Carbon Materials and Manufacturing
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Lecture – 43
Graphene: Introduction and Crystal Structure

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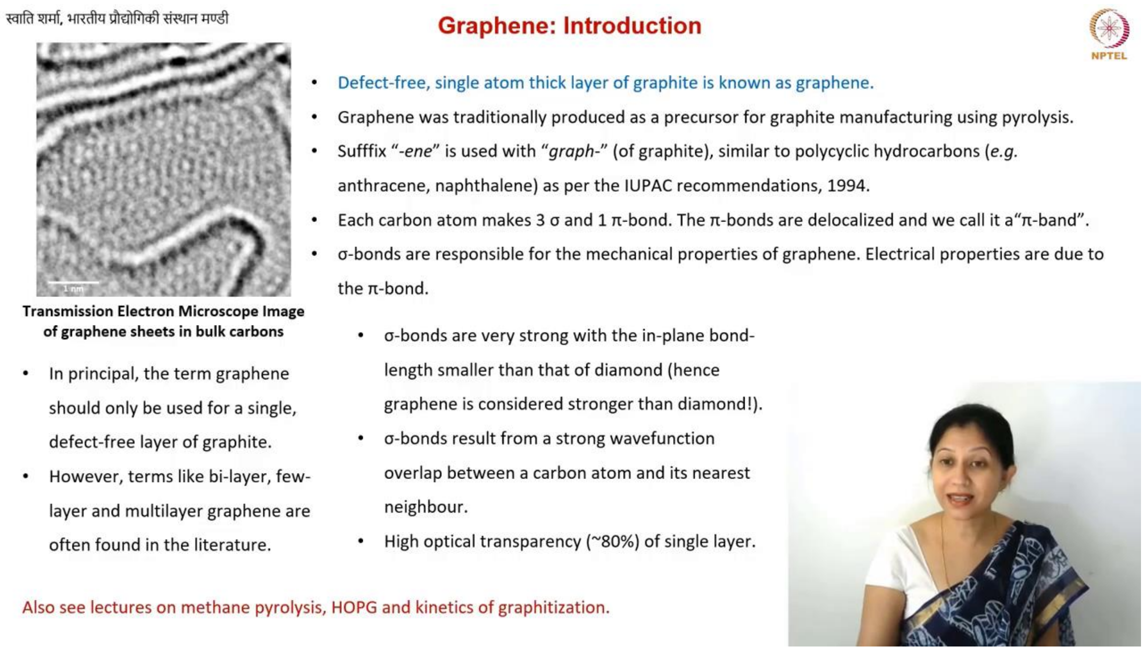
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Graphene: Introduction

- Defect-free, single atom thick layer of graphite is known as graphene.
- Graphene was traditionally produced as a precursor for graphite manufacturing using pyrolysis.
- Sufffix "*-ene*" is used with "*graph-*" (of graphite), similar to polycyclic hydrocarbons (*e.g.* anthracene, naphthalene) as per the IUPAC recommendations, 1994.
- Each carbon atom makes 3 σ and 1 π-bond. The π-bonds are delocalized and we call it a"π-band".
- σ-bonds are responsible for the mechanical properties of graphene. Electrical properties are due to the π-bond.

Transmission Electron Microscope Image of graphene sheets in bulk carbons

- In principal, the term graphene should only be used for a single, defect-free layer of graphite.
- However, terms like bi-layer, few-layer and multilayer graphene are often found in the literature.

- σ-bonds are very strong with the in-plane bond-length smaller than that of diamond (hence graphene is considered stronger than diamond!).
- σ-bonds result from a strong wavefunction overlap between a carbon atom and its nearest neighbour.
- High optical transparency (~80%) of single layer.

Also see lectures on methane pyrolysis, HOPG and kinetics of graphitization.

Hello everyone.in this lecture, we are going to discuss Graphene. What is graphene? By definition, this is the single layer of graphite that is defect-free. So, it must be defect-free and it must be one single layer only, then you call it graphene by definition. However, you will hear the terms like bilayer graphene and multilayer graphene, and also even defect containing graphene.

So, we are going to discuss all of these things, and we are going to discuss why is this confusion and what is graphene as such. This is one transmission electron microscope, I purposely showed you this picture because this is not of single layer graphene separately prepared, this is a picture of bulk industrial carbon.

And even in bulk industrial carbons, you will often find these kinds of structures, graphene-like structures or graphenes. Because graphene is indeed the building block of all the carbon materials except diamond-like materials. So, anything that has sp^2 or even

sp^{2+n} type hybridization is somehow related to graphene, because it contains these hexagonal structures. So, this is a picture where you can see graphene-like sheets and this is from glass-like carbon.

