelines such as the National Standards for Computer Engineering[3]. The study and analysis of key nonlinear semiconductor devices including diodes, transistors, and operational amplifiers are foundations for advanced courses in other technologies, cf. reference[4]. However, introductory undergraduate courses in electronics and devices rarely provide a strong linkage between the underlying device physics and the circuit design and analysis. Such courses tend to focus either on semiconductor physics or on electronics analysis. Consequently, student pursuing a devices track may not have prerequisites for electronics applications and students pursing an electronic circuits track may not have prerequisites for device physics. Besides educational and career flexibility, breadth of understanding can have great advantage in inter-area and interdisciplinary technologies. For instance, dedicated hardware for embedded systems may require device and circuit design knowledge for an optimized chip layout with regard to performance, power, size, etc.

This paper describes a sophomore-level electronic devices course that gives a balanced treatment of semiconductor physics and associated circuit analysis. The course serves as a requirement in the electrical engineering and computer engineering curricula at Missouri University of Science and Technology (formerly the University of Missouri-Rolla). It was developed in response to concern about the number of lower-level coursework options for majors, development of the computer engineering program, comments from employers wanting more electronics instruction, and other pedagogical issues. The scope, objectives, design, assessment instruments, and associated laboratory for the course are presented. The course provides a stronger link between basic physical principles and device behavior and strengthens the electronics sequence in both degree programs. The course gives prerequisite content for upper-level courses in electronics, semiconductor physics, semiconductor circuit layout, sensor instrumentation, and optoelectronics. It can facilitate students pursuing dual-degree options and minor programs.

II. Curricula Development

The Electrical and Computer Engineering Department at Missouri University of Science and Technology undertook a curricula revision with the intention of:

- Strengthening the electronics component of the curricula,
- Providing additional in-major coursework at the sophomore level,
- Supporting both electrical and computer engineering programs with common required courses, and
- Providing mechanisms to assess the undergraduate programs (with regard to electronics fundamentals and design in the context of this work).

The motivations for the curricula revision included concern about in-major coursework options in the sophomore year, development of the computer engineering program, how best to incorporate device physics instruction, comments from employers wanting more electronics instruction, and desire to have more hardware experience at the sophomore level. A major aspect of the revision was to create an Introduction to Electronic Devices course.

A. Change to EE and CpE Curricula

Selected courses in the prior curricula for B.S. degrees in electrical engineering (EE) and computer engineering (CpE) are shown in Figure 1. Although the degrees were offered within the same department, the EE degree requirements and the CpE degree requirements had limited overlap. Common in-department requirements were limited to basic circuit analysis and computer engineering content, i.e. Circuits I EE 151, Circuits II EE 153, and Introduction to Computer Engineering CpE 111, and associated laboratories. (The EE and CpE course numbers are designated such that the first digit refers to the year, e.g. 1XX course for sophomore level; the second digit for the area, e.g. 12X for devices and 15X for circuits; and the last digit for the specific course.) Prerequisites for many upper-level courses in EE made it difficult for CPE students to cross over and vice versa for EE students wanting CpE courses. New elective courses tended to be developed for either EE majors or for CpE majors.

