Nanotechnology Science and Applications
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Lecture - 25
Graphene, a 2 D nanomaterial

Hello. In this class, we are going to look at graphene. It is a nanomaterial, in the sense that it is a 2-dimensional nanomaterial and it has interesting properties it has and also as a concept it is very interesting that you, we can access materials that are two-dimensional. And over the recent years more effort has been put into looking at similar systems which are all 2-dimensional in nature and people are trying a lot to very hard to try to synthesize such materials, isolate them, stabilize them and study them. So, in this class, we will focus on graphene and then from there you can always look up additional material on materials of similar nature.

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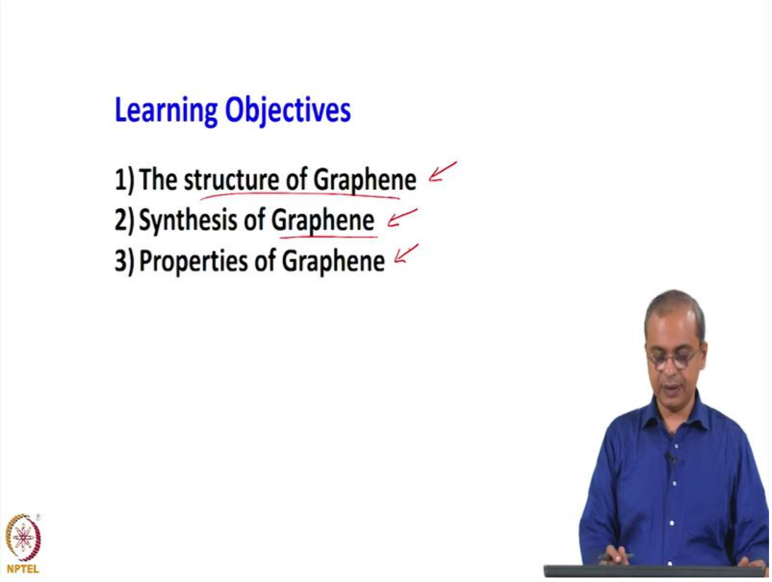

So, our learning objectives for this class are to look at the structure of graphene and see what peculiarities we have there. We will look at the synthesis process of grapheme. Some very interesting techniques have been tried to for the synthesis of graphene. And of course, we will look at properties of graphene, wide range of interesting properties that it has.

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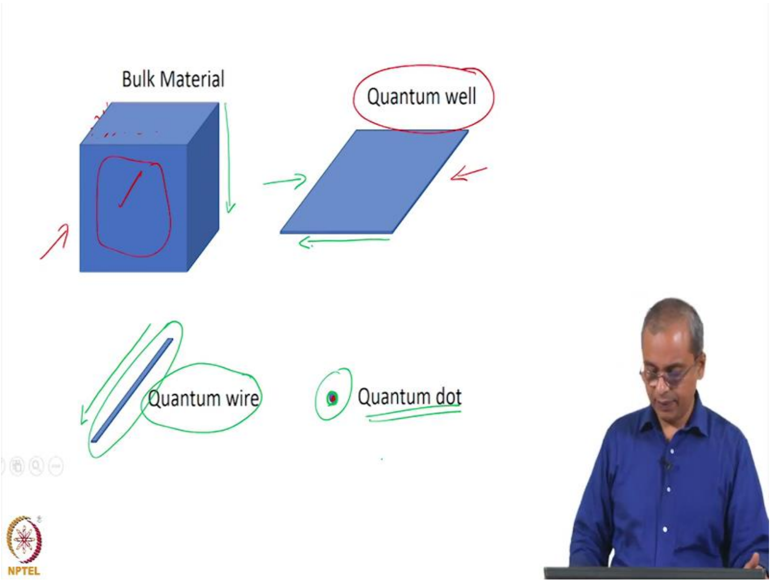

So, before we look at graphene specifically, we need to understand the context in which we are looking at different materials. So, first of all, there is this bulk material which is of this nature that we see here and that is the kind of material we are normally used to. So, any you buy a steel tube, you buy a rod for some purpose, block of metal, anything even your plate if you buy a stainless steel plate or even a ceramic plate even though it looks flat at the material level at the material science level, it is bulk material. It is a several millimeters thick, maybe a millimeter thick or something like that and that is bulk from the concept of material science.

Now, you can start reducing the thickness of this material and then if it becomes a really thin material then essentially it is a 2-dimensional material. So, when it is a 2-dimensional materials material and if it you are getting down to this nanometer scale, then we describe it as a quantum well that is the kind of description we use. You can also further now take this, so this. So, we are basically started here and you have reduced one-dimension. So, you reduce you go about reducing this dimension that will result in a material that is of that nature. Then you take this 2-dimensional material and you reduce one-dimension, then you will arrive at something called a quantum wire. That is the material that you see here. This is a quantum wire and.

And then so, you can make many of the tube-like structures that we make carbon nanotubes etcetera, they are getting close to this or of this nature essentially a quantum well kind of nature. And then you can take this 2-dimensional material, I mean sorry one-dimensional material now, which is a quantum wire and again reduce it in one more dimension. When you do that you arrive at something called a quantum dot. So, this is another type of material.

So, in each of these cases, we are reducing dimensions. So, what happens is many of the things that you see as a material property is because of the three-dimensional interaction of the atoms in that material. And as a result, microscopically we put some probe to measure some property and we get some response over that. When you start reducing one-dimension the kind of interactions that those atoms are having with each other starts changing or maybe a certain type of interaction is no longer there because you have removed one set of atoms in one direction so that interaction is not there.

Therefore, those atoms which are other which would have otherwise the atoms and electrons which would have otherwise interacted in that direction now do not have that interaction and so they are now free to do something else. And therefore, the property that you see for a 2-dimensional material there is a very high chance that many of the properties that it will display are going to be different from that of a three-dimensional material.

Similarly, you go down to one-dimensional material, you are going to see some differences and then when you come down to a more or less a zero-dimensional material which is a dot and therefore, a quantum dot you will see some differences in the properties. Largely, like I said got to do with the fact that now the bonds are not saturated in all direction, and not just that the number of such bonds as a fraction of the total bonds present is very large. So, even in a bulk material if you see even in a bulk material all the atoms that are on the top, whatever atom is sitting on the top here it has bonds that are not saturated, but you have this huge volume inside which is all saturated I mean saturated with respect to whatever is the crystal structure and bonding etcetera there.

Therefore, the property that you measure is dominated by this. This bulk is what dominates that property. Now, when you go down to a quantum dot the bulk is very tiny whereas, the surface that you see around it is remarkably large relative to the bulk. And therefore, the properties get dominated by the surface. So, this is pretty much what we are looking at.

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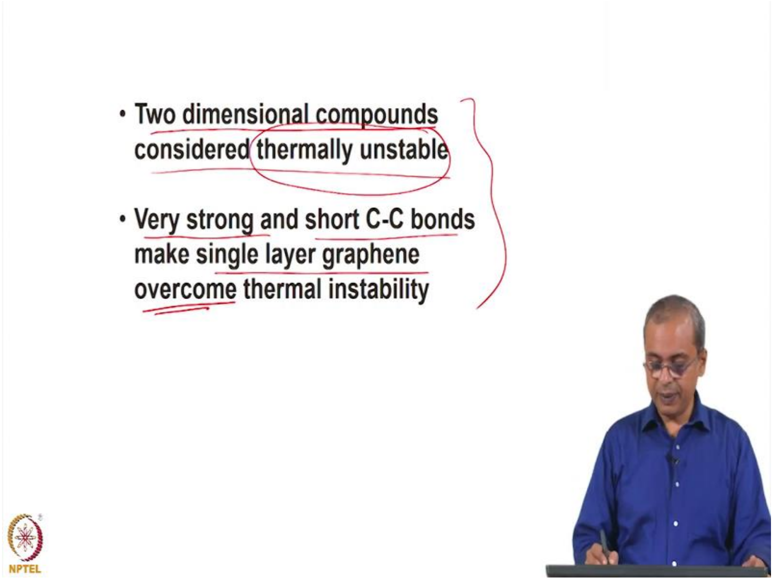

Now, the reason these 2-dimensional materials have become interesting is that theoretically for a long time it was considered that 2-dimensional compounds, purely 2-dimensional compounds would actually be very difficult to make. In fact, literally impossible to make at room temperature because they would be thermally unstable. They were considered thermally unstable and that they would react in some form or no collapse in some manner and then, therefore, you would not never actually be able to make those compounds at room temperature. You would pretty much the only way you could do this is to go predict a very close to 0 Kelvin and that is where you had the chance of making a 2-dimensional material.

