

2006-928: A SOLID-STATE MATERIALS AND DEVICES COURSE FOR SOPHOMORE ELECTRICAL ENGINEERING STUDENTS

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An electronic materials and devices course for sophomore electrical engineering students

Abstract

This paper describes a new engineering course on electronic materials and devices offered to second-year electrical engineering students. The course covers the basic concepts of quantum mechanics, electrons, atoms, solid-state materials and related devices. The emphasis is placed on the properties of semiconductors and optoelectronic devices such as photodiodes, solar cells and thin film transistors. In most universities, this type of course is offered to third-year or higher students. We believe that there are great advantages to offering this course to second-year students. The students are introduced to a set of key knowledge in modern engineering and the course promotes a greater level of interest in electrical engineering before the students are officially admitted to the School of Engineering. The main challenge in offering this course to sophomore students is to achieve a balance between mathematical theory and experiential learning. Real-life examples and laboratory activities were designed to provide the students with hands-on experiences and to enforce the understanding of theoretical materials. The paper describes in detail how the course concepts were organized and instructed, examples of the lab activities developed, and evaluation data on two pilot offerings of the course.

Introduction

Up to winter 2004, the course EGR 255 Materials for the Electrical Sciences in School of Engineering at GVSU was offered to sophomore students in electrical engineering major. The course covered crystal structure, mechanical behavior of metals, phase diagrams, ceramic properties, polymer properties, electrical/thermal/magnetic/optical properties. There was not much time spent on solid state materials and devices. However, with the fast progress of modern electronics, it is essential that electrical engineering students be exposed to solid state materials and devices. In the preface of their text book¹, Murarka and Peckerar wrote “Electrical Engineers usually have little specialized knowledge of chemical reactions or solid state mechanics. And yet, our ability to fabricate semiconductor devices depends critically on our understanding of these items.” To fulfill the needs of industry, in winter 2005, EGR 255 course was revised to Introduction to Electronic Materials and Devices to provide students with a sound understanding of existing electronic materials and devices so that their studies of electronic circuits and systems are meaningful and to develop the basic tools with which they can learn about newly developed materials, devices and applications. In traditional solid state materials and devices course², the contents of atomic theory, quantum mechanics, conductors, insulators, and magnetic properties are often neglected. However, it is clear that engineers and scientists who work on electronics will continually learn about new materials and devices in the future, which often require that knowledge. With this in mind, the revised EGR 255 combined traditional materials course³ and solid state materials and devices course with emphasis on solid state materials and devices.

Course description

The revised EGR 255 course covers the basic quantum mechanics theory, properties of conductors/ insulators/ semiconductors with emphasis on electrical/optical/magnetic properties

of semiconductors, and fundamental of semiconductor devices with emphasis on basic diodes/optoelectronic devices/organic devices. Since this course is offered to sophomore students, balance between mathematical theory and experiential learning became a challenge. Laboratory activities were developed to provide students with hands-on experiences and to reinforce the understanding of theoretical materials. The objectives of this course are outlined as following:

In completing this course, students will be able to:

- Describe the concepts and definitions of electronic materials
- Demonstrate an understanding of existing devices to help their studies of electronic circuits and systems
- Characterize the properties of electronic materials in electronic and optical devices
- Design and characterize an electronic device
- Effectively communicate technical concepts

The revised course composes of three modules: atomic theory and basic quantum mechanics, material properties, and semiconductor devices. Each module requires different teaching technique. In this paper, these three modules are described in detail.

Atomic theory and basic quantum mechanics module

The following topics, which are most important to solid state theory, are covered in this module:

- Review of atomic theory
- Introduction to quantum mechanics
- Wave-particle duality
- Discreteness of energy
- Quantum tunneling
- The Heisenberg uncertainty principle
- Schrodinger wave equation and hydrogen atom

The prerequisites of this course are PHY 234 Engineering Physics and CHM 115 Principles of Chemistry. PHY 234 covers the classical physics including electricity, magnetism, and basic ideas in optics. CHM 115 includes the structure of matter, nuclear chemistry, periodic properties, bonding, molecular shape, etc. Students have learned atomic theory in CHM 115 course. In EGR 255, concepts such as protons, neutrons, electrons, atomic number, and atomic mass are reviewed. To study the particle behavior at an atomic level and to explain questions such as why atoms are stable, why periodic table has the structure it does, basic quantum theory are introduced. Problems arise when students first encounter the theory of quantum mechanics. The first problem is that quantum concepts are largely mathematical and the second is that it is difficult to connect it with “reality”. My approach in this module is to (1) qualitatively discuss the quantum theory and (2) investigate the important observations that led to the development of quantum theory and then explain these observations using the theory.