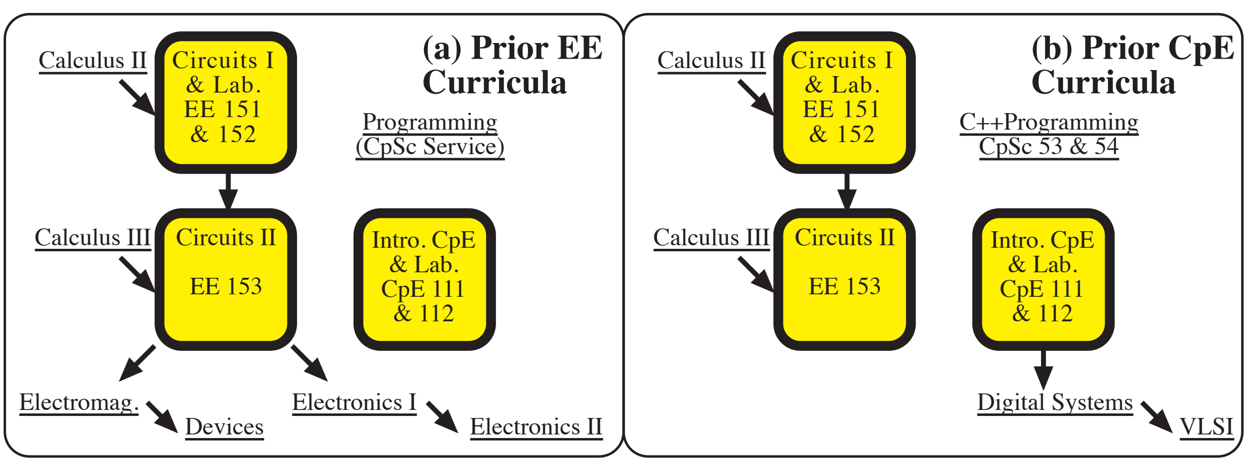

Figure 1. Selected Required Courses for (a) EE Majors and (b) CpE Majors in Prior Curricula

In the prior curricula, Electronics I EE 253 was a required junior-level course for EE majors and an elective course for CpE majors. It required both Circuits I EE 151 and Circuits II EE 153 courses as prerequisites and provided a traditional exposure to diode and transistor circuits, amplifier design, and small signal analysis with an emphasis on analog concepts. The elective Electronics II EE 254 course provided a continuation with an emphasis on digital electronics. Also, the Electronic and Photonic Devices EE 225 course provided traditional coverage of semiconductor device physics and structures, but it required a background in electromagnetics. EE 225 was a requirement for EE majors. (Few CpE majors took EE 253, EE 254, or EE 225.) The Introduction to VLSI (very-large-scale-integrated) Design CpE 311 course was an elective for EE and CpE majors, but it required CpE digital systems courses as prerequisites which were taken by few EE majors. Also, other aspects of the degrees differed such as the computer science (CpSc) requirement; EE majors took the service (not-for-CpSc majors) programming course and CpE majors took the programming course with CpSc majors.

In the revised curricula, the set of common courses is expanded and elective flexibility is improved. Figure 2 shows selected courses in the revised structure (effective for students entering as freshmen in Fall 2007). The common EE and CpE background was revised to include the Introduction to Electronic Devices EE 121 course (the focus of this paper and a new course), the Discrete Systems EE 215 course (a modified course from the systems sequence), and the more rigorous CpSc C++ programming course. Other courses and prerequisites were modified as needed. The credit hours for the new EE 121 course were obtained from the EE 225 requirement for EE majors and a technical elective for CpE majors.

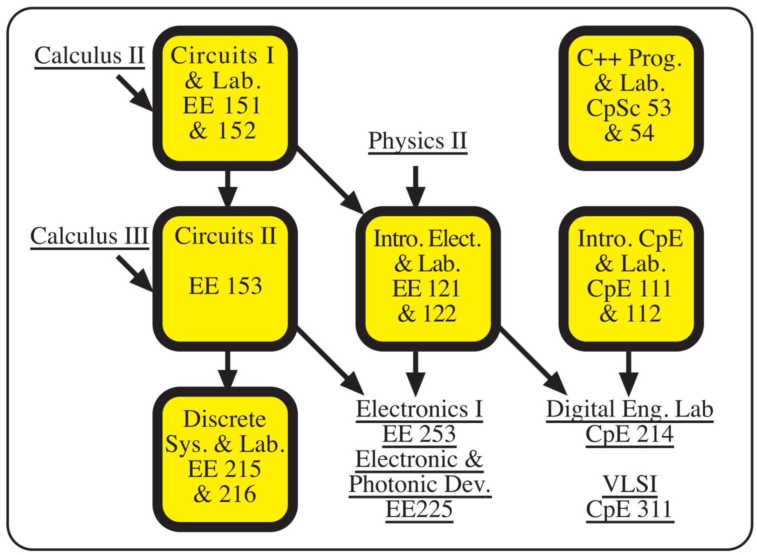

Figure 2. Common (Highlighted) and Selected Courses for EE and CpE Majors

The new course EE 121 immediately follows the second required physics course. It is a prerequisite for Electronics I EE 253, Electronic and Photonic Devices EE 225, Digital Engineering Laboratory CpE 214, and related continuation courses. While not a formal prerequisite for Introduction for VLSI CpE 311, it occurs in the recommended and practical course sequence well before EE or CpE majors would take CpE 311 as an elective. Hence, these upper-level courses start at a higher level and more advanced topics are included. For instance, about one-quarter of the prior topics for both Electronics I EE 253 and Electronic and Photonic Devices EE 225 were replaced with more advanced content, additional examples, etc. Also, EE 121 is a prerequisite for proposed elective courses in instrumentation and optical engineering.

