(Invited Paper)
Nanotechnology: The emerging cutting-edge technology
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Advances in Atomic & Molecular Nanotechnology

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By

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Abstract

In this report the author is presenting the advances made in the atomic and molecular nanotechnology, ability to systematically organize and manipulate properties and behavior of matter in the atomic and molecular levels. It is argued that through nanotechnology it has become possible to create functional devices, materials and systems on the 1 to 100 nanometer (one billionth of a meter) length scale.

The reasons why nanoscale has become so important are presented. Historical aspects of nanotechnology are introduced starting with the famous 1959 lecture by R.P. Feynman. It is suggested to name the nanometer scale the *Feynman* (ϕnman) *scale* after Feynman's great contributions to nanotechnology (1 *Feynman* [ϕ] $\equiv 10^{-9}$ *meter* $= 10^{-3}$ *Micron* [μ]=10 *Angstroms* [Å]). Recent inventions and discoveries in atomic and molecular aspects of nanotechnology are presented and the ongoing related research and development activities are introduced.

It is anticipated that the breakthroughs and developments in nanotechnology will be quite frequent in the coming years. Development of an international initiative through the avenues of the United Nations for a more just global impact of this technology is recommended.

Introduction

The author of this paper has spent almost 35 years of his adult life researching into the atomic and molecular based study of matter. This has included prediction of the behavior of fluids and solids and their phase transitions starting with the consideration of interatomic and intermolecular interactions among atoms and molecules of the systems [1-3]. A few years ago he was introduced to the fascinating subject of nanotechnology and the fact that it will lead us to the next industrial revolution [4,5]. What you read in this report consist of a reflection of the experiences of the author describing nanotechnology from the atomic and molecular interactions point of view.

If one likes to have the shortest and most complete definition of nanotechnology one should refer to the statement by the US National Science and Technology Council [4] which states: "*The essence of nanotechnology is the ability to work at the molecular level, atom by atom, to create large structures with fundamentally new molecular organization. The aim is to exploit these properties by gaining control of structures and devices at atomic, molecular, and supramolecular levels and to learn to efficiently manufacture and use these devices*". In short nanotechnology is the ability to build micro and macro materials and products with atomic precision.

The Greek word "nano" (meaning dwarf) refers to a dimension which is one thousand times smaller than a micron. One nanometer (NM) is one billionth of a meter and it is also equivalent to ten Angstroms. 1 NM is 10,000 times smaller than the diameter of a human hair. One cubic nanometer (NM^3) is roughly 20 times the volume of an individual atom. A nanoelement compares to a basketball like a basketball to the size of the earth.

The Importance of Nanoscale:

Nanscale is a magical point on the dimensional scale: Structures in nanoscale (called *nanostructures*) are considered at the borderline of the smallest of human-made devices and the largest molecules of living systems. Our ability to control and manipulate nanostructures will make it possible to exploit new physical, biological and chemical properties of systems that are intermediate in size, between single atoms, molecules and bulk materials.

There are many specific reasons why nanoscale has become so important some of which are as the following [5]:

(i). The quantum mechanical (wavelike) properties of electrons inside matter are influenced by variations on the nanoscale. By nanoscale design of materials it is possible to vary their micro and macroscopic properties, such as charge capacity, magnetization and melting temperature, without changing their chemical composition.

(ii). A key feature of biological entities is the systematic organization of matter on the nanoscale. Developments in nanotechnology would allow us to place man-made nanoscale things inside living cells. It would also make it possible to make new materials using the self-assembly features of nature. This certainly will be a powerful combination of biology with materials science.

(iii). Nanoscale components have very high surface to volume ratio, making them ideal for use in composite materials, reacting systems, drug delivery, and chemical energy storage (such as hydrogen and natural gas).

(iv). Macroscopic systems made up of nanostructures can have much higher density than those made up of microstructures. They can also be better conductors of electricity. This can result in new electronic device concepts, smaller and faster circuits, more sophisticated functions, and greatly reduced power consumption simultaneously by controlling nanostructure interactions and complexity.

