The Weird World of Nanotechnology

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In the annual meeting of the Americal Physical Society, held on 29 December 1959, the Nobel Laureate physicist Richard Feynman delivered a talk entitled "There's Plenty of Room at the Bottom". In this talk he said, "What I want to talk about is the problem of manipulating and controlling things on a small scale ... What I have demonstrated is that there is room – that you can decrease the size of things in a practical way. I now want to show that there is plenty of room ...".

The essence of Feynman's lecture was that there is a lot of scope for research on materials on a very small, i.e. nonometre scale. However, there may be new laws of physics governing the behaviour of matter at such (nano) scale. This may give rise to new kinds of forces and new kinds of effects. Anticipating this, Feynman said in his lecture, "At the above level, we have new kinds of forces and new kinds of possibilities, new kinds of effects. The problem of manufacture and reporduction of materials will be quite different".

This historic lecture of Feynman, running to 7000 words, was published in the February, 1960 issue of *Engineering and Science.* However, the person who was instrumental in popularising nonotechnology, the technology operating at the nano scale, was K. Eric Drexler. In 1986, he published his book entitled *"Engines of Creation: The Coming Era of Nanotechnology"*. He also founded an institute, the Foresight Institute, and became its Chairman.

What is 'Nano'?

The word nano comes from the Greek work 'nanos' meaning dwarf. But, the prefix nano actually stands for a billionth (10^{-9}). Thus, one nanometre means one billionth of a metre (1 nm=(10^{-9}). To have a feel of how much one nanometre is, imagine ten hydrogen atoms being laid side by side. The combined width of all these atoms would equal one nanometre. Incidentally, one nanometre is also one thousandth the length of a typical bacterium or one millionth the size of a pinhead.

It may be noted that a nanometre is not the extreme in minisaturisation. One can scale down by one thousandth of a nanometre and get picometre (1 pm=(10^{-12}). Scaling down even further in steps of one thousand, one first encounters femtometre (1 fm=(10^{-15}) and finally one attometre (1 am=(10^{-18}).

Then, why are the scientists busy conceiving machines, implements and devices at a nanoscale? In fact, the properties and behaviour of materials undergo a sea change as we go from the macroworld (where the bulk properties of materials emerge from the collective behaviour of trillions of atoms) to the world of individual atoms and molecules. For instance, a 5-centimetre metal piece would have similar properties as a 1-centimetre piece or even a 1-millimetre piece. However, a few isolated atoms of that metal are expected to show quite different properties. But, at what stage does this change of property begin to manifest itself? The transition from the atomic to the bulk properties occur at the nanometre scale, say scientists. At this scale, the atoms combine to form clusters. These clusters are variously called nonoparticles, quantum dots, Q-particles, artificial atoms, and so on. The diameter of a cluster usually ranges from 1 to 100 nanometres. These clusters are too large to be considered as molecules and too small to be treated as bulk material. Therefore, they give rise to an entirely new class of material called nanomaterial.

What are the laws that govern the behaviour of such material? At the atomic scale, the laws of quantum mechanics are applicable while the laws of classical physics govern the macroworld. However, the nanoworld can neither be described by the straightforward application of quantum mechanics or can it be described by the simple laws of classical physics. The nanoworld can, therefore, be described by an exotic combination of the laws of classical and quantum mechanics. These laws are not fully well-understood. However, the scientists have been busy unravelling these laws for almost past two decades now.

The New Laws of the Nanoworld

In 1987, Bart J. van Wees of the Delft University of Technology and Henk van Houten of the Philips Research Laboratories were studying the flow of current resulting from the movement of electrons through narrow conducting paths within a semiconductor. By symmetrically varying the width of the conduction paths, the researchers measured the changes in the conductance values. They were indeed surprised to find a staircase pattern. Later, David Wharam and Michael Pepper of the University of Cambridge observed similar results.

The above studies clearly revealed that the electrical conductance is quantised. Later, Michael Houkes, Thomas Tighe and Keith Schwab discovered that thermal conductivity is also quantised.

Another phenomenon seems to manifest at the nano scale. In 1985, Konstantin Likharev, a young physics professor at Moscow State University, working with Alexander Zorin and Dmitri Averin, proposed that it would be possible to control the movement of single electrones on and off a special conductor, called Coulomb Island, that is weakly coupled to the rest of a nanocircuit. This phenomenon wherein the coulomb island allows conduction of only one electron at a time is called coulomb blockade. This could form the basis for an entirely new type of device, called a single-electron transistor. In 1987, thanks to the advances in nonofabrication, Theodore A. Fulton and Gerald J. Dolan of Bell Laboratories indeed succeeded in constructing the first single-electron transistor.

Thus, it is seen that on the nano scale the laws of electrical and thermal conduction get quantised and the electrons while passing through a special conductor (called coulomb islands) become highly 'disciplined'; they pass one by one through the conductor.

Understanding the basic science of matter at the atomic level have helped scientists in fabricating structures at the nano scale. As a result, varied approaches to fabricating nanostructures have emerged in the nanoworld. The invention of scanning tunnelling microscope (STM) by Heinrich Rohrer and Gerd K. Binning of the IBM Zurich Research Laboratory, for which they received the Nobel prize in physics in 1986, not only allowed scientists to observe the atomic world but also enabled them to create nanostructures. The success of the STM led to the development of another scanning probe device, called atomic force microscope (AFM). The pyramid-shaped tip on the AFM, which is about 2 to 30 nm wide, can be used to physically move the nanoparticles around the surfaces and to arrange them in patterns.

Indeed, the invention of the scanning probe devices (STM and AFM) has provided new innovative tools to the scientists for viewing, characterising and for manipulating the nanostructures. This will help them in creating implements that can be put to varied uses.

Lithograph techniques are used for fabricating electronic devices such as microchips. Besides conventional photo lithography scientists have also evolved soft lithograph and dip-pen lithograph techniques; the latter uses atomic force microscope. However, all these lithograph techniques are called top-down methods because they begin with bulk structure and slowly reduce it to the nano scale for carving out nanostructures. Thus, nanoelectronic structures can be developed using top-down methods. However, scientists have found these methods neither very convenient nor cheap. So, researchers have shown growing interest in bottom-up methods which start with atoms or molecules and build up to nanostructures.

The bootom-up methods use a basic principle of nature, called self-organisation, discovered by J.M. Lehn for which he received the Nobel prize. Atoms, molecules, groups of molecules and even bigger units tend to structure by themselves towards well-ordered units. This self-assembling property of atoms and molecules can be used for making the smallest nanostructures, with dimensions between 2 and 10 nm, easily and inexpensively. Nanotubes, which are graphite cylinders with unusual electrical properties, and quantum dots – the semiconducting crystals containing a few hundred atoms – are examples of self-organising structures.

This knowledge about self-organising structures can be used for technological applications, i.e. in the production of new materials or in life sciences research. Materials ten times as hard as steel and considerably lighter at the same time and destruction of tumour are just two examples of nanotechnology in the fields of material and life sciences.