Contemporary electronics: A focussed concept laboratory

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Contemporary Electronics is an advanced undergraduate lecture and laboratory introduction to analog and digital electronics. Fundamentals of analog measurements, analog data collection, and digital data collection are included in this one-semester course. Laboratory exercises introduce diodes, transistors, operational amplifiers, and their use in simple circuits. Focus and continuity are provided by the construction of a printed circuit board nanoammeter. The nanoammeter is used to measure the tunneling current generated by a commercial field emission electron microscope. An introduction to LABVIEW programming allows each student to create a ''virtual instrument'' for data collection and analysis. An analysis of the tunneling data using Fowler–Nordheim theory is the focus of a midterm and a final exam.
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I. INTRODUCTION

Several years ago we faced the daunting task of updating a junior-level electronics course that had stagnated for almost 20 years. During that time, integrated circuits and operational amplifiers had largely replaced discrete components in complex circuits, and printed circuit boards had competed successfully with conventional wiring techniques. In 20 years the digital revolution had made data reduction and analysis by computer routine and instrument control by computer had become commonplace. We wanted our electronics course to incorporate each of these advances without the lack of focus and the ''black box'' stigma that could easily intrude into a laboratory incorporating modern technology. The result has been a ''Focussed Concept Laboratory,'' a phrase we coined to describe a learning environment in which a physical concept of research interest provides a focus that leads to a well-defined goal at the end of one semester (see Fig. 1).

Contemporary Electronics was designed as a three-credit course that includes a 1-h lecture and a 4-h laboratory session. In developing the courseware for Contemporary Electronics, we decided that a measurement of a small dc current could provide the focus for a series of laboratory exercises in analog and digital electronics. These exercises would lead to the fabrication of a printed circuit board ''nanoammeter,'' with analog and digital outputs that could measure input currents from 10 nA to 1 μA. The current would be supplied by a tunneling diode whose current versus voltage ($I-V$) characteristic would be obtained, measured, and analyzed by each student. We chose a commercial tunneling diode called a ''field emission electron microscope,'' or FEEM,[1] to make the tunneling phenomena visual and; therefore, more tractable. Field emission tunneling provides the conceptual framework for the course. A theoretical explanation of field emission tunneling[2] was an early success of quantum theory. In 1938, the FEEM was introduced.[3] The FEEM was the first microscope capable of examining organic molecules[4] on a nanometer scale. The FEEM cathode, scaled to micron dimensions, has been used in microelectronic applications[5] such as high powered microwave tubes and flat panel displays. The historical background of the FEEM and its link to research and technology has enhanced student interest in the course.

II. COURSE OUTLINE

Contemporary Electronics is divided into two segments. The first segment concentrates on analog electronics (see Table I). The lecture during the first week reviews conduction in solids. The lab presents the basics of photolithography. Both the lecture and the lab are intended as a buffer for those students who enter the course in week 2. We have found that confusion generally reigns in the first week of the semester when students are attempting to choose their class schedule. During week 2 each student fabricates a printed circuit board that will be used later in the course to mount their nanoammeter. A ''breadboard'' is introduced in week 3 as a convenient way to mount and troubleshoot components (in this lab the components of a dc power supply). Weeks 4 and 5 explore transistor and operational amplifier circuits. In week 6 an operational amplifier with feedback is used to assemble a transimpedance amplifier, or current-to-voltage converter that functions as a nanoammeter. In week 7 the nanoammeter is assembled on the printed circuit board and calibrated. During week 8, students use their nanoammeter to record, manually, the $I-V$ characteristics of the FEEM. The apparatus required to record the $I-V$ characteristics of the FEEM is shown in Fig. 2. Design and construction details of the apparatus is supplied with the courseware. Week 9 is reserved for a take-home (midterm) exam. This exam provides an opportunity for students to analyze their $I-V$ tunneling data using an established protocol[6] derived from Fowler–Nordheim theory. A student must learn how to collect and analyze data by hand before the capability of collecting and analyzing digital data with a computer is introduced.

