Nanostructure and Nanomaterials: Characterization and Properties

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Lecture - 28
Carbon Nanostructures

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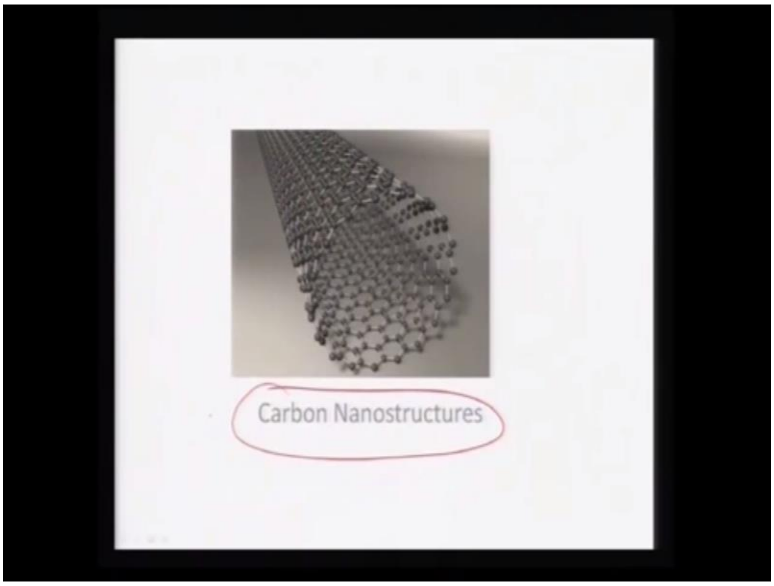

In this lecture we learn about carbon nanostructures. Carbon is one of the most abundant elements on the earth and forms a basic form of life. So, there are many polymers of carbon which are available and eventually they go on to forming nanostructures. So, we learn about certain of those nanostructures which belong to that of carbon in this lecture.

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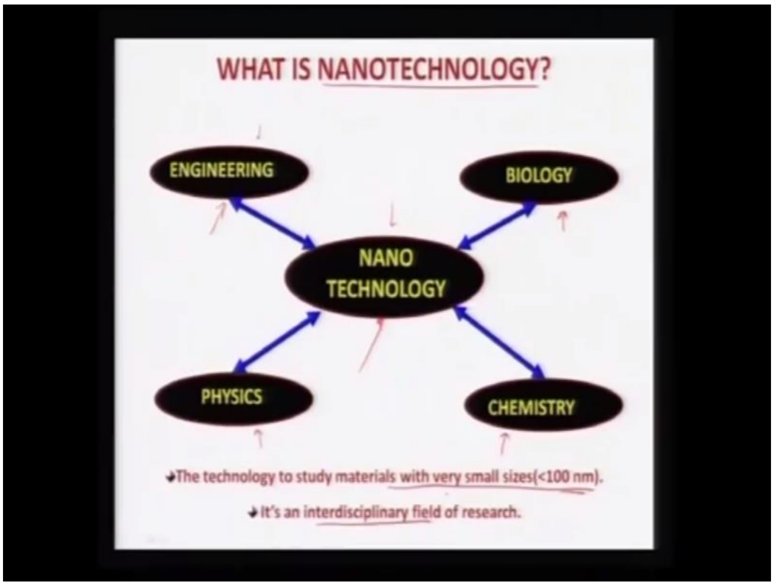

WHAT IS NANOTECHNOLOGY?

- The technology to study materials with very small sizes(<100 nm).
- It's an interdisciplinary field of research.

But before we go into that we are more interested in what is nanotechnology because carbon nanostructures, if we can somehow engineer them. We can tell them to suit certain properties or certain applications. We can make them as sensors or we can also make them reinforcing entities. We can also eventually get some data out of it, like we can make them as bridges between 2 entities and we can pass the current through them and we can again allow some properties to be measured from that aspect.

So, that nanotechnology is emerge as a very strong tool because of these nanomaterials, but nanotechnology it comes out as a combination of not only engineering, but also some other sizes such as chemistry biology and physics. Initially the sciences were very different. In the case we will go only with say physics biology or chemistry. And engineering was supposed to be a different field of study like making things work, but right now the paradigm is that everything is merging at a common podium.

So, if we if I want implant a chip in a body I also need to see the physics of it how those things will really make that happen. I also need to understand about how do I engineer it means how I can make that device work while it is in the body. Well, I also need to understand the biological aspects of it if it is in contact with blood what do I do with it.

So, now the paradigm of using this nanotechnology has merged all the disciplines whether its science or engineering we need a common platform for working on that. So, that is how the nanotechnology has brought all the disciplines of engineering. It is not only about the material, but also about the mechanical and the electrical aspects as well. So, if that chip is being implanted into the body, it has to sustain certain forces or certain stresses. So, I need to design it using mechanical engineering.

I need to design a material I need materials engineering if I want to pass some current into it I want to sense something I also need to worry about the electronics of it. So, that it does not degrade with time. In case I am also worried about releasing some drug using that particular device it can be a martial and I want to release some drug into the body. I need to have a very controlled degradation of that particular material. So, I also need to study about the biological part of it, that how much drug is to be released foe a certain stipulated period of time.

So, these are these aspects makes things much more complicated, but now it has brought all the aspects up to make this nanotechnology and interdisciplinary field of study. So, in nanotechnology we are worried about materials which are very, very small in sizes, order of less than hundred nanometres and that has made it an interdisciplinary field of research. If I am worried about certain catalyst to release a certain drug, I also need to worry about the surface area of that particular catalyst.

I need to worry about the red kinetics involved in that. So, I am also worried about the chemistry part of it. So, there are many many aspects which make things very, very complicated and the certainty are somehow ignored or some sometimes if I want to engineer it to that extent I will also need to worry about those certain aspects. So, that is how it has become a very complicated to. And when I am using a nonmaterial I need to also understand things at the nanoscale because right now the bulk, the bulk physics is very, very different than what you might expect at the nano level. So, again it is a very complex phenomena and to engineer that we always need to worry about the nanotechnology.

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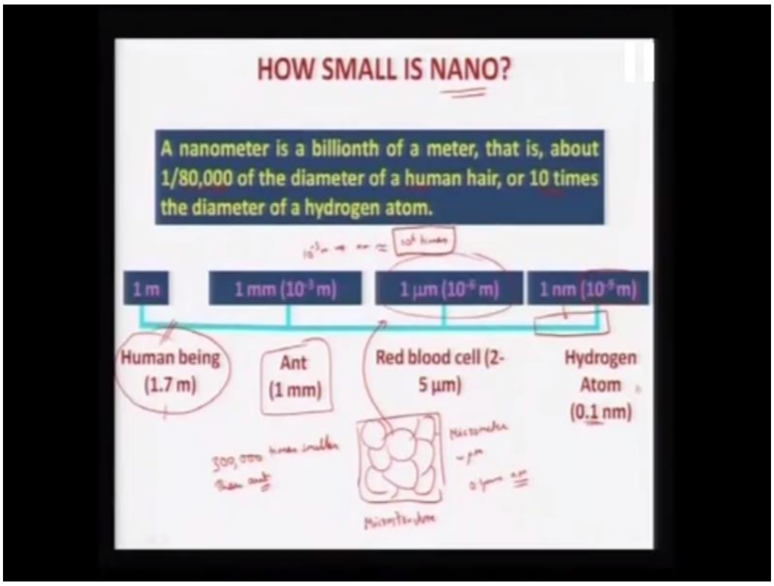

HOW SMALL IS NANO?

A nanometer is a billionth of a meter, that is, about 1/80,000 of the diameter of a human hair, or 10 times the diameter of a hydrogen atom.

1 m

1 mm (10^{-3} m)

1 µm (10^{-6} m)

1 nm (10^{-9} m)

Human being (1.7 m)

Ant (1 mm)

Red blood cell (2-5 µm)

Hydrogen Atom (0.1 nm)

And again coming back to how small is nano. Nano has nothing but any entity which is less than around hundred nano metres. And to see it visualise it physically a nanometre is ((Refer Time: 04:15)) of a metre, but it is about 1 by eighty thousand of the diameter of a human hair. Human hair is approximately 100 250 micrometres in diameter or this nanometre is approximately 10 times that of a diameter of a hydrogen atom.

