Semiconductor Optoelectronics
Prof. M. R. Shenoy
Department of Physics
Indian Institute of Technology, Delhi

Lecture - 1
Context and Scope of the Course

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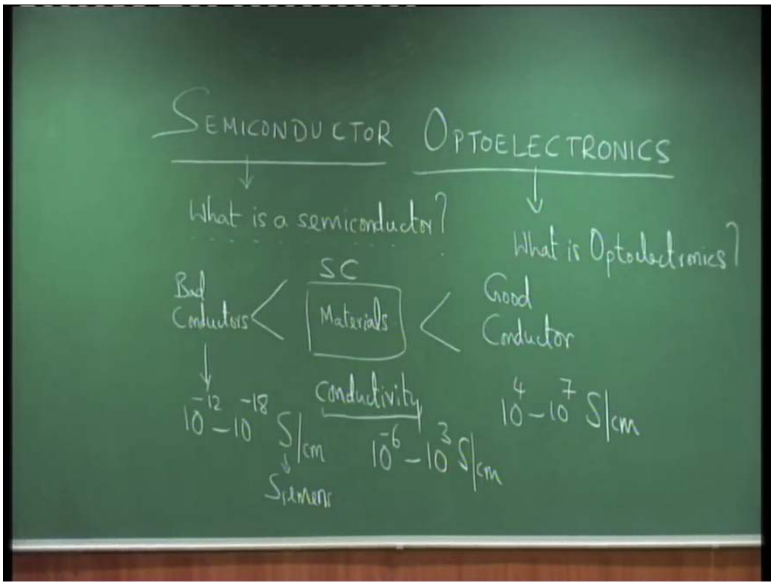

Welcome to this course on semiconductor optoelectronics. So, semiconductor optoelectronics; let us start with the title semiconductor optoelectronics. What is the subject matter of this course comprised. So, semiconductor, let us start with the title as such, semiconductor; we know about what is the semiconductor, what is a semiconductor? And we also see what is optoelectronics? And then we understand the subject matter of this course on semiconductor optoelectronics. What is a semiconductor? We all know what is a semiconductor? How do we know what is a semiconductor?

As the name indicates it is a material, which has conductivity between a material, which has conductivity between those of bad conductors or insulators, bad conductors and good conductors in a very, very elementary action that we see good conductors, between bad conductors and good conductors, or metals and insulator, conductivity; conductivity between, those of bad conductors and good conductors. what kind of number set we are talking, conductivity is one over resistivity, inverse of resistivity what kind of numbers we talk for bad conductors, bad conductors or insulators, typically have conductivity in the range 10 power minus 12 to 10 power minus 18, units are Siemens per centimeter. Words of resistivity 10 to the power minus 12 to 10 to the power minus 18, resistivity as you know units of ohm centimeter, so this is essentially ohm inverse Siemens, 10 power Siemens per centimeter. And for good conductors, it is typically approximately 10 power 4 to 10 power 7 Siemens per centimeter.

Semiconductors; so semiconductors let me here, a conductivity have conductivity approximately in the range 10 power minus 6 to 10 power 3 Siemens per centimeter. First step that what is a semiconductor, we are trying to attempt to answer this question, what is a semiconductor. A material has conductivity between those of good conductors and bad conductors. So, the typical numbers of conductivity of semiconductors are this. But does this quantify a material to be a semiconductor, just if it has conductivity between those of good conductors and bad conductors; no. then it not, it would not have had such important applications as we have today; that is the primary applications of semiconductors have come out, because of the following.

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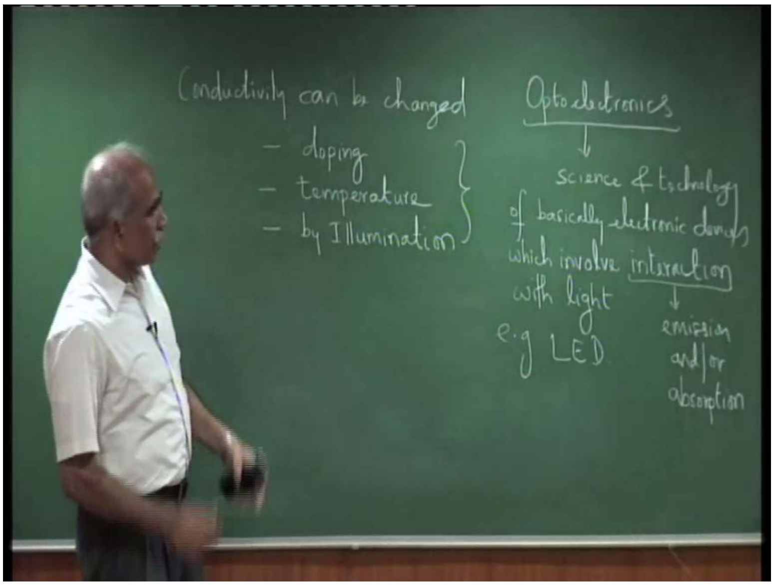

That conductivity of semiconductors can be varied by orders of magnitude. The conductivity can be varied, conductivity can be changed by orders of magnitude, by one, by doping, doping the semiconductor, by doping, by changing the temperature of the material. As we will see later the conductivity depends on the doping concentration semiconductors are normally doped, p doped, and n doped semiconductors are used in devices. So, doping the semiconductor can change conductivity by orders of magnitude. And temperature, changing the temperature can also change the conductivity, and we can also change the conductivity by illumination, with the light of appropriate wavelength, by illumination with light of appropriate wavelength.