The second segment of the course concentrates on digital electronics (see Table II). In week 10 an 8-bit analog-to-digital converter (ADC) is breadboarded and calibrated. In week 11 it is added to the nanoammeter on the printed circuit board and a final calibration is performed. The calibration provides a least-squares fit of nanoammeter output voltage to input current. The resulting digital nanoammeter provides the capability for collecting $I-V$ tunneling data with a computer (see Fig. 3).

The lecture and laboratory in weeks 12 and 13 are devoted to a LABVIEW™ tutorial. Students are required to purchase LABVIEW Student Edition,[7] which includes a tutorial that is

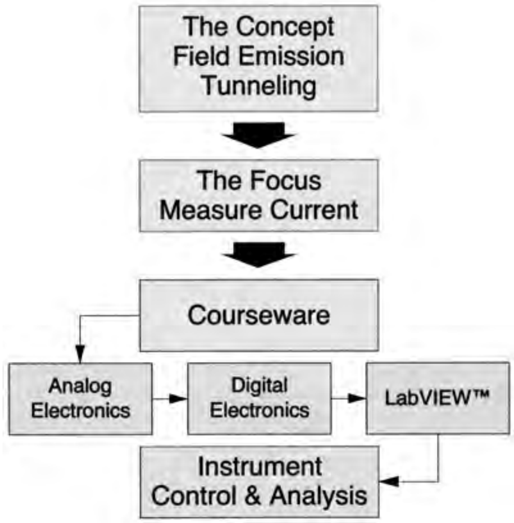

Fig. 1. A Focussed Concept Laboratory.

adequate for introducing the basic concepts and operations of the software. The laboratory exercise in week 14 introduces the use of LABVIEW serial port drivers. In week 15 students create a LABVIEW application that reads the FEEM voltage and the corresponding digital output of their nanoammeter. In week 16 each student records digital $I-V$ data using the apparatus shown in Fig. 2. At this point each student is ready to prepare the final exam. The final exam consists of creating a LABVIEW application that duplicates the data analysis performed by hand for the midterm exam. When the final exam is completed, students have a much better idea of when to use a computer to collect and analyze experimental data. They begin to realize that it is important to collect and analyze data by hand before a computer program can be written to perform the same task. They also realize that it takes time to write and debug a computer program, which usually means that this time is only a good investment when many sets of identical data must be processed. In week 17 the instructor reviews the digital data that were collected, grades each final exam, and schedules an interview with each student. The results of the interview, the final exam grade, and the midterm exam grade determine the grade in the course.

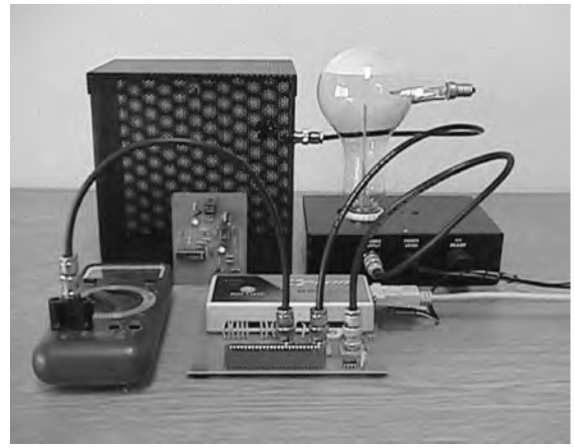

Fig. 2. Apparatus used for data collection.

III. HARDWARE

When the course was designed, we had to decide what digital protocol would be used to transfer data from the nanoammeter to the computer. There are several transfer protocols used for industrial and research applications. Of these, the IEEE-488 (GPIB) and RS-232 (serial) protocols are in common use. GPIB (general purpose interface bus) has become an industry standard because of its ability to transfer data rapidly, with up to 32 instruments, using 8-bit parallel transmission of data. Serial communication, on the other hand, is usually much slower because data can be sent to only one instrument, one bit at a time. In either case, data transmission and instrument control is implemented by transferring strings of ASCII characters. The American Standard Code for Information Interchange (ASCII) is most commonly used to encode the keystrokes from a computer keyboard. We decided to use serial communication for data transmission between a student nanoammeter and a computer. Serial communication is less expensive to implement than GPIB because most computers have a serial input, whereas GPIB requires an expensive interface that is com-

Table I. Course outline for the first half (analog segment) of Contemporary Electronics.

