Fundamentals of Semiconductor Devices
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Lecture - 38
Introduction to compound semiconductors

Welcome back. So, if you recall in the last lecture we have wrapped up our portion for MOSFET MOS transistors we have finished up the MOSCAP MOSFET with all the short channel effects and the derivation of graduation approximation the I_D-V_D. The I you know related things like a charge sharing in the short channel model and back substrate bias effect , subthreshold slope things and all. So, we now have a basic understanding of MOSFET and please be advised and remember that MOSFETs are the building blocks of most of the modern digital logics and circuits.

So, now whatever we have learnt till now has been primarily based on silicon, because silicon is the most widely used semiconductor, almost all the electronic devices are made of silicon. However, today we shall start a new topic of compound semiconductors many of you may not be familiar with compound semiconductors, but please remember that actually unknowingly we keep using compound semiconductor devices everyday in our life. And they are extremely critical and crucial for our technology today, every time you connect to the internet you are actually using compound semiconductor devices.

So, these are non silicon devices and they are not there to replace silicon or compete with silicon, but the compliment silicon there are certain functionalities that silicon cannot do for example, silicon cannot emit light right. You need light at different wavelengths for example, that is that is an opto part, even in electronics there would be some limitations of silicon in terms of getting very high speed operation in terms of RF power amplifier or very high power switching. So, compound semiconductor comes in those applications where silicon you know does not perform or cannot perform for example and they are very crucial elements from modern technology ok.

Your cell phone is a very smart phone is very good example of how different types of compound semiconductor technologies have come together to actually enable the smart phone that you are using today. So, today and the next few lectures we will essentially start with the introduction to compound semiconductor and their band diagrams of compound semiconductor and when you have different materials you call them hetero structures. So, we will cover hetero structure band diagrams current flow, current transport and some of the common devices like transistors based on compound semiconductor quantum wells and so on.

This will also from the basis for LEDs and other devices that we will study subsequently ok. So, let us come through the white board and will assume that you know you recall the basic semiconductor device fundamentals from the earlier classes like things like p n junction, drift diffusion continuity equation, mobility, all these things you know so will be using them here very often.

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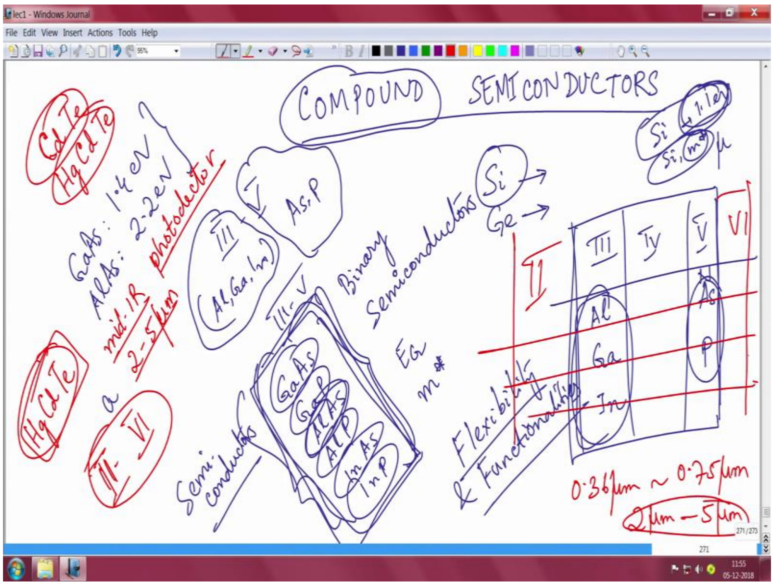

So, today we shall start compound semiconductor and many text books as well as courses probably do not treat compound semiconductors in details, but these are an essential element you know essential ingredient of our life today.

So, compound semiconductors are when you combine 2 different semiconductors for example, 2 different elements for example, silicon is a single element so, it is called elementary semiconductor and germanium is also elementary semiconductor, but you might want to combine 2 elements of different groups ok..

So, if you look into the periodic table. So, in group III you will have many elements, then group IV you will have many elements, then group V you have many elements. So, typically they are many kinds of and categories of compound semiconductor.

But the word compound semiconductor means that you are combining 2 different elements of 2 different probably groups of the periodic table and making a semiconductor. Now all sorts of possible combinations will not give a semiconductor there are certain combinations of your elements of different groups in a periodic table that will give you your compound semiconductor. For example, in your group III you will have aluminium, you will have gallium, you will have indium for example.

In group V you will have you know things like arsenic and phosphorus and of course, nitrogen and so on right. So, if you combine this group with that group you might get what is called the conventional III V semiconductors. Conventional III V semiconductor means you are combining the group III which is aluminium or gallium or indium these are the group III; group III elements you can say and in group V you are combining either arsenic or phosphorus ok. So, these combinations are called conventional III V semiconductors they are widely used in a lot of devices and applications actually.