So, for a long time, this was considered to be the case. And so, while lot of experiments associated with 2-dimensional materials were attempted and people tried making those things at some level there was no great surprise that they were not I mean it was not as successful or that there were a lot of constraints in enabling that experiment to happen etcetera. So, this is the way in which it was all looked at.

And so, even 2-dimensional materials would largely be something that would be held together by some two other three-dimensional materials. So, some such thing would be done or you would have a substrate which would hold it with things like that we are done. So, this is how two-dimension work was and surprisingly people found that they could make graphene which we are going to see the structure of it, but it is essentially a

2-dimensional version of carbon, of carbon atoms arrayed in a 2-dimensional. And, this was actually when they first stumbled upon it or they made it there was considerable sense of you know, I mean difficulty to understand how they managed to pull it off because the theoretical expectation was that it was perhaps not possible.

So, what has since happened is that people have understood that the very strong and short carbon-carbon bonds that exist in graphene is what is fundamentally responsible for enabling people to make a single-layer graphene. And because of this short bond and strong bond that exists, which I mean they are interrelated because it is strong it is a very short bond because they that exists that is able to overcome the thermal instability present in the system. So, that is a very important combination of things that have come together in the case of graphene that has enabled this to happen.

So, therefore, this has happened and as a result of this even though there was theoretically there was the feeling was that it is not possible, they saw it happen and they were able to interpret it as a result of this short carbon-carbon bonds.

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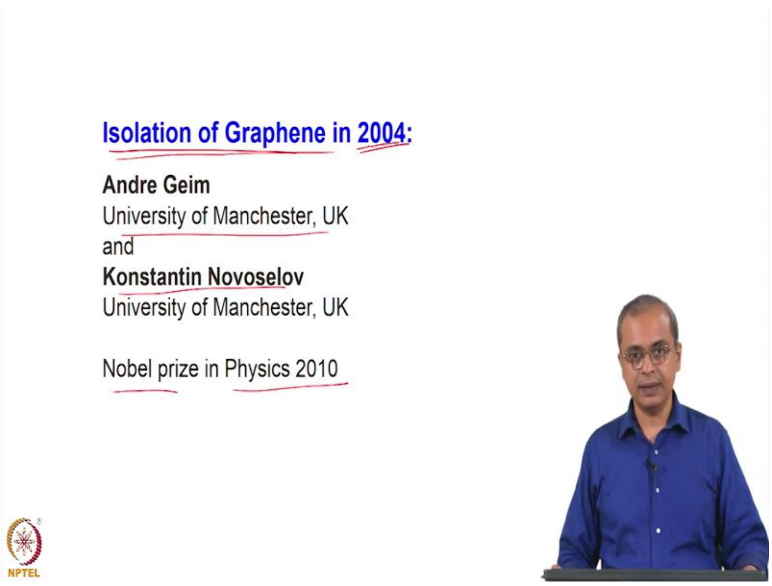

So, the people have like I said if you look at the literature a lot of people, have tried have said theoretical things about grapheme, have tried to tried various efforts to actually synthesize it etcetera, but really the work took off with the isolation of graphene as single layer in 2004. So, in 2004 this was done at the University of Manchester in the United Kingdom. So, Andre Geim and Konstantin Novoselov where the people who were credited for having pulled this off for the very first time and for that they receive the Nobel Prize in Physics in 2010.

So, that tells you how important this is. I mean that tells you how important discovery this was to show that you can actually do this. It was not a small thing. And it also tells you how important material sciences is. In material science you mean you have a Nobel Prize in physics, but it is essentially a material science activity that you have a material and you have found a new form of it or you have found a way to isolate a section of the material.

Just to do that to isolate a section of the material you end up getting a Nobel Prize. Because it is that important because that opens up all sorts of possibilities with respect to those materials because that was not possible before. So, that is the importance of it. That is the importance of material sciences, the importance of the contribution of these two people in the area of material science.

So, in 2004 they isolated it. We will see how; we will see briefly how they did it there were some interesting ways things that they tried and which is how it ended up happening. We will see that briefly as we look at the synthesis of graphene.

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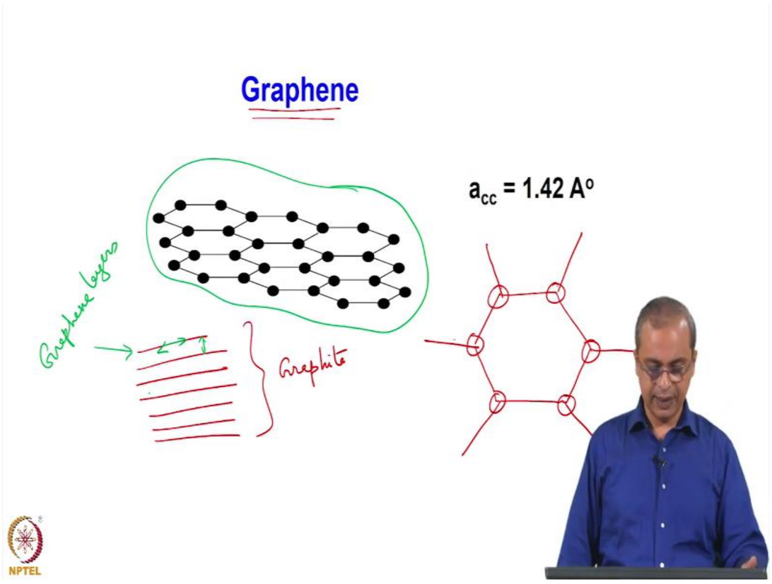

So, if you see graphene actually structurally is this hexagonally bonded the carbon atoms, so you have this hexagon. So, at each corner, you have the carbon atom. So, this is the hexagon and then from there you build more hexagons all around. This is how you build the graphene structure. So, graphite is full of these sheets, graphite is full of graphene sheets. A single layer of carbon atoms bonded in this manner is graphene and then you stack them up that is what is graphite.

The reality is, that even though I describe it that way the reality is that the opposite is how we end up seeing this material what we get in nature is graphite. So, it is already stacked up, it is already a full stack of these layers, so you have all these layers stacked up. And so, this is how we get it in nature as graphite. So, this is already available. And these individual layers are graphene. So, you stack the graphene layers and then you get graphite or graphite consists of a stack of graphene layer. So, in nature that is the way it is come.

So, now, in that layer this is what you see here, what you see up here is what you would see of that layer. Like I said graphite has been (Refer Time: 11:22) for a long time and we know its properties and so on. There has always been interest to see if they can isolate a layer of graphene. It is very interesting because between the layers the bonding is weak, this bonding is weak, but in the layer the bonding is very strong.

So, there is some possibility always existed that you could sort of peel off that layer and you can get it as a separate layer in some form, either peel it off or grow it in that single-layer form and then you should be able to see this graphene. And so, a lot of work was you know, there is lot of theoretical interest in made people calculated many things associated with it and so on.