We can change conductivity of materials by a very large amount. And this is the primary reason why semiconductors become very important, where the conductivity can be changed by orders of magnitude. And the elementary definition of a semiconductor, is materials which have conductivity between those of good conductors and bad conductors, and whose conductivity can be changed by orders of magnitude by doping, or by changing the temperature, or by illuminating the material with light of appropriate wavelength.

Then come to the second part optoelectronics, what is optoelectronics. Optoelectronics basically deals with science and technology of electronic devices, of basically electronic devices, yes; which involves interaction with light. just to give a example, for example an LED, a light LED diode is basically APN diode, APN diode is an electronic device, but it involves emission, when you pass a current through a forward bias L E D it emits light, and exactly like that photo detectors, where when light is incident on photo detector, it generates current, which is an electronic device, but involves interaction. Interaction here primarily refer to emission and absorption, emission and or and or absorption. So, semiconductor optoelectronics therefore, deals with devices phenomena, which of electronic devices, basically electronic devices, semiconductor electronic devices, which involves interaction with light or emission or absorption of light, so that is semiconductor optoelectronics.

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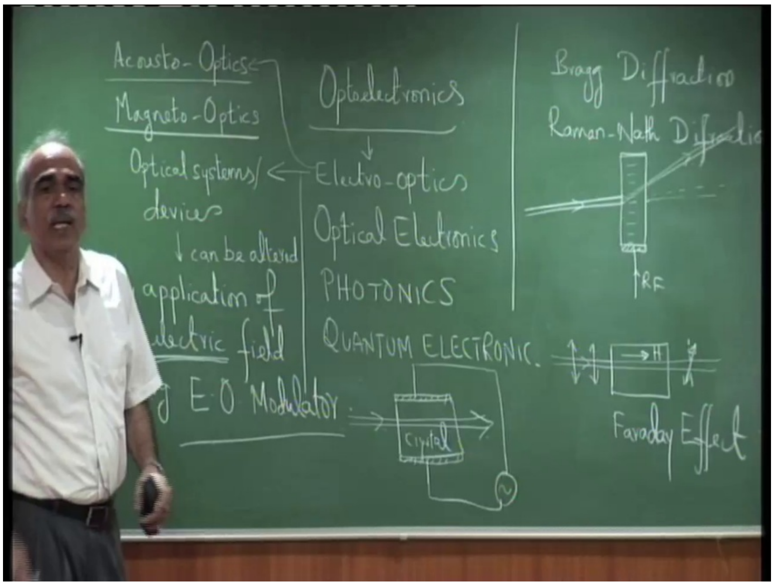

Let me write again semiconductor optoelectronics. I want to spent few more minutes' semiconductor optoelectronics on this terminology, because there are similar terms synonyms, or similar looking terms optoelectronics we also have electro-optics, and optical electronics, terms such as optical electronics, there are books on optical electronics. Electro-optics, all books cycled electro-optics optical electronics, photonics quantum electronics, and so on, a number of similar looking terms. It is very difficult to give a precise definition of a precise domain. However as we discuss just now, optoelectronics deals with electronic devices which involve interaction with light. In electro-optics we basically deal with optical systems optical systems or devices, where the propagation properties or characteristics of the device can be altered, by application of an electric field.

The propagation properties of white to these devices are altered by application of an external electric field. For example, let me give an example of electro-optics modulator, E O modulator, electro-optics modulator usually this is a optical devices, may be a crystal through which the beam of light propagates light. If you apply an electric field to this crystal, I am showing metallic electrodes here if you apply an electric field. It is possible to modifying the output properties of light. For example the polarization can be modulated, the application of the electric field here, the application of the electric field, let's say e field, yields to variation in the in the refractive index of the medium, and that can result in variation of the phase of the light. This is the basic principle of phase modulator.

So, electro-optic modulator is a device which is electro-optics. So, electro-optics primarily deals with optical devices and optical systems, where the application of an external electric field modifies its properties. In their definition also, there are similar terms as acousto-optics, and magneto-optics, all effects are discovered in the 1970 magneto-optics. Acousto-optics refers to optical systems, where the characteristics are altered, when the propagation properties are altered by application of an acoustic field. We replace electric field here by an acoustic field; we get the acousto-optics, what is this acoustic field. For example if we try an R F, if we try an R F crystal for example, so we have crystal here, and then the (( )) is there, absorber here (( )) is the, to which we applying an RF, which forms standing waves in medium.

There are mechanical waves which propagate through this medium, which form a standing wave, and due to this there are compressions and radifractions frozen into the medium, act like a base medium, and then an incident optical beam here, can get diffracted in particular direction satisfying the base matching conditions, and this was the original form, and acted to an angle, it is called Bragg diffraction, there are two important diffracts which are, Bragg diffraction and Raman-Nath diffraction. In Raman-Nath diffraction we get multiple diffraction orders, and Bragg diffraction the base matching conditions satisfied, that we have the entire energy can get transferred to a particular diffraction of. So, these are properties these are diffects, which are discussed in the case of acousto-optics. Similarly magneto-optics, if you alter this definition and replace an electric field by magnetic field, what you have is magneto-optics.