So, right we are worried about 0.1 ((Refer Time: 04:32)) that is hydrogen atom, the diameter of that and I am talking about scales 10 times and hydrogen atom. So, that makes it around 1 nanometre. We can see a human being a human is generally couple of metres like 11.5 to 2 metres. So, that is a height of a human being around 1.7 metre an ant is approximately 1 millimetre the length of the length of an ant is approximately 1 to 2, 2 to 3 millimetres.

Then we have red blood cells which range in the order of microns or 10 power minus 6 metres. And when we talk about a material we find that a material has certain polycrystalline grains into it and the grains also extent to the order of couple of micrometre. So, the grain size can vary from micron to some micron and now we are worried about the microstructure of a material. And that is approximate that approximates to the micrometre land scale. So, I am worried about micrometre land scale.

I am talking about couple of micrometres, size of the grains. When I define the grains to some micro metre range less than 0.1 micrometre then I am talking about something at nanometre level. So, that is what the range is approximately here, that I am worried about 1 nanometre or 10 power minus 9 metre or that is approximately 10 times the diameter of the hydrogen atom and that is what is nano.

To give a physical sense if an ant if it starts holding a nano gear. So, if I have an ant which is approximately 1 to 2 to 3 millimetre in length and if it is holding a nano gear that nano gear will be 3 hundred thousand times smaller than that, times smaller than the ant itself. So, we can see an ant is approximately 10 power minus 3 metre and we are going to nano metre that is approximately 10 power 6 times bigger than a nanometre. So, that is what the overall feel of this nano land scale.

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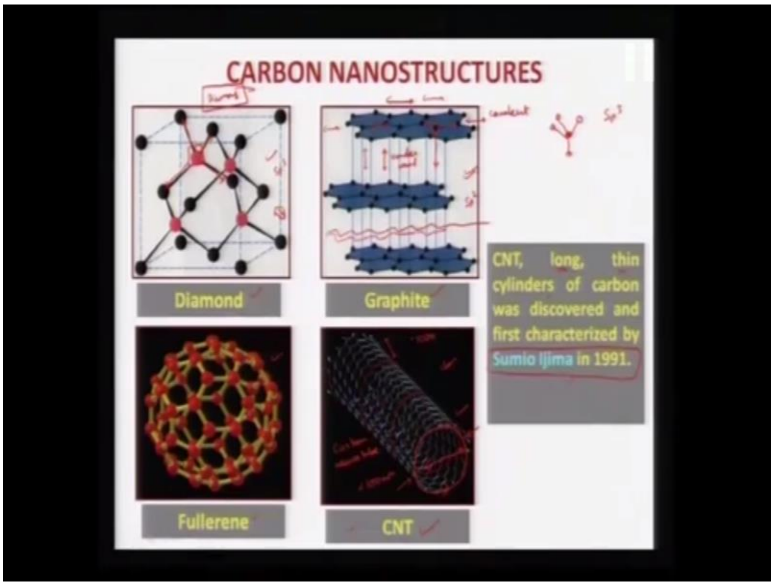

CARBON NANOSTRUCTURES

Diamond

Graphite

CNT, long, thin cylinders of carbon was discovered and first characterized by Sumio Ijima in 1991.

Fullerene

CNT

Now, coming to the nano structures. So, we can see the carbon has many many polymorphs which are available with it. So in this case we can see we have a diamond structure, we have a graphite graphitic structure we have fuller in structure and then we have something called carbon nanotube. In the case of diamond we can see we have s p 3 hydronization. It means that each carbon atom is now attached to 4 other carbon atoms. So, we have 1 carbon atom which is not attached to 4 other carbon atoms. And that is what it gives a very strong strength a very high hardness a very high stiffness to the diamond. So, this is a diamond structure.

So, each carbon is sitting at either tetrahedral and it is now connected to the 4 carbons along their width. So, that is why we can see that carbon can exist as a diamond which is in which is one of the very hardest known material and that requires hybridisation of s p 3. Though we say that diamond is forever, but diamond is not the equilibrium form of a carbon, it is a graphite which is actually the equilibrium or the thermodynamically stable form of carbon.

And in graphite we can see we have only 1 carbon is now attached to only 3 other carbon atoms. And fourth one is forming some wonder world bonding with the layer which is beneath itself or above itself. So, we can see in this case we have s p 2 type of hybridisation in a graphitic structure. So, we can expect that conductivity of strength will be much higher along this lands scale. So, we can see that we have free to free electron available and that can basically hop. And in this case we can achieve very high strength why because in this case, we have a covalent bond.

Whereas, along the vertical direction I have vender ball attraction. So, in this case in a graphitic structure I can get very high strengths along this horizontal axis and apparently this vender ball forces are pretty weak in comparison to that of covalent bonds. So, I can easily slide these 2 layers. And I can basically slip those graphitic place over each other and that gives the overall lubricating property to the graphite. Whereas, that thing is not possible in the diamond structure because diamond structure it has all the bonds which are covalent.

So, that is a problem in diamond, but we can get very good lubrication in this graphitic structure because we have a vender ball force which is joining the 2 sheet 2 layers of graphite. So, that is what defines the overall graphitic structure and then we have something called fullerene, this is also known as buck minster fullerene which is on the name Buckminster fuller which Buckminster fullerene, fullerene which has actually developed this structure of ((Refer Time 09:50)) and based on his structure this structure was dedicated to him.

Now, coming to c m t this is nothing but a single layer of when a single layer of graphite is rolled in to kind of a tubular structures. We can see a tubular structure is made and that basically is forming a diameter which is approximately less much less than hundred nanometre. That is why we are calling it carbon nanotube. It is a hollow structure therefore, it is a tube. So, I am taking a layer of graphite and I am rolling it in a manner that I get a tubular structure and that is called a carbon nanotube.

So, carbon nanotube are nothing but long and this cylinders of carbon. It was initially discovered by Sumio Iijima in 1991. That actually popularised the application of carbon nanotubes in the nanotechnology. So, we can see there are couple of nanostructures. We also have structure of a amorphous carbon. So, again that part we won't be covering out here, but again we have also have a amorphous carbon which can also exist as one of the allotropes of carbon which are very widely used are diamond.

So, diamond is s p 3 hybridization, we can see and it is one of the very hardest known material and very high thermal conductivity as well. Then we have graphitic structure it is very well used as a lubricant and it is s p 2. And it is s p 2 hybridization where along this layer thickness along the layer we have covalent bonds whereas, along the vertical direction the interaction between the 2 layers is through vend valve forces. And these bones are weak. So, they can easily glide over each other and when a certain stress is applied.

So, it can be very very good lubricant, then we have fuller in structures. So, that is composed of certain pentagons and hexagons that complete the soccer ball type of a structure. And then we have carbon nanotubes. Carbon nanotubes are nothing but very long and thin cylinder. So, we can get aspect ratio, which is nothing but the length to the diameter ratios as high as thousand or more than that. And that was discovered by Sumio Iijima in 1991. So, that is what we can say the overall how the carbon nano structures are being developed.

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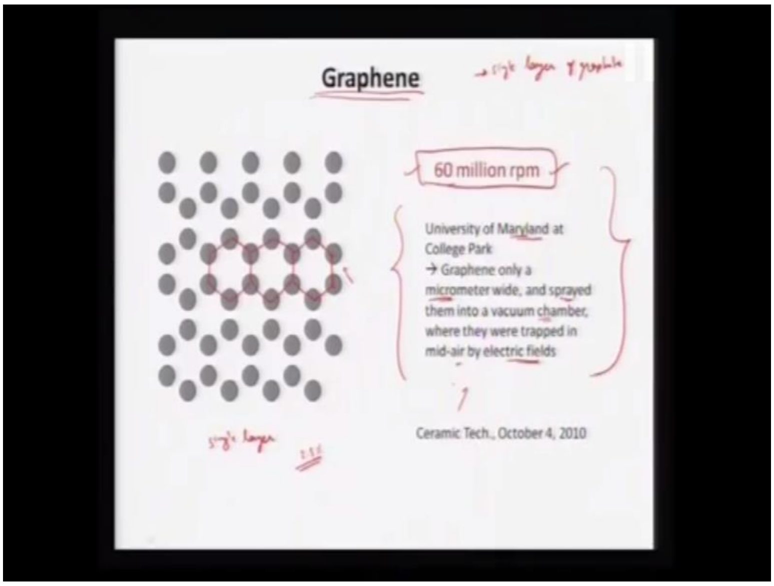

Graphene

→ single layer of graphite

60 million rpm

University of Maryland at College Park
→ Graphene only a micrometer wide, and sprayed them into a vacuum chamber, where they were trapped in mid-air by electric fields

Ceramic Tech., October 4, 2010

The first thing is graphene. We learnt about graphite, but graphene is nothing but a single layer of graphite. So, we are talk talking about only a single layer which is present in the graphite and that constitutes the overall graphene and we can see the overall hexagonal structure which is predominate in the graphene layer. That is what we can see out here that we have this hexagonal structure which basically develops in the graphene.