B. New Minor and Dual Degree Options

A minor in electrical engineering was approved for Fall Semester 2013. It requires twelve hours, e.g. four courses, beyond the basic circuit analysis requirements. The Introduction to Electronics course facilitates having a strong electronics component in a minor and allows the additional EE coursework to begin at the sophomore level. Note that computer engineering majors only need three additional courses beyond the common core of Figure 2 and that these courses could satisfy technical and free electives.

An option in electronics, as shown in Figure 3, provides considerable depth in electronic devices and design. Similar options in fiber optics or antennas, as shown in Figure 4, emphasize applied physics devices and applications. Such minor programs may be attractive to other majors that are interested in sensing, instrumentation, robotics, aerospace systems, engineering physics, etc.

Also, a minor in computer engineering was approved for Fall Semester 2014. It requires twelve hours beyond the first electrical circuit analysis course and the sophomore Introduction to Computer Engineering course CpE 111. This minor allows Introduction to Electronic Devices EE 121 as one of the elective courses.

Figure 5 shows a possible minor option that incorporates both electronics and VLSI design. Note that electrical engineering majors already have the EE 151, EE 121, and CpE 111 courses in the common core and that they can incorporate additional CpE courses in the junior and senior electives.

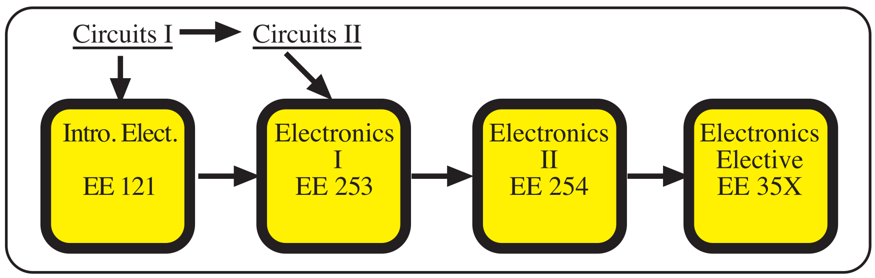

Figure 3. Possible EE Minor Emphasizing Electronics

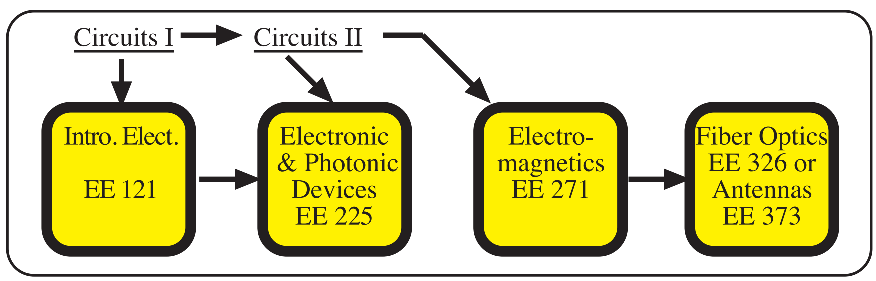

Figure 4. Possible EE Minor Emphasizing Fiber Optics or Antennas

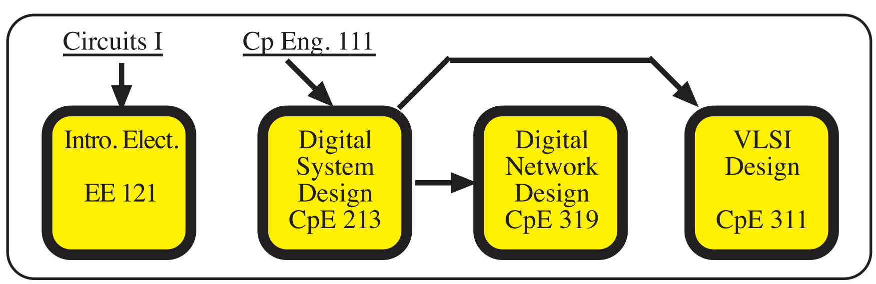

Figure 5. Possible CpE Minor Emphasizing Digital Electronics

Dual-B.S.-degree programs in EE and CpE are facilitated in the revised curricula. Both B.S degrees (each requiring a minimum of 128 hours) can be obtained by completing 145 hours (approximately one extra semester) if electives are chosen for maximum overlap[5], cf. Table 1. The additional common in-major courses, i.e. Introduction to Electronic Devices EE 121, Discrete-Time Linear Systems EE 215, Introduction to Programming (Computer Science C++ course), and the accompanying laboratories, provide significant degree overlap. And, the EE program adopted the more rigorous computer programming course. These common hours made a dual-degree option more attractive (circuit analysis, introduction to computer engineering, and the senior projects courses were already joint requirements) and more common. In 2012, 14 students received both EE and CpE B.S. degrees out of a total 83 EE graduates and 51 CpE graduates. By comparison, one or two students per year obtained dual degrees in prior years.