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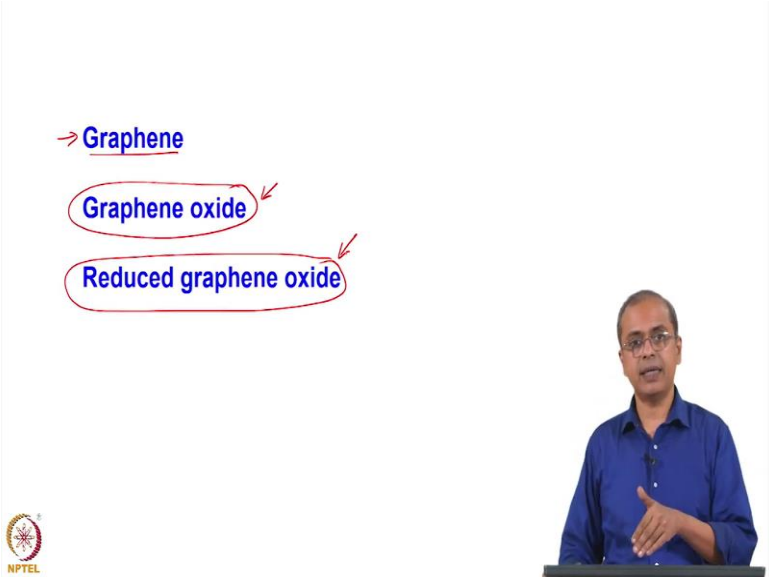

So, now graphene itself if you look at literature, you look at suppliers who are trying to send you cell graphene as a product that you can work with and so on, you will find 3 terms that are regularly there which we run into. The first is this term graphene, which is what I just described as the single layer of hexagonally bonded carbon atoms. So, graphene itself is a sort of a product or something that we can work with, a material that we can work with. But you will also often find in the literature two other terms that are used; one is called graphene oxide and the other is called reduced graphene oxide.

So, in graphene literature, you will find these two you. In fact, many quite often you will find that these two are you will be running into these two terms much more than you are running into just plain graphene as the material. And so, it is of interest to see how they relate to each other and why should we even be bothered about graphene oxide and reduced graphene oxide.

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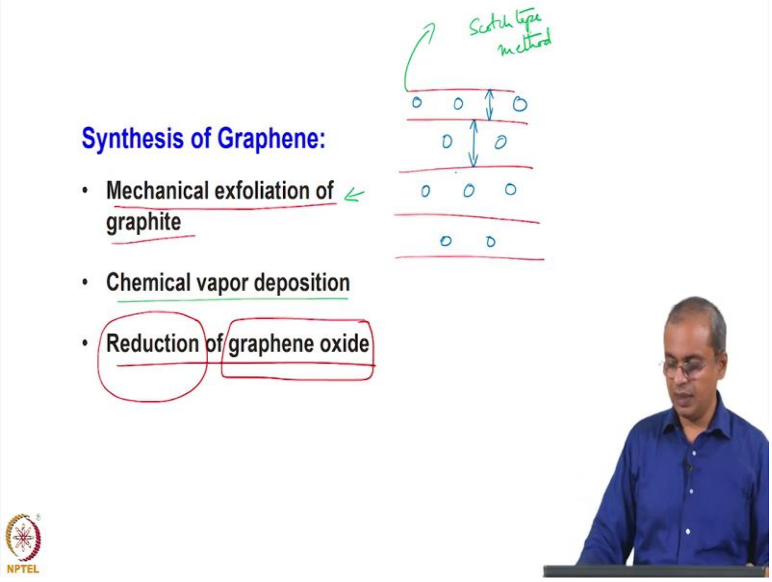

So, for that, we need to go back to how the synthesis of graphene is done. So, from there we have to see. So, there are broadly 3 major ways in which we can synthesize graphing and they are listed here. So, the first way is this thing called mechanical exfoliation of graphite, mechanical exfoliation of graphite. Exfoliation means removing something layer by layer. So, taking layers and taking them apart as layers is called exfoliation. Mechanical exfoliation means you are actually doing this using mechanical means.

So, what is that? So, you basically have these layers of graphene, you want to use some mechanical process by which you are able to sort of peel off this layer, you have to peel off that top layer. So, that if you do is mechanical exfoliation. So, now, if you look at what the Nobel Prize-winning scientists did with respect to graphite which is how they discovered that they could make this separate layer stable, is that they actually did this mechanical of exfoliation.

So, in fact, they came up with a method which is often described as the scotch tape method and that has got to do with the particular tape that particular brand of tape that they use they are quite regularly called as scotch tape. But essentially you take graphite and then you put the tape when you peel it off you put a tape peel it off and you can keep repeating this and seeing what you have pulled peeled off on the tape and you continue this process. And so, they did that several times and then they found and when they kept on doing this again and again and again, suddenly they were seeing separate layers of graphene coming off with the tape.

So, this was actually every is if you look back at it looks like a very simple way in which they managed to pull it off, but that is indeed what it was they managed to put it pull off something phenomenal, they managed to pull off peel of a single layer of a material and then to use more advanced techniques to prove that in fact, they had pulled off a single layer.

So, is pulling it off is one thing and then to prove that they have actually pulled off a single layer was is a more involved thing. But they managed to show that they could actually use this method pull off a single layer and that it was stable layer and so on and that is how they were able to prove this I mean synthesis of graphene was demonstrated. And for this, they got the Nobel Prize.

And so, this is still a technique that you can use for creating single-layer graphene, but it represents a certain little lack of enough control in how the product shows up. So, they have looked at other ways of you know, people have looked at other ways of creating graphene chemical vapour deposition is one form where you essentially have high carbon-containing gases condense on some surface and then based on how the substrate is and what conditions you have you may end up creating graphene. But the technique that is often actually used is this one which is called reduction of graphene oxide.

So, to do this basically what they are doing is they are taking graphite because that is the material that is easier for us to obtain. So, graphite is taken and then you subject it to very strong oxidizing conditions. So, it is subjected to seeing highly acidic environment, highly oxidizing environment etcetera and in this process, the layers of graphite simply separate out and they separate out. And so, it is in some liquid medium, so they all separate out in that liquid they are all just floating around as the separate layers. But this has happened because this oxidation processes gotten through to this layered structure. And that is how this thing all the layers have separated out.

Now, you can take individual layers out and at that point, those are oxidized layers, so they are actually this graphene oxide. So, by doing the oxidation you end up getting this graphene oxide which has a significant amount of oxygen-containing species. And then, but that is not what you want, you want grapheme, you want pristine graphene without other species attached to it, and so, you have to reduce it. So, you subject it to some reducing conditions and the various ways to subject it to reducing conditions and so, you get this reduction of graphene oxide, reduced graphene oxide that is what basically it is. So, you remove some amount of those oxygen-containing compounds and then you get this reduced graphene oxide.

So, in terms of a larger-scale synthesis, this seems to be the method that most people use which is this using of this reduced graphene oxide, takes starting from graphene oxide. The only issue with that is that it seems like an easier way for us to get the handle of that material and therefore, use it.

But the issue with that is that you are never able to completely eliminate all the oxygen-containing compounds from that graphene, from the graphene oxide. So, you are left with some residual oxygen presence in that layer and given that you are already working with essentially a 2-dimensional layer, even a few atoms on it is a significant number of atoms overall.

And therefore, the properties the theoretical properties that people often predict for graphene you may not get the best of those properties, I mean or the property to that complete degree that you may expect when you take a single layer of this graphene oxide which has then been reduced. So, a reduced graphene oxide usually comes close to graphene, but is usually not the best way in which you can know present the graphene and therefore, any theoretical expectation we will get water down a little bit, so because of this presence of oxygen compounds.