So, we can see that we have a single layer of graphite and that is called a graphene. The beauty of this one is if that has a very high thermal conductivity as well it has a very high strength. The strength can be as high as around 200 Giga Pascal, whereas the modules can be as high as 1 Tera Pascal. So, that is what we are talking about graphene. Apparently graphene has very high transparency to the order of 97 percent which can be utilised for making transparent screens out of it can absorb as much as 2.3 percent of the incident radiation.

And that is what makes it very very special because if you are depositing this graphene a single graphene layer we can really see the change in the opacity and we have 2 layers that will be much more opaque. So, even we can detect this opacity via our naked eye. If we go about characterising it because to see a nano we need very sophisticated tool such as t a m or something like that, at the order of electron microscopy. So, but if we just ((Refer Time: 13:49)) single layer of graphene we can just observe it using this our naked eye.

So, that is a beauty of this graphene structure. So, it can utilise for blocking the radiation whenever it is required at the same time providing a very good conductivity. So, that is what because the single layer of graphene is very highly conductive as well. And it conductivity can go as high as maybe more than hundred around hundred times that of a 10 to hundred times that of a silver or copper. So, it can be highly conductive as well.

So, that is a beauty of this graphene layer. Apparently a group in the marry lane at college park they have isolate a single layer of graphene and what they have done, it is approximately 1 micrometre wide. And they have spread them in a vacuum chamber and they were they held it in mid air by using some electric fields. So, once it is being held in the electric field in vacuum it is kind of floating and up in this floating they have applied magnetic fields. And then from that they have seen the rotation of this or rotation of this graphene. And it can rotate as high as 60 millions r p m that is highest ever observed.

So, it means that graphene that graphene layer or that graphene particular layer is rotating at a speed of 60 million r p m. So, it is rotating in that speed, apparently if I try to rotate anything even its a 30 thousand r p m or forty thousand r p m or even 1 lakh r p m its will start heating up like anything. Whereas, this graphene layer does not heat up and is still stable at 60 million r p m. And it is actually been proposed that this is not the top speed of this graphene layer. So, we can make very wonderful things out of graphene without letting it disintegrate.

So, that is these are the recent application which are coming in this particular arena. So, graphene is one of the very fascinating materials and if you want to rotate it like using some magnetic fields, you can make certain rooters or motors out of it and from that we can generate very high power as well and they can go speed to the 60 millions r p m without even disintegrating. So, that is what is one of these applications of these graphene layers?

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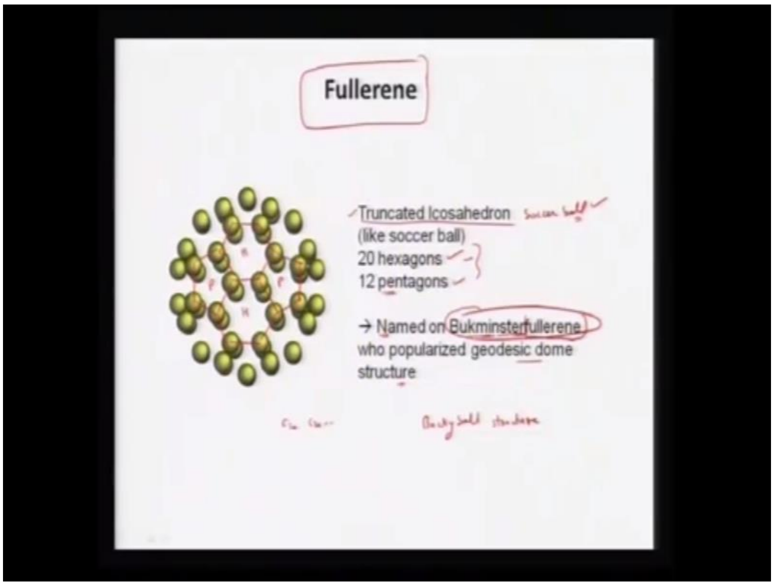

Fullerene

- Truncated Icosahedron soccer ball
- (like soccer ball)
- 20 hexagons
- 12 pentagons

→ Named on Bukminsterfullerene who popularized geodesic dome structure

C_{60} C_{70}...

Bucky ball structure

Now, coming to fullerenes fullerene again it is nothing but a geodesic dome type of a structure where you can see that you have a truncated icosahedral. So, it appears more like a soccer ball. So, your structure which is kind of a soccer ball and it has around twenty hexagons and twelve pentagons which gives the overall curvature because of we have only hexagon and we rotate it will form some sort of a tube not really a ball kind of a structure or a sphere kind of an entity.

So, you need to have pentagons to give it a curvature and that is what is happening here. And all this pentagons are not really joint with each other they do not sheer the edge, but it is being sheered through the hexagon. So, we can see we have hexagons out here and that thing is being joined by a pentagon. So, that as what we can see out here. Hexagon then again we have a pentagon. So, we have pentagon hexagon, pentagon hexagon kind of a structure and that is how it is being joined to give it a curvature. So, that is the beauty of this particular fullerene structure.

And it is being named on the Buckminster fuller and who has popularised the geodesic dome structure. So, fullerene is again one of the polymers of the carbon. It has a structure which is truncated icosahedral. So, it appears more like a soccer ball and it is around twenty hexagons, it has hexagons and twelve pentagons to give a this kind of a spherical structure there are other entities also possible like c twenty c seventy and so on, but this is the one which was initially been discovered and it was basically named on

Buckminster fullerene. It is also called a Bucky ball, Bucky ball structure and to shorten the form it is called as a to shorten the form of Buckminster fullerene it is called as a fullerene only.

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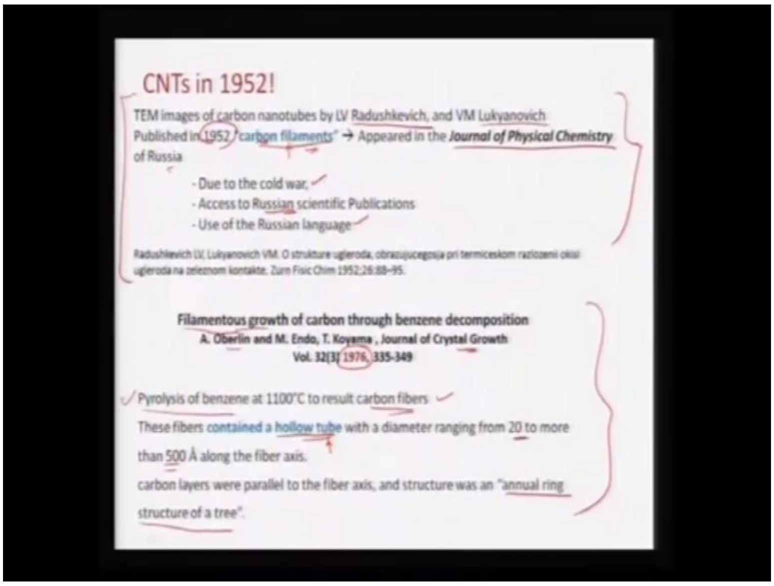

CNTs in 1952!

TEM images of carbon nanotubes by LV Radushkevich, and VM Lukyanovich

Published in 1952 "carbon filaments" → Appeared in the ***Journal of Physical Chemistry*** of Russia

- Due to the cold war,
- Access to Russian scientific Publications
- Use of the Russian language

Radushkevich LV, Lukyanovich VM. O strukture ugleroda, obrazujucegosja pri termiceskom razlozenii okisi ugleroda na zeleznom kontakte. Zurn Fisic Chim 1952;26:88–95.

Filamentous growth of carbon through benzene decomposition

A. Oberlin and M. Endo, T. Koyama , Journal of Crystal Growth

Vol. 32(3(1976, 335-349

Pyrolysis of benzene at 1100°C to result carbon fibers

These fibers contained a hollow tube with a diameter ranging from 20 to more than 500 Å along the fiber axis.

carbon layers were parallel to the fiber axis, and structure was an "annual ring structure of a tree".