Table 1. Dual Options for EE and CpE B.S. Degrees

<table>
<tr><th>Program Components</th><th>EE Program</th><th>CpE Program</th><th>Credit Hours</th></tr>
<tr><td>General Education Requirements</td><td>X</td><td>X</td><td>24 Hours</td></tr>
<tr><td>Science, Mathematics, Programming, etc.</td><td>X</td><td>X</td><td>45 Hours</td></tr>
<tr><td>Common EE and CpE Requirements*</td><td>X</td><td>X</td><td>19 Hours</td></tr>
<tr><td>Senior Project</td><td>X</td><td>X</td><td>4 Hours</td></tr>
<tr><td>Electives in EE and CpE **</td><td>X</td><td>X</td><td>9 Hours</td></tr>
<tr><td rowspan="2">Other EE or CpE Requirements (These do not overlap between degrees)</td><td>X</td><td></td><td rowspan="2">17 Hours</td></tr>
<tr><td></td><td>X</td></tr>
<tr><td>EE or CpE courses used for Free Electives</td><td>X</td><td>X</td><td>5 Hours</td></tr>
<tr><td>Total for First Degree</td><td>-</td><td>-</td><td>128 Hours</td></tr>
<tr><td rowspan="2">Additional Requirements for Second Degree (minimum)</td><td></td><td>X</td><td rowspan="2">17 Hours</td></tr>
<tr><td>X</td><td></td></tr>
<tr><td>Total for Dual EE and CpE Degrees</td><td>-</td><td>-</td><td>145 Hours</td></tr>
<tr><td colspan="4">* The Introduction to Electronic Devices course and associated laboratory are included in this listing.
** These electives may be chosen to overlap EE and CpE requirements.</td></tr>
</table>

C. Course Scope

The Introduction to Electronic Devices course is intended for both EE and CpE majors at the sophomore level. Furthermore, it provides a balanced treatment of semiconductor physics and electronic circuit analysis. Traditional introductory electronics instruction focuses on electronics circuit design and analysis with minor coverage of the underlying physics of semiconductor devices. Traditional devices instruction focuses on semiconductor physics and structures with minor coverage of electronic circuits and applications. With a more balanced approach, the introductory course serves as a single prerequisite for a wide variety of more advanced courses. The challenges involved in designing such a course include:

- Selecting the topics for a fundamentals course at the sophomore level,
- Linking concepts in semiconductor physics and electronics circuit analysis, and
- Supporting prerequisite needs in both electrical and computer engineering curricula.

A satisfactory textbook was not found, so custom course notes have been developed[5].

The course immediately follows the basic physics sequence and the first circuit analysis course and it links the concepts in the context of electronic devices. The following physics-related concepts were identified as necessary for understanding the operations and limitations of junction semiconductor devices (see Appendix A for detailed physics content):

- Electrons and holes as charge carriers in semiconductors,
- Charge movement in semiconductors and through junction structures,
- Fabrication and material requirements for semiconductor devices, and
- Photon absorption and emission in semiconductors.

Prior EE and CpE curricula did not include any significant required content in photonic and optoelectronic devices. This course provided an opportunity to incorporate a brief introduction to laser diodes and photodiodes and their applications. Note that the twenty "Greatest Engineering Achievements[1]" of the twentieth century includes technologies in lasers and fiber optics and in imaging as well as electronics and that the electronics area is interrelated with these photonic and optoelectronic applications.

Topic selection was influenced by electronics-related content on the Fundamentals of Engineering (FE) Examination[2] and content in the National Standards for Computer Engineering in Electronics[3] (CE-ELE). A significant percentage of FE questions have relevant content in the AM Engineering component, the PM General component, and the PM Electrical Engineering component as shown in Table 2. Also, relevant CE-ELE categories are shown in Table 2.

Table 2. Electronics-Related Content on FE and CE-ELE

FE Components	**Category**	**Questions**
AM Engineering (120 Questions)	Electrical Circuits * Computers	12 7
PM General (60 Questions)	Electrical Circuits * Computers	6 3
PM Electrical Engineering (60 Questions)	Analog Electrical Circuits Instrumentation Solid State Electronics and Devices	6 3 6

* Both AM and PM sessions include diodes, transistors, and operational amplifiers.