So, magneto-optics deals with optical systems, where the propagation properties are modified by an applied magnetic field. The very important effect which we are aware is the Faraday Effect, where you have a linearly polarized beam, let's say a linearly polarized beam, propagates through this optical medium, if you applied a magnetic field h, then the polarization state gets rotated to an angle theta, and this angle is proportional to the strength of the magnitude. We are aware of this, the Faraday Effect where the state of polarization is rotated due to an applied magnetic field. There are several applications of pole faraday effect, and Bragg diffraction. So, acousto-optics and magneto-optics and electro-optics, all these three are known well in the 19th century.

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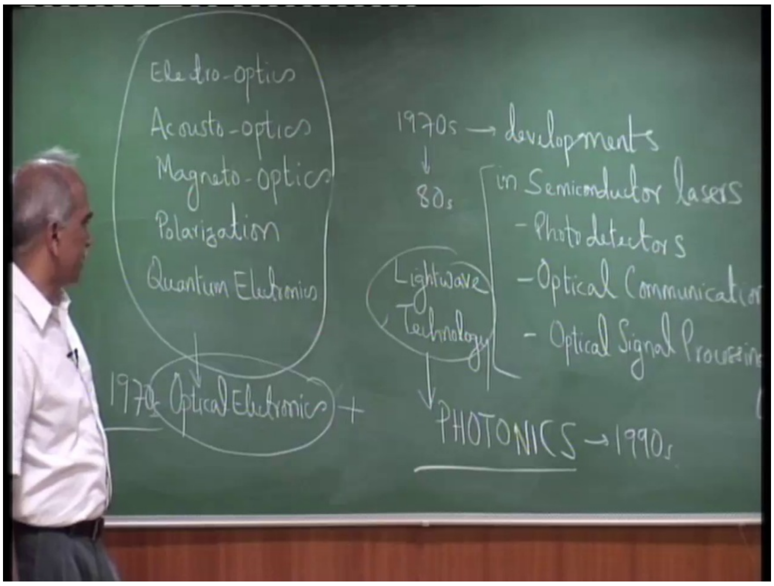

So, come to some of the other terms, what is this optical electronics, before that let we see what is quantum electronics. quantum electronics; the branch of science where we study the interaction, it is the branch, where we studied the science and phenomena, which involve interaction of radiation with matter interaction of radiation with matter quantum electronics, finally reveals with the study of devices and phenomena which involve interaction of the radiation with matter. And the most important device, a quantum electronic device is a laser, laser is a quantum electronics device. non-linear optics which have several effects, non-linear optics also part of quantum electronics, which involve interaction of radiation with matter, what is optical electronics. In the 19 century sorry in the earlier 20th century we had electro-optics, acousto-optics, magneto-optics, optics itself polarization, quantum electronics, which included lasers and non-linear optics, including non-linear optics.

All study of all these together, the subject matter which comprised study of all these, are called together as optical electronics, optical electronics in the 1970; the famous book of Yariv, optical electronics by Yariv. The first edition in 1970 is widely used text book on optical electronics, which described all these effects, and other propagation properties of light through medium. In the 1980 the light wave technology, developments in light wave technology rapidly progressed, due to the advents of semiconductor lasers, and optical fiber communication. So, in the 1970s the development in semiconductor lasers, photo detectors, optical communication, so both 70s to 80s optical communication, optical fiber communication, fiber optics, optical signal processing. Rapid developments in these area lead to light wave technologies, becoming an almost independent branch, light wave technology becoming an important branch technology, light wave technology. Rapid developments in the light wave technology lead to an entire branch under optical electronics which is called photonics in 1990.

So, photonics encompasses optical electronics, plus the earlier optical electronics, and all the modern communication technologies which are included in light wave technology here, this plus this get the first term, so find as photonics, which is analogous to a branch, analogous to electronics, photonics in the 1990, and the first book was fundamentals of photonics by Saleh and Teich, it widely used as the text book. So, this much about a terminologies, various terminologies that are relevant and today the branch is very widely known as photonics, complete branch which involve interaction of photons and electrons of interaction of photons and. Then we go little bit further, and trying to present the context this lecture, and presenting the context, scope, and contents of this course.

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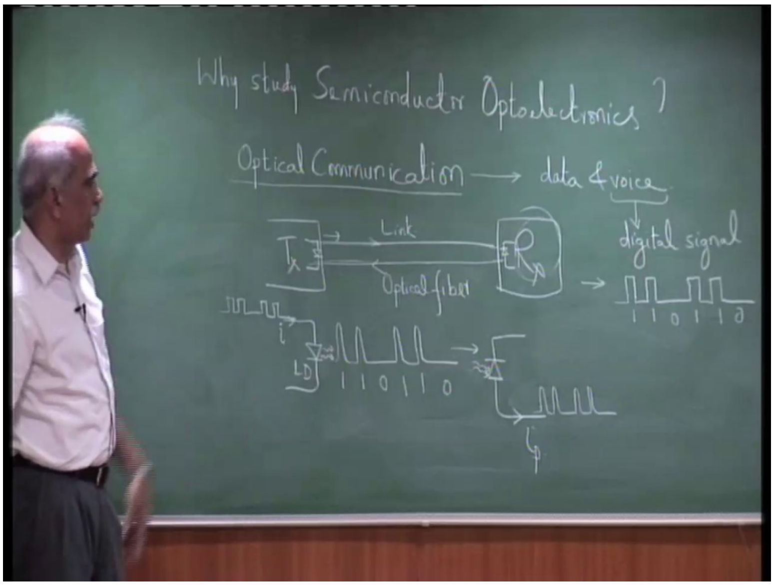