For example so, you can have different combination you can have gallium arsenide, you can have gallium phosphide, you can have aluminium arsenide, you can have aluminium phosphide right, you can have indium arsenide, you can have indium phosphide these are a combinations you can have in terms of 2 2 elements, each these each of these has 2 2 elements and these are semiconductors; these are semiconductor. So, they display properties that are you know that define them as semiconductors you can dope them n type p type and so on.

So, these are semiconductors and these are compound semiconductors, but they are binary semiconductors; the reason we call them binary semiconductors is because they have only 2 elements that are there. And of course, each of this will have its own band gap, so, it will have its own band gap and band gap is a very fundamental property or parameter you know of a material. So, each of these has their own band gap that is great. So, maybe for example, gallium arsenide has a band gap of 1.4 eV. For example, aluminium arsenide has a band gap of around 2.2 eV, so that is great.

So, you have different band gap. So, different elements here different compounds will of course, have different band gaps and along with band gaps each of this material will have also have its own effective mass you remember. The effective mass of gallium arsenide effective mass of gallium phosphide they will all be different that is great. So, you have a lot of you know its like a zoo of materials that you can play with the silicon has a fixed band gap which is 1.1 eV, silicon also has a fixed effective mass of course, that depends on the direction.

But you know silicon is only one element and you have a fixed band gap, you have to live with a fixed band gap, you have to live with a fixed effective mass and hence at a fix mobility at a room temperature. You have a fixed you know you cannot you do not have the flexibility of doing many things with silicon for example. So, here you have so many different compounds they have different band gaps, they have different effective masses they will have different mobilities. So, what happens is that you can have more flexibility in designing devices right, you can get more functionalities in designing devices.

Because you can combine material that have different band gaps and they will the different band gaps and different you know your effective masses and so on. They will give different properties you can actually harness them to make devices that are not possible with silicon; its like you have only you know one type of food that you are eating with silicon, but here you have a; you have a lot of cuisines, lot of food types that you have to eat.

So, you can get you can select a lot more possibilities from this compound semiconductors and that will give you new devices which are not possible with silicon that is what I am trying to say. Now each of this material each of this semiconductor also will have its own lattice constant.

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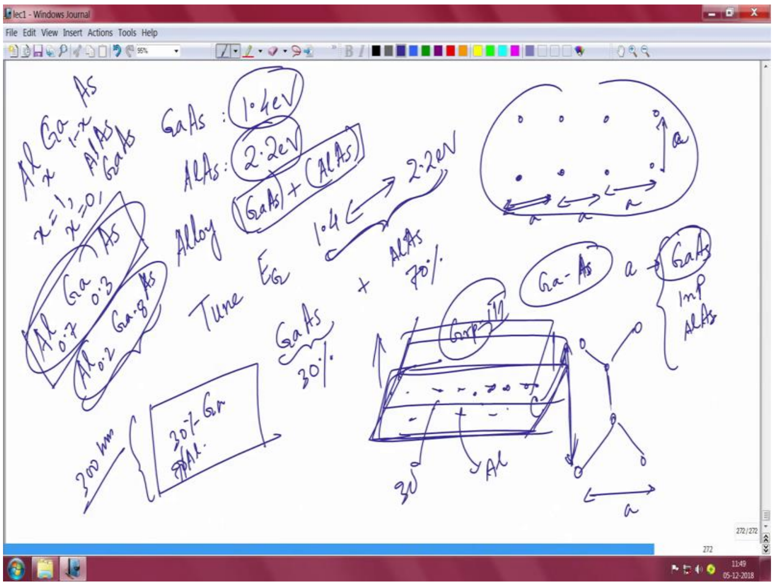

If you remember; if you remember what is lattice constant you know the element these compounds will have this spacing the spacing between these atoms there constant its always constant this is called a you know the lattice constant. Of course, I am drawing a simple picture it may not this is called c this is the direction, but the c and a may not be equal it may be simple cubic and it may be equal. Anyways the lattice constant lattice constant of this different elements gallium arsenide, indium phosphide, you know aluminium arsenide.

All these things the lattice constant also will be different and that has a major role actually we will see that very soon. And of course, when I say lattice constant it is not like gallium gallium gallium gallium its a gallium arsenide. So, you will have a gallium atom, you will have a arsenic atom and it will have its own crystal structure and when I talk about lattice constant I talk about the yeah I do not talk about the spacing between gallium to gallium atom or a arsenic to arsenic atom I look at the unit cell.

And in the unit cell you know if you have a unit cell like this for example, its a if you have unit cell like that then you will have to look at the dimension of the unit cell in order to be able to tell what is the spacing, what is the lattice constant ok.

So, anyways this they are different kinds of crystal structures hexagon FCC BCC and so on. So, crystal structure will define what is the spacing in the lattice. So, in a way the lattice constants of this different materials are very different and so, that has a big role to play we will see that. Now this is only group III V I am talking about now one interesting thing is that for example, I have gallium arsenide and this a compound semiconductor and this is 1.4 eV for example, and then I have aluminium arsenide which is for example, 2.2 eV.