Atomic and Molecular Basis of Nanotechnology

Having worked on the molecular theory of matter one always is exposed to the quantum-mechanical Heisenberg Uncertainty Principle with the consequence that the position and momentum of an object cannot simultaneously and precisely be determined [6]. Then the first questions that may come into mind is how could one be able to brush aside the Heisenberg Uncertainty Principle, Figure 1, to work at the atomic and molecular level, atom by atom as is the basis of nanotechnology. The Heisenberg Uncertainty Principle helps determine the size of electron clouds, and hence the size of atoms. According to Werner Heisenberg "The more precisely the POSITION is determined, the less precisely the MOMENTUM is known". Heisenberg's Uncertainty Principle applies only to the subatomic particles like electron, positron, photon, etc. It does not forbid the possibility of nanotechnology which has to do with the position and momentum of such large particles like atoms and molecules. This is because the mass of the atoms and molecules are quite large and the quantum mechanical calculations by the Heisenberg Uncertainty Principle places no limit on how well atoms and molecules can be held in place [4].

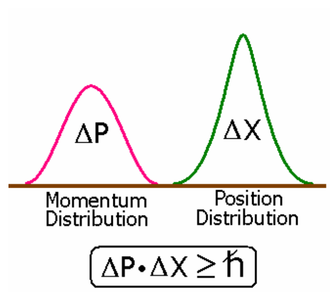

Figure 1: Heisenberg Uncertainty Principle

Historically nanotechnology was for the first time formally recognized as a viable field of research with a lecture given by Richard P. Feynman with the title "*There's Plenty of Room at the Bottom*" on December 29th 1959 at the annual meeting of the American Physical Society [8]. Feynman described then the advances made in this field in the past and he envisioned the future for nanotechnology. His lecture was published in the February 1960 issue of Engineering & Science quarterly magazine of California Institute of Technology**.**

In his talk Feynman described how the laws of nature do not limit our ability to work at the molecular level, atom by atom. Instead, he said, it was our lack of the appropriate equipment and techniques for doing so. Feynman in his lecture talked about "*How do we write small?*", "*Information on a small scale*", possibility to have "*Better electron microscopes*" that could take the image of an atom, doing things small scale through the "*The marvelous biological system*", "*Miniaturizing the computer*", "*Miniaturization by evaporation*" example of which is thin film formation by chemical vapor deposition, solving the "*Problems of lubrication*" through miniaturization of machinery and nanorobotics, "*Rearranging the atoms"* to build various nanostructures and nanodevices, and behavior of *"Atoms in a small world*" which included atomic scale fabrication as a bottom-up approach as opposed to the top-down approach that we are accustomed to [7]. Bottom-up approach is self-assembly of machines from basic chemical building blocks which is considered to be an ideal through which nanotechnology will ultimately be implemented. Top-down approach is assembly by manipulating components with much larger devices which is more readily achievable using the current technology.

It is important to mention that almost all of the ideas presented in Feynman's lecture, and even more, are now under intensive research by numerous nanotechnology investigators all around the world. Later Feynman in 1983 suggested that a scaleable manufacturing system could be made which will manufacture a smaller scale replica of itself [9]. That, in turn would replicate itself in smaller scale, and so on down to molecular scale.

We have made substantial progress on the fundamentals of bottom-up approach nanotechnology. Some of the important achievements include the manipulation of single atoms on a silicon surface [10], positioning single atoms with a scanning tunneling microscope [11] and the trapping of single 3NM colloidal particles from solution using electrostatic methods [12].

Feynman's 1959 lecture [8] initiated a number of research activities among the scientists at the time. A good example is the publication of two books on "Thermodynamics of Small Systems" by T.L. Hill [13] in early 1960s. Thermodynamics of small systems is now called "nanothermodynamics" [14]. The author of this report was privileged to offer a short course on nanothermodynamics to a large group of university professors, other scientists and graduate students during last May [15].

In 1960s when Feynman recognized and recommended the importance of nanotechnology the devices necessary for nanotechnology were not invented yet. At that time, the world was intrigued with space discoveries and exploration and desire and pledges for travel to the moon, partly due to political rivalries of the time and partly due to its bigger promise of new frontiers that man had also not captured yet. Research and developments in small (nano) systems did not sell very well at that time with the research funding agencies and as a result little attention was put in it by government agencies.

It is only appropriate to name the nanometer scale the *Feynman* (ϕnman) *scale* after Feynman's great contribution and we suggest the notation "ϕ " for it like Å is used for Angstrom and μ is used for micron.

One *Feynman* (ϕ) ≡ 1 *Nanomete*r (NM)= 10 *Angstroms* (Å)= 10^{-3} *Micron* (μ) = 10^{-9} *Meter* (m)

Recent Discoveries and Inventions

Nanotechnology received its greatest momentum with the invention of scanning tunneling microscope (STM) in 1985 by Binnig and Rohrer [16].