So, this is the basic idea of how graphene is synthesized. And I mean since that we are at the talk you should talking about this topic you should understand that this layered structure of graphene is what has enabled many of these things to happen. It is very interesting kind of compound because of this weak bonding between the layers with while they are strong bonding within the layer. So, in fact, when you look at lithium-ion batteries many times, they have carbon-containing compounds present as the anode material instead of just the plain lithium itself because lithium can go and sit here, lithium atoms can go and sit here and then you can get. So, these are called intercalation compounds; intercalation compounds.

And this process of something entering inside the layers of graphene, sorry layers of graphite a process of entering into layers of graphite is called interrelation. This process of entering into the layers of the, however, it is called intercalation. And so, graphite-based intercalation compounds carbon-based intercalation compounds have been extensively studied and used even in fact, quite extensively even used. So, this process is always been there that things could penetrate into the carbon structure. Now, we are considering a process by which we are doing this oxidation penetrating the structure and opening it up completely, so that is an idea here.

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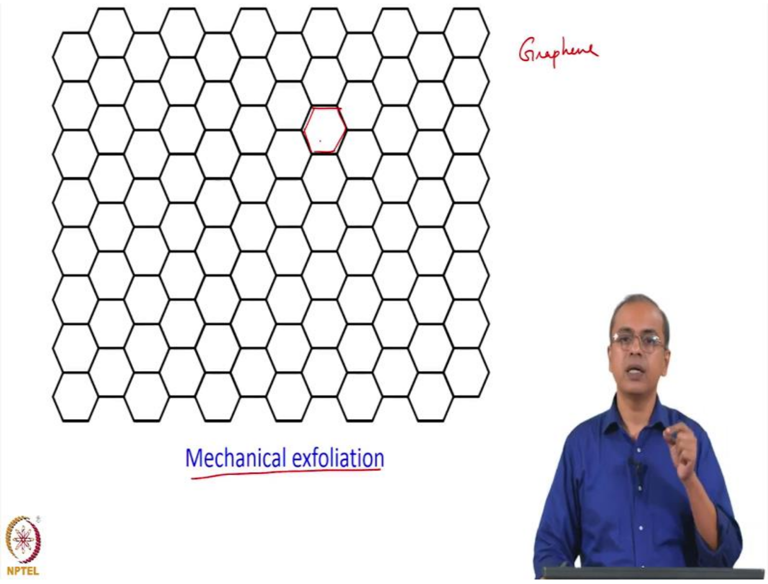

So, what you see here is a graphene layer. So, what you see here is a typical graphene layer. So, technically if you were to do this mechanical exfoliation, mechanical removal of layers of graphene then this is the kind of layer you should get. You can see that you only have hexagonally bonded carbon atoms, to the extent that your original graphite was defect-free, you can get if especially if you start with this highly oriented pyrolytic graphite kind of thing. You have a very good quality graphite very large crystals of graphite and then from that if you peel off layers you should get something like this. You should only see hexagonally bonded the carbon atoms which is what you see here all hexagonally bonded carbon atoms through and through and through and nothing else.

And you should have this material, once you do the analysis of the material it should the data should show that this is all you have, that this is basically what do you have. And typically, mechanical exfoliation enables you to do that because you have not introduced any other chemical species into the graphene into the graphite structure itself, and as long as your graphite structure originally was pure and clean your graphene that you obtained will also be pure and clean.

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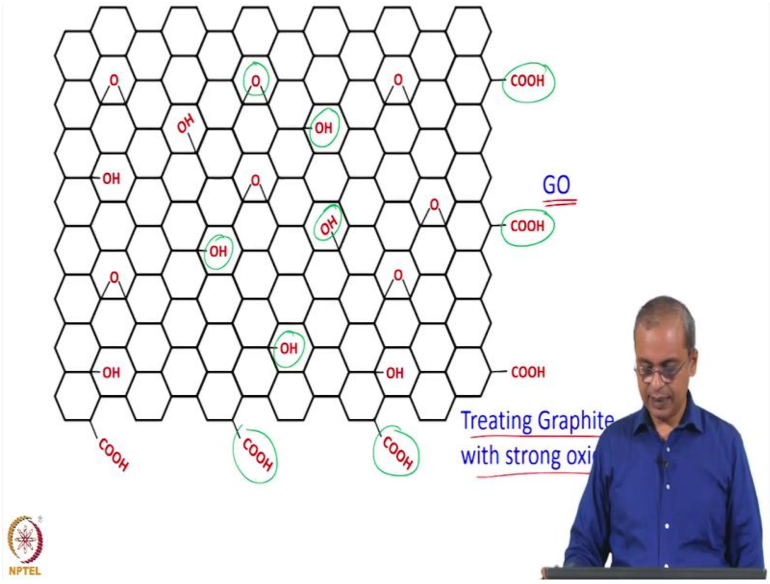

Now, if you take graphite and you treat it with strong oxidizing agents which is what I have indicated here then the sheet that you get is different. It as you can see it is different from what you have here. Here you have only the carbon atoms bonded to each other, but you can see here you have a lot of other groups, you have an OH group here, you have an OH group here, you have oxygen itself bonded to this structure, many at the edges you often see the COOH group.

So, lot of such groups attached here. And so, this is what you have. You have lot of oxygen-containing groups which have now attached themselves to the graphene structure, because of the way in which you have done the oxidation process. And so, this is what you will get by treating graphite with strong oxidizing agents and so, this is called graphene oxide. So, graphene oxide is what we end up having here.

So, and so, this is actually given this short form GO. So, when you see literature if you see this term GO this is what they mean graphene oxide is what they are referring to. So, like I said this amount of oxygen presents you can see here I mean this is of course just a schematic, what I am showing you on screen is just a schematic, but it represents this idea that you will have lot of these oxygen-containing compounds on either side perhaps of the graphene layer and that is what you have.

So, now given that it is a 2-dimensional structure and you are trying to make measurements of properties of it, all these other groups which are hanging out from this structure are going to impact that property because they form a significant fraction of that material that you are testing. So, therefore, we have to take this graphene oxide and reduce it. So, we get this reduced graphene oxide sample which is essentially graphene oxide with fair bit of these oxygen-containing compounds removed. So, this is reduced graphene oxide.

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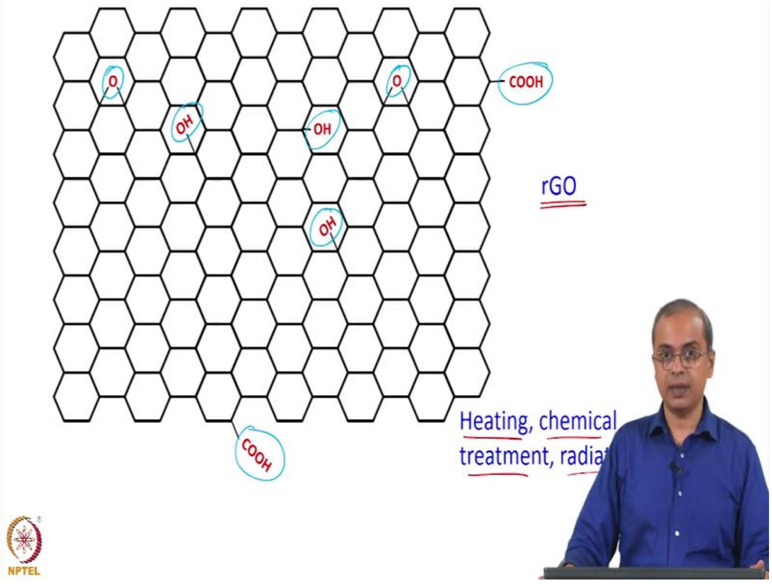

So, you can see the number of groups here has decreased. You do still have some groups here. Again, I mean this is only a schematic, so I mean it is not that exactly it comes down from that number to the number that you see here, but this just to show you that we have a few groups sitting here, you have a lot more group sitting here. You have several of these entities sitting in this graphene oxide you do the reduction and suddenly there is a decrease in the number of such compounds. And so, this is referred to as reduced graphene oxide rGO. So, again, so GO and rGO are two terms that you will keep seeing GO you will see in literature quite a bit of mention of GO and quite a bit of mention of rGO.