For us graphene has been a material that was used for preparing graphite right. If you have learnt, if you have gone through the previous lectures in this course, you know that when we make highly oriented pyrolytic graphite, we first pyrolyze a hydrocarbon then we get pyrolytic graphite. Why pyrolytic graphite?

Because these are graphite-like sheets. These are flat sheets rather than curved carbon structures. So, they have some waviness, but still, there is a possibility that they can be converted into graphite and that is why we use the terms like pyrolytic graphite or pyrographite.

Also, often pyrocarbon is also a term that is used, but the idea is that these are flat structures. Now, we anneal them at very high temperatures or we perform hot pressing. So, we can convert it into pyrolytic graphite and then followed by highly oriented pyrolytic graphite at higher temperatures. This is what we have learned, this is an industrial process that has been used for several decades now.

Now, what happened in the last couple of decades, people realize that this raw material does not really need to be converted into graphite. We can also use individual flakes because these individual flakes indeed offer very interesting properties. Why? Because of everything about this pi-electron that we have. We have this unhybridized p-orbital in our sp2 carbons, and the electron in that unhybridized orbital is indeed responsible for all the interesting properties.

When we have 3D structure AB AB type structure or even turbostratic structure, the influence of that pi-electron is a bit lost. But in the case of a single layer, the effect is very dominant.in that case, why not just use this individual flake for certain electronic applications because the electronic properties are also very interesting mechanical properties.

So, this is how this graphene was developed. We used it in the past for making graphite. Now, you would say that maybe the term graphene is new, in the past it was called single-layer graphite, but now it is called graphene. Well, this terminology was also suggested by IUPAC in 1994. So, it is not very new.

So, *ene* is the suffix that we use with a lot of carbon materials, a lot of hydrocarbons, for example, annulenes and naphthalene. And *graph* comes from graphite. So, we started using this term graphene. However, in the early 21st century we started using this term more extensively and more commonly. But the term can be found can be found in the literature also after 95.

What do we have here? You know that you have sigma bonds and pi bonds, this is something we already discussed, so I would in fact recommend that you also go through the crystal structure of graphite – the lecture on Crystal Structure of Graphite, also Pyrolysis of Hydrocarbons and HOPG - Highly Oriented Priority Graphite Preparation. All of these lectures are also very strongly connected to the graphene lecture.

This is not completely independent because after all, we are talking about the structural unit of graphite. So, we have 3 sigma bonds that we have sp2 hybridization. And there is 1 unhybridized p-orbital and 1 pi bond, now the 6 pi bonds. I have some graphene for you here. You have this kind of structure.

This is just an individual hexagon. We also have many such hexagons connected to each other. You have 6 electrons. When we learned about hybridization, there also we talked about all of these things in detail. So, these 6 electrons from the pi-orbitals will then form a cloud, they become delocalized and that is what leads to all the interesting properties.

You also know one more thing when we talk about pyrolytic graphite or graphene sheets, then we talk about turbostratic structures. You have this is one hexagon, and this is another(refer to video at 5:40). So, if you have AB or BA type arrangement which will look something like this, then you have graphite. But if you have a completely random rotation, so it can be at any angle that is your turbo static structure.so it can be at any angle. So, this is the turbostratic structure.

Instead of annealing, now we are already stopping at the turbostratic structure. If you have like five layers of graphene, this will definitely have a turbostratic structure because it has not been annealed at higher temperatures yet. If you use a single layer of graphene which is what graphene should be, then there is no question of turbostratic or AB BA arrangement because we are then talking only about the single layer.

So, the point is all the interesting properties of graphene or at least most of them are because of this pi band which is the delocalized cloud of all the electrons sitting in these unhybridized orbitals. How about the mechanical properties? Well, mechanical properties are actually determined by the sigma bond. So, sigma bond is the bond between these carbons.

So, the in-plane bonds. These are the sigma bonds. Sigma bonds actually determine the mechanical properties. What is very interesting is that the bond length in the case of graphene that is 1.42 Angstrom. In the case of diamond, it is 1.54 Angstrom which basically means that you have a shorter bond length in the case of graphene which would in principle make it mechanically stronger than that of diamond. And that is why you will also hear that graphene is the strongest material on earth.it is much stronger than diamond.

So, whenever you hear these kinds of things you should understand what is the scientific reason behind it. Rather than just thinking of graphene as a wonder material. Especially for the students, I am saying that make sure that when you are talking about new fancy material. You remain scientific in your approach, do not just start a believing in graphene.

You should understand what are the properties of graphene? Why do we call it mechanically strong? So, this is because the carbon-carbon bond length.in the case of graphene is shorter than that of diamond. However, if you want to make a cutting tool, you will rather use the diamond. Because the property that we are describing here is for a defect-free single layer of graphene.