STM allows imaging solid surfaces with atomic scale resolution. It operates based on tunneling current, which starts to flow when a sharp tip is mounted on a piezoelectric scanner approaches a conducting surface at a distance of about one NM. This scanning is recorded and displayed as an image of the surface topography. Actually the individual atoms of a surface can be resolved and displayed using STM. After the Nobel prize award in 1986 to Binnig and Rohrer for the discovery of STM it was quickly followed by the development of a family of related techniques which, together with STM, may be classified in the general category of Scanning Probe Microscopy (SPM) techniques. Of the latter technologies, the most important is undoubtedly the atomic force microscope (AFM) developed in 1986 by Binnig, Quate and Gerber [17]. AFM, as shown in Figure 2, is a combination of the principle of STM and the stylus profilometer. It enables us to study non-conducting surfaces, because it scans van der Waals forces with its "atomic" tips. Presently several vendors are in the market with commercial AFMs. AFM and STM possess three-dimensional resolutions up to the atomic scale which cannot be met by any other microscope. The AFMs sold by most manufacturers are generally user-friendly and they produce detailed images. AFM has found versatile applications in nanotechnology as well as other fields of science and engineering.

Figure 2 shows a schematic of the typical AFM tool that we use in our laboratory at UIC. The main components of this tool are thin cantilever with extremely sharp (10 Å to 100 Å in radius) probing tip, a 3D piezo-electric scanner, and optical system to measure deflection of the cantilever. When the tip is brought into the contact with the surface or in its proximity, or is tapping the surface, it being affected by a combination of the surface forces (attractive and repulsive). Those forces cause cantilever bending and torsion, which is continuously measures via. the deflection of the reflected laser beam. 3D scanner moves the sample or, in alternative designs, the cantilever, in 3 dimensions thus scanning predetermined area of the surface. A vertical resolution of this tool is extremely high reaching 0.1 Å (1 Å is on the order of atomic radius).