As I said earlier that the carbon nanotubes were discovered in 1991 by Sumio Ijima, but these CNTs or the carbon nanotubes were discovered been they have been actually named as carbon filament. Even as early as 1952 that is what we can see here. So, the transmission electron microscopy of thee carbon nanotubes were mentioned no as early as in 1952. Maybe like forty years before in journal of physical chemistry of Russia, but these findings did not come to limelight during that time, because it there was a cold war going on between Russia and America.

And also there was a problem of exchange to the Russian scientific publications and also the language of Russia was not that predominant during that time. So, that is the reason that this finding did not emerge even till very late. So, this paper was written by rather Kavich and Lukanovich in 1952. And they mention them as carbon filaments and not as carbon nanotubes. So, that was the earlier finding of carbon nanotube. Even later on the filament is growth of carbon was again being mentioned by overlay and ando and kkoma in general of crystal growth and as early 1976.

And they had told that they can form this filament as carbon by pyrolysis and benzene seen and they are more worried about the carbon fibres which also incidentally contained a hollow tube. Now, we have gone from carbon filaments to filamentous growth which is also showing a hollow tube with a diameter approximately of 2 to 50 nanometre along the fibre axis. And again they have also formed an annual ring of structure of tree. So, that is what we are, they also mention that by the pyrolysis of benzene at around 11 degree centigrade they can form carbon fibres which with the presence of some hollow tube, which has a diameter of around 20 to 500 angstrom that means 2 to 50 nanometres along the fibre axis, but again these finding also did not come to lime light as such. Why that thing happened that now, the discovery of carbon nanotube is dedicated to 1991 to Sumio Ijima because first thing was in 1952 the Russian general were not that accessible. The cold war was going out and those Russian publications were not available to everyone and again the Russian language was also not so popular.

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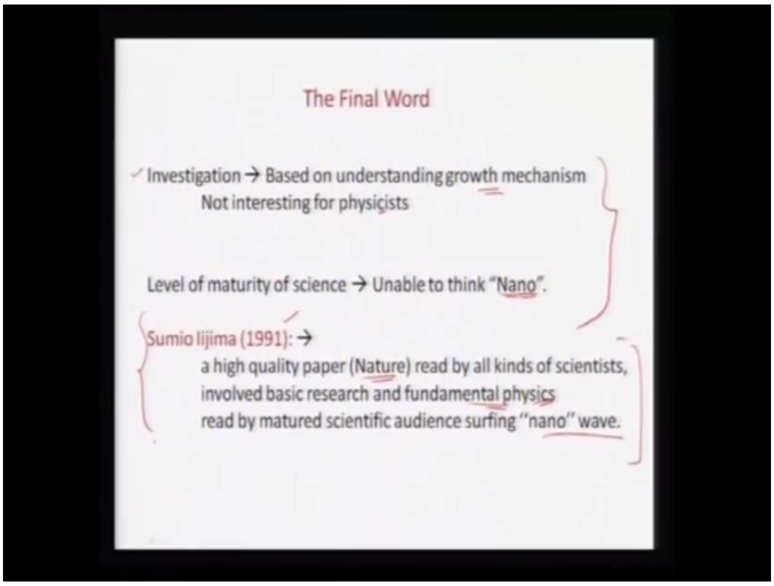

The Final Word

Investigation → Based on understanding growth mechanism
Not interesting for physicists

Level of maturity of science → Unable to think "Nano".

Sumio Iijima (1991): →
a high quality paper (Nature) read by all kinds of scientists,
involved basic research and fundamental physics
read by matured scientific audience surfing "nano" wave.

In 1976 again I talked about this filamentous growth of carbon, but the problem is that time they were studying about avoiding this formation of this filamentous carbon in certain area, certain regions. It was some mineralisation was some process was going on and they wanted to remove the formation of filamentous carbon and they were more worried about hoe this growth is occurring and all that. At that time the nano wave had not come.

So, that is the one of the biggest thing which really came into that. And all these investigation was based on some growth mechanism and that was not so interesting for the physicist. Even the majority of science was not there and they were not able to think nano during that time, because nano was popularised much later in 1980’s 1985. So, that nano wave had not caught in the people.

And since they are worried about the growth of the filamentous carbon where they want to avoid this formation, this did not really interest the physicist, whereas in 1991 this paper was published by Sumio Iijima in nature. And that ids read by all kinds of scientist you know academicians which were which were all basic research and fundamentals and physicist read them very easily.

They are very widely read by physicist. So, that nano wave had caught, now people are more aware of what is happening around the world. It was written in English and it was read by all the physicist nano wave was catching a and the term here coined it was carbon nanotube. Now, it had caught the wave because it was publish in nature written in English, physicist are it is accessible to all the physicist. And it is being read by matured scientist because the science has developed to that extent.

And that basically popularise the discovery of carbon nanotubes, though we can see that a filamentous carbon had was forming in as earlier as 1952, later on it was again report in 1976 that they are observing a growth of hollow tube kind of a structure and apparently all these 2 journals 1952 1976 they also have reported t m images.

Transmission electron microscopy images showing the filamentous carbon, but still it got popularised only in only in 1992 by ((Refer Time: 23:09)) who coined the term carbon nanotube and their nature paper. So, that actually created the way and that popularise the application of carbon nanotubes of basic research as well as for further application. Apparently the carbon nanotubes they have hexagonal lattice.

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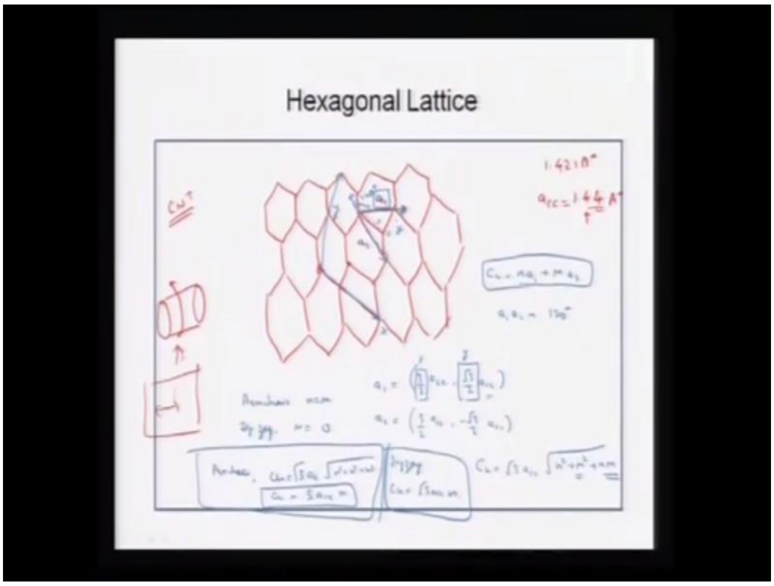

Hexagonal Lattice

So, we the lattice goes like this. So, it is a symmetric hexagonal lattice and then. So, we can see that kind of lattice which is forming in the hexagonal that is nothing but the graphitic layer of carbon nanotube. And the distance between carbon to carbon atom is approximately 1.4 to 1 angstrom in graphite, but because of curvature there is an increase in this particular ball bond distance between carbon carbon and that comes around to around 1.44 angstrom. That is a better approximation word what researcher generally used. This can go even high when the curvature if depending on the curvature. So, that is what is being. That is what it basically being accepted as a value for this bond bond length between carbon carbon and a C N T structure.

So, we have C N T it is a hollow tube. So, higher the curvature higher the stretching between the bonds. So, once you have a flat layer if you can cut them up it will be an equilibrium, but once you start putting the curvature the bond length between the carbon carbon will start increasing. So, if you can define a carol vector and we can also compare it with the Cartesian coordinate. It can go like this that carol vector we have something like this going along this direction. And second entity which is going along this direction and second entity which is going along this direction. So, we can see that we have a 1 along this direction a 2 along this direction. And then we also going to define it using a Cartesian coordinate. So, if I take this one as an origin I want to define it coordination I will take let me just change the colour of the pen. So, I can...

So, if I take this is origin I will take it has x and I will take this as a carat or carol vector is defined as the direction along which if a tube is rolled that becomes its circumference. So, the carat can be given as n times a 1 plus m times a 2, with a 1 and a 2 they are nothing, but the vectors of the hexagonal lattice. So, there around 2 vectors with around 120 degrees of opening.