Now, actually you know what I can make an alloy; I can make an alloy based on gallium arsenide and aluminium arsenide ok. I can make an alloy based on gallium arsenide and aluminium arsenide and what it will do is that if I mix these in some proportion in some fraction then I will be able to tune the band gap actually. I can the tune the band gap anywhere between 1.4 you know to 2.2 eV I can I can tune the band gap, I can get the band gap anything I want between these two while making an alloy appropriately ok.

So, that kind of flexibility is not a silicon, you can actually decide what band gap you want. For example, if I might want to take like you know I might want to take say for example, I might want to take 30 percent of gallium arsenide and I mix it with 70 percent of aluminium arsenide ok. It means if I have a you know if I have a plane of atoms here all these atoms are there 70 percent of the group III atoms sites, you have group III sites atom sites that were group III elements can go, 70 percent of those sites are occupied by aluminium and the rest 30 percent are occupied by gallium.

So, this 1 layer or 1 monolayer of this thing will be 30 percent gallium and 70 percent aluminium and you keep growing layer by layer; you keep growing layer by layer. So, you will get eventually a bulk you will get a semiconductor which is like thick bulk may be say 1 micron yeah 300 nanometer and so on and this will have 30 percent gallium of you know the gallium arsenide and 70 percent it will have aluminium in group III sites. So, I can call that aluminium 70, gallium 30, arsenic both of them are arsenic of the right. So, this is called Al Ga As aluminium gallium arsenide and here I am using 70 percent aluminium, 30 percent gallium I can use anything I can use 20 percent aluminum, then I will use 80 percent gallium.

So, essentially I am using an alloy and the band gap of this will change. So, by mixing these alloy in appropriate amount you can actually change the band gap from gallium arsenide 1.4 eV to aluminium arsenide 2.2 eV. And so, the generic expression would be I am using aluminium x fraction where x is less than 1 and I am using gallium which is 1 minus x and then arsenic. If x is equal to 1 then you get pure aluminium arsenide right and if x is equal to 0 then you get pure gallium arsenide.

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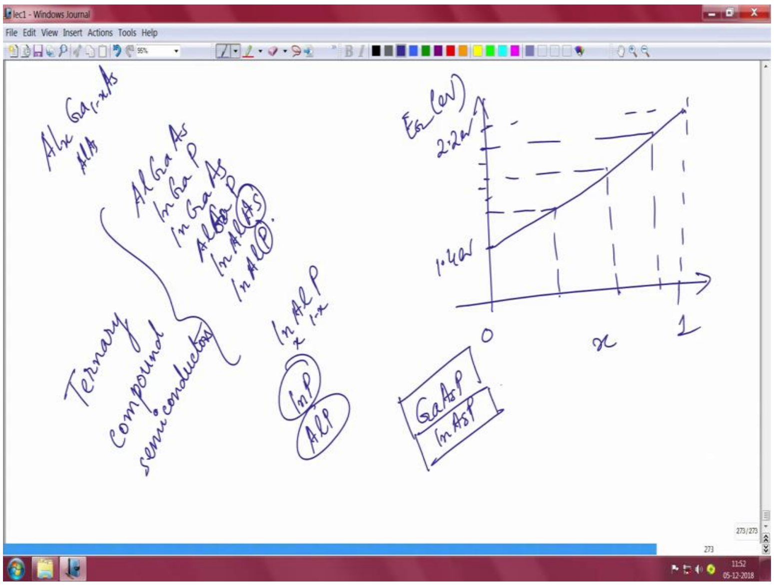

Which means; which means by changing the band gap changing x; x is the mole fraction from 0 to 1 right. So, I told you aluminium gallium 1- x arsenic. So, when you have a 0, you have and on the y axis I am plotting for example, the band gap in eV. So, when I have x is equal to 0 which means aluminium is 0 and gallium is 100 percent right and then I will have a band gap of 1.4 eV here right. And then you know as I keep increasing to 1 at 1 when I have x equal to 1 I will have only aluminium arsenide which band gap is 2.2 eV. So, may be 2.2 eV is here right.

So, I will have a change in the band gap like this right. So, essentially and I can go to any band gap I want and I can choose the x that I want you agree right, that is there is the beauty of telling tailoring the band gap ok. So, I am changing the mole fraction I am doing there. So, this kind of compounds say for aluminium, gallium arsenide I am not writing the x here, but it is always assume there or indium gallium phosphide, indium gallium arsenide, aluminium gallium sorry aluminium gallium phosphide, indium aluminium arsenide right.

So, many combinations indium aluminium phosphide these are these type of materials some compound semiconductors are called ternary because they have 3 elements these are called ternary compound semiconductors ok; ternary compound semiconductors. And in ternary compound semiconductors you are actually able to tune the band gap between the 2 edges of the binary ok. So, for example, if I take indium aluminium phosphide it means I have x here, I have 1 minus x here, I can have the band gap of indium phosphide I do not recover the values, but you can look up into Google. And then you have aluminium phosphide, you can go from band gap of indium phosphide to aluminium phosphide by changing the mole fraction.