Week 1	Lec 1 Methods of Conduction
	Lab 1 Photolithography
Week 2	Lec 2 Semiconductors
	Lab 2 Printed Circuit Boards
Week 3	Lec 3 Diodes and Transistors
	Lab 3 Diodes & Rectification
Week 4	Lec 4 Transistors
	Lab 4 Transistor Circuits
Week 5	Lec 5 Feedback
	Lab 5 Operational Amplifiers
Week 6	Lec 6 Vacuum Tunneling
	Lab 6 Transimpedance Amps
Week 7	Lec 6 Tunneling Theory
	Lab 6 Analog Nanoammeter
Week 8	Lec 7 Midterm Review
	Lab 7 Collect Analog Data
Week 9	Midterm exam
	(take home)

Table II. Course outline for the second half (digital segment) of Contemporary Electronics. DACs are digital to analog converters. ADCs are analog to digital converters.

Week 10	Lec 9 Numerology and DACs
	Lab 9 ADCs
Week 11	Lec 10 Numerology and ADCs
	Lab 10 Digital Nanoammeter
Week 12	Lec 11 LABVIEW Tutorial I
	Lab 11 LABVIEW Tutorial I
Week 13	Lec 12 LABVIEW Tutorial II
	Lab 12 LABVIEW Tutorial II
Week 14	Lec 13 GPIB & Serial VIs
	Lab 13 Serial Talk I
Week 15	Lec 14 The ASCII Code
	Lab 14 Serial Talk II
Week 16	Lec 15 Final Review
	Lab 15 Collect Digital Data
Week 17	Final exam
	(take home)

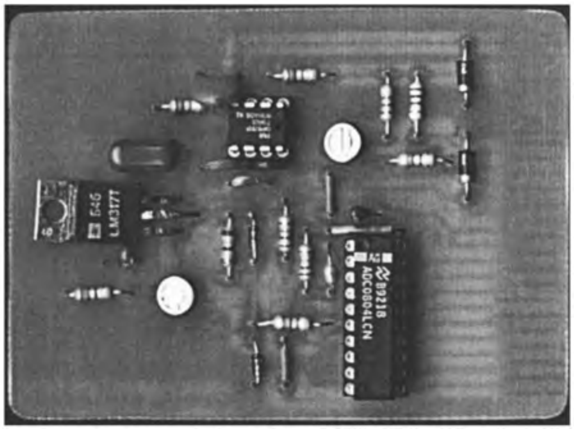

Fig. 3. A student nanoammeter.

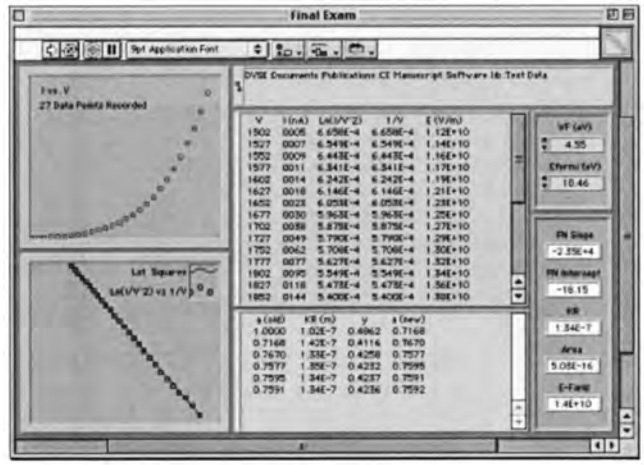

Fig. 4. The final exam created by each student in LABVIEW.

puter dependent. It is also easier and less expensive to convert the 8-bit binary output of the nanoammeter to the RS-232 protocol. The conversion was accomplished by connecting the output of the nanoammeter to the input port of an inexpensive microprocessor[8] that has a serial output. The interface card shown in Fig. 2 was designed for this purpose. The microprocessor also contains an eleven channel, 12-bit, analog-to-digital converter (ADC). Students use one channel of the ADC to read the output of a 1000:1 voltage divider that monitors the FEEM voltage.