So, why study semiconductor optoelectronics. Why study semiconductor optoelectronics? Try to address this question why study semiconductor optoelectronics. This course here, this course is a core course of the program on optical communication, optoelectronics and optical communication, it is a core course. Therefore, let me take an example in the context of optical communication to take a simple optical communication mean, then you have a transmitter, and link here, and transmitter receiver and the communication link. If it is optical fiber communication, and then this link is an optical fiber. It could be a two way link, or optical fiber. Then it becomes optical fiber communication, transmitter receiver, and optical fiber. Now the transmitter here, if we use this optical communication, optical communication is used, optical fiber communication is used for data as well as voice, data and voice including all video data, digital data, as well as voice.

If we look at voice; that is the normal voice communication telephonic conversation, then voice is first digitized, therefore communication could have digital communication. So, digital signal, voice is digitized; for example, you have a n r z pattern. This is digital one, digital one, here is digital 0, this is 1 and go on, a digital sequence, the signal which is for the voice is first digitized, and here is the digital sequence. So, the digital signal can be this transmitter, this comprises of whole the electronic processing part, which converts the voice signal into a digital signal, and the last component here is the light emitting diode, or the laser diode, where the bias current is modulated by the same digital sequence 1 1 0 1 1 0. So, the bias current through this laser diode L D, L D is semiconductor laser diode, modulated, and therefore the laser diode output yields pulses corresponding to digital ones, and no pulse corresponding to.

This is right pulses now, gives of right pulses, in accordance in the current signal, we need current signal. This is a digital 1, digital 0 1 1 and 0. So, the last component here, which the right output is sent coupled to the optical fiber, right output is coupled to the optical fiber here, and transmitted towards to the receiver. So, the last component here is the semiconductor laser diode, or the light emitting diode here. similarly at the receiver the received optical signal, the incident optical signal, is the received optical signal, is incident of photo detector, on which the incident signal is incident, the optical signal is incident when the photo diode, which generates a reverse current i p here, which again corresponds to the digital signal that we have constant. The photo current generated due to the incident optical pulses, are of the same pattern as that of the original.

Of course, pulse shaping and others things have to be processed, it could be processed in this receiver here, the receiver combines all the electronic devices and the signal processing devices, but the first component here, is the laser diode, the photo detector, and the last component. Here the first component is the photo detector, and the last component here is it. So, in the context of a simple optical communication system, we need a transmitter, a laser diode it is a transmitter, and a photo detector is the receiver, so which are semiconductor optoelectronics devices. Then the context of optical communication, let us a simple example, actually on the link there are other amplifiers optical amplifiers, which will also involve photo diode, photo detectors, and laser diode here, but this is on communication first time.

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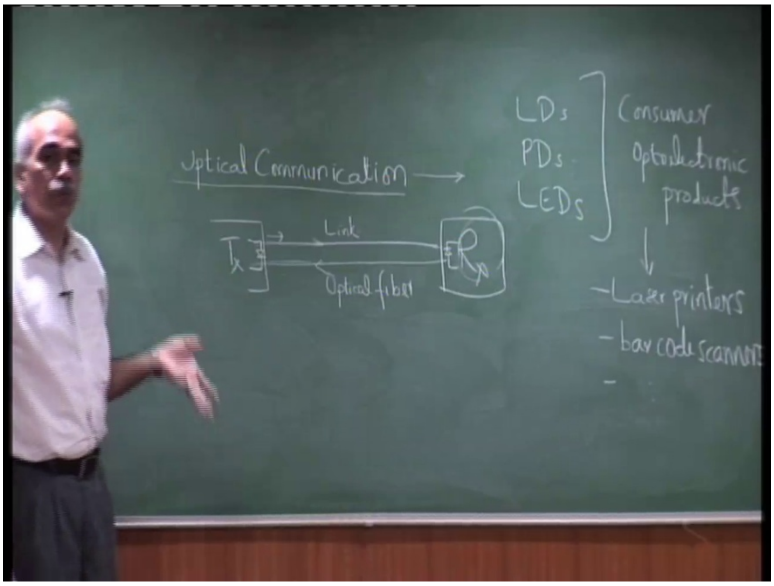

But optical communication is not the only application, because we know that semiconductor lasers semiconductor, lasers laser diodes, photo detectors, LEDS are widely used in consumer electronic and consumer optoelectronic products, consumer optoelectronic products, such as for example, in information technology we have laser printers, C D drives, barcode scanners, and number of applications; the laser pointers, the C D players, D V Ds everywhere you need optoelectronic components. A large consumer electronic market exists; where optoelectronic components are might be used optical communication is being just one. Historically one of the earlier, earliest optoelectronic component, one of the earliest optoelectronic component is the opto-coupler.