So, that is what is a 1 and a 2. So, we can see that a 1 and a 2 will go along this direction, around 120 degree of opening with the. And using the Cartesian coordinate I can define a 1 is equal to 3 by 2 times a c c where a c c is the bond length of carbon root 3 by 2 a c. And then your a 2 can be given as 3 by 2 a c c minus root 3 by 2 a c c. So, we can see if it has to traverse. So, I need for a 1, I need to traverse along x. I need to travel 3 by 2 times or the bond length at along why I need to traverse root 3 by 2 of bond length of carbon. So, that is how I can go from here to here. So, I had to traverse along x I travel some distance, along y I traverse some distance.

So, this is x this is y and that goes me x and y in the Cartesian coordinate, apparently if I take its chiral vectors. So, chiral vector is nothing but n times a 1 plus m times a 2 and that comes out to be. So, c h that is a chiral vector that comes out to be root 3 bond length of carbon n square plus m square plus n m. So, we can see that the c l is a circumference of this tube or which is defined as the chiral vector of this particular carbon nanotube. So, that is how it is coming out for the carbon nanotube. Apparently we can define carbon nanotubes in 2 certain forms. So, once I come to that I will also discuss how we can really form it.

So, let me first go back to this carbon nanotubes structure. And then let me explain it further. Let me say that for armchair we have n equal to m and for zig zag my m is equal to 0. So, for armchair my chiral vector becomes when m is equal to 0, sorry n equal to m I can get root 3 a c c, n square plus n square plus n square that becomes root 3 again. So, root 3 n square it I get 3 a c c n. So, that is what my chiral vector is for armchair that chiral vector is 3 times n multiplied by a c c for zig zag structure my m is equal to 0. So, chiral vector becomes root 3 a c c multiplied by n because m is 0 and m is also becomes 0 for zig zag my chiral vector is root 3 a c c multiplied by n where is for armchair my chiral vector is 3 a c c multiplied by n. So, there is only difference of root 3.

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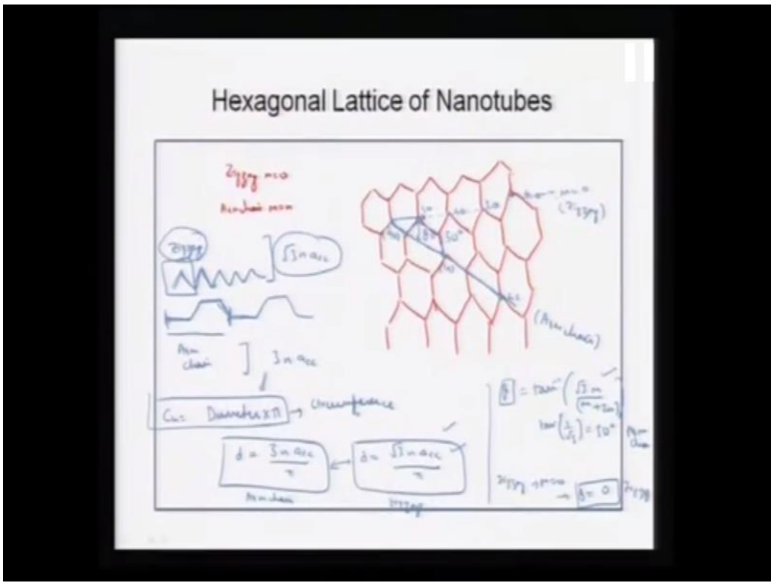

Hexagonal Lattice of Nanotubes

Now, if I can see a how a zig zag structure will look like. So, for a zig zag m is equal to 0 for arm chair m is equal to n. So, if I get this lattice of carbon nanotube layer, something like this. So, what I am getting is let me again change the colour. So, I can give it a better feel. So, let me start with here if I am traversing along this side I am getting 1 0 2 0 3 0 4 0 and so on. if I am traversing at the 30 degrees what I am getting is I am getting to the this point this becomes my 1 1. I go from here to here becomes my 2 2 and so on.

So, if I am traversing along this side what I am finding is, this is if I am traversing along this side my m is equal to 0. it is forming my zig zag. C N T I am traversing along here this is my 0 0 I am traversing along here I am getting a armchair. So, zig zag I can see I can get this sort of a traverse where is in zig where is in armchair I am traversing like this and I see this sort of a structure. So, that is what I am getting that I am traversing here, I am seeing something, something and then again I am coming back to this. So, I have a repetition of from here I have a repetition of something like this this is forming my armchair and whereas, this one is forming my zig zag.

So, we learned that the chiral vector for zig zag it was root 3 and a c c for, armchair the chiral vector was 3 times n a c c. So, depending on the n that is the vector which has been traverse along on a particular side. So, n is along direction x and along a 1 and m is along a 2. So, that part we can see here and from that we can all. And chiral vector is nothing but it is kind of a length which has been traverse that forms some sort of a diameter sorry the circumference by the pie that forms the circumference. So, that chiral vector is something like a circumference of that particular tube.

So, when I have this type of structure I can always find what is the approximate diameter of the tube? Because the diameter multiplied by pie will give me chiral vector. So, that diameter is equal to 3 times and n a c c divided by pie for armchair and d is equal to root 3 n a c c by pie for zig zag. So, from this from the chiral vector I can always identify what is the diameter of that particular entity.

So, if I want to find a zig zag, I just need to roll them along this particular direction. So, depends I will just you the examples of zig zag and armchair configuration. Apparently I can also find the theta that what theta I am rolling this particular entity. So, for armchair theta is equal to tan inverse of root 3 m by m plus 2 a. And this case m is equal to n. So, what I get is 1 by root 3 tan inverse of 1 by root 3 that is equal to 30 degree for armchair for zig zag my m is equal to 0.

So, I get theta also equal to 0. So, just couple of things that in zig zag I get kind of a ((Refer Time: 34:41)) that I go up go down go up go down that is forming a zig zag and chiral vector is given by root 3 n a c c. Whereas, armchair I see I traverse I go up traverse come down and that is forming a armchair because that is more like sitting on a chair with a rest arm rest on that. That is why it is called armchair.

And chiral vector is nothing but some sort of some sort of a circumference which is being achieved in the structure. So, I get chiral vector I can relate it to the diameter of that particular carbon nanotube and from that I can get the overall diameter. Apparently the theta at the angle at which I am rolling it to get this particular nanotube that can also be achieved using this particular relation and for armchair it is 30 degree. So, the theta value I am talking about is the fed back theta is 30 degree with respect to the Cartesian coordinate and that thing is 0 for the zig zag where it is around 30 degree for the armchair.

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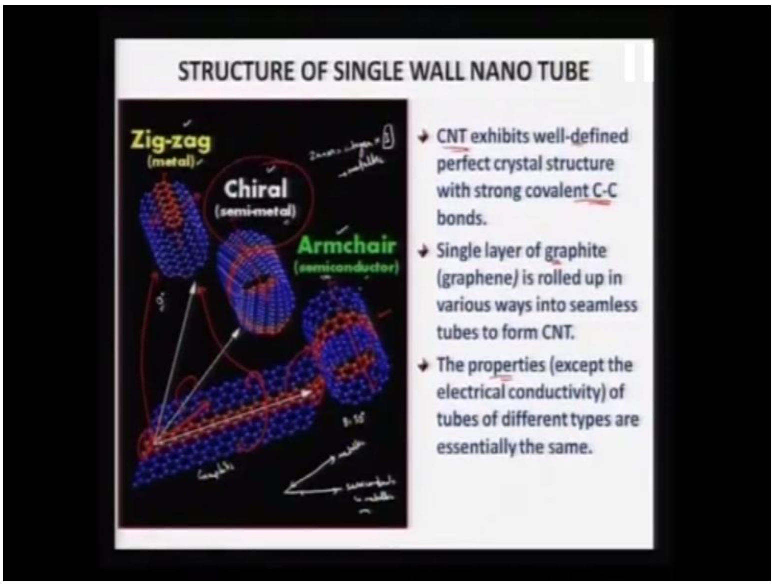

STRUCTURE OF SINGLE WALL NANO TUBE

- CNT exhibits well-defined perfect crystal structure with strong covalent C-C bonds.
- Single layer of graphite (graphene) is rolled up in various ways into seamless tubes to form CNT.
- The properties (except the electrical conductivity) of tubes of different types are essentially the same.