IV. LABVIEW

LABVIEW™ was created by National Instruments of Austin Texas. It was introduced in 1986 on the Macintosh, because it was the only computer platform at that time capable of using the revolutionary graphical and icon scripting environment of the software. Over the years, LABVIEW has evolved into a cross-platform, defacto standard for instrument control and analysis in industry and academe. LABVIEW stands for ''Laboratory Virtual Instrument Engineering Workbench.'' We chose LABVIEW for Contemporary Electronics because it is a powerful, general purpose software package that facilitates instrument control and data analysis with a plethora of internal routines designed for this purpose. We also learned from our graduate students that experience with LABVIEW programming is a definite employment asset! LABVIEW is based on a data-flow, icon driven language that is unfamiliar to most students. As a result, we decided to incorporate a LABVIEW tutorial into the courseware. Using the tutorial meant that students were able to create their own applications in LABVIEW, rather than using existing software for digital data collection and analysis. The LABVIEW paradigm is based on the concept of using a computer to access one or several instruments, or a combination of selected features from each instrument. The results is a virtual instrument which behaves like a custom instrument, complete with controls and indicators, on the screen of a computer. All of the virtual instruments that a student is asked to create are included with the courseware, including those in the final exam. The LABVIEW environment is unique in that virtual instruments can be supplied with the courseware without access to the code that created them. In the vernacular of LABVIEW, ''The front panel can be examined but the diagram is password protected.'' When a student is asked to create a virtual instrument, the layout of the controls and indicators on the computer screen (front panel) can be copied from an example supplied with the courseware, but the student must create the code (diagram) that makes them functional. This feature of LABVIEW provides a definite pedagogical advantage: the example of a virtual instrument can be run and its output can be compared with the output of the virtual instrument that the student is creating. The instructor also benefits from the virtual instruments supplied with the courseware. In addition to facilitating lab preparation, the virtual instruments supplied with the courseware make grading the exams very easy. The final exam virtual instrument duplicates, in digital fashion, the analysis of the midterm exam. Therefore, the midterm and the final exam can be graded by entering the student's $I-V$ data, running the final exam virtual instrument, and comparing its output with the student's exam (see Fig. 4). In fact, students are encouraged to use the same procedure to check their results before their exams are submitted for grading.

V. FIELD EMISSION TUNNELING

A series of experiments were performed between 1918 and 1928 that could not be explained in terms of the classical physics of the time. In the latter experiments, a sharply pointed needle-like metal cathode was placed several centimeters in front of a flat metal anode in high vacuum as shown schematically in Fig. 5. When a dc potential difference of several thousand volts was placed across the electrodes, an electron current, I, was detected. According to classical physics, no current could flow across the vacuum

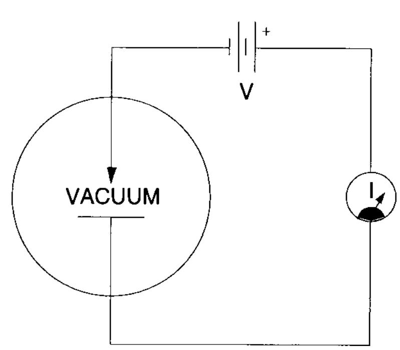

Fig. 5. A schematic diagram of a field emission apparatus.

gap between the electrodes unless the cathode was heated to a very high temperature (thermionic emission) or bombarded with energetic photons (the photoelectric effect). However, a current was detected, and was related to the voltage by the expression:[9]

$$I = B \exp(-C/V), \tag{1}$$

where B and C are constants. The magnitude of the current increased (at a fixed voltage) if a more sharply pointed cathode was used. No current was observed with a flat, planar cathode. The experimental observations implied that the electron current depended on the electric field at the cathode surface because the electric field depends on the voltage and the curvature of the cathode. In 1928, Fowler and Nordheim published a paper[2] that predicted the experimental observations. Their theory was based on the quantum mechanical process of electron tunneling in a high electric field, a phenomenon that had not been observed before. According to the Fowler–Nordheim theory, an electric field at the surface of a metallic cathode reduces the width of the energy barrier that confines electrons to the interior of the metal. When the barrier is reduced to ≈10 Å, electrons will tunnel with high probability from inside the metal into vacuum. Electron tunneling is a phenomenon of quantum mechanics. It has no classical counterpart. The success of the Fowler–Nordheim theory was one of the earliest confirmations of quantum mechanics. Fowler and Nordheim assumed that the electric field at the cathode surface was given by