CE-ELE Items	**Description**	**Core/Elective**
Item 0	Introduction and History	Core
Item 1	Materials	Core
Item 2	Diodes and Diode Circuits	Core
Item 3	MOS Field-Effect Transistors	Core
Item 5	Bipolar Junction Transistors	Core
Item 9	Operational Amplifiers	Core
Item 13	Amplifier Design	Elective
Various Items	Semiconductor Fabrication and Structure	Elective

III. Course Overview

A. Course Description and Objectives

The Introduction to Electronic Devices course has the following catalog description.

> "Materials and device structures for applications in analog and digital electronics. Topics include characteristics and basic circuits for diodes, field-effect transistors, bipolar junction transistors, and operational amplifiers."

The course objectives are:

- To understand basic crystal physics including steady-state resistivity and carrier transport,
- To understand basic characteristics of diodes, field-effect transistors, bipolar junction transistors, and ideal operational amplifiers,
- To apply DC analyses to the devices listed above in digital and analog applications, and
- To introduce fabrication techniques and junction structures in semiconductors.

As a common sophomore-level course that is prerequisite to multiple parts of the curricula, EE 121 and the other EE and CpE courses shown in Figure 2 have a common final and degree requirements (both for EE and CpE programs) of passing the courses with a C or better. These aspects help maintain course consistency and promote a working proficiency with the content.

B. Course Design

The course material is divided into three topical sections for a one-semester course. Each section includes physical background, device descriptions, and basic circuit analysis. All basic device characteristics are related to the underlying physics to avoid a superficial "black-box" understanding. To keep the level appropriate for sophomores, to rely on a single basic circuit analysis prerequisite, and to provide time for examples and for problem reinforcement, the devices are discussed from a constant input or low-frequency point of view, e.g. what operating point is produced for a given input. Frequency analysis and small-signal models are left for follow-on courses. The structure lends itself to having three examinations (one after each topical section) and the comprehensive final.

The topical sections are given below.

Section I

- Semiconductor Materials and Crystal Physics
  - Electronic configuration of materials and energy band structures
  - Dopants and carrier concentrations
- Carrier transport and Junction Physics
  - Drift and diffusion currents
  - Abrupt pn junction behavior
- Diode Circuits
  - Diode models and current-voltage characteristics
  - Diode applications (rectifier and limiters/clipping circuits)

Section II

- Bipolar Junction Transistors (BJTs)
  - Physics of npn and pnp BJTs and current-voltage characteristics
  - BJT applications (common-emitter circuit variations and Darlington amplifiers)
- Field-Effect Transistors (FETs)
  - Physics of n- and p-channel FETs and current-voltage characteristics for junction FETs and depletion-mode and enhancement-mode metal-oxide-semiconductor (MOS) FETs
  - FET applications (single FET circuits and the basic inverter circuit)
- Semiconductor Device Fabrication
  - Common device fabrication procedures for silicon (qualitative)
  - Example planar structures for devices in integrated circuits

Section III

- Operational Amplifiers (OpAmps)
  - OpAmp models and ideal OpAmp analysis
  - OpAmp applications (buffer, inverting, non-inverting, adder, subtractor, integrating, differentiating, and instrumentation amplifier circuits)
- Optoelectronics
  - Physics of semiconductor light absorption, and semiconductor light emission.
  - Structures for semiconductor photodiodes, light emitting diodes, and laser diodes
  - PIN and avalanche photodiode circuits

This topical order flows from one section to the next. The pn diode behavior is needed to understand the transistor behavior; integrated transistor circuits are used to implement operational amplifiers, and the optoelectronic discussion returns to diode behavior. A detailed topical listing is given in Appendix A. These topics meet the CE-ELE guidelines in Table 2 for items 0, 3, and 5 and exceed these guidelines for items 1, 2, and 9. Item 13 is partially meet.

The course instruction allows for ample reinforcement of the material. Students are typically given lectures with weekly short quizzes over intermediate concepts and regular in-class numerical examples. Content from circuit analysis and physics prerequisites are explicitly referenced. Students have weekly homework assignments to provide more complex problem practice. Student understanding is tested for each major topical section with an in-class examination. Applications and links to more advanced material are regularly highlighted, e.g. the use of coupling capacitors is qualitatively presented to prepare students for Electronic I material. The course final is comprehensive over all topical sections and the final content is well defined so that students are encouraged to revisit all topics. The final is further described in Appendix B. The intent is to reinforce circuit analysis skills, to ingrain the basic device characteristics (e.g. transistor current-voltage relationships), and to develop proficiency with input-output and DC operating-point relationships. Student performance on the final and on selected assignments is used as partial measures for ABET outcomes as described in the Course Implementation Section.