And this reduced graphene oxide like as I said has a significantly lower number of these oxygen-containing compounds. And so, this product actually behaves much closer to graphene much closer to graphene in terms of what you can expect from it and therefore, for certain types of industrial applications where they want to make graphene or something that is very close to graphene will suffice for them or at least at the moment surfaces for them this is the method that they prefer that they can actually get this reduced graphene oxide, and then use it for some application. They are using it for coating or they using it for some other application then this is the way they would, they are more likely to do.

And now this reduction process itself you can do by heating, you can also do it by chemical treatment, you can also do it by radiation. So, various different options you have here for treating your graphene oxide to arrive at this reduced graphene oxide and that is really useful for us. So, these are the ways in which we synthesized graphene.

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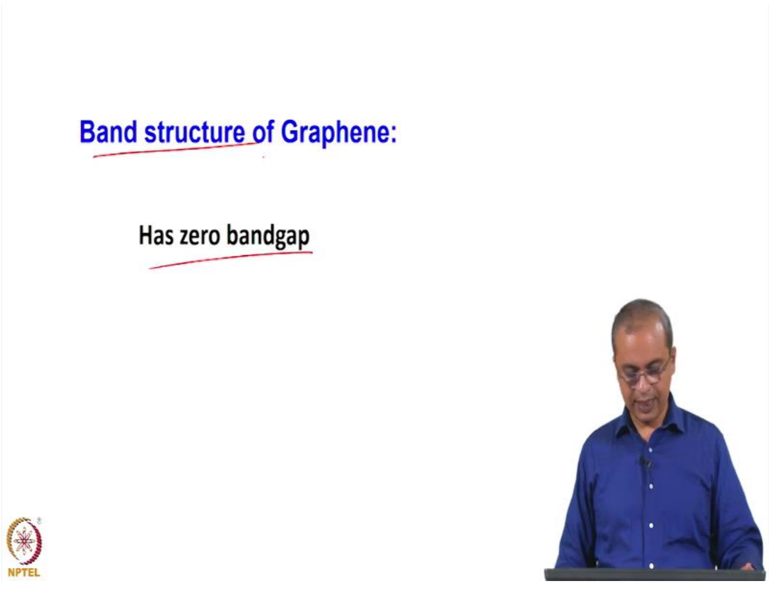

So, now let us look at some properties of graphene and some interesting aspects associated with graphene. So, if you look at the band structure of graphene you find that it has a zero-band gap. So, the band structure is a zero-band gap. So, which means the conduction band and the valence band just about touch each other. So, just about touch each other and for all practical purposes the band gap is zero. So, in k space in momentum space you have to see exactly where you are look at the Brillouin zone and see which locations this contact is happening, but regardless this is what is happening. So, if you look at bandgap it is a zero-band gap material.

This naturally impacts many properties of the material in terms of how it interacts with respect to say light how it interacts with respect to say any other radiation that is incident on it and in terms of electronic applications if you want to use it for some electronic application, how will it behave, all those things depend on the bandgap. And so, having a zero-band gap provides that that kind of a situation for that material that you can actually do something with it.

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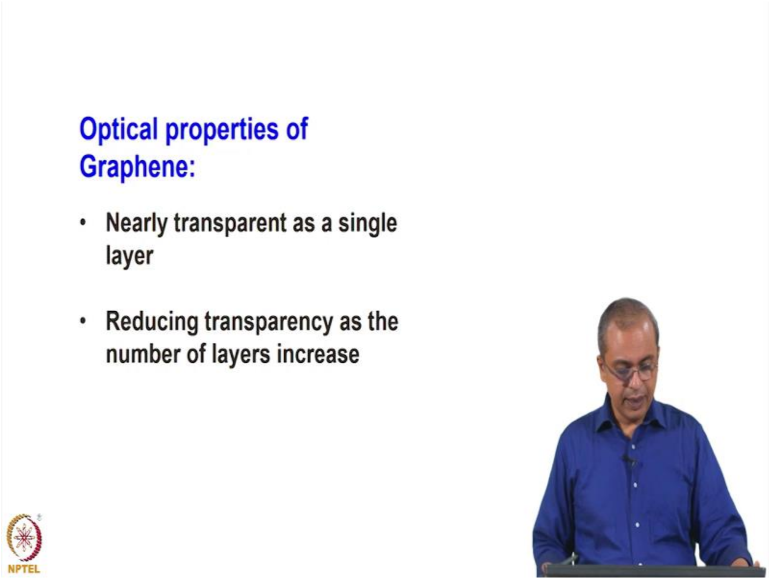

In terms of optical properties, the interesting thing is if you actually separate out a single layer of a graphene it is nearly transparent as a single layer. So, it is theoretically they estimate that you are looking at about 2 to 3% absorption through a single layer, but you have to understand that it is a single layer. So, it means that even if you put like 10-20 layers the absorption starts climbing up that is why as you move towards from graphene as you move towards graphite you are actually going from you are getting into something that is like completely opaque. So, as a single layer it is transparent and as I mentioned here the transparency reduces as the number of layers increase. So, that is point here.

But as a single layer, it is transparent, so to the extent that you can use it as a single layer you find many optoelectronic applications where light has to go through perhaps to some other layer. You can put this as a layer on top, you can now still let the light go through and you can still continue to get some properties out of the graphene in a way that is still acceptable to you for that application. So, that is nice to know.

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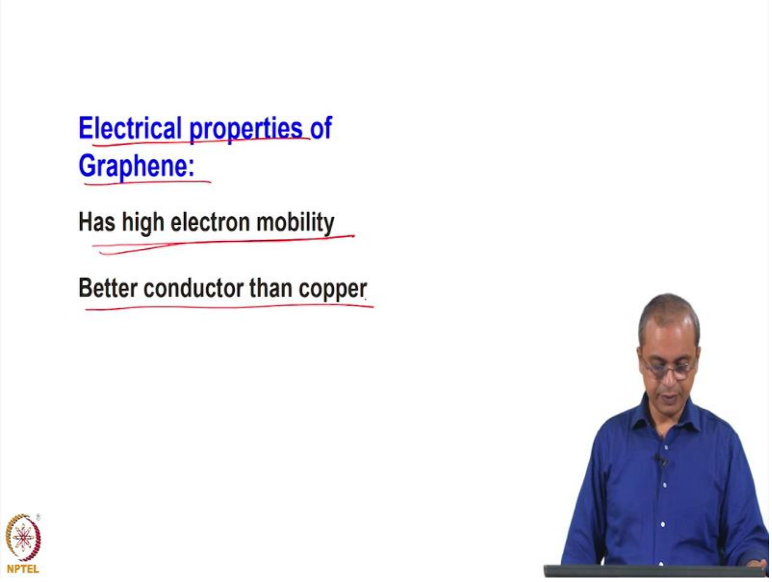

In terms of electrical properties, again because of the bandgap, band structure that it has very high electron mobility, very high electron mobility and therefore, the estimates are there. If you look at the literature this variation on the numbers and that is always to be expected when you are looking at a new material which is relatively more recent and because also because there is variation in the quality of the material. As I said, some people work with the graphene coming out of mechanical exfoliation which is cleaner, but has some other constraints are many other people have working with reduced graphene oxide which has this other constraint of some oxygen-containing groups.