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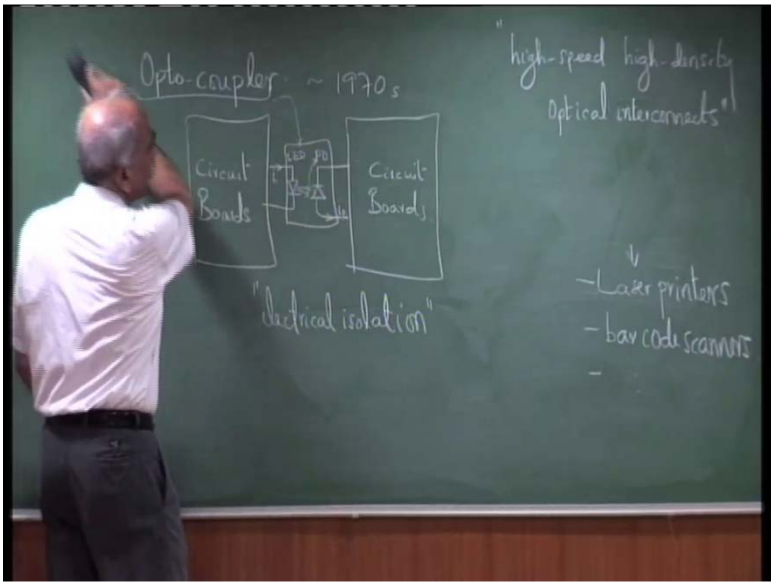

Let me discuss this the opto-coupler, this was in the earlier 1970. Opto-coupler is basically comprise of components at the, and photo detector, it is a coupler, it is for historical. Then it should have electronic circuit boards, these are circuit boards, which have to be connected, but have to be electrically isolated. There are two circuit boards which have to be electrically isolated, then you want electrical, complete electrical isolation. This is an electronic circuit board, it is a p c b lets say, printed circuit board, and there is an electronic circuit board here, which requires complete electrical isolation. There are certain processing, circuits which have ground as a common terminal, whereas some of the other circuits which have positive or negative, the main line, the main supply as the common terminal. Then in such cases you need complete electrical isolation.

And one of the component which we choose was opto-coupler, it was very easy, because any, the L E D here, it was based on L E D and photo detector, so this was an L E D light emitting diode, and this was photo diode. So, the L E D would give, depending on the current i through the L E D, it would give out light there, and the photo detector will generate the same current i or current proportional to the i here, it will generate photo current p, which will then go to the next circuit board. So, the current photocurrent generated here, is proportional to the current to the L E D. this was one of the earliest optoelectronic component proxy opto-coupler, widely used in electronic circuits, but today a similar thing, which is according much more different scale is used for high speed, high density optical interconnect. For this reason I sort of mentioning this earliest simple device opto-coupler; that in renewed interest in this kind of coupling between two circuit boards, which handle very large high speed optical interconnects.

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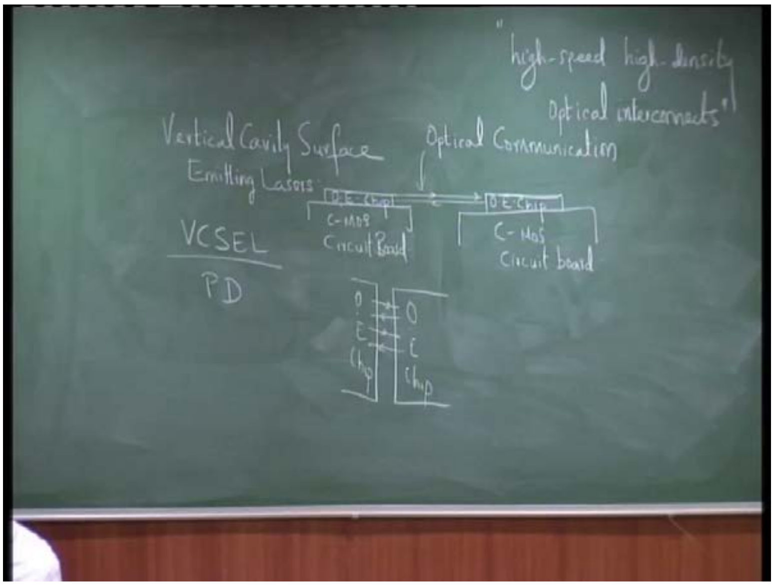

That is you have A M O S device here, and you have C-M O S device here, there is a C-M O S electronics, C-M O S circuit board; there is another C-M O S circuit board, very high speed electronics, giga bit, the data speed very fast. You need communication between them; one of the case of course, you could have electrical wires, large number of electrical wires, but the electrical wires will have their own electrical losses and inductance, that very high speeds, very high data rate, it becomes (( )), and one of the ways which is used now, which is in developed, is optical high speed high density optical interconnects, where you have an optoelectronic chip. The electronic circuit board is connected to an optoelectronic, O E chip here, and there is an O E chip here, optoelectronic chip O E chip, what is this O E chip. O E chip is a chip which contains optoelectronic components; such as laser diodes and photo detectors, and you can have communication between these, communication between these two O E chips, high speed communication in the optical domain, this is optical communication.