So, now let me show you how this structures look like? So, we can see that once we have graphitic plain the way we roll it we can achieve either armchair chiral or zig zag type of a carbon nanotube. So, in case when we have a armchair we have theta of 30 degree. So, we have 30 degree theta when we have armchair. And in zig zag we have theta of 0 degree. So, depending on that it just matters on way we define it. So, we have 0 degree to in zig zag and armchair is around 30 degree.

So, we can see that the nature or the electrical nature of this one can be very, very different like in zig zag it can be highly metallic, in chiral it is a semi metal and armchair it is a semi conducting. So, depending on that the way we the way we are rolling it we can achieve different type of conductivities in the carbon nanotube. So, that is what we can see out here. Generally armchair we have everything is semi conducting, chiral it can range from semi conducting to metal.,

So, once we have this relation when 2 n plus m is an integer multiplied by 3 then we get something which is metallic. And other cases it is generally semi metallic. So, if you can roll it. So, the rolling is like this. So, this particular part will be metallic whereas, this part will be semi metallic, semi conducting to metallic. So, along this side it will be metallic. And that basically corresponds to the zig zag structure or the 0 direction and in this corresponds to the armchair type of a fabrication which is semi conducting to metallic. And carbon nanotubes they exhibit well defined perfect crystal which a covalent carbon to carbon bond.

And again this graphite is now rolled into various ways. So, I can roll it like this I can roll them like this to get this armchair type of configuration in that manner I can roll it to get a zig zag kind of a structure when I roll them along 0 direction. And then again I can. So, basically I am joining this side with this side to get this armchair. If I can roll them like this s I can see that this things will come at the end the extremists will come at the end and if I am rolling it like this I am getting zig zag.

And if I am rolling them in any other direction then I am getting this chiral type of a structure. And these properties they are very different basically along different directions. So, apart from the conductivity. So, I conductivity can be very very different along armchair or zig zag. Whereas, other properties like if I want to rein force them that also will depend on the covalent bond strength of the covalent bond. So, that will depend again which is essentially the same in all the 3 cases because I again have covalent bonds along the length of the tube.

So, I can get pretty much very uniform properties along this side. And also they are much uniform along the cross section as well. So, depending on where I am loading it, if I am loading it loading it along this I might get very, very high properties whereas, in other case transverse direction it might be different.

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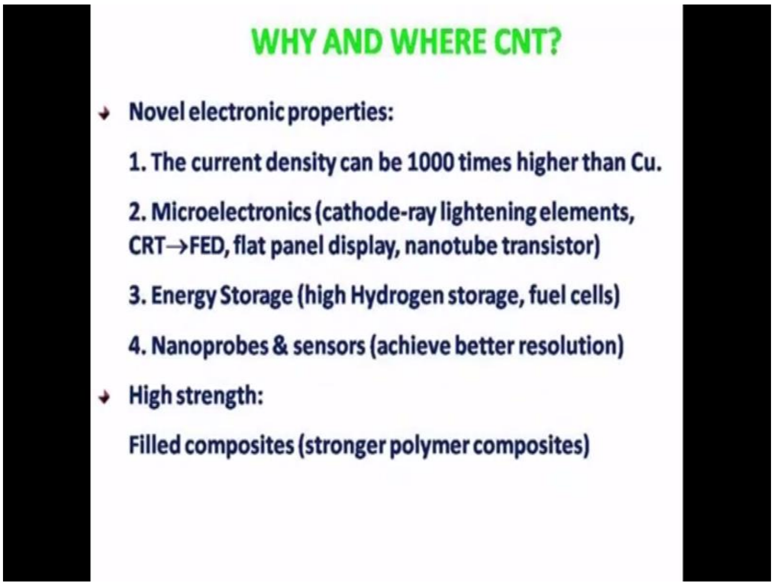

WHY AND WHERE CNT?

- Novel electronic properties:

  1. The current density can be 1000 times higher than Cu.

  2. Microelectronics (cathode-ray lightening elements, CRT→FED, flat panel display, nanotube transistor)

  3. Energy Storage (high Hydrogen storage, fuel cells)

  4. Nanoprobes & sensors (achieve better resolution)

- High strength:

  Filled composites (stronger polymer composites)

So, why do we want to use carbon nanotubes? The current density can be thousand times higher than that of copper because there are no problems associated with the electro migration as in case of copper, but this does not mean the carbon nanotube also have lower resistivity then that of copper. We can see that the carbon nanotube has resistivity to the order of 10 to 50 micro ohms metre. Whereas, that for copper it is 0.01 micro ohms metre. Even if I am conducting silver, it is approximately around hundred times than that of a silver. It can be utilised in microelectronics. So, this cathedral lighting elements c r t flat panel displays nanotube transistors. The idea is that what we achieve in L C D's we have some sort of pixelated picture.

And each pixel has certain dimension. So, because each pixel will give us certain colour and that will eventually produce some pixel which we are looking at with different colours. If we can replace all this pixels by C N T. So, the diameter of C N T is nothing but couple of nanometres. So, if you can replace them by a C N T, I can get more number of pixels in the similar area. So, eventually what I am getting? I am enhancing the resolution of the screen.

So, it will appear more like I am watching face to face anything. And I am it will appear very very much it want the picture will not appear pixelated, but it will appear like I am watching someone face to face and that will produce the clarity in a picture or in a particular display panel. So, that is the idea behind using carbon nanotube. Also carbon nanotube are being utilised for energy storage because it has a hollow structure. It can store hydrogen very easily and then it can be utilised for the application in fuel shells. Also for nano props and censors, if the censor is the smallest possible entity then I can detect that much. So, that particular sensor to that much sensitive to grabbing or detecting a particular species.

If my sensor itself is very very big it will require very high concentration of that species to be able to detect. So, this carbon nanotubes are very, very small entity. So, they can be used as a nano pro. And they can also sense it very easily. So, I can achieve very high resolution that is the advantage again with using C N T which are nano they have nano metre diameter nano metre length diameter. They can only also visualise for very high strength applications.

So, if I can somehow reinforce a material. So, just polymer or a metal matrix with carbon nanotubes I can achieve very high strength as well. So, again C N T's very wide applications like an electronic novel electronic applications because of their high conductivity in microelectronics. Again in energy storage it can be utilised. I can also utilise them as nano props and censors to collect particular signal from a particular species. It can be also utilised for enhancing the strength of the composite. Again it can also be utilised for some biological application. So the application C N T's are just plenty in number.

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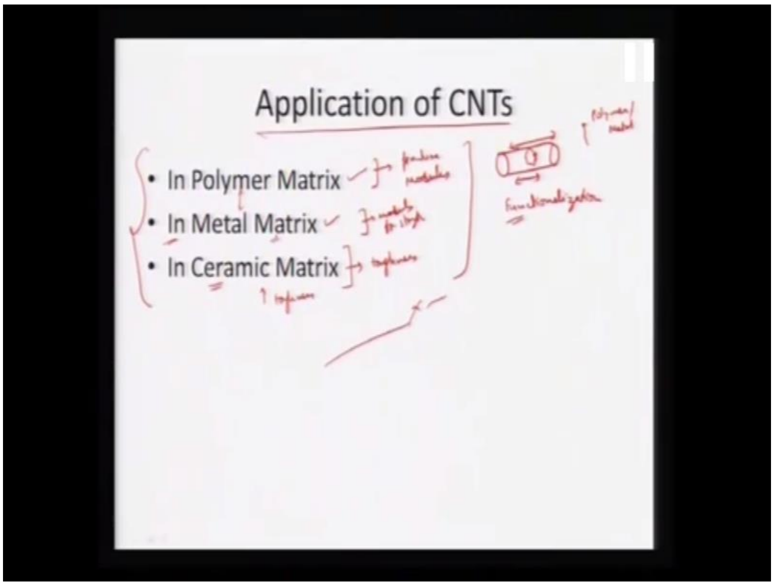

Application of CNTs

- In Polymer Matrix
- In Metal Matrix
- In Ceramic Matrix

So, application C N T are basically utilised for enhancing the strength and polymer matrix, enhancing the model. Again in the metal matrix, but in ceramic matrix the modulus is pretty high already, but what the lack is nothing but the toughness. So, in polymer I want to utilise C N T for enhancing the fracture style, enhancing the modulus. In metal matrix I have enough toughening available, but I want to enhance the modulus or fracture strength.

