ELEC4705 – Fall 2009

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LECTURE 1
Introduction

Contents

1.1. Why do we study materials and their properties?

The study of the electrical and physical properties of materials and the development of the electrical engineering profession are closely connected. The discovery of new materials and effects has driven the development of new devices. An example of this is semiconductor devices. The transistor was a logical outcome of a large amount of preceding research in to the electrical properties of materials.

The progress in device performance followed improvements in material technology.

- MOS patent 1930's
- Commercialized 1970s due to improved understanding of oxide-Si interface
- Rapid progress using Si and SiO2 in 80;s
- 90's extreme performance demands new materials low k, Cu
- 2000+ Nanotechnology and biotechnology.

The search for faster and lower power microelectronic devices has pushed the level of research into material science to unprecedented levels. To produce modern state of the art microelectronic devices, which are both extremely small and very complicated, material science plays two very important roles. The manufacture of the devices requires a great deal of sophistication and knowledge in the manipulation and processing of the various metals, insulators and semiconductors. Secondly, the design and analysis of the devices requires a thorough understanding of the electronic, optical and other physical properties of the materials used to construct the devices.

Materials and material science are the "life blood" of microelectronics and if you wish to understand or design devices you must understand what they are made of.

Technology changes! The underlying physics does not!

Not quite true push to smaller and smaller device means a transition to quantum mechanics from classical physics. Bio/organic technology means more chemistry less physics.

1.2. Course Material

This course is intended to provide a basic understanding of various aspects of material science as applied to electrical engineering. The course consists of an introduction to the elementary quantum mechanics needed to understand basic material properties. This is followed by a discussion of band structures in materials and their implications. A discussion of conduction in metals and semiconductors is followed by the analysis of a few simple illustrative semiconductor devices. Optical properties of materials are then discussed with an emphasis placed on the importance of band transitions. This leads naturally into the use of light emitting diodes, semiconductor lasers and fiber optics as examples of optical devices. Fiber optics are discussed. The use of photodiodes and avalanche diodes are then used to complete an optical communication system.

Throughout the course the aim will be to illustrate basic material science through the analysis of simple relevant devices.

1.3. Why do we need Quantum mechanics?

This course deals with the electronic, optical and magnetic properties of materials and the application of these properties to electronic devices. The manifestation of these properties is, in general, the interaction of an external electro-magnetic field (DC, AC or optical) with matter. Matter is, of course, comprised of atoms which are themselves built up of electrons, protons and neutrons. The fundamental laws of nature governing the behavior of these basic building blocks on nature can only be described by quantum mechanics. In very large aggregates (10^{23} atoms) the behavior of matter is well described by the classical laws of physics. However, for the effects that we deal with in this course the properties are determined by the interaction of far fewer particles (i.e. very thin layers used for band engineering).

We will need to see how the QM basis for the material properties brings about the classical expressions that we use such as Ohms law. These classical laws will be seen to break down under certain conditions and it is important to know when the classical laws still hold and when QM is needed to get a good result. In addition, some effects that are apparent on a macroscopic scale such as laser phenomena can only be explained by QM.

A number of devices such as the tunnel diode and the semiconductor laser can only be understood as the manifestation of a quantum mechanical effect.

1.4. How much Math do we need?

QM is very mathematical and not very physical and in this course you will see as complex math as you have ever seen before. In particular the beginning of the course will be quite challenging and will stretch you a little bit.

However, three things should be noted:

- Your math background is very good for this type of work (i.e. diff. equations. Fourier transforms.)
- We will stress concepts and physical effects. The text takes the same approach.
- Most math in the lectures, less in the assignments, less than that in the exams.

1.5. What we hope to Achieve

The aim of the course is not to make you into a QM whiz but into an engineer who is aware of the complications that arise when matter and energy interact and the devices that use these effects. It is intended to "bring you up to speed" in a variety of physical technologies:

- Electronics (integrated circuit technology)
- Photonics (the technology of light)
- Nanotech (the technology of the quantum level)

At the end of the course you should be able to converse intelligently about material science and it's applications.

1.6. Classical versus Quantum*

Physics (mechanics – movement of bodies) is generally divided into two categories Classical and Quantum mechanics. Roughly QM came into being after about 1900.