And in that case, can you have these very large crystals very large 2D crystals? Even if you do have very large 2D crystals, in that case, can you use it in a cutting tool? Will it not have the flexibility because these are sheet-like structures? So, there are all these things and you need to make sure that you understand. Even though this is in principle the strong material or stronger than diamond but for the technological applications still you will use diamond.

So, these are some of the things about graphene. Also sigma bonds result in a strong wave function overlap with its nearest neighbors. These are the properties that are basically used for number 1 - describing the pi band, number 2 - also describing the Hamiltonian of graphene. This is something, I am going to talk a little bit about some of the vectors that we use for some other.

So, some other crystal structure parameters that I am going to discuss in the next couple of slides. However, maybe I will not go too much into the details of physics. I will recommend some other NPTEL lectures. So, these are some of the concepts that are already available within NPTEL.

Anyway, our goal is going to be how do we make graphene? What are the properties that are for technological applications very important? So, this is going to be our primary goal. There are many properties; one of them is also the optical transparency of graphene. This is interesting because then you can actually see the graphene sheet under an optical microscope.

And you can actually see the edges of graphene under an optical microscope. You can actually search for these optical images of graphene and then you will find many such images. So, this material like all carbon materials offers some sort of optical transparency, but only when there is a single layer. When it is a multi layer structure like graphite then it does not offer transparency to the light in the visible wavelength .

So, I have already mentioned that the term graphene should only be used for single and defect free layers, but that is not the case; we also use multi and bilayer structures. I think the reason for that is when we make pyrolytic graphite or hydrocarbon is pyrolyzed on top of a certain substrate.

In that case, you do have these wavy sheets, you have these turbostratic sheets. A lot of them also contain some defect and so on. Before we anneal them out, what do we call that material? So, if we use it in bulk, we call it pyrographite. But when we are using individual sheets?

Now, let us say individual sheet separation is very difficult.it is extremely difficult to obtain, this needs to be highly controlled. We will talk about this when we talk about the manufacturing process. But it is very difficult to get defect-free individual sheets.

So, you will often end up getting sheets that are turbostratic and which are more than one sheet. So, what do you call them? You cannot call them graphite because it needs to have an AB AB A arrangement. You can also not call them glass-like carbon or any other non-graphitizing carbons. Because non-graphitizing carbons have a curved carbon structure.

So, what is that material? When you have a few sheets of sp2 hybridized carbon, but they are randomly rotated on top of each other, they are turbostratic. So, in that case, you can just call them multi-layer graphene for convenience, but graphene by as per the IUPAC definition is only the single and defect-free layer.

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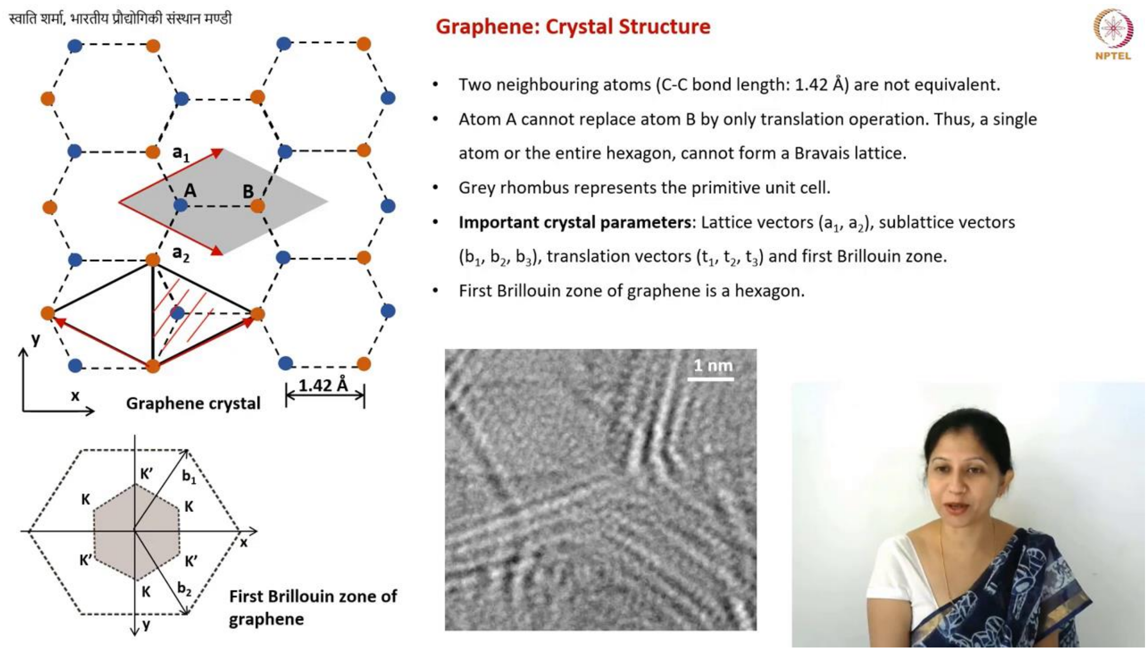