And in ceramic matrix I want to enhance the toughness, but the problem with C N T is this, that they have very low surface energy because there are no bonds available for it to bond with anything. So, we want to somehow break the bonds of this carbon to carbon and then make some bonds available for reacting with the nearby species that is nothing but polymer metal. So, once we are breaking the bonds of carbon and we are attaching some additional molecules we call it functionalization. Functionalization, it means we are breaking the bonds of carbon those graphitic bonds where allow allowing 1 bond to basically tangle out and then give out a additional bond which is available for bonding with the interfacing species.

It can be polymer of metal and that is what we are interested in, but that if you are damaging this carbon bond then this there will be some damage to the carbon nanotube itself. So, I can have single layer of carbon nanotube single layer of graphene and then I can roll it to form a single wall carbon nanotube. If I am damaging the structure basically I am detonating the properties. So, I may want to go for a double wall or multi wall carbon nanotube. It means I am taking a multiple layers of graphene and then I am rolling it to form carbon nanotube. So, even when I damage the top layer I still have some layers available beneath that to take care of the additional load or to deliver the stress. So, that is what is sudden design criteria which are which need to be considered for designing the carbon nanotube based composites.

So, they can utilise in polymer matrix metal matrix or ceramic matrix. And the utilisation of C N T is very different then all the 3 cases because in polymer I am more interested in reducing the density as well and also enhancing the fracture and the modulus. And metal matrix I again want to enhance the modulus and fracture strength. In ceramic I want to enhance the toughness.

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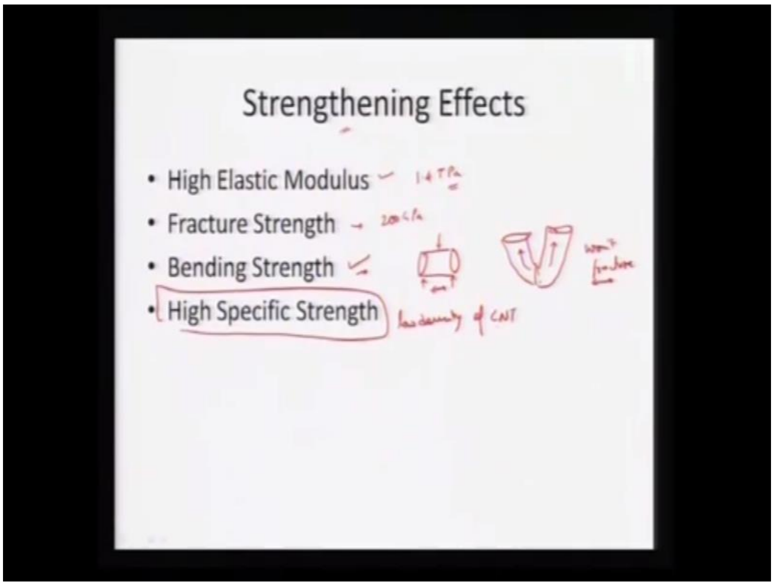

Strengthening Effects

- High Elastic Modulus
- Fracture Strength
- Bending Strength
- High Specific Strength

So, how do I basically enhance the strengthening. I can utilise the higher electric modulus of carbon nanotube that ids to the order of 1.4 tera Pascal which is very very high fracture. Strength can as high as 2 hundred giga Pascal. Also very good binding strength, but advantage is that carbon nanotube they can bend completely. So, I have a carbon nanotube and if I have if I apply certain stress to it certain load to it. It will basically bend completely without breaking. So, it can just bend completely without breaking and that is the advantage of it because of its high strength at the same time it would not fracture. So, it would not fracture

So, it can absorbed very high energy in terms of bending. So, it is stiffness is being utilised and it is modulus also is being utilised in delivering the bending strength to a particular composite. At the same time it is very high specific strength because of its low density. So, because of low density of C N T if I dispersing them in a particular matrix it can also yield very high specifics strength or the overall strength. It can be fracture strength ell strength it can be basically be enhanced because of presence of carbon.

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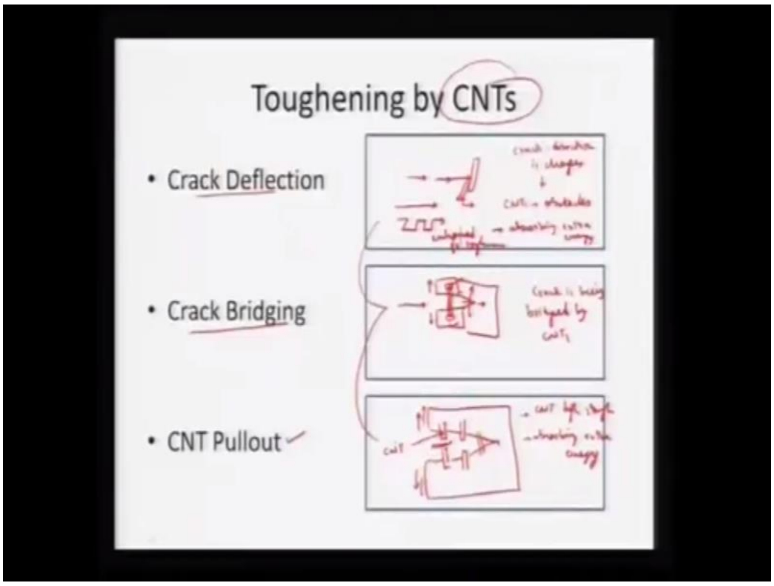

Toughening by CNTs

- Crack Deflection
- Crack Bridging
- CNT Pullout

Apart from that we can also achieve toughening specifically in ceramics. I can achieve toughening by carbon nanotubes by crack deflection. So, if a crack is progressing I can always have some C N T’s to disallow the propagation of crack along this direction and it will have to change its direction. And once the crack direction is changed, it requires additional energy to propagate. So, because now it has to go again in this direction. So, the energy required to change its direction is pretty high. So, C N T's they act as obstacles and they help in absorbing extra energy. That gives rise to crack deflection and crack will not only propagate through them, because of the high modulus and high strength. So, it would not be able to fracture carbon nanotubes right now.

So, in that case we can achieve crack deflections. So, instead of crack propagating straight it has now ((Refer Time: 47:32)) path and that results in the enhancement of the fracture toughness, enhance fracture toughness. Second criteria is crack bridging. In crack bridging what is happening if a crack is trying to propagate and I supply crack is trying to propagate along this side, but then I have a carbon nanotube which is present between particle a and particle b. So, it can it would not allow the crack to propagate further because I have a bridge kind of entity which is out there.

So, for crack to propagate these 2 entities have to go apart, but because of C N T it is holding the 2 particles together or that 2 structures together the 2 surfaces together. So, crack will find very hard to propagate further because it does not have the space. It cannot make these 2 things go apart. So, in the process this is called crack bridging. So, I have crack which is being bridged by the carbon nanotubes. There is a second way of toughening it is called crack bridging.

And third thing is crack C N T pull out. So, in this case when its goes to an extreme I can also get C N T fracture. So, if I had a crack like this when some excessive load is being applied this might start fracturing. So, I have carbon nanotube and applying loading like this. So, it can eventually it can fracture some of the carbon nanotube, but C N T's have very high strength. They are very high fracture strength. So, it is now absorbing extra energy. Ideally that energy would have gone to enhance the crack lane, but now that is gone in fracturing the carbon nanotube. So, eventually the crack length is much shorter than what it would have been in absence of carbon nanotubes.

So, in presence of carbon nanotube it is just restricting the flow of crack in that particular direction. So, we can see carbon nanotubes can enhance the crack deflection. They can cause crack bridging it can also cause C N T pull out. So, by all these 3 processes it can render a toughening to the ceramic. So, in crack deflection the cack has to change the direction. So, it would not be able to propagate. In crack bridging we still have some carbon nanotube left between the 2 surfaces. So, it would not allow it to go further apart.

In C N T pull out we are using some energy to fracture carbon nanotube and since carbon nanotube is a very high fracture strength of a fracture or inner strength or even the bending strength that energy is not being utilised in fracturing C N T rather than fracturing the composite. So, what is happening that overall crack length is not a very short it is now a very shorter length in comparison to what it would have been in absence of carbon nanotube. So, that is how we can get we can get different sort of toughening by the presence of carbon nanotube.

