Physics of Functional Materials and Devices

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Lecture – 05, Week 1:
Introduction to Nanomaterials and functionality

Welcome to the fifth lecture of this first week, which is the introduction to the functional materials and types of materials which we will be investigating in this course physics of functional materials and devices. Till now, we have discussed about solid state materials, what are solid materials, then we have discussed about ceramics, then we moved on to polymers and then finally, we had in the previous lecture, we had discussed about composites. In today's lecture, let me introduce to you a very niche area which is becoming extremely useful to all of us and that area is the area of nanomaterials. And the technology associated with nanomaterials or nanosized devices are is called as nanotechnology. We will start today's lecture by defining and explaining to you what are nanomaterials? How do they differ from bulk materials? Why the properties change at nanoscale? And then just like in previous lectures, we will classify nanomaterials into subgroups. By the end of the lecture, you will also be told about the range of applications where these nanomaterials are being utilized.

The word nano stands for a billionth, which means 1 into 10^9. So, if you have 1 nanometer, what would it mean? It would mean 1×10^{-9} meter. So, we are talking about materials whose particles have the dimensions in the range of 10^{-9}meters or devices which have similar dimensions which I just mentioned. The term nanotechnology is relatively new, but the concepts and the knowledge that the materials show different properties when they go from bulk to nano size is known to mankind for significantly many centuries.

If you look into your books, the old Vedas and anywhere you read about medicinal use of nanoparticles, you will find that nano sized gold or nano sized silver were being utilized by our ancestors for centuries and centuries and centuries. They knew that nano-sized gold or silver had medicinal applications, they were antibacterial applications or they could be used to treat certain kinds of diseases, we could because they could attach certain bacteria's to them and then take out those bacteria's along with them as they were thrown out of the body. Therefore, the exact time when humans started using the advantages of nanomaterials is not actually clear, but it is being used by our ancestors is absolutely clear and undoubted. If you come to recent past, then the use of nanomaterials and the shift towards the research in this field can be said to be around 175 to 200 years old. This all started around 1850s when Michael Faraday published his results to explain the way metal particles affect the colors of church glasses.

The use of dispersoids or certain dopants to modify the color of glass which was then being used on the windows or the walls of the churches was well known, but the reasons leading to those modifications were not very well known. Michael Faraday started this work and published his research around 1857. Then came a famous work by Gustave Mee in 1908. But Richard Feynman is considered to be the father of modern day technology. Richard Feynman in his famous APS lecture, the American Physical Society meeting which is held annually in one of these meetings in 1960 Richard Feynman gave a lecture with the title there is plenty of room at the Bottom, where he indicated that novel, a novel means what? New, new physics which is not known till that particular time can evolve if nano size materials were investigated carefully.

So, he gave that lecture and challenged the world that move in this direction and you will be able to find new physics, if you are able to find new physics you will be able to find new applications of these materials. At the same time Ralph Landor who was working at IBM using the quantum mechanical models explained the properties that these nanomaterials will show and the laws of physics that would drive these modifications. So, there were predictions, there were experiments and people were working on modeling, they were all working independently, but they all knew that there would be changes in properties when you move from bulk to nano sized. And if you see right from 1857 now we are in 2023 work is continuing and newer and newer phenomena are being observed. But as new phenomena were being observed many people started working in this area and the whole area became too chaotic and there was confusion as to what is being called nanomaterial.

Even micron-sized particles were being called as nano-sized particles means 1000 nanometers that is not the way one should define these materials. Why? Because 1000 nanometer size particles were not showing modifications in the properties of those materials which were less than 100 nanometers. So, there was a lot of confusion around. Hence many government agencies, research councils from different parts of the world, and countries came together and they defined a specific definition for nanomaterials. These are a special class of materials that have at least one of the dimensions in the range of 1 to 100 nanometers.