So, you can get alloys these are ternary semiconductor of course, yeah here the group III element is fixed as phosphide or arsenide you can also have things like gallium arsenic, arsenide phosphide or indium arsenide phosphide, but those are little bit more you know they are they are they are there they have been also widely studied, but we will not talk much about them it is also not very easy to grow them. And also those are also used in many other devices, but we are only talking about when the group V is only one which is arsenic and so, you have say indium gallium arsenide for example.

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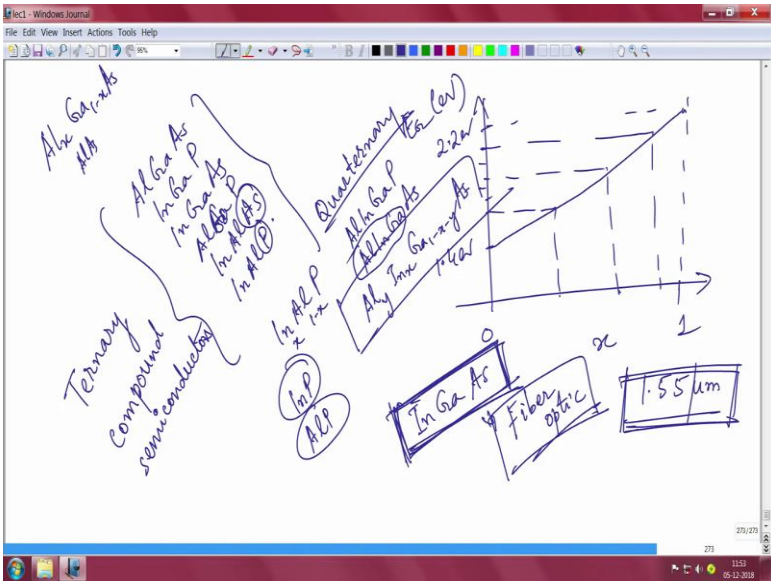

These kind of materials which is by the way indium gallium arsenide this is very widely used in fiber optic by the way, fiber optic communication you will realize actually. So, any time we are connecting to internet using you are using fiber optic communication and you are actually using indium gallium arsenide. You know laser diodes for example or detectors to send the signal at around 1.55 micron that is the wavelength of the infrared signal at which your optical fiber carries the information and every time you are using the internet you are actually using 1.55 micron wavelength of signal that goes in the fiber optic cable.

InGaAs detectors InGaAs laser diodes are being used here. So, every time you connect to the internet you are actually using compound semiconductors we do not just know that yet right. So, there this different things with one you know family of semiconductor of course, there is also something called a quaternary and that those are also used, but not as much probably quaternary semiconductors. You will have 4 elements it is like aluminium indium gallium phosphide, so, aluminium indium gallium arsenide these are four different elements will be there.

So, you will have the total of this has to be one ok. So, it will be like aluminium y, indium x, gallium 1 minus x minus y arsenic, these are also quaternary semiconductor where you can tune the band gap even more. Although of course, those are used for some special cases we will not discuss so much about them here. Anyways so, what we have now seen is that group III V semiconductors are one of the most common and you know widely studied compound semiconductor, but there are also other compound semiconductors that you can actually you know get by mixing and matching the elements from different groups.

So, this is III V, but there is also you know there is also you have II IV; II IV means II IV compound semiconductor means you are actually using elements from group II and group VI sorry not this is not IV II VI to II VI for example, cadmium, telluride cadmium telluride is a group II VI semiconductor, you will have alloys of that also something like say mercury cadmium telluride. So, these are semiconductors that also have a very wide range of applications and these are elements of group II and group VI that we are combining to make group II VI semiconductors.

For example mercury cadmium telluride is very very promising and widely used for mid IR; mid IR photodetector ok, because the band gap of this materials can be are very low actually; when the band gap is very very low then the wavelength that you can detect is very very large. So, mid IR means around 2 micron to 5 micron wavelength. Remember your human eye is visible it can only see from around 3.36 micron to around 0.75 micron probably right that is the range of human eye.

And when I say mid IR I am talking about 2 micron wavelength to 5 micron wavelength and you need a very small band gap and mercury cadmium telluride for example, is a very promising semiconductor in that it can actually detect your mid IR or detect signals.

Mercury cadmium telluride is a group II VI tell you group II here right group II here and then group VI here. So, its a group II VI sort of a compound semiconductor that is also there you know. So, so they are many kinds of semiconductors that are there is also antimonides in case antimonides ok.