C. Associated Laboratory

An associated laboratory is required for both EE and CpE majors. The Electronic Devices Laboratory EE 122 has the following catalog description.

> "Laboratory tools and measurement techniques for basic electronic circuits using diodes, field-effect transistors, bipolar junction transistors, and operational amplifiers. Topics include DC biasing and applications in analog and digital electronics."

Its objectives are:

- To understand laboratory documentation of measurements and procedures;
- To verify the theoretical behavior of diodes, transistors, and operational amplifiers;
- To analyze common circuits for digital and analog device applications; and
- To introduce the use of circuit simulation for nonlinear devices.

This laboratory gives students hands-on experience with practical circuits and nonlinear device simulation earlier in the curricula than in prior years. Also, the laboratory incorporates a design project. To keep the design project appropriate for the sophomore level, a starting circuit is provided and the students are asked to set values, incorporate extra components, etc. An example design project is given in Appendix B.

IV. Course Implementation

A. ABET Instruments

As common course for the EE and CpE programs, the Introduction to Electronic Devices course and its laboratory have roles in the department ABET plan[6]. Selected examinations and assignments are partial measures for ABET Outcome e and Outcome b.

For Outcome e, Criterion e.2 "Solve electrical and computer engineering problems involving basic theory of circuit elements, electronic devices, and digital logic," three measures are the overall score on the common final and two selected problems on the common final with a goal of the median score being 80% or better.

- Final: Students are required to have a C or better on the final examination, e.g. 65%-70% (the minimum cutoff percentage selected for each final) .
- Problem: Students will be given a transistor (BJT or FET) circuit and will be asked to determine the DC operating point.
- Problem: Students will be given an OpAmp circuit and will be asked to determine the output voltage or current as a function of input signal(s).

For Outcome b, Criterion b.3 "Relate features in experimental data to device theory," a measure is a selected laboratory assignment with a goal of the median score being 80% or better.

- Laboratory Assignment: Students will be obtain IV curves for diodes and will build and test diode-based rectifier and limiter circuits. Students will turn in a technical memorandum that describes device/circuit behavior related to theory, documents the experiments with plots and tables, and discusses performance limitations of various rectifier configurations.

Six semesters of results for the lecture course are shown in Table 3. In general, the median percentages meet the goal and that the average percentages are similar. Some variation is present in the OpAmp scores and this topic is targeted for future attention. Overall student performance is similar to that for the other sophomore-level ECE courses.

Table 3. ABET Measures for Introduction to Electronic Devices Course

Semester	**Students**	**Measure**	**Average Percentage**	**Median Percentage**
Fall 2012	60	Overall Final Transistor Problem OpAmp Problem	71.8% 78.7% 72.1%	70.5% 84.0% 84.0%
Winter 2012	82	Overall Final Transistor Problem OpAmp Problem	71.4% 80.9% 49.9%	72.5% 84.5% 52.0%
Fall 2011	78	Overall Final Transistor Problem OpAmp Problem	70.8% 90.0% 65.1%	72.8% 100.0% 80.0%
Winter 2011	84	Overall Final Transistor Problem OpAmp Problem	76.3% 78.8% 77.2%	78.0% 80.0% 84.0%
Fall 2010	67	Overall Final Transistor Problem OpAmp Problem	74.3% 81.0% 61.0%	74.5% 92.9% 60.0%
Winter 2010	73	Overall Final Transistor Problem OpAmp Problem	70.8% 74.9% 75.5%	74.0% 80.0% 92.0%

B. Course Observations

The course has had several positive outcomes from the instructors' perspective.

- As a sophomore-level course with only the first circuit analysis course as a prerequisite, the course has helped with scheduling classes. In particular, transfer students who often have many of the out-of-major classes finished have an additional in-major option.
- A single course supports both the electrical and computer engineering programs. Dual-degree and minor programs are facilitated. In particular, the dual-degree option has become more popular. The course is listed as an option for students pursuing minor programs in both electrical engineering and computer engineering.
- Students seem to appreciate seeing amplifier applications and doing design laboratories.
- While students report that the material is not easy always, the well-defined topics and examination guidelines make preparation the main concern.