It could be free space optical communication, or it could be this O E chip, is connected to this O E chip through optical fibers. Thus chips are being such high density optical interconnects are being developed. So, the advantage being a very high speed, there is no digitalization of the data, there is no digitalization of the data to handling the optical. The higher version of this, includes chip to chip, through chip to chip communication, direct chip, this is O E chip, this is an O E chip, which talk to each other direct pieces. The sources here are monolithic V C S E L S, and the detectors are photo detectors. So, V C S E L is short form of vertical cavity vertical cavity surface emitting lasers, you can draw an array of V C S E LS on the chip, which emit vertically upwards, or it emits vertically, and you can have an array of photo detectors here. the both array of V C S E L S and photo detectors, the array of V C S E L S and photo detectors, you can have free space chip to chip communication at very high data rates; that is tens of giga bits, and several of the, many of its what is been developed now, and therefore, this is original, it is a highly improved version of the original opto-coupler.

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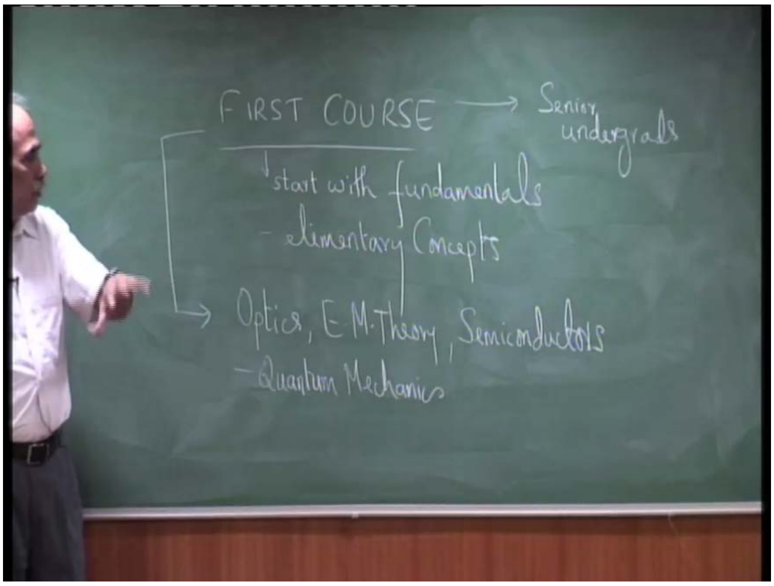

So, let me come to the context, this is the context of the course, and let me come to the scope of this course. It is first it is a first, by first course I mean, most of the times we start with fundamentals, elementary concepts. So, elementary concepts we start with fundamentals and elementary concepts and build on it. So, it is a first course, which would require background of optics, some background of optics, E M theory, electronics or semiconductors, little bit of quantum mechanics, are simply a first course for under graduate have done a course on applied physics, and graduate program on applied physics, or first year undergraduate level. A first year undergraduate level of background of optics E M theory, semiconductors, and quantum mechanics, what could be, but it is a first course, which could be for senior undergrads, or for first semester masters. So, that is the level of course, and thus we have here, the students who take this, are from various backgrounds, they are from electrical engineering background, optics, physics background, applied physics background, and also some people from mechanical engineering background. So, we really do not require any specific preliministic other than some basics concepts, in the area of optics diplomatic theory, and quantum mechanics at the first year level.

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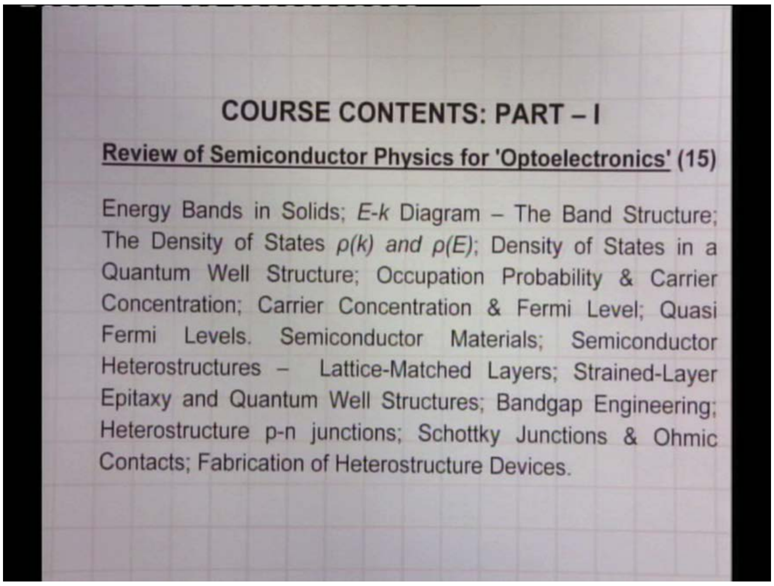

So, let me give you the contents of this course; the course will have a four parts. The first part we review semiconductor physics for optoelectronics; that is essential semiconductor physics for optoelectronics. So, we start with energy bands in solids the E K diagram, the band structure, the density of states; the density of states in quantum well structures. a little bit of quantum well quantum mechanics would be required here, but we will discuss from the basics. Then we will go over to occupation probability of carriers, and carrier concentration in semiconductors. The carrier concentration and it is dependence on the Fermi level; the quasi Fermi levels, which are very important in optoelectronic devices. Semiconductor materials; we briefly discuss essential semiconductor materials for optoelectronics. Semiconductor materials we will not be able to go into details of all semiconductors, but those which are widely used in optoelectronics, just to name a few silicon, germanium, gallium arsenate, indium phosphate and so on.