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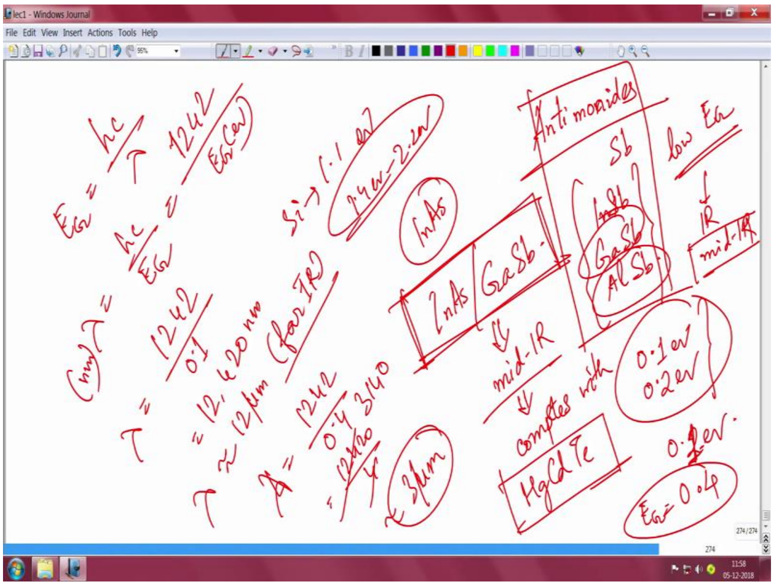

You these are all compound semiconductor antimonides. So, antimony you know antimony is Sb. So, antimonides will have Sb. So, you have say indium antimonide or gallium antimonide, aluminium antimonide this antimonides also compound semiconductors and antimonides have very low band gap typically, very low band gap and so, they are also useful for IR detection mid IR detection for example, and their mobilities are very high the band gaps are very low.

Their band gap can be as low as 0.1 eV, 0.2 eV the very very low band gaps materials gallium arsenide, gallium phosphide could be slightly bigger larger band gap than silicon. If silicon is 1.1 eV you can see that these band gaps are much smaller gallium arsenide, gallium phosphide their band gaps are 1.4 eV to 2.2 eV those are in that range they also a little bit larger band gap than silicon.

Of course, indium arsenide has a little lower band gap and indium arsenide and this gallium antimonide for example, this hetero structures are actually used when I say heteros I will come to hetero structure this kind of stacks are used also for mid IR mid IR detection and they compete.

For example this technology competes to it I just told you mercury cadmium telluride. So, this mercury cadmium telluride from mid IR detection for that area is also competed with indium arsenide gallium antimonide and sort of a structure. So, these are also low band gap material for example, I told you the band gap of a material is easy then the light it can detect for example, hc/λ. So, lambda will be equal to hc/E_G and one of this easiest way is that you. So, it is 1242 divided by the E_G in eV will give you the band gap and the wavelength in nanometer.

So, for example, if you have a band gap of 0.2 eV so, it will be a 0.1 eV for example, 0.1 eV 0.1 eV that will give you around 12420 nanometer which is equal to 12 micron which is actually far IR; far IR this is far infrared detection that is far infrared detection. For example, if you have you know a band gap of say the band gap of a material is around say 0.4 eV, then you will have λ is equal to 1242 by 0.4 that will be basically 12420 by 4; so, that is like 314 or so on.

So, it will be around 3 micron, so, that is mid IR. So, you see if band gap is 4 0.4 eV can be used for mid IR spectroscopy mid IR detection. So, these are also antimonides are also a class of very important materials for you know optical detection, mid IR detection. And nowadays Intel also is doing a lot of research on antimonides for high speed transistors next generation very low power, these are low band gap materials they can enable high speed devices.

So, there also so many categories of compound semiconductors we are only talking about of course, inorganic semiconductors these are all inorganic materials and inorganic semiconductors, but there can be also organic semiconductors which is not within the limit of this textbook.

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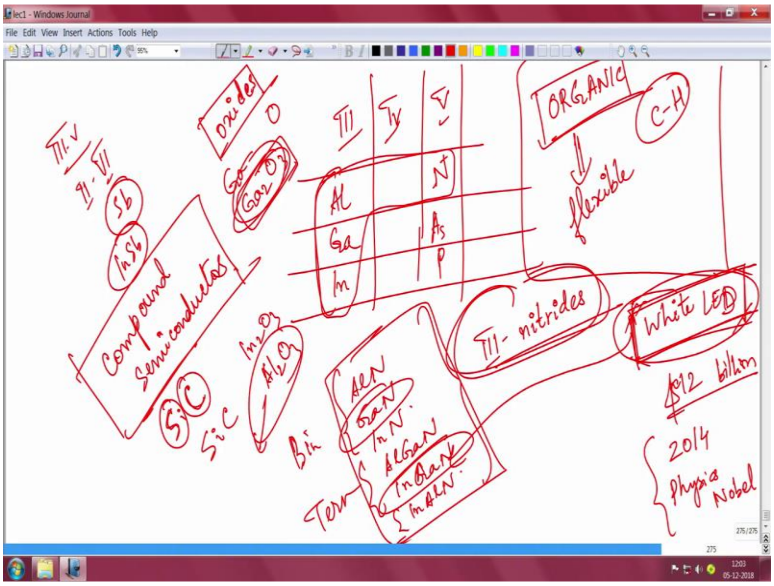

So, will of this course, so, we will not discuss on them. But organic semiconductors are basically carbon oxygen hydrogen bond based or complex organic molecules organic semiconductors have their own specialty in that you can bend them. So, they can be used to make flexible devices you can make flexible displays, you can make transparent displays and many of your smart phone touch screens and many of such applications actually use organic semiconductors you just may not be aware of that right.