Dimensions mean if you look into a three-dimensional particle what do you know? You have the x-axis, you have the y-axis and you have the z-axis. So, if the dimensions around a axis is a along y is b, and along z is c then any one of these dimensions should be in the range of 1 to 100 nanometers. That was the definition that was given. Now, immediately, you will get a question suppose you are only saying it is one of the dimensions. No, let me take two dimensions in the range of 1 to 100 nanometers.

Then the follow-up question would be let us take all three dimensions in the range of 1 to 100 nanometers. What would happen? Will the properties change? Based on these questions some classifications were defined and you will see that based on this confinement that size range which is there you can have 1D structures, you can have 2D structures and you can have zero-dimensional structures depending upon the dimensions which have been confined along the three directions which I just mentioned. Just to take it further you trying to explain it using animation. Suppose you have the three-axis and you have a bulk particle, you have a bulk particle large size particles. It is a 3D particle which is large.

Then what do you do? You start cutting this particle from the top. So, you start cutting this particle from the top. So, if you are cutting it from the top, what would you get? You will get a planar structure. So, you have the three axes, but you can see that the dimensions along the z direction in these two are quite different.

And if they are different then what will happen? The properties can be expected to be different. But if this dimension that I have obtained is now in the range of 1 to 100 nanometers, this will be called a dino material. And now what do you do? You start taking this particle and cut it from one of the sides. So, you start cutting it from one of the sides. And what do you get? You get a structure that has three dimensions, but two of them are much smaller than the magnitude in the third direction.

If the dimension in the two directions let's say z and x direction are in the range of 1 to 100 nanometers, again you have a type of nano material. What is the third logical step? Now, let us start cutting it from the third side. So, I start cutting this material from the third side. What will you get? You will get a particle, this is a slightly zoomed picture, you will get a particle which has all three dimensions in the range of 1 to 100 nanometers. Hence, you can see from this animation, what is that transition we are following. You are following from bulk to a condition where one of the dimensions goes in the range of 1 to 100 nanometers, then you transform to a condition where two dimensions are in the range of 1 to 100 nanometers and then you transform to a condition which is leading to a particle that has all the three dimensions in the range of 1 to 100 nanometers and that is where we define the nature and the type of particles.

So, if you start from a bulk-type structure, then if you go to a condition where one of the three dimensions have been reduced significantly, then it is called as quantum well-type structure or a quantum well type nanomaterial. If you go to a condition where two of these dimensions go in the range of 1 to 100 nanometers, you call them as quantum wire. If you have all three dimensions in the range of 1 to 100 nanometers, they are called as quantum dot. You can imagine how a well looks like. So, you have one of the dimensions which is smaller in comparison to the depth and hence you have the well structures, the wire structures.

So, if you look into the wire, what do you get? You have two dimensions which are smaller, but the length of the wire is much larger. So, you have a quantum well, a wire, and a dot structure. Similarly, you can draw it for a spherical-shaped bulk particle. You can go from quantum well to quantum wire to quantum dot-type structures. The previous was the animation that was used to explain the types of nanomaterials you can see.

This slide gives you real examples of various types of materials that are formed such that their sizes are in the range of 1 to 100 nanometers. You can see the scales which are mentioned 20 nanometers, 100 nanometers, and 50 nanometers and if you can then reduce, you can just count the three dimensions, you will find that they are in the range of 1 to 100 nanometers. These are called 0D type nano material. So, 0D would be related to what type of nanomaterial? Those would be quantum dots. Then you have 1D structures.

1D structures are what? These are the structures where one of the dimensions is much longer than the other two. So, what would be this kind of structures? These structures would be nanowire type structures and the third would be two-dimensional nano materials. That means, two of the dimensions you can see are planar structures, you can clearly see these are materials with planes in them, you can see these materials. So, you can see these materials. There is another material at the bottom, there is another particle at the bottom.