- Students report that the transistor operating-point experience is useful when doing the small-signal work in the follow-on Electronics I course.
- Students have more exposure to diode and OpAmp circuits than in the prior curricula.
- Students are introduced to photonic concepts and optoelectronics than were not included in the prior curricula.
- Students seems to handle the in-major physics content better with this sophomore course immediately after the basic physics requirements as opposed to later in the junior or senior years.

V. Discussion and Summary

Considerations for effective electronics instruction include:

- Placement of first instruction within curricula sequence,
- Amount of instruction and reinforcement related to electronics,
- Linkage of electronics instruction to other curricula areas, and
- Laboratory experience with electronics hardware.

Early instruction can enhance student motivation for and interest in electrical and computer engineering study. An electronics sequence can provide progressive reinforcement for content mastery. Linkage of content to other areas and to laboratory experience enhances the usefulness.

The Introduction to Electronic Devices course helps address these considerations. It gives a balanced treatment of semiconductor device physics and electronic circuit analysis. This sophomore-level course serves as a prerequisite for upper-level courses in electronic circuits, semiconductor physics, and semiconductor circuit layout. It enhances the required instruction regarding device physics, diode applications, OpAmp circuits, and optoelectronics. The associated laboratory provides simulation tools and hands-on experience. Course handouts are available in the references[5].

Students seem to benefit from the course at Missouri University of Science and Technology. They are performing well on examinations and report a more positive experience in follow-on courses. The course serves the departmental plan to better integrate instruction in electrical and computer engineering topics and to facilitate flexible degree content through more accessible electives, minor programs, and dual-degree options. In particular, many students are pursuing the dual-degree option that is promoted in part by this course. Students seem to readily use the content for projects, senior design, etc. Future work is planned in providing additional course resources such as on-line problem examples and design content in the laboratory. The OpAmp lectures are being revised for more clarity and for added examples. The course is a prerequisite for proposed upper-level course work in device physics, sensor instrumentation, and optoelectronics. The minors with the electronics option will be promoted for other engineering and science majors.

Acknowledgements

The assistance of the Electrical and Computer Engineering faculty at Missouri University of Science and Technology is acknowledged.

Appendix A. Device Physics Component of the Course

The topical listing below for the Introduction to Electronic Devices course is used to assist students preparing for the final examination. It follows the concepts as presented in the lecture material. Note the physics content at the beginning of the course, i.e. describing materials from a resistivity point of view, and the physics introduction to each device type. To accommodate the level and the physics and circuits content, some detailed equations are not derived such as the Fermi-Dirac distribution function, the low-level injection diode equation, and the transistor current equations. However, students are responsible for doing carrier concentration calculations, current density calculations, energy band analysis, and abrupt junction solutions. Key topics such as the electron and hole characteristics of p+n and n+p junctions are discussed to properly understand the optimization design for transistors. Also, the students seem to benefit from having an immediate in-major course that builds on the second required physics course.

- Electrical Concepts – current, current density, voltage, electric field, Ohm's law, insulators, conductors, resistance, resistivity, conductivity, temperature dependence, and units.
- Crystals and Carriers – electronic configuration of atoms, valence electrons, use of the periodic table, bonding types, nearest neighbors, band structure for insulators and semiconductors, valence band, conduction band, energy gap, steady-state and equilibrium conditions, elemental and compound semiconductors (Column IV and Column II-V), intrinsic and extrinsic semiconductors, carrier concentration vs. temperature, identification of dopants, and definitions.
- Charge Carriers – calculation of carrier concentrations for complete impurity ionization, Fermi levels, compensation, drift current in an electric field, resistivity, resistance, conductivity, mobility, variation of mobility with impurity concentration, diffusion current in a concentration gradient, diffusion coefficient, and Einstein relation.
- Junctions and Diodes - contact potential, energy band diagrams, charge density diagrams, abrupt junction in equilibrium and under bias, low-level injection diode equation, geometry and circuit symbol with voltage and current conventions, graphical load line-diode characteristic solutions of operating point, forward-bias qualitative effects (on diode equation) of high-carrier injection and ohmic losses, reverse-bias effect of breakdown, p^+n and n^+p junctions, and diode circuits.

- Transistors – symbol, structure, terminal names, and characteristics for all JFET and MOSFET types; energy band diagrams and carrier specifics for equilibrium and typical bias; pinch-off or turn-on voltage and saturation current; design optimization; regions of the IV characteristic; current equations for unsaturated and saturated regions; and circuits.
- Semiconductor Fabrication – requirements and basic procedures.