So, organic semiconductors also widely used that is not within this course a limit. So, will not discuss about them; whatever else whatever we are discussing till now is actually we are discussing your inorganic semiconductors. So, all these are inorganic semiconductors I told you about the what did I tell you about conventional III V semiconductors gallium arsenide, gallium phosphide based I told you about II VI cadmium- telluride mercury cadmium telluride and they are quite a few others there actually. And then I also told about the antimonides gallium antimonide and all indium antimonide they are very very low band gap material 0.1 0.2 eV sort of things.

There are also few other compound semiconductors; there also a few other compound semiconductors. So, for example, I did not tell you about the applications I will come through the applications once I introduce the semiconductors here, there is a lot and lot of applications I will come to that. So, for example, in group III and this is group IV for example and then you have group V I told you about aluminium and then gallium and then indium right, I told you about like arsenic and phosphorus and so on, but there is also in group V you know arsenic and phosphorus you have.

But also there is excuse me there is nitrogen here and this group elements can actually combine it also nitrogen to form either aluminium nitride or gallium nitride or indium nitride you can also make alloys of that I told you right like aluminium gallium nitride, indium gallium nitride these are binary; these are binary right, these are ternary you can make indium aluminium nitride these are quaternary these are ternary and quaternary can be in aluminium gallium nitride.

These are also III V, but we call them typically III nitrides ok; III nitride semiconductors and III nitride semiconductors are also very very important you know every time you see a white LED. You know white LEDs you can by now from Big Bazaar and Amazon and every other shop that in your neighborhood shop will have you white LEDs Syska LED and all these things right. This white LED actually is made up of indium gallium nitride by the way gallium nitride. So, III nitrides have enable the white LEDs which is more than 12 billion dollar market, its a 12 billion dollar market more than more than that actually.

It has got the Nobel Prize in 2014 by the way, Physics Nobel Prize you can check that Physics Nobel Prize in 2014, 4 years back 5 years back. So, white LEDs are one of the areas where this III nitrides have revolutionized you can buy white light LEDs everywhere and the reason they are replacing the incandescent lamp and tube light is that they may be little expensive right now, but they are cheap becoming cheap becoming cheaper every day.

They actually a much more efficient they do not become warm if you touch them they are not warm like that incandescent bulb which means, they are very efficient they will last very long and they save your power essentially.

That is why all the parking garages street light, stadiums if you go to airports and all everything is white LED. So, you have this III nitride semiconductors also compound semiconductor one of the applications of III semiconductor is that white LEDs is literally touching our lives every day. So, these are they are different categories of semiconductors I told you there also some unique semiconductors like silicon carbide silicon and carbon combined silicon carbide.

Silicon carbide is also a semiconductor it is a compound semiconductor, it is a group IV IV semiconductor silicon is group IV carbon is also group IV, but silicon carbide is a group IV group IV IV it is a compound semiconductor.

Then their oxides you know then their oxides essentially like they also compound semiconductor. For example, you might take gallium and you might take oxygen, but the compound is typically gallium oxide 2 gallium 1 oxygen 3 oxygen. Gallium oxide is also a semiconductor these days it is getting a lot of attention if you want to do research and PhD gallium oxide is a very hot topic these days. For next generation power electronics these are also materials they also indium oxides and so on.

Aluminium oxide by the way is sapphire, its actually very white its insulator almost, but people are trying to also dope it. So, gallium oxide is oxides are another family of compound semiconductors right.

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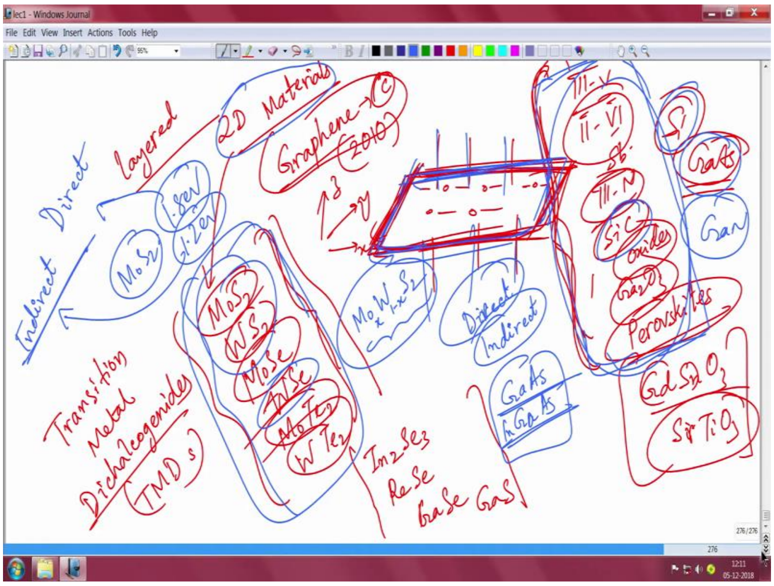

And then let me come back to new slide. So, I have told you about group III V, I have told you about group II VI, then I told you about the antimonides, then I told you about the group III nitrides, then I told you about silicon carbide, then I told you about the oxides. Oxides not only have things like gallium oxide, but it will also have more complex oxides you can have perovskites which are little bit more advanced in complicated kind of materials.