Following is an example of how the lecture “Introduction to the quantum mechanics” was taught. In the beginning of the class, matter was explored. All matters are stable and they consist of atoms, in which electrons constantly move around the nucleus. Based on the classical physics,

electrons would eventually spiral toward the nucleus and the atom would collapse, so would all the matters. Why didn't atoms collapse? This can only be explained by the new theory – quantum mechanics theory. The basic concept in quantum theory is the wave/ particle duality, which was introduced using the examples of light and electrons. Light is a wave and it has all the characteristics of a wave. The famous photoelectric effect experiment also showed that light is a particle. Therefore, Light has the wave/particle duality. On the other hand, it is well known that electrons are particles. The famous Davisson and Thomson experiment, in which interference fringes were observed when electron beams hit crystal surfaces and thin metal films, indicated that electrons have a wave-like behavior. Therefore, electrons have the wave/particle duality. All matters exhibit the wave/particle duality and the wavelength relates to the momentum through $\lambda = h/p$. Electrons moving in atoms are bound to the nucleus by electrostatic attraction and electron waves are standing matter waves, which indicates that electrons in atoms have quantized energy – they will not spiral toward the nucleus.

Schrodinger wave equation was introduced to students semi-quantitatively based on postulates of quantum mechanics and the conservation of energy. In this course, the emphasis is not on how to solve Schrodinger equation. The emphasis is placed on Schrodinger equation concepts: what is the wave function/probability of finding a particle, what is the wave equation, why is it important, what kinds of problems can it solve. To help students further understand Schrodinger wave equation, two simplest problems were solved. One was the one-dimensional potential well problem and the other was hydrogen atom problem. It was seen from these examples that the allowed energies are quantized and they are related to three quantum numbers which are used in the arrangement of periodic table.

After this lecture, students had two clear quantum mechanical concepts in mind: electrons exhibit wave-like behavior and their allowed energies are quantized, and the probability of finding an electron in a certain position at a certain time is determined by the wave function.

A survey was conducted after the delivery of the first module. The topic was divided into two parts: atomic theory and basic quantum mechanics. For each part, there are two categories: difficulty of the material and the degree of understanding. The students were given a scale of 1 – 5 with 5 being the most difficulty (difficulty category) and the best of understanding (understanding category). Table 1 shows the results of the survey.

	Atomic theory		Basic QM	
	difficulty	understanding	difficulty	understanding
5		100%		
4.5				30%
4				30%
3.5			60%	40%
3	5%		40%	
2	95%			
1				

Table 1 the matrix of the survey

Material properties module

The following topics are covered in this module:

- Classification of materials
- Properties and applications of conductors
- Properties and applications of insulators
- Properties of semiconductors
 - Basic concepts such as energy band structures, electrons and holes, effective mass, intrinsic and extrinsic semiconductors, and Fermi-Dirac function and density of states
 - Carrier concentration under thermal equilibrium
 - Carrier motion: drift and diffusion

This module begins with the classification of materials – conductors, insulators, and semiconductors. For conductors, the properties of normal metals, alloys, and non-metallic conductors were introduced and the applications in contacts, heating, and thermionic emission (CRT, electron microscope) were addressed. For insulators, the properties of dielectrics and their application in capacitors were covered.

The emphasis of this module was placed on properties of semiconductor materials. Semiconductor materials have both negatively charged (electron) and positively charged (hole) carriers, which differs from other materials. How carriers distribute and behave are the important topics which involve many mathematical equations. MATLAB was introduced to help students comprehend these equations graphically. Following shows the example using MATLAB.

Density of states is an important parameter since it is an essential component in determining carrier distributions and concentrations. From an analysis based on quantum mechanical consideration, density of states (energy distribution of states) can be determined which is shown in equations 3a and 3b.

$$g_c(E) = \frac{m_n^* \sqrt{2m_n^* (E - E_c)}}{\pi^2 \hbar^3} \quad E \leq E_v \quad \text{----- (3a)}$$

$$g_v(E) = \frac{m_p^* \sqrt{2m_p^* (E_v - E)}}{\pi^2 \hbar^3} \quad E \geq E_c \quad \text{----- (3b)}$$

Where $g_c(E)$ and $g_v(E)$ are the density of states at an energy E in the conduction and valence bands, respectively.