So, you have planes and the two dimensions of this planar-like structure is more than 100 nanometers, but the dimension in the third direction is what? In the range of 1 to 100 nanometers. So, this is a real example. These are scanning electron microscopes or transmission electron microscope pictures of nanosheets or nanoplates or nano walls or nano discs like nanomaterials which are two-dimensional nanomaterials. So, what did we see? These are nano-structured materials, 0D structures are called quantum dots, 1D structures are called quantum wires, and 2D types are called quantum wells. But then what do we actually mean by 0D, 1D, or 2D? This dimensionality is related to the direction in which a free electron or a conduction electron is free to move in this nano material.

If you look into quantum dot structures. So, if you look into a quantum dot, this particle has all a, b, and c in the range of 1 to 100 nanometers. This means if there is a free electron or a conduction electron, it can go in the direction of 1 to 100 nanometers and then it gets restricted. So, the motion is confined, it is restricted in x direction. Similarly, if it is moving in the y direction, it can only go in up to 1 to 100 nanometers.

So, its motion is again restricted. So, you have confinement in the y direction, and a similar concept is there in the z direction. Hence, this 0 dimension means that the confinement is all in the 3 directions. 1D structures mean what? You have confinement in 2 directions, but the conduction electron or the free electron at least has 1 dimension where it can move freely. So, if you look into a wire-like structure, the conduction electron is restricted in this direction is restricted in the other direction, but it can move freely in the third direction.

Similarly, if you look into a planar structure, if you look into a planar structure, what do you get? The particle is free to move in this direction, in the other direction, but the third direction which it has is much much smaller than the other 2 directions. So, it can be free to move in the x axis direction, in the z direction, but it is confined in the y direction and the dimension along the y direction is in the range of 1 to 100 nanometers. So, 0D, 1D and 2D is the way where you define the directions in which the conduction electron or the free electron is able to move in these kinds of nanomaterials. Now, what is the basic thing which changes the properties of these nanomaterials? So, if you have a bulk particle, then for example, if you have a sphere you will have the radius r, the surface area would be $4\pi r^2$, the volume would be $\frac{4}{3}\pi r^3$ and surface-to-volume ratio would be $\frac{3}{r}$. As you go on reducing r, so you go from a much larger size particle to a smaller size spherical particle which is a transformation we are talking about.

What is changing? You are changing the value of r which is diameter 2r. Let us say r'. Now, as you transform from a much larger size particle to a smaller size particle, you are reducing the value of r. If you are reducing the value of r, the surface-to-volume ratio becomes r in the denominator. So, $\frac{S}{V}$ is becoming what? Becoming much larger.

And if this ratio is becoming much larger means what? More particles are becoming available on the surface. So, you have more number of particles on the surface. For example, if you want to have catalysis where there is the transfer of electrons. Now, these transfers of electrons are going to take place between the particles. Now, if you have more particles on the surface, there are more active sites where this transfer is going to take place and hence the catalysis or the catalytic reaction is bound to increase.

Hence, in any application where interaction with the particle is going to play a critical role, their nanomaterials will have the advantage. Why? Because more particles are on the surface and hence you will have more interactions taking place and that is the first thing that gives the advantage to these nanomaterials that is surface to surface-to-volume ratio. Then comes the number of electrons and density of states considerations. If you have the number of conduction electrons which are given by n which is a function of energy, this depends on the value of the energy and also on the dimensionality of the space. You can clearly see that if you have a large size particle or a small size particle, the way these conduction electrons can move would be very different and hence the dimensionality of space also becomes critical.

In a 1D structure, the Fermi region containing the electrons has a length of $2k_f$ where k_f is the Fermi surface. In 2 dimensional structure, you have the area, so that is $\pi {k_f}^2$ and similarly, in 3D structures, you have $\frac{4}{1}\pi {k_f}^2$ is the Fermi region. Then we define another parameter called density of state which denotes the relation dn/d E. This means it gives us the number of electrons d n with an energy E within a narrow range of energy dE, let us say you are taking between the range E_2 and E_1. So, what is the number of electrons which is present in that small range, and that will define the way your conduction electron, the conduction mechanisms, the semiconducting properties, the thermal properties, and the catalytic properties would occur.