These are not they are used for solar cells by the way perovskites solar cells are very very very hot topic in research and then you have double perovskites and so on. You might have things like gadolinium strontium oxide, I am not able to recall the formula here exactly, but gadolinium strontium oxide you have strontium titanium oxide right strontium titanium oxide. So, there are different kinds of oxides also there they also called complex oxides and they are they may not be necessarily semiconductor some of them are semiconductors you can dope them and stuff like that.

Those are also different categories of semiconductors compound semiconductors that are giving you know new functionalities new types of devices and so on. Then there is this wide a very large you know proliferating in a very large range of devices that are going on which are based on layered 2D materials; layered 2D materials. And you should be aware of this because this is a very hot area of research and future of electronics people say that it will lie in 2D materials you never know. It sorted with the boom of graphene that you might have heard and the graphene that got the Nobel Prize I guess in 2010 Novoselov and Geim had got that graphene is a sheet of 1 dimensional say 2 dimensional sheet of carbon atoms.

And because its only carbon is not compound semiconductor typically technically speaking, but there is a zoo like 100s of 2D materials have been discovered and synthesized, then grown these days. And you have so many varieties and they are mostly compound semiconductor MoS 2 molybdenum sulphide, tungsten sulphide. For example, sorry molybdenum selenide, tungsten selenide, molybdenum telluride, tungsten telluride these are and they are many added these are layered 2D materials and are called you know transition metal dichalcogenide you should be aware of this things.

Transition Metal Dichalcogenides TMDs these are layered 2D materials they are many many others out of them. I am just giving you few example, there is indium selenide right, there is randium selenide, there is gallium selenide, there is gallium sulphide, so many materials are there. So, many there is a phosphorene then so many other things these are layered 2D, all these are layered 2D materials like graphene only.

In the sense that you can have just 1 sheet of 1 layer 1 monolayer 1 layer of atoms of 2D you know of 2D its a 2 dimensional sheet just 1 layer you know conventional silicon or gallium arsenide or gallium oxide and all these things are actually like a bulk you know it is a thick layer of you know, it is a thick vapor or a thick layer right. But this is just 1 layer 1 atomic layer I repeat 1 atomic layer 1 sheet of atomic layer of material can be made. You can also make 2 layers, 3 layers, 4 layers and multi layers and so on, but with gallium nitride for example, or silicon for example or gallium phosphide gallium arsenide and all these things it is not easy or its not it is not common to be able to get 1 layer of say you know gallium arsenide and just suspended you know like that. You can grow gallium arsenide layer by layer 1 layer by 1 layer, but on top of some substrate on some platform.

These are these can be standalone and this can be done by scotch tape method which is also you know research area, but that is that is a different thing, but these are 2 dimensional material. So, essentially it is like a sheet of atoms that do not have out of plane bonds, they are very weak out of plane bonds. You see if you have a bulk material bulk crystal then you have bonds in all three directions x y z here you will have only in x and y direction the z direction is free there is only 1 sheet 1 layer. So, that z direction bonding is weak Van der Waals forces that is very weak and you can peel them off layer by layer.

So, we can peel on layer of say molybdenum sulphide, you can put on 1 layer of molybdenum telluride, you can put 1 layer peel 1 layer of the tungsten telluride and put it on silicon or whatever right that kind of flexibility and you know ability to put any material on any substrate or any material on any combination is very very difficult nearly impossible to achieve in all these conventional compound semiconductor. These are also compound semiconductor, but these are different kinds of compound semiconductor they are called 2D layered materials.

The reason it is almost impossible to get this kind of a flexibility in this conventional semiconductor you will see later on is that this conventional semiconductors this conventional semiconductors have to be grown on some plat form because they are bulk, they are thick. And when you grow on platform there is a lot of problem with lattice mismatch we will come through that; this materials actually do not have that problem you can peel them off one layer and put it on another layer somewhere and you do not have the problem of lattice mismatch because out of plane bonding is very weak out of plane bonding is very weak. So, these are actually a very new categories of material that you should be generally familiar should be aware of these are things that are being done to in today's world ok.

And lot on new sensing photo detection and transistor applications are enabling this the next generation belongs to materials. You know human civilization has always progress from materials stone age bronze age, iron age those ages are defined by the material that are used iron age at iron bronze age, at bronze we are living in a silicon age where everything we do and see around is defined by silicon because our semiconductor technology is the one that is driving our civilization now right. Similarly, the next generation will be of different material is the material that defines the technology right.

So, 2D materials are believed to be the next generation of low power high speed computing and many other things you should be generally aware of that. So, band gap lattice constant effective mass of all these also will be different the band gap of MoS 2 for example, it is around 1.8 eV if it is one single layer..