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Graphene: Crystal Structure

- Two neighbouring atoms (C-C bond length: 1.42 Å) are not equivalent.
- Atom A cannot replace atom B by only translation operation. Thus, a single atom or the entire hexagon, cannot form a Bravais lattice.
- Grey rhombus represents the primitive unit cell.
- **Important crystal parameters**: Lattice vectors (a_1, a_2), sublattice vectors (b_1, b_2, b_3), translation vectors (t_1, t_2, t_3) and first Brillouin zone.
- First Brillouin zone of graphene is a hexagon.

Coming to the crystal structure of graphene, this is something very important to us. This kind of diagram, you must have seen it multiple times in this course when we were talking about graphite. You see that I have drawn two types of atoms; one is in blue color and one is in orange color. These kinds of structures are also known as honeycomb structures.

These are basically just hexagons connected to each other. Honeycomb because well honeybees make these kinds of structures. They seem to be very smart and they came up with a very good structural design. They are making hexagons, never mind. So, this is our graphene structure.

What is very important for us to understand in terms of crystal structure is why do we have these A and B sites? Why do they look different? Why did I draw them using two different colors? The point is that we cannot take just one atom of this entire structure as your crystal lattice.

So, what is the crystal lattice? Again what is the unit cell unit? Cell is the smallest repeating unit in any crystal, primitive unit cell is what we call it. This is the smallest one that can exist. And if we repeat it, then we should always get the same structure. So, when it comes to selecting this primitive unit cell, it becomes very important whether it is just one atom.

Why do not we just take one atom or one complete hexagon as the unit cell? Why make it more complicated? So, the idea is that in that particular unit cell, you should be able to repeat the entire structure, and can we do it if we select one single atom?

The answer is no because the atoms A and B as I have mentioned here are not equivalent, why are they not equivalent? So, if you move from A to B, and you move let us say 1.42 Angstrom. So, after A after 1.42 angstrom, you will find atom B. But if you move from B, if you move further in the same direction, then after 1.42 angstrom, there is nothing. So, this means that A and B are not equivalent. So, this is as simple as that.

However, after B let us say you move a little bit up or down to the next nearest neighbor. In that case, after 1.42 Angstrom there is something, but here you will not find anything somewhere here. Well, the nearest neighbor is not equivalent, but the next nearest neighbor is equivalent.

Basically, you only have two types of atoms and not more than that. So, you have A and B type atoms, that does not mean that there is any chemical difference between these two atoms. They are both carbon atoms. They behave the same, everything is same about them, but in terms of crystal geometry they are not equivalent.

We also cannot take the entire hexagon because you will see that you do not have what is known as translational symmetries. Translation basically means well moving in one direction, not rotating, just moving like that, which is known as translation. Basically, from A to B, you should be able to reach with just one translation operation which is not possible because A and B are not equivalent.

Now, how do we select the unit cell? When we were talking about graphite and the first thing, that the very intuitive thing that will come to you is why do not we take the entire hexagon? Why do we take three layers in the case of graphite? So, the point is that again you need to have a repeating unit.

In the case of graphene, you have this kind of this gray region that I have shown. It is a rhombus because this again we did in the case of graphite. So, I am not going to repeat it, but this angle here is 120°, and this angle here is 60°.

This is known as a rhombus structure, this gray area is our unit cell. Now, you have one A atom, one B atom. What is a little bit non-intuitive here again is that when you select this primitive unit cell or this lattice, you do not have atoms at the corner all corners of the lattice, and that is why it is sometimes not very intuitive.

However, there is also another option of selecting the unit cell. And in fact, in some of the publications, you find the other second one which I have shown with the black rhombus. This is also a way of selecting the unit cell of graphene. If you will see that this is pretty much the same, the shape is exactly the same, then the number of atoms is also exactly the same. In the case of the gray one, you will see that you have 2 complete atoms inside the unit cell. So, the total number of atoms is 2. If you also calculate it for the other one, you will still find 2 because again this calculation was done when we talked about the crystal structure of graphite. And I definitely recommend that you go through that lecture.

There is one full atom, but it is shared with top atom and bottom atom top layer and bottom layer in the case of graphite. Here you just need to make sure that you do not divide your atom in half because there is no top or bottom layer.