$$E = V/KR, \tag{2}$$

where R is the radius of curvature of the cathode surface. The field enhancement factor, K, is a dimensionless constant of proportionality introduced to account for the exact electrode geometry. The result was an expression for the current as a function of the applied voltage which agreed with the experimental observations:

$$I = a' V^2 \exp\left(\frac{-b'\phi^{3/2}}{V}\right), \tag{3}$$

where a' and b' are defined by

$$a' = A \frac{6.2\times 10^{-6}}{(\mu+\phi)(\alpha KR)^2}\sqrt{\frac{\mu}{\phi}}, \tag{4}$$

$$b' = 6.8\times 10^{7}(\alpha KR). \tag{5}$$

In these equations, α is the dimensionless Nordheim image-correction factor, μ is the Fermi energy of the metal, and ϕ is the average work function of the emitting area, A. Equation (3) is generally written as

$$\ln\left(\frac{I}{V^2}\right) = m\left(\frac{1}{V}\right) + b \tag{6}$$

and called the Fowler–Nordheim equation, where the slope $m = -b'\phi^{3/2}$ and the intercept $b = \ln(a')$.

VI. FOWLER–NORDHEIM ANALYSIS

A Fowler–Nordheim analysis typically consists of three parts: (1) a plot of Eq. (6) that shows the linear relation characteristic of Fowler–Nordheim tunneling; (2) a determination of KR from the slope of the Fowler–Nordheim equation; and (3) a determination of the emission area from the intercept of Eq. (6). The iterative procedure that follows[6] is used to find KR.

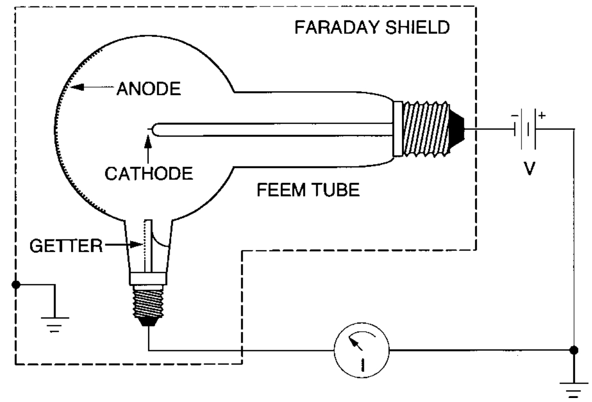

Fig. 6. A schematic diagram of a field emission electron microscope.

(1) Assume $\alpha_{\rm old} = 1$.

(2) Find KR from the slope of Eq. (6):

$$KR = \frac{m}{-6.8\times 10^{7}\alpha_{\rm Old}\phi^{3/2}}. \tag{7}$$

(3) Find the average field strength, E, from the applied voltage:

$$E = \frac{V}{KR} = \frac{(V_{\max}+V_{\min})}{2\,KR}. \tag{8}$$

(4) Find a new value for the Nordheim image correction term:

$$\alpha_{\rm new} = \sqrt{(1-y)}, \tag{9}$$

$$y = \frac{3.8\times 10^{-4}\sqrt{E}}{\phi}. \tag{10}$$

(5) Go to step (2). Let $\alpha_{\rm old} = \alpha_{\rm new}$ and repeat the iteration until

$$(KR - KR_{\rm previous}) \leqslant 10^{-10}. \tag{11}$$

The equations are expressed in cgs units (with ϕ in eV). Note that the radius of curvature of the cathode surface, R, must have units of centimeters because K is a dimensionless constant. The emission area A is found from Eq. (4) using the intercept, b, of the Fowler–Nordheim equation and the final value of the Nordheim image-correction term α. A theoretical value for the Fermi energy of tungsten, $\mu = 10.46$ eV, and the experimental value of the work function $\phi = 4.55$ eV, are used for the calculations. The midterm and the final exam require each student to perform the Fowler–Nordheim analysis as outlined above.