We then discuss semiconductor heterostructures, lattice matched layers; the need for lattice matching, strained layer epitaxy, which usually have certain advantages, and which also deal with quantum well structures, or the layer thicknesses are small enough, so that we discuss quantum well structures. We also discuss band gap engineering; that is tailoring of band gap, various techniques for tailoring of band gap. And then finally, in a device we have p n junctions, Schottky junctions that is junction between metal and semiconductors and ohmic contacts. So, we will discuss the last part here; namely p n junctions, schottky junctions, and ohmic contacts, from a point of view of the final device, and briefly overview fabrication of heterostructure devices. There are several techniques which are used; we will briefly overview fabrication of heterostructure devices. We will not again go into the details, because there are full courses on the fabrication technology of semiconductor devices. This is part one of the course, so approximately the first fifteen lectures will cover most of the essential semiconductor physics or device physics.

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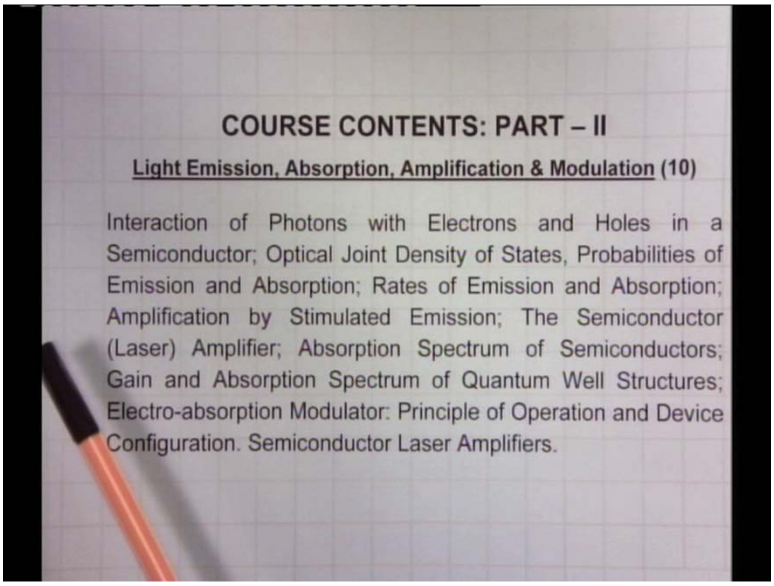

In part two of the course, we will discuss light emission, absorption, amplification and modulation, approximately ten lectures. We start with the interaction of photons with electrons and holes in a semiconductor. we will discuss optical joint density of states, probabilities of emission and absorption, rates of emission and absorption, amplification by stimulated emission, which is the basic principle for laser action, and we discuss the laser amplifier, absorption spectrum of semiconductors; gain and absorption in quantum well structures, one of the important devices based on the absorption spectrum of quantum well structures, immediately follows namely the electro-absorption modulator. We will also discuss the principle of operation and device configuration here, and in this part, finally we conclude with semiconductor laser amplifiers or SOS.

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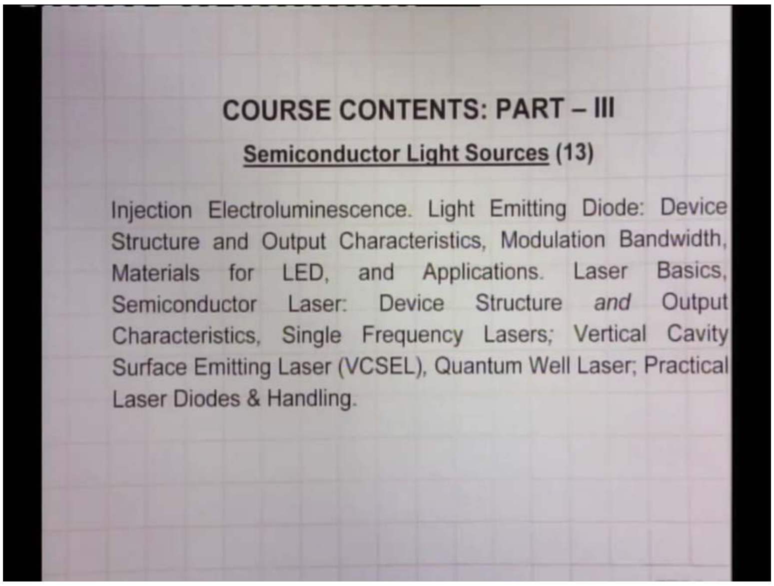

In part three of the course, is the part three or different modules, this can be treated as different modules. Semiconductor light sources, we start with injection electroluminescence, light emitting diode, device structure and output characteristics, modulation bandwidth, and materials for light emitting diodes and their applications. Then we come to laser basics in particular semiconductor laser, the device structure and output characteristics, we discuss singe frequency lasers, the distributed feedback and distributed Bragg diffracted lasers we will discuss here. Also the vertical cavity surface emitting laser, about which I mentioned just now. And we will also discuss quantum well lasers and practical laser diodes, laser packages, and handling of these devices.