But if you will calculate the number of atoms, it remains the same again. In this particular structure, you will find 2 atoms. In the case of graphite, we had one because of the sharing of top and bottom. So, these two are accepted crystals primitive unit cells for graphene. You see a1 and a2, I have shown with the red arrows, these are the lattice vectors.

So, what else? If you just noticed that here I have shown again with these arrows, lattice vectors can also be taken this way. And again in the literature at some point, you will find these two a1 and a2 lattice vectors, or you will find these kinds of lattice vectors.

This angle here is 120, and traditionally or conventionally when you are choosing the lattice vectors in the case of a rhombus, you will often choose the ones that form an obtuse angle. So that is why there is a community of scientists who believe that the lattice vector should be taken like the second strategy, and not the first one. So, all of these things exist, and you will find different types of crystal structures in different publications.

Now, one more important is that there is something known as the sub lattice of graphene. So, sub lattice is nothing but if you draw a line here and then you have you know these two triangles. So, now, if I take this triangle here this one, then you have one center atom and then that center atom which is of A type is connected to 3 B atoms.

The neighboring B atoms this can be no called A sub lattice. So, one sub lattice in this type of geometry would have these you know one central atom, but on the other side it is empty. Anyway, these are also known as graphene sub lattices. And there are also certain vectors that define these sub lattices or these which connects the two sub lattices. So, we are going to you know quickly talk about all of these things.

This shaded region that I have drawn here, is what is known as the sub lattice of graphene. These kinds of structures are also often visible in some of these very nice transmission electron micrographs. This particular image is also present as the title image of your course, this is a very beautiful structure that we found in a glass-like carbon. Again this is not a picture of multi-layer graphene or single-layer graphene. This is a picture of glass like carbon.

And however, you can see these triangular junctions. And these triangular junctions are also present in this. These are present in all kind of sp2 carbon structures. Now, let us briefly talk about some of these crystal parameters before we move further.

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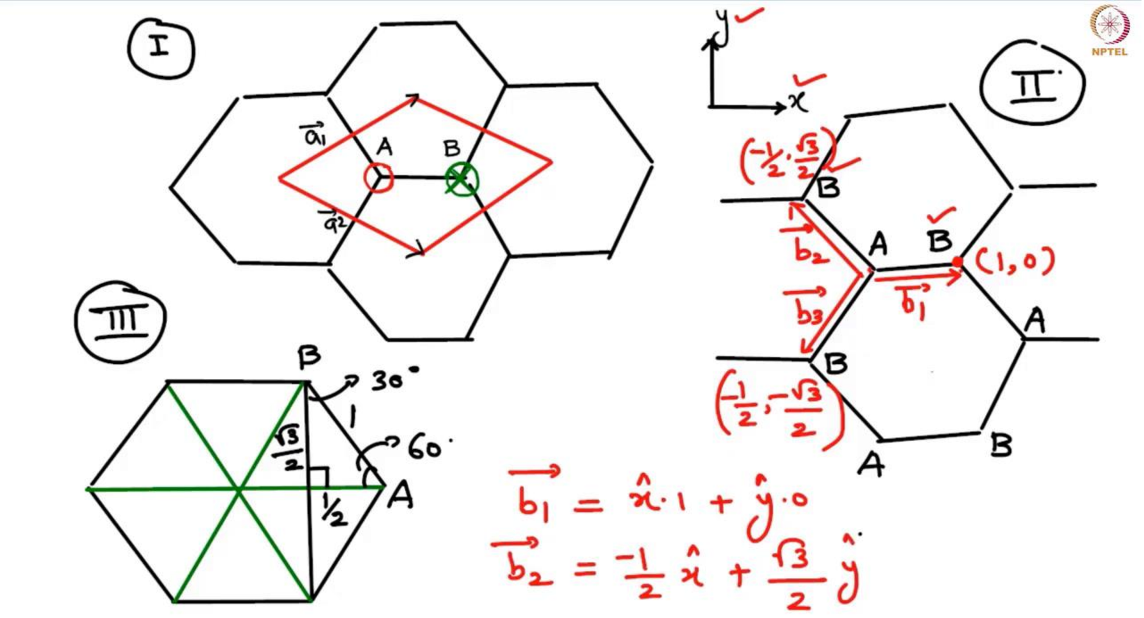

Here I have again drawn the primitive unit cell of graphene. So, this is your image number I. And here you can see also atoms A and B that are two non-equivalent sites. You can see a1 and a2, these are your primitive lattice vectors. Now, we are going to define another set of vectors which is very useful for calculating various properties related to graphene.

For example, for calculating the Hamiltonian of graphene or for calculating the electronic band gap of graphene and other electronic properties accordingly. So, we are going to use this diagram number II for this purpose. This set of vectors basically connects the two sublattices of graphene. So, what are the two sub lattices? We know that we have A type atoms and B type atoms.