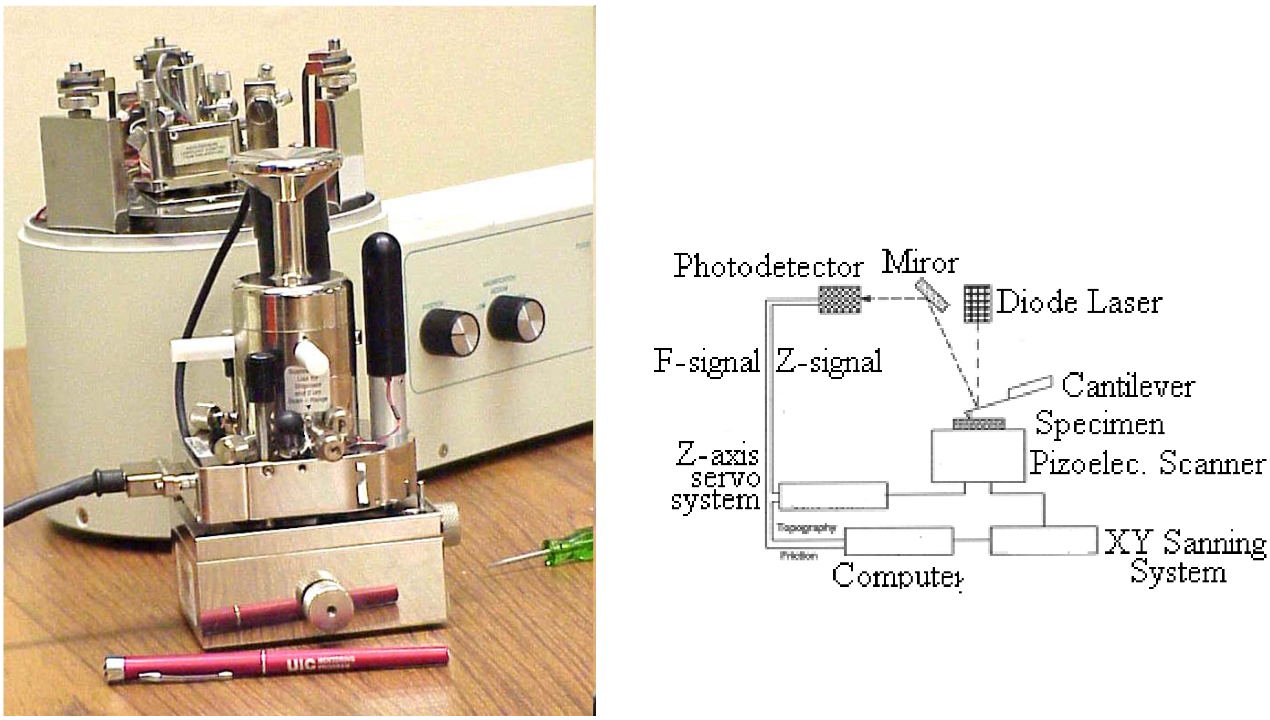

Figure 2: Schematic of the typical AFM and its function

Buckminsterfullerene (or fullerene), C60, as is shown in Figure 3 is another allotrope of carbon (after graphite and diamond), which was discovered in 1985 by Kroto and collaborators [18]. These investigators used laser evaporation of graphite and they found Cn clusters (with n>20 and even-numbers) of which the most common were found to be C60 and C70. For this discovery by Curl, Kroto and Smalley were awarded the 1996 Nobel Prize in Chemistry.

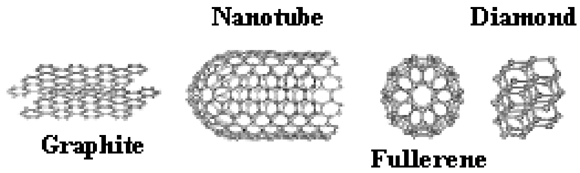

Figure 3

Since the time of discovery of fullerenes over a decade and a half ago, a great deal of investigation has gone into these interesting and unique nanostructures. They have found tremendous applications in nanotechnology. In 1990 a more efficient and less expensive method to produce fullerenes was developed by Krätchmer and collaborators [19]. Further research on this subject to produce less expensive fullerene is in progress [20]. Availability of low cost fullerene will pave the way for further research into practical applications of fullerene and its role in nanotechnology.

Carbon nanotubes were discovered by Iijima in 1991 [21] through vaporizing carbon graphite with an electric arc under an inert atmosphere and its chemical vapor deposition.

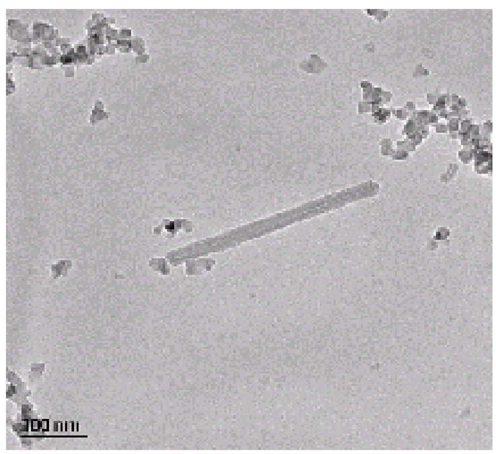

Figure 4: TEM image of a multiwall carbon nanotube surrounded by soot particles [22]

The nanotubes produced by Iijima appeared to be made up of a perfect network of hexagonal graphite, Figure 3, rolled up onto itself to form a hollow tube. Figure 4 is the electron microscope image of a nanotube found in soot [22].

There is a great deal of interest and activity in the present day to find applications for fullerene and carbon nanotube. Considering the tremendous applications which these nanostructures could have in nanotechnology it will be necessary to understand their physicochemical properties, their stability and behavior under stress and strain, their interactions with other molecules and nanostructures and their utility for novel applications. Figure 5 demonstrates an electron microscope image of the peculiar behavior of water in a nanotube under variations of temperature [23]. Whether these peculiarities are due to phase separations and transitions, interfacial effects, fragmentation and/or other unknown phenomena is not understood yet.