Why? Because these are the number of electrons that are going to take part in various phenomena. Without going into details, because details we will discuss from next week onwards, you can clearly see if I plot n(E) as a function of E or dE as a function of E, the nature of curves are very different. This curve gives you the variation of n(E) and dE as a function of E for 4 quantum structures. What do we mean by that? So, you have 4 quantum structures one after the other which have been considered. So, you can have 4 quantum dots or 4 quantum wires or 4 quantum well, and that has been considered.

If you have only one, then you can understand you will have to consider only the first part of the curve. You can see that the natures are quite different. If you consider the density of state for a quantum dot with that of a quantum wire, it is very different. If you go to quantum well, it is again quite different from that of the other two and bulk has an altogether different behavior. Hence, you can see that the number of conduction electrons as well as the density of states will change significantly as we move from one structure to the other and as that happens, all the electrical properties, the thermal properties, the semiconducting properties, they are bound to show modifications.

In addition to the enhanced surface-to-volume ratio, immediately you will be able to realize that as you go to smaller dimensions, what is happening? You have reduced transport lengths for both mass and charge transport. Mass transport means division processes. So, you are moving mass. Charge transport any electrical phenomena.

So, the charge can be an electron or it can be an ion. So, you have various applications of these and if you are reducing the transport length, then you have an advantage. The advantage of high surface area has been discussed earlier. In addition, because you are reducing the size, the immediate advantage comes in as low density. If it is low density, what is the advantage? If you can maintain low density without compromising the property that you want to obtain from that material, it means you will have to use less amount of material to obtain similar performance. Less amount of material means what? You can immediately lead to a reduction in the cost and hence, you see that there are significant advantages which are associated with nanomaterials and hence, they are finding application in the field of energy, both energy generation as well as energy storage devices.

Storage devices like supercapacitors, batteries, generation devices such as solar cells, fuel cells, or even wind turbines. It is difficult to imagine how nanomaterials are being used in wind turbines, but when it comes to the use of nanomaterials in detail, then you will be able to see how these nanomaterials are being utilized in wind turbines. Then, you are using these materials in medicines and drug delivery. The concept of nanobots means nanorobots, which are called as nanobots, targeted drug deliveries. So, these are being conceptualized and they are actually being tried now in the field because people have now obtained proficiency in the fabrication of nanomaterials which have to be used here.

Then, you have seen memory chips, you are using them in touch screen layers or electronic gadgets. For example, everybody talks about ICs. ICs means what? Integrated circuits and circuits are divided into various sub-classifications based on the number of components that are there in a given IC. You have small-scale integration SSI, medium-scale integration MSI, you have large scale integration, very large-scale integration and you have in today's world ultra large scale integration. SSI means you were integrating 1 to 12 components such as the resistance, the transistor, and the diodes in one chip.

And now, from SSI in the same area, in the same size chip, you are going to a condition where you are able to fabricate more than a million components in the same size chip. So, more than a million components let us say in a 1 square inch size chip that is the capability that we have now and that is where the use of nanotechnology in electronics is being felt and is being utilized massively all across the industries. Similarly, you find their application in optical sensors for imaging, and optoelectronic devices, the non-linearity of these materials is being used in different types of optical sensors and devices and then you have their massive applications in the field of photonics. With this, we conclude this lecture. Hopefully, you have understood the definition of nanomaterial.

You must be able to define what a nanomaterial is. You should understand the range of applications that these nanomaterials have in today's world and if you look around, you will find that you are surrounded by nanomaterials and devices which are fabricated using nanotechnology. Being an introductory lecture, I have tried to keep the discussions brief and when we come to the week where we will be talking about nanomaterials in detail, you will be able to understand much more and in more detail about these materials and you will find that the field of nanotechnology is rapidly evolving and in coming decades, this will become even more rapid. These are the references that were used to get the data and information for the preparation of this lecture it brings us to the end of the lectures of the first week and from next week, we will start talking about the synthesis of the materials that have been introduced to you in this first week and the importance of synthesis protocols before we start talking about the properties and characterization of those materials. Thank you very much. Thank you.