You actually need to pick any one A type atom and connect it with all its B type neighbors. So, in this particular case, these are the B-type neighbors. So, you can also do it for yourself. If this is B, this is A here, and then B again, and then A again. You will find that these will be the neighbors that will be the B type neighbors. Now, the vectors we are talking about, are the three vectors. So, this is number 1, number 2, and number 3.

In the literature, sometimes you will find the name b1, b2, b3 for these vectors and sometimes you will find the name $\delta 1$, $\delta 2$, $\delta 3$. We are going to use b1, b2, and b3 here. So, you just need to calculate the value or of these vectors. What does that mean? That means that you need to find the coordinates of the points, for example, if I take this B point, so for all three B neighbors, we need to find the coordinates.

For this one, well, this is just simply 1 and 0 because this is our x-axis and this is the y-axis. So, this is easy. For this second B point, although this is also very simple geometric calculations, I will show it to you here. For this purpose, we are going to use this image number III, this diagram number III here.

You can see this is your A side, and this is your B side where you would like to reach. Now, if I draw A line here, if I draw A line here, then this distance here is half. Of course, the edge length of your hexagon is assumed to be 1 in all cases. So, this one is half, and this is the edge length. So, this is equal to 1.

Now, using very simple trigonometric calculations, you can find out. This angle here is 90, and this one is 60, 60, and this one here is 30. Now, you can very easily calculate that this is √3/ 2. What are the coordinates again for this point? The coordinates will be -1/2 and √3/ 2.

Similarly, if you want to calculate it for this B side, you are going to get -1/2 and -√3/ 2. Now, accordingly, you can define your vectors. What is your vector number b1?

$$\overrightarrow{b_1} = \hat{x} \cdot 1 + \hat{y} \cdot 0$$

In the case of b2, what you have?

$$\overrightarrow{b_2} = \frac{-1}{2}\hat{x} + \frac{\sqrt{3}}{2}\hat{y}$$

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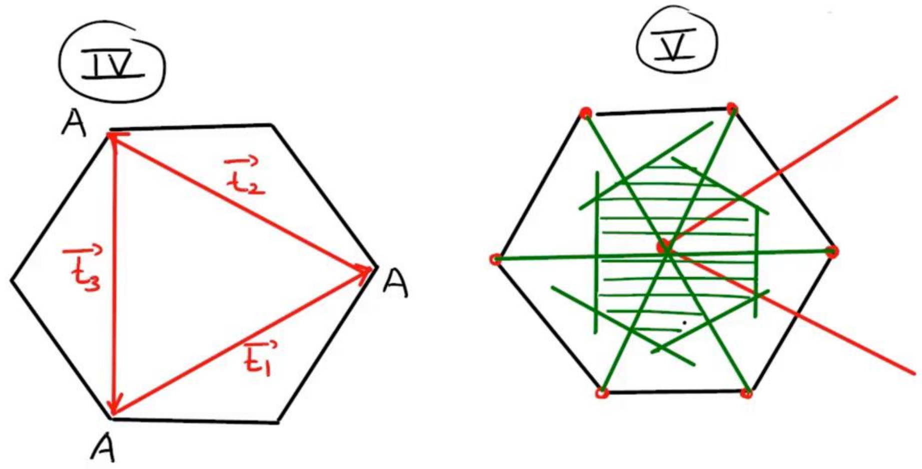

Another type of vector is a set of vectors that are used for some of the calculations, for example, if you want to use the reciprocal vectors and you want to use the orthogonality relationships, in that case, you might require what is known as the translation vectors.

So, what are translation vectors? Translation basically means you need to move in one direction of you move in one direction how much distance is required for one A site to reach another A site or B to B basically. So, you have your A type atoms here, here, and here. And you can easily see what the distance between A and A is.

So, this one here is your t1 vector - translation 1, this one here is your t2, and this here is your t3. Now, what is very useful when you use these t1, t2, and t3 type vectors? You can now represent these vectors in the form of your b1, b2, and b3 vectors for various calculations.

Now, one more concept that we are going to learn is the concept of brillouin zone. So, what is a brillouin zone? Again what you need? Here we are going to use this last image. So, you take any lattice point. So, in the case of graphene generally, these lattice points are not very obvious. Because they do not contain atoms at their corner, but you know that this is our primitive lattice or it is a primitive unit cell.

So, you can take the corner atom of this one here, this the corner here. Remember that there is no atom sitting there. Now, you need to connect this point to all the nearest neighbors. So, these 6 atoms are the nearest neighbors right. And now you can draw lines here. And I will tell you why.