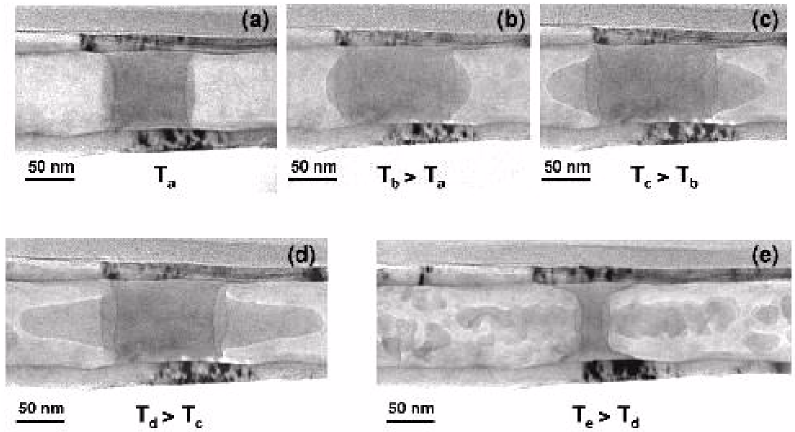

Figure 5: Complex temporal behavior of a water inclusion upon heating with the electron beam [23]: (a) initial state, (b), (c) expansion of the inclusion, possibly due to gas dissolution into the liquid under high pressure, (d) Formation of long tongue protrusions near the axis, and (e) disintegration of the inclu-sion and formation of a thin membrane. The observed events were irreversible after (b).

Another recent observation of the behavior of fluid water in a nanotube [24] is what is shown in Figure 6. According to this figure the vacuum condition outside of the nanotube is not capable of removing the water droplets and bubbles out of the nanotube.

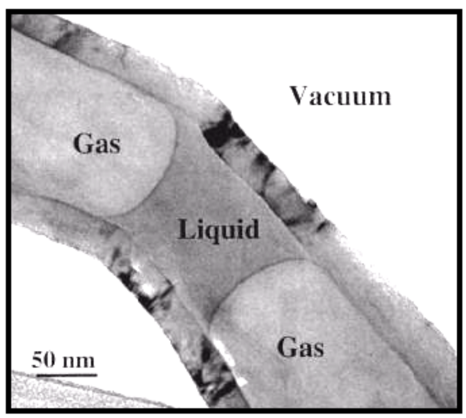

Figure 6: Attoliter fluid experiments in individual closed-end carbon nanotubes: Liquid film and fluid interface dynamics [24]

Ongoing Research and Development Activities

The atomic-scale and cutting-edge field of nanotechnology which is considered to lead us to the next industrial revolution is likely to have a revolutionary impact on the way things will be done, designed and manufactured in the future.

Nanotechnology is entering into all aspects of science and technology including, but not limited to aerospace, agriculture, bioengineering, biology, energy, the environment, materials, manufacturing, medicine, military science and technology. It is based on bottom-up (atomic and molecular) manufacturing for building chemically and physically stable structures one atom or one molecule at a time. Presently the active nanotechnology research areas include lithography, nanodevices, nanorobotics, nanocomputers, nanopowders, nanostructured catalysts and nanoporous materials, molecular manufacturing, carbon nanotube and fullerine products, nanolayers, molecular nanotechnology, nanomedicine, nanobiology, organic nanostructures to name a few.

We have known for many years that several existing technologies depend crucially on processes that take place on the nanoscale. Adsorption, lithography, ion-exchange, catalysis, drug design, plastics and composites are some examples of such technologies. The "nano" aspect of these technologies was not known and, for most part, they were initiated accidentally by mere luck. They were further developed using tedious trial-and-error laboratory techniques due to the limited ability of the times to probe and control matter on nanoscale. Investigations at nanoscale were left behind as compared to micro and macro length scales because significant developments of the nanoscale investigative tools have been made only recently.

The above mentioned technologies, and more, stand to be improved vastly as the methods of nanotechnology develop. Such methods include the possibility to control the arrangement of atoms inside a particular molecule and, as a result, the ability to organize, analyze, and control matter simultaneously on several length scales. The developing concepts of nanotechnology seem pervasive and broad. It is expected to influence every area of science and technology, in ways that are clearly unpredictable.

Nanotechnology will also help solve other technology and science problems. For example, we are just now starting to realize the benefits that nanostructuring can bring to:

(a) wear-resistant tires made by combining nanoscale particles of inorganic clays with polymers as well as other nanoparticle reinforced materials,

(b) greatly improved printing brought about by nanoscale particles that have the best properties of both dyes and pigments as well as advanced ink jet systems,

(c) vastly improved new generation of lasers, magnetic disk heads, nanolayers with selective optical barriers and systems on a chip made by controlling layer thickness to better than a nanometer,

(d) design of advanced chemical and bio-detectors,

(e) nanoparticles to be used in medicine with vastly advanced drug delivery and control characteristics capabilities,

(f) chemical-mechanical polishing with nanoparticle slurries, hard coatings and high hardness cutting tools.