- Operational Amplifiers – OpAmp model with finite resistances, ideal OpAmp parameters and model, all circuits given in class including buffer, inverting, non-inverting, etc.
- Optoelectronics – wavelength, frequency, photon energy, phase velocity, refractive index, absorption coefficient, semiconductor absorption, semiconductor emission (injection luminescence), photodiode equation, photodiode efficiency, photoconductive mode, pin photodiode structure, avalanche photodiode structure (APD), photodiode biasing circuit, LED operation, three requirements for a laser, and laser diode operation.

Appendix B. Content Description for the Final and the Laboratory Project

A comprehensive final for the Introduction to Electronic Devices course is common across the sections and the content follows strict guidelines. Physical constants, an equation sheet, and a periodic table are provided. The content guidelines with example problems are given below.

- Semiconductor Crystal and Junction Physics (2 Problems)
  - Example: Identify dopants as donors or acceptors and calculate equilibrium carrier concentration values
  - Example: Calculate junction parameters such as contact potential
- Diode Circuits (1 Problem)
  - Example: Solve for circuit parameters in a diode circuit
- Bipolar Junction Transistors (2 Problems)
  - Example: Solve for circuit parameters in a common-emitter circuit
  - Example: Design a transistor circuit for a specified operating point
- Field-Effect Transistors (2 Problems)
  - Example: Determine bias conditions and current for a field-effect transistor
  - Example: Solve for the operating points in an inverter circuit
- Operational Amplifier Circuits (2 Problems)
  - Example: Determine the output of an ideal circuit given the input(s)
- Optoelectronics (1 Problem)
  - Example: Solve for the input or output parameters in a photodiode circuit and calculate relationships between wavelength and photon energy

An end-of-course design project is included in the laboratory. These projects include reading datasheets, design task(s), simulation results, hardware verification, and a report. An example project is shown below in Figure 6 for a touch switch circuit. The student design tasks included choosing input voltages, parameter values, and some output device. Output action choices included an indicator light, a display, a buzzer, etc.

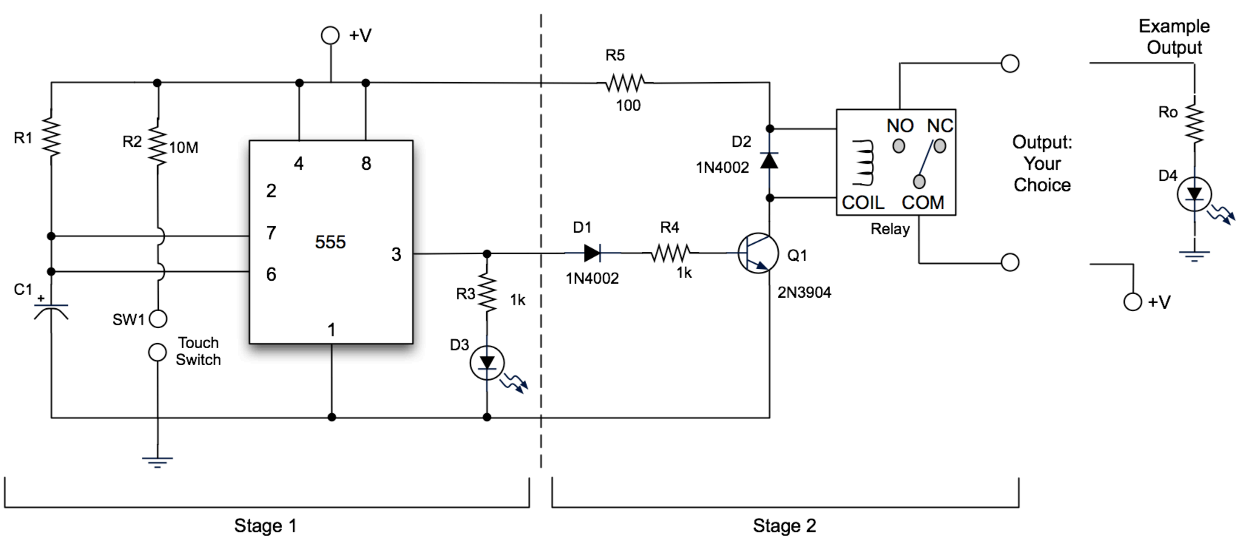

Figure 6. Laboratory Design Project: Touch Switch

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