Historically, classical mechanics came first, while quantum mechanics is a comparatively recent invention. Classical mechanics originated with Isaac Newton's Laws of motion in Principia Mathematica, while quantum mechanics didn't appear until 1900. Both are commonly held to constitute the most certain knowledge that exists about physical nature. Classical mechanics has especially often been viewed as a model for other so-called exact sciences. Essential in this respect is the relentless use of mathematics in theories, as well as the decisive role played by experiment in generating and testing them.

Quantum mechanics is of a wider scope, as it encompasses classical mechanics as a sub-discipline which applies under certain restricted circumstances. According to the correspondence principle, there is no contradiction or conflict between the two subjects, each simply pertains to specific situations. The correspondence principle states that the behavior of systems described by quantum theories reproduces classical physics in the limit of large quantum numbers. Quantum mechanics has superseded classical mechanics at the foundational level and is indispensable for the explanation and prediction of processes at molecular and (sub)atomic level. However, for macroscopic processes classical mechanics is able to solve problems which are unmanageably difficult in quantum mechanics and hence remains useful and well used.

Analogous to the quantum versus classical reformation, Einstein's general and special theories of relativity have expanded the scope of mechanics beyond the mechanics of Newton and Galileo, and made fundamental corrections to them, that become significant and even dominant as speeds of material objects approach the speed of light, which cannot be exceeded. Relativistic corrections are also needed for quantum mechanics, although General relativity has not been integrated; the two theories remain incompatible, a hurdle which must be overcome in developing the Grand Unified Theory.

The following are described as forming Classical mechanics:

- Newtonian mechanics, the original theory of motion (kinematics) and forces (dynamics)
- Hamiltonian mechanics, a theoretical formalism, based on the principle of conservation of energy
- Lagrangian mechanics, another theoretical formalism, based on the principle of the least action
- Celestial mechanics, the motion of heavenly bodies: planets, comets, stars, galaxies, etc.
- Astrodynamics, spacecraft navigation, etc.
- Solid mechanics, elasticity, the properties of (semi-)rigid bodies
- Acoustics, sound (= density variation propagation) in solids, fluids and gases.
- Statics, semi-rigid bodies in mechanical equilibrium
- Fluid mechanics, the motion of fluids
- Soil mechanics, mechanical behavior of soils
- Continuum mechanics, mechanics of continua (both solid and fluid)
- Hydraulics, mechanical properties of liquids
- Fluid statics, liquids in equilibrium
- Applied mechanics, or Engineering mechanics
- Biomechanics, solids, fluids, etc. in biology

- Biophysics, physical processes in living organisms
- Statistical mechanics, assemblies of particles too large to be described in a deterministic way
- Relativistic or Einsteinian mechanics, universal gravitation

Most of engineering is (or has been) based on classical physics.

The following are categorized as being part of Quantum mechanics:

- Particle physics, the motion, structure, and reactions of particles
- Nuclear physics, the motion, structure, and reactions of nuclei
- Condensed matter physics, quantum gases, solids, liquids, etc.
- Quantum statistical mechanics, large assemblies of particles

Philosophically, some very big changes with QM. Classical mechanics is deterministic. If you know the starting point and all the physics you know where everything is going. No Free Will? QM is stochastic and random. Particles are never precisely pinned down to a place/time or state. Back comes Free Will? Perhaps? Some people think that QM and consciousness are very closely linked. A lot weird results and a lot of arguments (Einstein and Bohr). Still not closed or understood.

There is natural tendency to draw a line between the two. However, it is difficult and leads to more problems. Get into SciFi stuff such as many worlds, teleportation etc.

We have a very good intuition for CM. It is, basically, the physics of our time and length scale. We understand Newton's laws because we evolved to understand them! If we did not we would die! QM is the physics of the small and the energetic. This is not our natural domain. We have a very poor feel for the physics. Everything is vague often counter intuitive and sometimes down right bizarre.

However, QM is correct – never been shown to be wrong, CM is an approximation of QM.

Science proceeds by a series of approximations to the truth. We have an agreed set of facts, which grows over time as our experimental techniques improve. As these facts invalidate a theory another theory replaces the last one. Paradigm shifts are used to describe this phenomena. Usually, the last theory is found to be a limited approximation of the latest one. A theory makes predictions based on premises and facts and the application of logic and math, if the predictions are found to be in error then the theory is lacking or incorrect. No predictions, then no theory, just speculation.

* Material from:http://en.wikipedia.org/wiki/Mechanics#Classical_versus_quantum