So, given this variation in your starting material even though in principle it is more or less the same material there is some variation there, naturally some variation in the results also that you are obtaining, but generally the expectation is that it is a better conductor of electricity than copper. So, that is always a big plus I mean, so you have a material a solid material that is conducting better than copper. So, many applications become suddenly feasible. It is a single layer and it is doing something better than copper.

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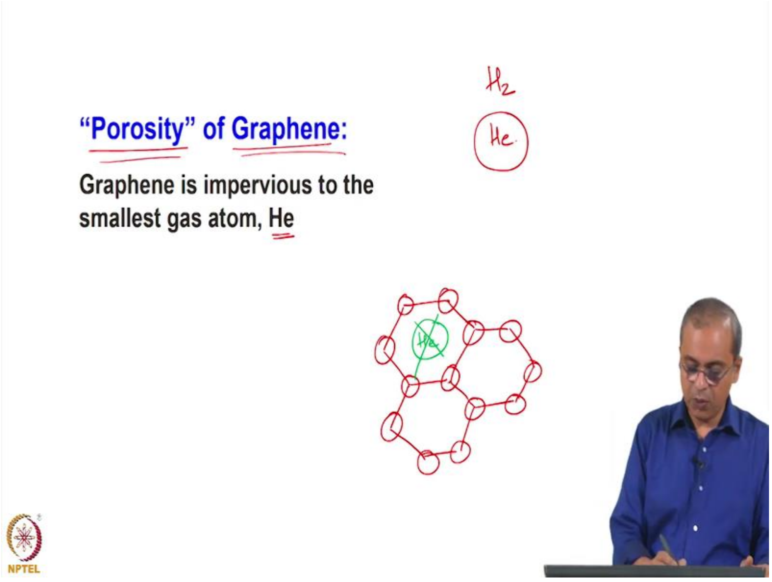

The other interesting thing is about the porosity of graphene. So, it turns out that graphene. So, if you look at the structure, so you have these hexagons. So, let me just draw a few of them, so that we can see what we are dealing with here. At least 3 of them let us see. So, now, if you allow gas to pass through this. So, you already have atoms here, you have atoms sitting here and now gas has to pass through this.

So, people have looked at this just to understand what it is that you have accomplished here because it is a thin layer its essentially one layer of atoms. So, you want to see what goes through. It turns out that even the smallest gas atom helium it is not hydrogen because hydrogen is H_2 and this is helium, this is a single atom that is two atoms and of course, it is if it is two atoms due to bonding there will be some reduction in size etcetera of those atoms, the way the structure is.

But all said and done this turns out to be the smaller of the lot if again if you go on the periodic table that is how it works out. And so, it is of interest to see what are the materials which are say allowing helium to go through; which are the materials that hold helium inside, etcetera and it turns out that this graphene material is impervious to helium. So, helium cannot go through this material.

So, helium cannot go through, it does not go through this graphene layer. This is very interesting because I mean it clearly it has technological implications and applications. If you make a helium-based balloon which is safer than having hydrogen-based, but on then that you will not lose the helium and helium is not a, it is not something that we that is easy to find. So, you cannot just assume that you can waste helium.

So, it is necessary that you utilize it as well as you can and therefore if you have a balloon which is based on helium you can use this layer and it will you will not have any leak of helium. And similarly, even I know cylinders which are holding helium etcetera can have this layer whereas, other materials it may be able to find its way through the structure here it will not be able to do so. So, it is impervious to the smallest of gas atoms which is helium. So, that is a very interesting property, again unique to graphite, graphene.

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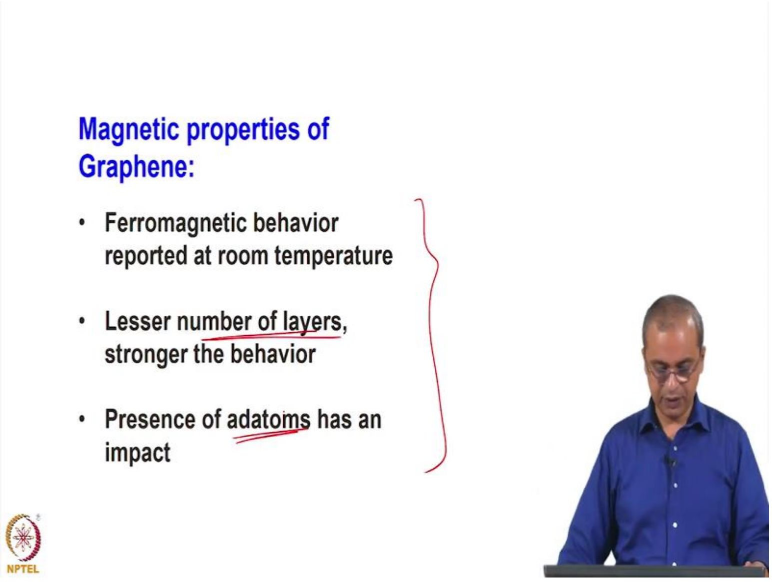

Magnetic properties of graphene. Actually, if you look at the literature you find that again based on the quality of the material that you have and that is got to do with any ad atom that is present there, any other features that are present there.

Generally, the literature indicates that it shows you ferromagnetic behaviour at room temperature and that this behaviour is a little stronger and more pronounced if the number of layers is less. If they you lower the number of layers then you see this behaviour in a much more prominent manner. And as I mentioned adatoms are atoms, I mean a presence of adatoms has an impact.

And adatoms are simply atoms that are absorbing to the surface. So, this is a single layer, so something fixes on to the surface, it's they will also essentially be a single set of atoms which fix onto the surface of this graphene and their presence makes a difference to the magnetic behaviour of the sheet as a whole. So, therefore, this seems to make a difference.

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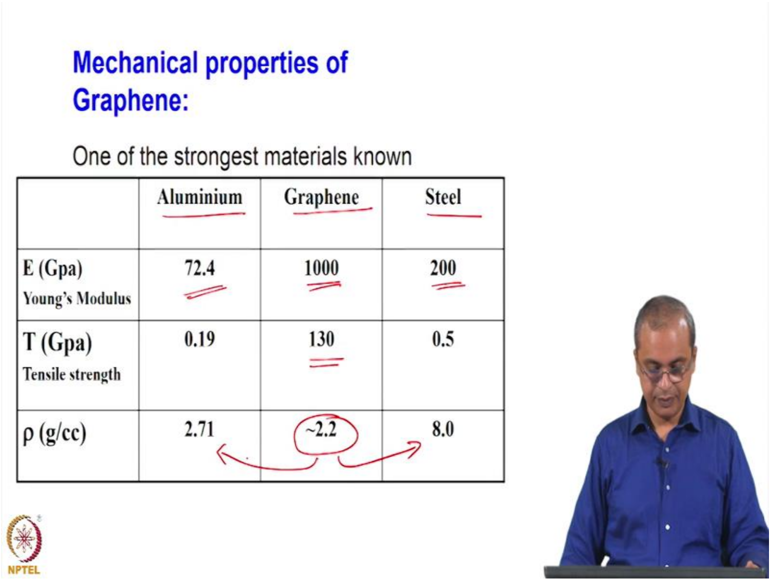

Mechanical properties of graphene. This is very interesting from technological application perspective. So, just for comparison I have put 3 materials down here, aluminium, graphene and steel. So, if you take Young's modulus of elasticity, so how elastic the material is you find that graphene is an order of magnitude better than steel. So, stiffness wise, it is an order of magnitude better than steel, of course, it is distinctly better than aluminium.