It is important to understand the concept of the density of states, which can be related to the seating in the classroom. At a particular distance from the podium, there is the specific number of seats (density of states). Even though sometimes those seats may not be occupied, they are still there and available (energy states are available even when they are not occupied). Density of states is different in different materials and MATLAB was used to explore this.

The following program written in MATLAB calculates the density of states at different energy giving the effective masses of electron and hole and the energy band gap in silicon. In addition, the program plots the density of states vs. energy E.

```

%Density of states in silicon
mne=1.08*9.1e-31
mpe=0.81^(1/3)*9.1e-31
Ev=0;
Ec=1.12;
hbar=6.626e-34/(2*pi)

dE=0:0.05:2;
gc=(mne*sqrt(2*mne*dE*1.6e-19))/(pi^2*hbar^3);
gv=(mpe*sqrt(2*mpe*dE*1.6e-19))/(pi^2*hbar^3);
%density of states in unit: no./m3 J
gc=gc*1.6e-19; %density of states in unit: no./m3 eV
gv=gv*1.6e-19;
disp(gc)
close

plot(dE+Ec,gc); grid; hold on;
plot(-dE, gv); grid on;
xlabel('E (eV)');

```

Figure 1 shows the distribution of energy states in both conduction band and valence band for silicon. It can be seen from the graph that there is no available energy states in the energy gap and the density of states increases with the increase of energy. The shape of the density of states in conduction band is different from that in valence band due to the difference in effective mass between electrons and holes.

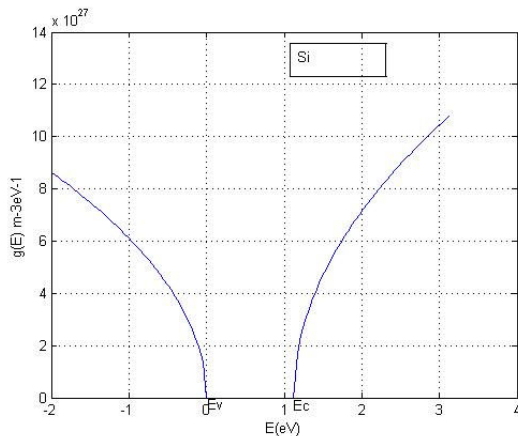


Figure 1a the density of states in silicon

How about the materials other than silicon? Do they all have the same density of states as silicon? If not, how does it differ from that of silicon? In above MATLAB program, effective masses of electrons and holes and energy band gap were changed to those corresponding to GaAs. When running the program, the density of states in GaAs was plotted as shown in Figure 1b.

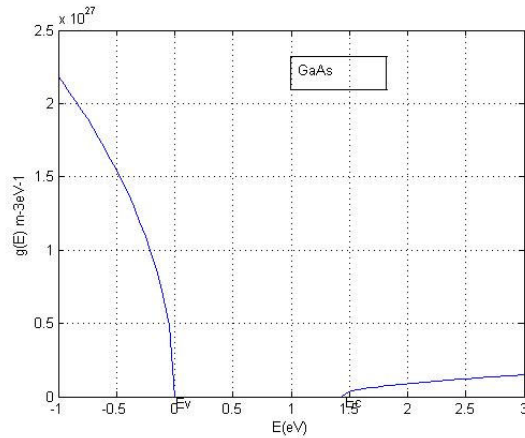


Figure 1b the density of states in GaAs

The density of states in GaAs is quite different from that in silicon. $g(E)$ increases much faster with energy in valence band than that in conduction band due to the bigger hole effective mass.

From above example, it can be seen that density of states is determined by electron and hole effective masses which are the characteristics of the material. Students were asked to write MATLAB programs to explore the density of states for different materials.