Now, once we draw all these lines, then you need to draw perpendicular bisectors of all these lines. So, for example, this one, and then the perpendicular bisector of this one. And similarly for all 6 of them, you need to draw these bisecting lines.

And what you get is what is known as the first brillouin zone. So, basically what you have here. Now this does not look like a perfect hexagon in this image. But basically you will get this first brillouin zone as the perfect hexagon in the case of graphene. And this is the center point is known as the gamma point.

By now you already know that what are the important crystal parameters for us. These are the lattice vectors a1 and a2. These sub lattice vectors you can say b1, b2, b3. One important thing about these sub lattice vectors are that we are working in a two-dimensional space. So, only two vectors are linearly independent.

So, you actually can write b3 in the form of b1 and b2.if you remember that when we were talking about the graphite crystal structure, we had c vector, but then we also had a1, a2 and then a3 vector. a3 was again a linear combination of a1 and a2, and that is why you can have two types of miller indices for graphite h k l or h k i l, where i is actually it is a combination of the other lattice vectors.

Similarly, in the case of graphene, b1, b2, b3 are not all independent. Only two of them can be independent, we are working in a two-dimensional space. Translation vectors t1, t2, t3 that you already know. And we have drawn the first brillouin zone and you know that this is a hexagon.

And this is how it looks like. If you draw a good diagram not like the one that I drew before, so this looks like a good hexagon with symmetric hexagons.

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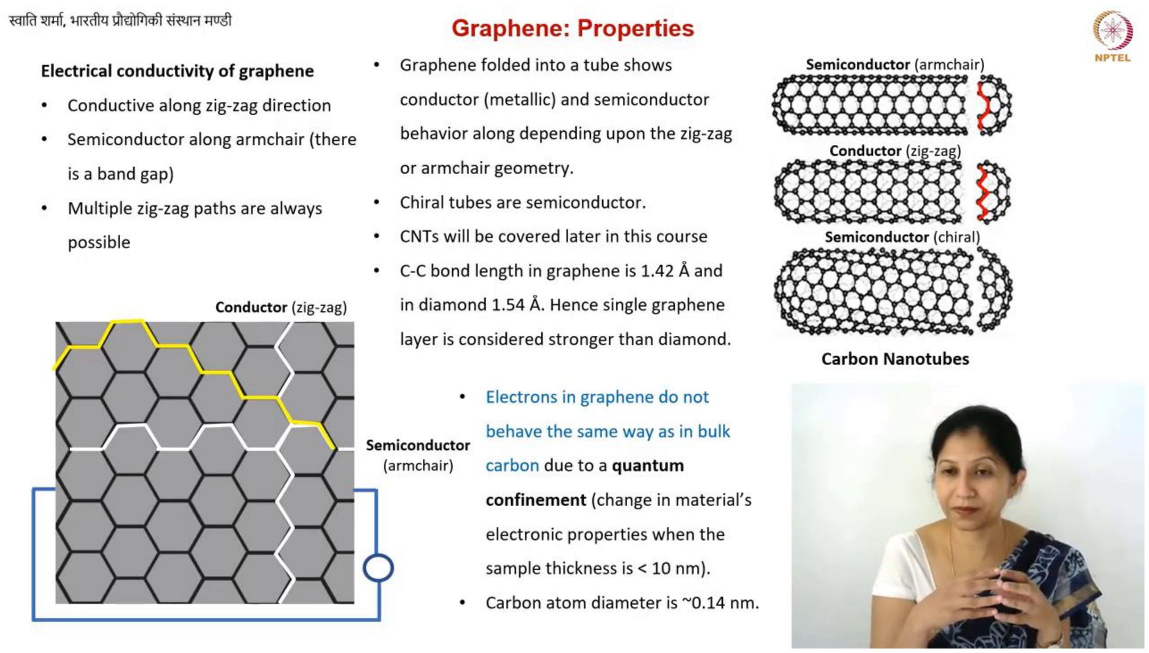

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Graphene: Properties

Electrical conductivity of graphene

- Conductive along zig-zag direction
- Semiconductor along armchair (there is a band gap)
- Multiple zig-zag paths are always possible

- Graphene folded into a tube shows conductor (metallic) and semiconductor behavior along depending upon the zig-zag or armchair geometry.
- Chiral tubes are semiconductor.
- CNTs will be covered later in this course
- C-C bond length in graphene is 1.42 Å and in diamond 1.54 Å. Hence single graphene layer is considered stronger than diamond.

- Electrons in graphene do not behave the same way as in bulk carbon due to a **quantum confinement** (change in material's electronic properties when the sample thickness is < 10 nm).
- Carbon atom diameter is ~0.14 nm.