So, as a solid material that is a very strong material, it is something that is stiff very stiff material. It is not going to be easily in a relative sense, it is going to be a very strong material for you to work with. So, it is not going to elastically deformed that easily, you have to put a lot of stress to make it deform.

It is tensile strength is also quite high. You are looking again at say two to three orders of magnitude better than that of steel or aluminium and of course, it is very light. So, you are looking at essentially the same kind of density as any other carbon material, most carbon materials are around 2 grams per cc, to little over 2 grams per cc. So, the estimates are and that is that it is about 2.2 grams per cc and grams per centimeter cube. And so, this is definitely less than what you see here, for steel it is also sort of less than what you see here for aluminium.

So, you are not only getting such high strength and modulus of elasticity you are getting it at extremely low density and that is like an amazing thing to have for any structural application. If you look at how aeroplanes have evolved, for example, that is the direction in which they have always been evolving. That is why even in older times the aeroplanes were not necessarily being made out of steel the minute people got to got a sense of all this and they knew how to handle materials and how to characterize those materials they prefer an aluminium to steel. So, the previous immediate preceding generation of planes, aeroplanes that existed were all made of aluminium because the specific strength was so high of aluminium relative to that of steel. So, that is strength per unit mass.

Now, if you take graphene-based. So, now, they have started moving from aluminium towards composites and those composites can be made amazingly strong if you put graphene as one of the layers in that composite. And so, by doing so, you will actually have vastly stronger material which is also very light. And so, the specific strain goes up even more significantly and naturally this means your plane can be bigger, it can carry a larger load and its own self-weight will be very less.

So, ultimately, when you move an aircraft it has got its own self weight and it has got the weight of its passengers and cargo and what not and it should have the strength to hold all of that together without breaking the wings for example, should take the full load of so many hundreds of tons and it should be able to not break. So, all that has to be done using some very strong material. So, this kind of a material is very important.

So, in fact, people even describe how strong this is by using an example that you can sort of support, if you take an animal of some weight you can support it using a graphene sheet which is so thin that the weight of the sheet holding that animal up is less than the weight of the hair of that of a single strand of hair of that animal. So, you will take a single strand of hair of that animal, you weigh it and the sheet that you will use will have weight equal to that or less than that and it will hold the whole animal up that is the amount of strength it has.

So, that very starkly shows you how a single layer of a material which is, single layer would be difficult for us to see, in fact, our eye will not even be able to see it that single layer would be able to hold an animal up. So, it will almost look like, it is floating invisibly floating. So, that is how strong graphene is and it is and therefore, this mechanical property is a very significant aspect of this graphene.

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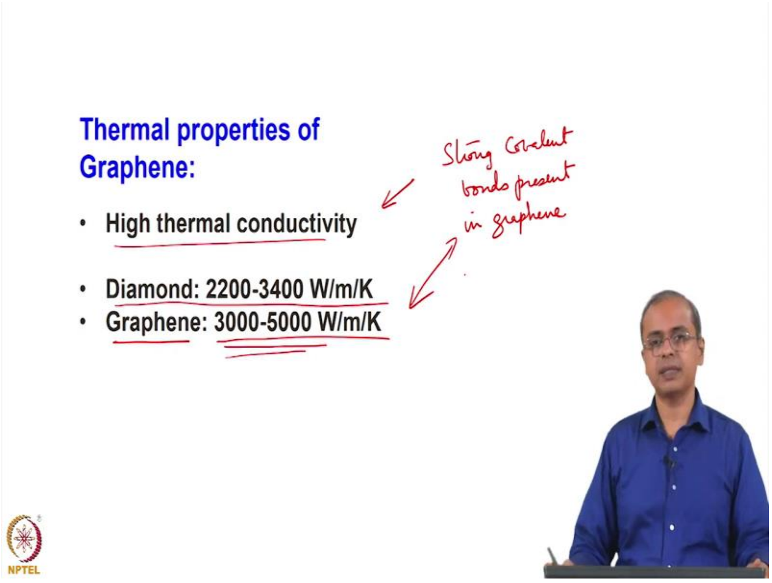

Thermal properties. So, thermal properties again very interesting property because got to do high thermal conductivity has got to do with its strong covalent bonds. So, please remember that when any time we look at a metal for example and you look at thermal conductivity or any material, you look at thermal conductivity, there are two contributions to the thermal conductivity process.

The first is due to the electrons. The electrons themselves keep moving around and essentially the higher the temperature, so if you put higher temperature on one side of the sample then the electrons which are close to that side equilibrate with that higher temperature by picking up higher energy. And then, as they float around they are essentially carrying that higher energy into that material which for us comes across as the temperature of that material is increasing as you go into that material and eventually, electrons on both sides of that sample start having this high energy because they are bouncing into each other and so on.

So, finally, the energy of electrons on this end of the sample also is high and so, you feel a high temperature and that is how the temperature got transmitted from an originally cold bar which went in contact with the hot surface on one end. Now, another way in which the same heat is transferred is due to the lattice vibrations. So, atom to atom they are connected, they are all connected by bonds, but each of the atoms is vibrating, so it is that is how they are vibrating.

And the amplitude of vibration etcetera has got to do with the energy that atom has. So, if this atom is closer to a side which has high temperature it will vibrate much more, this atom is a little away it will vibrate a little less, but because of this neighbouring atom vibrating more it will start picking up that vibration and so gradually you can sort of say that the heat has gone from this atom to the next atom and that is how the process continues and it comes to the other end.

Now, the stronger the bonds between these atoms the more quickly this movement begins to impact this movement. So, that is why a very strongly bonded covalently bonded material has very high thermal conductivity. It may not have good electronic conductivity because you may not have free electrons for electronic conductivity, but for thermal conductivity, both free electrons as well as the lattice vibrations help, for general electrical conductivity that we see at room temperature the lattice vibrations do not help.

So, if you have a material which only has good lattice vibrations, but not enough free electrons you will not have that great electronic conductivity, but you can have thermal conductivity. So, that is why diamond itself has been one such material, very high thermal conductivity, all essentially zero electronic conductive. So, it is an insulator electrically, but a very high thermal conductor.

Now, you see graphene which actually has good electronic conductivity also. Its electronic conductivity is comparable or better than that of copper and on top of it has thermal conductivity which is comparable or better than that of diamond. So, you have a material that is it is exceeding itself on a variety of friends, you are lot of different applications, you find that this is above and beyond what is the best material available for that category and that is why there is so much interest in graphene and trying to make it a product that everybody can use, very high thermal conductivity. Got to do directly with the fact that it has got exceptionally good covalent bonds in it.

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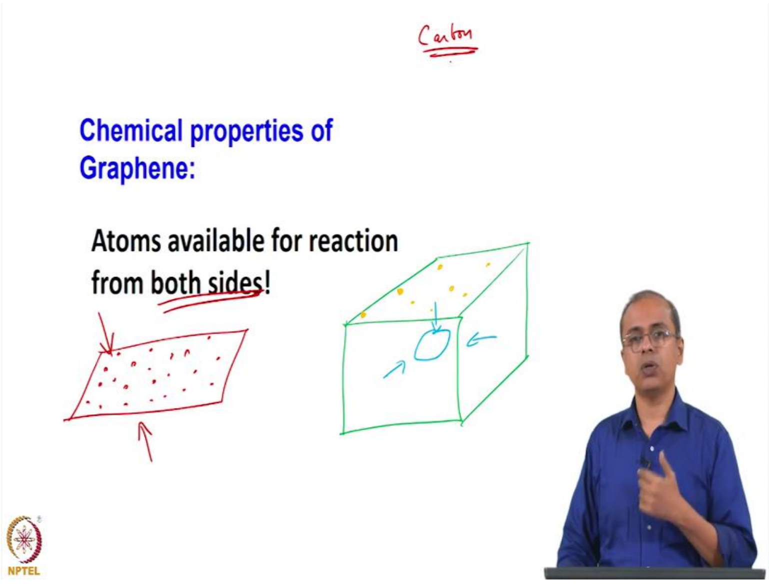

Chemical properties. This is a very interesting situation here because what we have is a layer. So, normally if you have a bulk, bulk material, what happens is again as we saw the it is the atoms at the surface that react, so whatever is the atom here, whatever is the atom here, these are the atoms that are reacting. Whereas, what is inside the bulk, so if I draw something inside a bunch of atoms which are inside this material in from all directions inside those atoms are simply not participating in the reaction for the most part. They are not participating in any reaction, only the atoms on the surface of that solid are participating in the reaction.