If you have many layers together then it will be 1.2 eV and many of these materials will be direct band gap, many of these materials will be indirect band gap; if you recall what is direct and what is indirect. In direct band gap material you can emit light in indirect band gap material you cannot emit light.

Silicon is indirect band gap gallium arsenide is direct band gap gallium nitride is direct band gap, but silicon carbide is indirect band gap so many things are there right. MoS 2 for example, is layered materials so very unique and beautiful. If you have a single layer of MoS 2 a single sheet of MoS 2 atoms it is 1.8 eV and this is direct band gap material. If you have many many layers of MoS 2 its stacked on top of each other its a thick MoS 2 crystal then your band gap is 1.2 and that band gap of 1.2 is indirect band gap material.

So, you can actually not only change the band gap of the material by the number of layers you are giving, but also you can change whether it is direct or indirect depending on the number of layers. This kind of beauty and fancy things are not available in many of the conventional semiconductors and must be certainly not in silicon. In conventional semiconductor like gallium arsenide and gallium phosphide you can indium gallium arsenide you can make this alloys; you can make this alloys and tune the band gap, tune the material parameters tune the mobility and so on and you can get lot of devices. Here you can also another dimension you have you have the number of layers that you can put.

You can also make alloys of this material like you can make molybdenum tungsten you know M o x W 1 minus x S2 this is called molybdenum tungsten sulphide, this kind of alloys can be made research is not very strong at on this alloys of this or you know of this kind of 2D materials, but is going on every day it has new papers coming out. So, these are areas that you can think of you know taking up research if you are interested in future lot of new things are coming up new technologies are coming up and all these.

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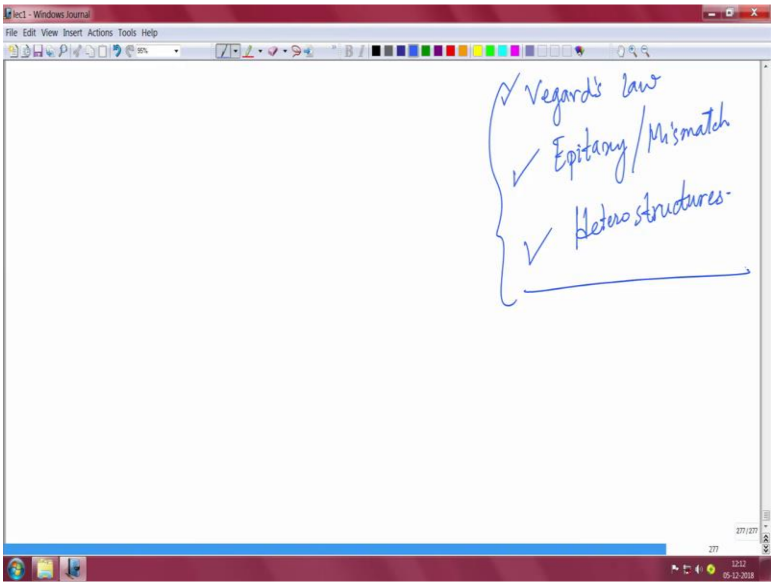

So, that was the brief introduction of compound semiconductor and now going here what we shall do we shall discuss a few things, we shall discuss something called Vegard’s law, I will tell you what Vegard's law is. We will discuss about things like epitaxy because those are important for practical things epitaxy and lattice mismatch ok. Epitaxy and lattice mismatch this is little bit of materials that you should be aware of when doing compound semiconductor, then talk about the hetero structures ok, we will talk about hetero structures ok. So, this three things will try to cover in the next class.

So, will end up the class here today, we will end up the class here today and what you have done today is that we have introduced compound semiconductor which are very this different from silicon that we have been always studying till now. You have seen that compound semiconductors have a wide range of variety that brings with them a wide range of band gaps and all the other associated properties like effective mass and hence mobility and so many other things. There are many types of compound semiconductor group III V II VI and III nitrides antimonides oxides so many they have so much of variety of band gap.

There is a new variety of material 2D materials that are also compound semiconductor, but they are 2D layered materials they have no out of plane bonding very weak out of plane bonding you can have layer by layer deposition layer by layer materials those bring an additional flexibility to designing devices, these are a huge area of research. In conventional semiconductor or compound semiconductor also there is a lot of research going on every time you are using the internet the smart phone the television the laptops you are actually using compound semiconductors in addition to silicon which is always there in your CMOS logic excuse.

All your processors memories and all since based on silicon, but apart from silicon also you have. So, many other things that compound semiconductors are making life better the white light LEDs the back lid panels the touch screen the high performance transistor that makes your radio signal you know you transmit and receive more efficiently in your cell phone. So, many other things are done by compound semiconductor..

So, we have made a very basic introduction to the different types of compound semiconductor what are the uses and what are the different ways we can understand them and so on. The next class we will study 3 things Vegard’s law epitaxy and hetero structures we introduce and thereafter we will continue next class we will continue it hetero structures and hetero structure band diagrams we will introduce some devices based on those, so, that we can understand them ok. So, I end the class here.

Thank you for your time.