You know that graphene is electrically conductive. In fact, its band gap and its electronic properties are of great interest not just to engineers but also to physicists. Because this is a very nice experimental model that can be used also theoretical studies. There are so many theoretical studies when it comes to graphene.

Because theoretically it is very easy to have a single layer, but it is not that easy when you actually perform the experiments. And anybody who has worked on graphene materials know that it is not easy to get the single layers. Well in the past it was believed that the single layers of any material or any 2D crystals are very unstable.

But now when we are using graphene for a lot of technological applications, we know that these single layers can also be very stable. This is something also very similar to fullerenes because before fullerenes were discovered, it was believed that curved carbon structures are not very stable.

So, well with carbon structures you can always find some sort of arrangement that is stable. And the reason for that is there are so many carbon bonds with itself and that is why it always finds an overall stable geometry that may not be if you had only a few carbon atoms let us say 10 or 20.

But if you find a very large number of carbon atoms, then all together it form overall stable geometry that is the most interesting property of our carbon material. Anyway let us first talk about the electrical conductivity of graphene. So, this is your graphene sheet. I said that this is conductive along what is known as the zigzag direction.

There are two things about all hydrocarbons, all carbon materials have zigzag and armchair like edges, and a sort of symmetry also defined in the terms of zigzag and armchair in the case of sp^2 carbons. So, what is this zigzag? Zigzag as the name suggests is this zigzag structure. I think here. So, this is the zigzag type geometry or path.

And there is also something known as armchair symmetry. If you have these are your two graphene sheets, if you move from here to here to here, so all the way(refer to video at 31:18). So, this upper half of your hexagon. If you just see this kind of structure that is known as armchair. And if you have various hexagons connected, for example like this, if you move along the path that I just showed to you like this, then that is known as the armchair symmetry.

If you have a large graphene sheet at some point, wherever you have the edge, wherever your sheet ends, you are either going to find the zigzag-like geometry or you are going to find the armchair-like geometry. Because these are the only two possible arrangements, you will have your hexagons like this.in the same structure actually, the top part is the armchair, and the sides are zigzag type fine.

So, let us talk about conductivity. It is conductive along this zigzag direction because you can see the electron can very easily move. It is well-connected path. However, now for the same structure, if you see sideways, then you do not have perfect connectivity, you now have sort of a little bit of gaps here.

So, here the electrical conductivity value should be slightly lower than what you have for this zigzag direction. Why? Because there is no continuous path for electrons to move, but it is not as straightforward as it was in the case of zigzag. However, these things are connected, it is not that the hexagons are not connected. It is just that the path is a little bit longer.

So, in this direction actually graphene sheet happens to be semi-conducting, but you will never know this. When you are performing an experiment, if you connect your graphene sheet to some external circuitry, you will never be able to identify because you cannot really differentiate between the zigzag and arm chair paths that your electron is taking.

The electron will always find some path. In fact, the path of the electron would often be a mixture of both armchair and zigzag paths, whatever is the most convenient one for the electron. So, when you are measuring the electrical conductivity of graphene, you will always get a certain value. You will never know which path was taken by the electron.

However, you can guess when you can when you make carbon nanotubes. What are nanotubes? tubes are basically folded. So, if this is your graphene sheet, and then you roll it up then you get a carbon nanotube. Now, this was my structure. This is a rectangular sheet of paper. So, either I roll it up like this one that I just showed to you, or I roll it up from top like this.

In that case, in one of these geometries is where I have the zigzag, and the other one I have the armchair. So, in the case of carbon nanotubes, it is very clear when they have the armchair symmetry that is also shown and with this red color. And when you have armchair symmetry, you have semiconducting carbon nanotubes.

When you have the zigzag type symmetry, then you have conducting carbon nanotubes or they are also known as metallic carbon nanotubes because they are conductors like metals. So, it becomes clear. The third one is what is known as chiral carbon nanotube. And this also happens to be semiconductor.

How will I make a chiral sheet out of it? If I fold it you know sideways so like that, then what I get is now it is sort of a combination of both. So, this is something very interesting about graphene’s electrical properties. This is something you will only know when you make tubes because, in the case of graphene, you will always find there is some path.

I have written something about diamond and graphite which is about the mechanical properties. Electrons in graphene do not behave in the same way as they would behave in graphite that you know because of the fact that your pi electrons are now available. And because the structure is very very thin. The diameter of a carbon atom is approximately 0.14 nanometer. So this is a single atom thick layer. This is extremely thin layer.

And when you have structures below 10 nanometer, then there is something known as quantum confinement. A lot of properties of materials change when they are smaller than

10 nanometer and that is why the electrons also behave differently in the case of graphene as they would in the case of graphite or other bulk carbon materials.