Now, as it becomes smaller and smaller naturally more atoms fraction of atoms participating keeps increasing. But with graphene you reach a very unique situation where every atom that is present in that graphene structure is now in a position to react. So, that is a very unique situation. You almost will never have that with any other material, you will not you are not going to find a sample in your lab which if it is not grapheme, you are not going to find any other sample that any other material that you are working with which is present in a situation where all items present in that material are ready to react or are in a position to react,.

So, they may be ready to react, but they are not in a position to react because they are sitting in the interior of the material. Here there is no interior this is a material that does not have an interior, everything is surface. So, everything is surface. Therefore, every atom that is present there is in a position to react. So, every atom on the surface is in a position to react. Not just that; not just that every atom is in a position to react, every atom is in a position to react from both sides, so it can react from the top, it can react from the bottom.

So, this is very unique. I mean you do not see you almost will not see another material which has this kind of a situation where you have some set of atoms and every atom can react and not just that every atom can react from both sides. So, this is very unique to the graphene structure and the and therefore, it impacts the properties in a very significant way in its ability to participate in reactions.

So, this is actually you can see here there is no series of properties whether we are looking at electrical property, thermal property, magnetic property, you are looking at now chemical reaction property, optical property, everything it provides you with a unique package. A unique package of what it can do? Simply, because you have this single layer. So, band structure is very different the reactivity is different, but these bonds are very strong and therefore, the strength is very high. So, all of this thing is a nice combination that exists for graphene and it is able to provide us this set of properties in a manner that is very usable.

The other very interesting thing about graphene with from the perspective of chemical reactivity is that if you take carbon in general; carbon, in general, is also a material that we associate with nature. So, it is not something that is of course, in that sense even polymers are like that, polymers are mostly carbon-containing compounds, but they are materials that do not degrade in nature and so on, so we have all those issues with them. But carbon in the form of graphite is always something that nature has been comfortable with. So, the expectation is that graphene is also something that the nature can handle very well. So, if you add that as a layer that helps give you this special property on top of this structure, then it is a very nice situation.

So, for example, even the electrical conductivity that we spoke about if you take a aircraft. So, an aircraft is out in out in the atmosphere and naturally as any of us who has travelled in an aircraft will recognize many times you are flying through rain. So, there is rain outside, there is lightning out there, we see from ground you see lightning in the sky, in the plane you are in that area you are in the thunderstorm area, of course, planes try to avoid it, but nothing prevents lightning from striking an aircraft. So, an aircraft can be hit.

In olden days the aircraft were metallic aircraft. So, you had aluminium essentially. So, that distributes that acts as a safety cage for the people inside. So, lightning hits it will just get the charge gets distributed and discharged. And so, when it touches the ground or some other place I mean as it is flying it can get discharged away from that material. It does not locally concentrate the charge. So, the charge builds up does not happen locally.

Generally, if you take a polymer the opposite is true because the conductivity of the polymer is poor, electrical conductivity is poor, if you strike you send a beam of electrons on the polymer, it is not charging, it will start charging. And charging is not simply a I mean it is not just a concept on its own it means that you are building up some energy in that area, you can possibly overheat that location, you can cause some other spark to happen there, you can damage some electronic equipment which is below that location simply because there is just excessive charge built up in that one area. So, all these problems can happen if the system is not conducting electrons very well.

So, we went from an aircraft which was made of aluminium to an aircraft which was made of composite materials primarily to reduce the weight and that is a significant help and therefore, we have gone in that direction. But when the aircraft is flying, we also need to safeguard the aircraft and the passengers from lightning strikes, which means you have to take care of conductivity. Now, if you go back to putting metals you are again raising the weight.

But now you see that you have this material called graphene which you can easily incorporate into any composite material because it is also a carbon-based material and suddenly you have the surface layer of conductivity. So, having this layer ability for you to know put this layer on top of something significantly helps you deal with a wide range of things that may not have otherwise been possible. So, therefore, this is a very interesting material.

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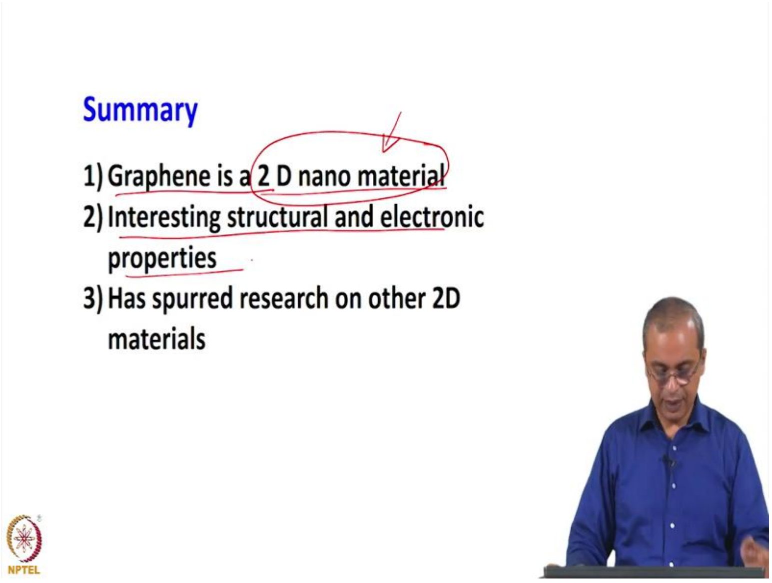

So, in summary, I would like to say that graphene is a 2-dimensional nanomaterial. So, it is actually been very, as we saw earlier in the class it is been actually very eye-opening for the scientists that you can actually create this kind of a 2-dimensional material independently and utilize it in various ways.

So, not only is it a very interesting 2-dimensional material by itself what we saw in the class lot of new properties it has and lot of new things that you can do with it, but it has also opened up the field of 2-dimensional nanomaterials which is an even bigger concept as a whole.

So, people are now much more actively searching other combinations of 2-dimensional materials which may give them properties that they have not seen in the three-dimensional version of the same material. So, like I always said through this course that is the beauty of nanomaterials as a whole that you are actually getting some totally new property out of a material which you would otherwise not get of the same material if it were in bulk scale. So, that is the beauty of it. And so, to the extent that graphene has been successful in existing as a 2-dimensional material, getting used as a 2-dimensional material and so on, it has spurred interest great amount of interest in 2-dimensional materials as a whole and a lot of people are working on this.

It has very interesting structural properties and electronic properties, because of the band structure that it has and the strong bonds it has all the properties the thermal, magnetic, etcetera, all of them are very different from what you see in graphite by itself, in metallic systems by themselves. And not just different it has been very special because it has set like a new level of capability in the materials. And like I said just said it is spurred research in other 2-dimensional materials and that has been a very significant contribution from the work on graphene, and so that has expanded the scope of material science research.

So, that is our class for today. We will halt here. We will pick up some other topics in the next class.

Thank you.