Fermi function $f(E)$ is another important concept which determines the probability of an electron/hole occupying an existing energy state. The dependency of $f(E)$ on energy E and temperature can be seen easily from the plots generated in MATLAB. The following program was written in MATLAB which calculates Fermi function in terms of energy at four different temperatures.

```

%Fermi function - probability of electron occupying an existing state

k=8.67e-5;
for ii=1:4;
    T=100*(ii^2-.9);

    kT=k*T;
    dE(ii,1)=-5*kT;
    for jj=1:101
        f(ii,jj)=1/(1+exp(dE(ii,jj)/kT));
        dE(ii,jj+1)=dE(ii,jj)+0.1*kT;
    end
end
dE=dE(:,1:jj);
close
plot(dE(1:4,1:jj)',f(1:4,1:jj)'); grid;
xlabel('E-EF (eV) ');

```

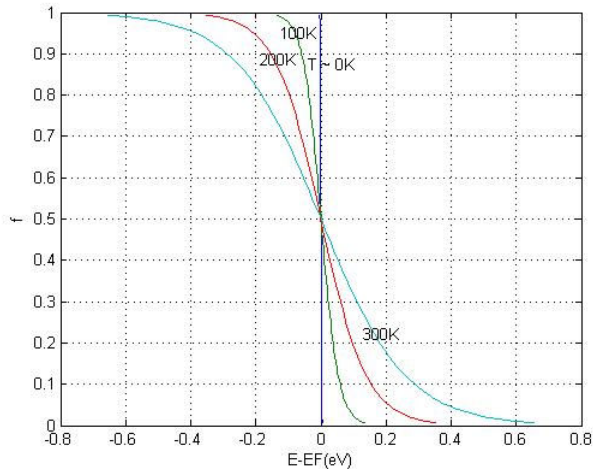


Figure 2 Fermi function at different temperatures

It can be seen from Figure 2 that at Fermi level E_F the probability of an electron occupying an existing energy state is 50% at all temperatures. As energy level goes lower, the probability increases and eventually goes towards 1. As energy level goes higher, the probability decreases and eventually goes towards 0. At $T \rightarrow 0K$, all energy states below E_F are occupied and all energy states above E_F are empty. As temperature increases, electrons begin to occupy the energy states above E_F . The higher the temperature, the more energy states above E_F are occupied.

Students were then asked to calculate density of states for Ge and Fermi function at 300K using MATLAB. In addition, they were asked to compute and plot the carrier distribution $g_c(E)f(E)$ and $g_v(E)(1-f(E))$, which showed that most of free carriers occupy the energy states near the band edges E_c and E_v .

Many concepts were illustrated using MATLAB whenever possible. Students not only gained more understanding of the concepts but also showed more interests to the material.

Semiconductor devices module

The following topics are covered in this module:

- Basic p-n junction diodes
- Photodiodes
- Light emitting diodes
- P-i-n solar cells

P-n junctions are fundamental to most of semiconductor devices. P-n junction diode analysis is of particular importance since it establishes basic concepts and analytical procedures that are of common use. A complete, systematic diode analysis was divided into three major sections. The first, which is the foundation for the entire analysis, was the equilibrium state of the junction and the flow of charge carriers under steady state condition. It was followed by modeling the steady state response and the transient response of the device. These concepts and procedures were then

applied to the special p-n junction diodes – photodiodes, light emitting diodes and solar cells. Hands-on laboratory activities were developed to help students better comprehend the concepts. Selected lab activities are listed below:

- Measure the photoconductivity of photoconductors/photodiodes
- Measure storage delay time t_s and minority carrier lifetime τ
- Study the reverse bias characteristics of p-n diode
- Design a high efficiency solar cell with the freedom of selecting materials and structures

Discussion and Conclusions

The revised course EGR 255 Introduction to Electronic Materials and Devices offered first time in winter 2005 was a success. Students received technical concepts in electronic materials and devices through the utilization of tools such as MATLAB and experimental exercises. Students taken EGR 255 showed more interest to the circuit course. In the course evaluation, students were satisfied with the techniques used to deliver the course materials. Several students also indicated in the course evaluation that they could understand the concepts (doping level, intrinsic carrier concentration, carrier concentration, Fermi level) in material properties module; however mistakes sometimes were made when using these concepts to solve problems. To respond to this concern, in current semester the relationship among these parameters was emphasized using energy band diagram and it was well received by the students. The first offering of the course in winter 2005 had only a few laboratory activities. In current semester, more hands-on laboratory activities were developed, especially the activities related to the concepts in material properties module. One of the activities is “Measuring the conductivity/resistivity of a semiconductor using four-point probe” which helps students understand the concepts of conductivity, resistivity, and sheet resistance. The other activity is “Demonstrate drift and diffusion of carriers through Shockley-Haynes experiment” which illustrates the concept of carrier action in semiconductors. A final project on solar cell application provides students with the real world design experience.

In the future, the structure of the course will be modified continually to increase the effectiveness of students’ learning. More challenge-based learning techniques will be incorporated.

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