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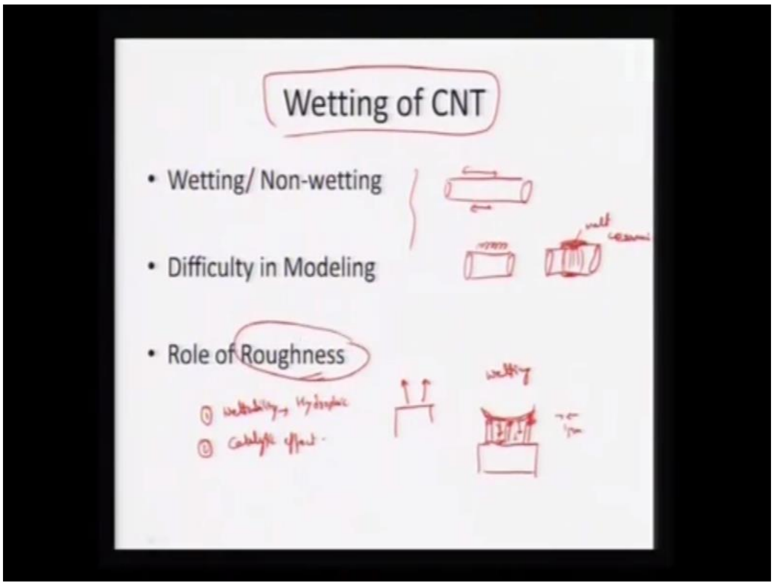

Wetting of CNT

- Wetting/ Non-wetting
- Difficulty in Modeling
- Role of Roughness

① wettability, Hydrophobic
② Catalytic effect.

Second thing is the wetting carbon nanotube. if I want wet carbon nanotube because all the surface it is very very it is very low surface energy because there are there are no free bonds available for anything to sit on this particular material. And if I have a ceramic material and I want to make it a stronger bond or a metal with a stronger bond with it. I need to melt that particular metal. So, that creates a difficulty in modelling because to melt a metal or to melt a ceramic I need to go the melting point plus some additional temperature to cause the melt wetting of the carbon nanotube surface.

So, I have a melt of say ceramic. So, that becomes very very difficult. So, I need to take this melt at very high temperature. So, that it can cover the carbon nanotube. Again the role if roughness. So, it C N T’s can also impart roughness to a structure. And in that case it will affect the overall wetting. What is happening is I have carbon nanotube on the surface and if I put some droplet of water it might just stay over these carbon nanotubes because they can support the water droplet because they are plenty in number without letting the water to get into the ((Refer Time: 52:05)) because it will require very high pressure for the ((Refer Time: 52:07)) to be filled in. A datum around 3 to 10 metres is might be required to fill in the cavity which is approximately 1 micrometre apart.

So, that is why I tells that role of roughness can be very very critical. I can change the overall surface properties. I can change the wettability. I can make it highly super hydrophobic. Second thing I can also enhance world catalytic property. In terms of absorbing or absorbing or detecting a certain species. So, that is that is how I can really alter the overall specification of the surface characteristic by adding roughness to the composite. So, those are all things which can happen in this case of carbon nanotube.

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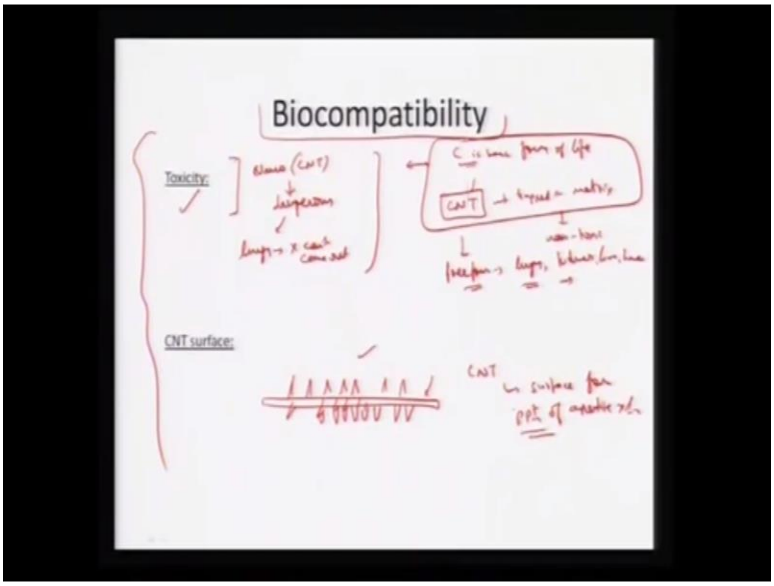

Biocompatibility

Toxicity:

CNT surface:

Again C N T’s are again they are being discussed as toxic as well as biocompatible. Why because toxicity is of a concern when I am using carbon nanotube in a particular biomaterial, there are 2 schools of thoughts. First thing is that anything in a nano form because I am talking about carbon nanotube. So, anything in a nonfarm it is anywhere dangerous because if those particles get into the lungs. It will be very hard for them to come out cannot came out.

So, they might cause some problems of the lungs and it can like it is more like silicosis that silicon guides deposit into the lungs and it cannot really come out, but on the other hand there is second school of thoughts which says that carbon is the basic form of life.

So, anything which is carbon should not harm the functionality because carbon is a basic form of life. And once this carbon nanotube is being reinforce or being trapped in a matrix, it is no more available as a free form. So, then it can be cannot be toxic. So, it is non toxic, but people they still do not know what will happen if C N T's are available in free form.

They might get deposited into either the lungs, kidney. liver or heart or they might even go to the brain and cause some damage. So, C N T's in free form might be dangerous, but once they are being interact in the matrix then they might be much be bio compatible. And apparently there are some researchers who have also shown that once we have a C N T carbon nanotube it can also allow the precipitation of appetite. Appetite is nothing but the mineral part of the bone. So, people are seen that researchers are seen that the appetite can really grow on the carbon nanotube as well. So, carbon nanotube surface can also act as a surface for precipitation of appetite crystals.

So, that is again which are certain concepts which are associated with the carbon nanotube in terms of their toxicity or their assistance in precipitation of appetite. So, again this has to be handled with an extreme care when a bio composite or biomaterial is being developed.

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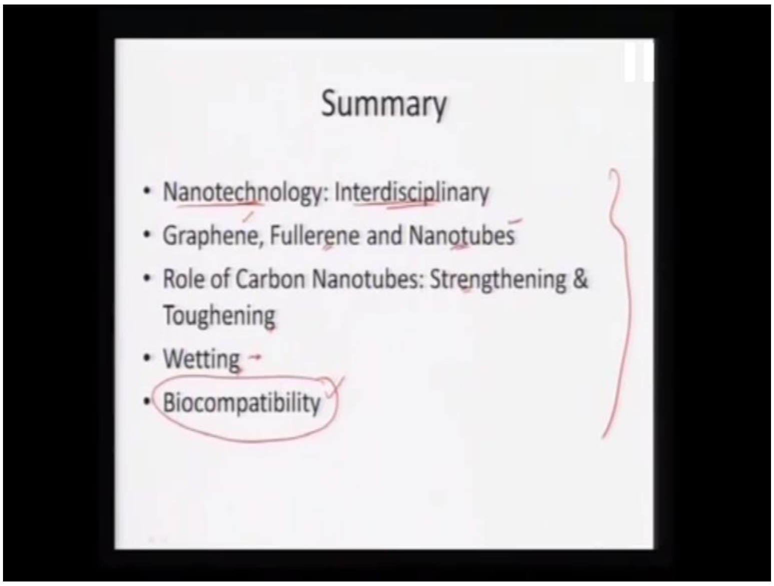

Summary

- Nanotechnology: Interdisciplinary
- Graphene, Fullerene and Nanotubes
- Role of Carbon Nanotubes: Strengthening & Toughening
- Wetting
- Biocompatibility

So, in summary we can see that nanotechnology is basically is interdisciplinary field of research which involves science as well as engineering. Then we learnt about this carbon nanostructures polymorphs specifically the graphene layer, the graphite, fullerene and nanotubes and we consider in all basically the nanotubes. In terms of strengthening and toughening the matrix and also learning about how the wetting can occur in carbon nanotube and why it is very very essential, because I can impart a different functionality to the bio composite or that particular composite.

And then I also worried about the biocompatibility, because I want to utilise their strength for enhancing the toughness of a ceramic that is the appetite. So, whether it can be utilised as a biocompatible material that is again it requires much more research before anything can come to a conclusion, but definitely once they are been incorporated in the matrix they can be used as a reinforcing or strengthening agents. So, with this I close my lecture.

Thank you.