VII. THE FIELD EMISSION ELECTRON MICROSCOPE

The field emission electron microscope[3] was invented by Erwin Müller. A FEEM tube consists of a cathode in the form of a sharply pointed metal wire placed several centimeters in front of a phosphor coated anode. A barium "getter" keeps the pressure in the FEEM tube below 10^{-15} Pa (see Fig. 6). As a high voltage (V) is applied between the cathode and the anode, a very high electric field is created at the

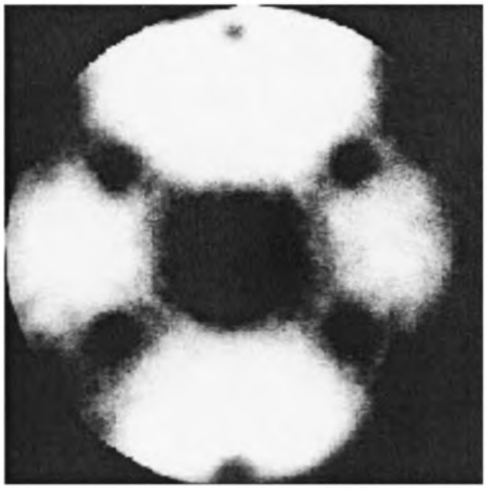

Fig. 7. A field emission electron microscope image of clean tungsten.

cathode surface. When the field reaches a few volts per nanometer, electrons can tunnel through the energy barrier at the cathode surface and will emerge as free particles in vacuum. The resulting current can be measured. Tunneling is

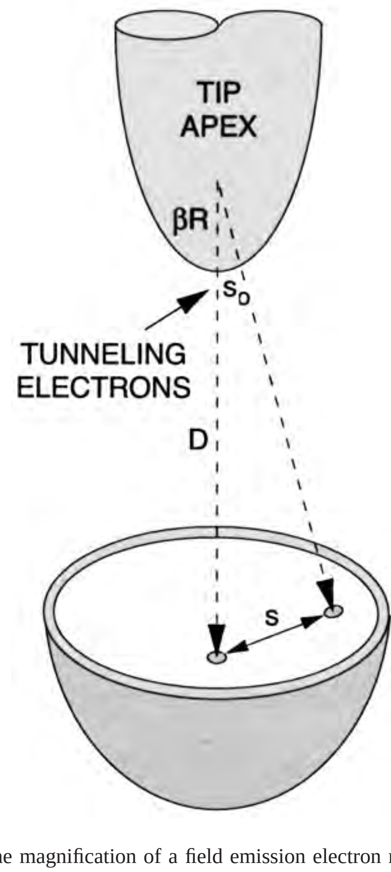

Fig. 8. The magnification of a field emission electron microscope.

a quantum mechanical process. The FEEM tube shows quantum mechanics in action.

The tunneling electrons accelerate to the anode where a phosphor coating makes each electron impact visible. The image that appears on a clean anode maps the intrinsic work function of the cathode surface (see Fig. 7). The image magnification, M, depends on the projection distance, D, the emitter radius, R, and a magnification correction[10] (β):

$$M=\frac{s}{s_0}=\frac{D}{\beta R}. \tag{12}$$

Magnifications greater than 10^5 are typically obtained for a projection distance, $D=5$ cm, and $\beta=1.5$ (see Fig. 8). The image resolution of the FEEM (about 20 Å) is calculated[6] from the Heisenberg uncertainty principle and the transverse component of velocity of the tunneling electrons.

VIII. SUMMARY

An advanced undergraduate lecture and laboratory introduction to analog and digital electronics is presented. Focus and continuity are provided by the construction of a printed circuit board nanoammeter used to measure the tunneling current generated by a commercial field emission electron microscope. A midterm and a final exam explore Fowler–Nordheim analysis of the tunneling data. Complete courseware for Contemporary Electronics can be selected and then downloaded, at no charge, from the National Instruments website of pre-written courseware: (http://www.ni.com/academic/edu_crs.htm).

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