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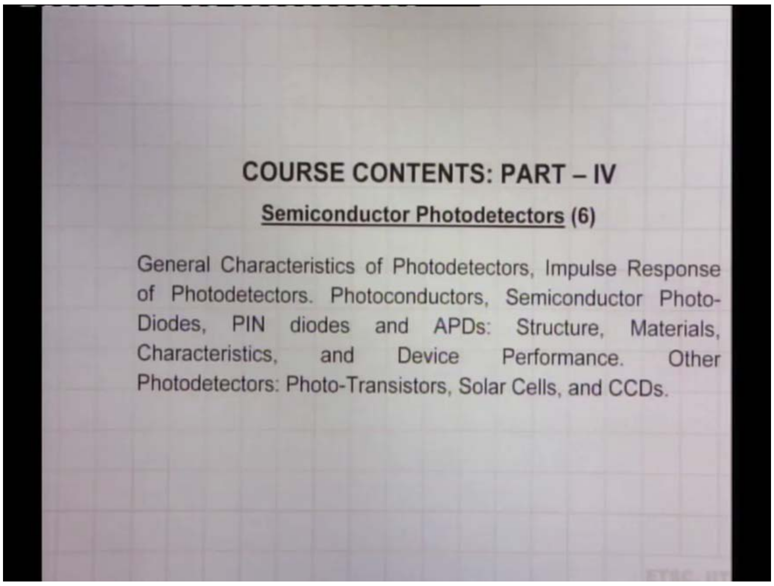

In the last part of the course, we will discuss about semiconductor photo detectors, it is a small part, because most of the characteristics, and device structures have already been discussed in the earlier parts. So, directly we go over to general characteristic of photo detectors, the impulse response of photo detectors. and one of the simplest photo detector being photoconductor, with the specific applications, we go to semiconductor photodiodes, to import and configurations being pin diodes and avalanche photodiodes, or APDS, the structure materials characteristics and device performance. We briefly discuss other photo detectors; such as photo-transistors, solar cells, and CCDs. As an epilog to these four parts, finally I would like to summarize, and view a top on photonic integrated circuits or PICS.

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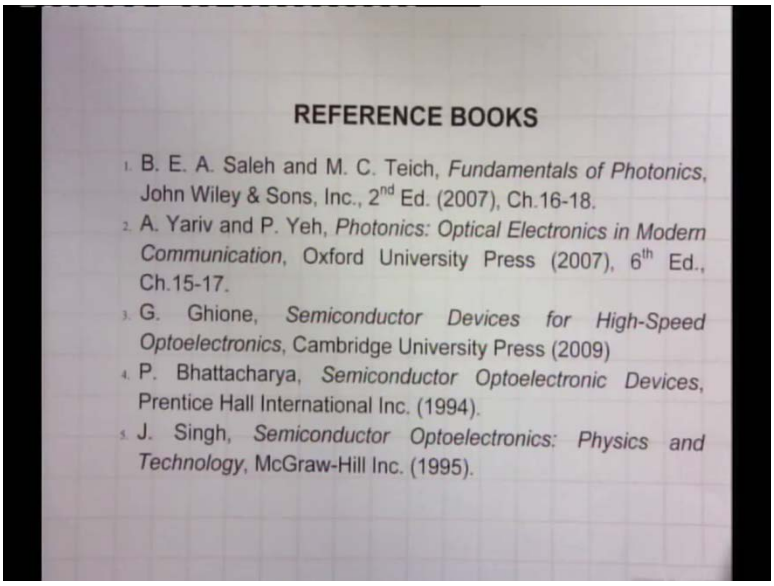

The reference book; here are some of the references which are listed; there are large number of books in the area of optoelectronics. So, I have listed some of the important text books; namely fundamentals of photonics by Saleh and Teich, chapter 16 and 18. This covers most of the photonic sciences and technologies, but chapter 16 and 18 is primarily deals with the semiconductor optoelectronics. Yariv and Yeh photonics, optical electronics in modern communication, the 6 edition of the original book optical electronics of the 1970 the first book. Here again chapter 15 to 17 would be useful. More recent book by Ghione semiconductor devices for high speed optoelectronics, and two classic books on semiconductor optoelectronics, the first books exclusively on semiconductor optoelectronics by Pallabh Bhattacharya and Jaspreet Singh.

Here I have listed them, although they are dated, but they are still very useful in terms of fundamentals and the earlier developments in optoelectronics. So, I would also strongly recommend you to go through these two books; the basics in semiconductor optoelectronics. So, these are the course contents, and as I said the course will have four modules, which have written as part 1 part 2 part 3 and part 4, the first part being, review of essential semiconductor physics for optoelectronics. Those of you, who have had a first course already in semiconductor physics, can even go directly to part two of the course. I think with this I will stop this first lecture, and we start with the part two. almost all lectures will follow as per the course contents listed here. So, we will start with the part one of the course; that is review of semiconductor physics. In the next lecture we start with energy bands in solids the E K diagram.

Thank you.