The following selected observations regarding the expected future advances are also worth mentioning at this juncture [5]:

(i). The most complex arrangements of matter known to us are those of living entities and organs. Functions of living organisms depend on specific patterns of matter on all various length scales. Methods of nanotechnology could provide a new dimension to the control and improvement of living organisms.

(ii). Photo-lithographic patterning of matter on the micro scale has led to the revolution in microelectronics over the past few decades. With nanotechnology, it will become possible to control matter on every important length scale, enabling tremendous new power in materials design.

(iii). Biotechnology is expected to be influenced by nanotechnology greatly in a couple of decades. It is anticipated that, for example, this will revolutionize healthcare to produce ingestable systems that will be harmlessly flushed from the body if the patient is healthy but will notify a physician of the type and location of diseased cells and organs if there are problems.

(iv). Micro and macro systems constructed of nanoscale components are expected to have entirely new properties that have never before been identified in nature. As a result, by altering and design of the structure of materials in the nanoscale range we would be able to systematically and appreciably modify or change selected properties of matter at macro and micro scales. This would include, for example, production of polymers or composites with most desirable properties which nature and existing technologies are incapable of producing.

(v) Robotic spacecraft that weigh only a few pounds will be sent out to explore the solar system, and perhaps even the nearest stars. Nanoscale traps will be constructed that will be able to remove pollutants from the environment and deactivate chemical warfare agents. Computers with the capabilities of current workstations will be the size of a grain of sand and will be able to operate for decades with the equivalent of a single wristwatch battery.

(vi). There are many more observations in the areas of inks and dyes, protective coatings, dispersions with optoelectronic properties, nanostructured catalysts, high reactivity reagents, medicine, electronics, structural materials, carbon nanotube products and energy conversion, conservation, storage and usage which are also worth mentioning.

(v). Many large organic molecules are known to forming organic nanostructures of various shapes as shown in Figure 7 the deriving force of which is the intermolecular interaction energies between such macromolecules [25-28].

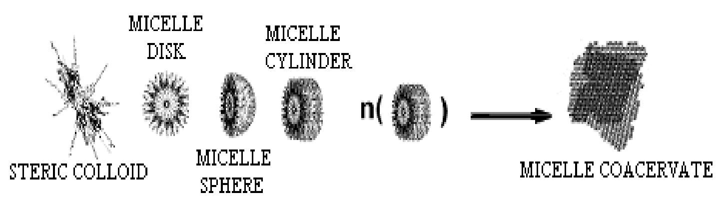

Figure 7a Organic nanostructure self-assemblies of various shapes [27,28]

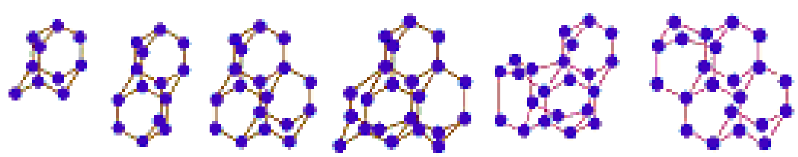

Figure 7b: Chemical structures of diamondoid organic nanostructures. Diamondoids are a particular class of organic nanostructures which will be studied in the course of this research project. These compounds [http://www.uic.edu/~mansoori/Diamondoids.html] have diamond-like fused ring structures which can have many applications in nanotechnology [http://www.foresight.org/Conferences/MNT05/Abstracts/Drexabst.htm]. They have the same structure as the diamond lattice, i.e., highly symmetrical and strain free. The rigidity, strength and assortment of their 3-d shapes make them valuable molecular building blocks.

There has been an appreciable progress in research during the past few years on organic nanostructures, such as thin film nanostructures, which have excellent potential for use in areas that are not accessible to more conventional, inorganic nanostructures. The primary attraction of organic nanostructures is their potential for molding, coating, and the extreme flexibility that they have in being tailored to meet the needs of a particular application. The organic nanostructures materials are easily integrated with conventional inorganic nanostructures (like semiconductor devices), thereby providing additional functionality to existing photonic circuits and components. Some progress has been made in understanding the formation and behavior of organic nanostructures that might be formed to serve as elements of nanomaterials and also on synthetic strategies for creating such structures [25-28]. The ultimate goal is to achieve a better understanding of the fundamental molecular processes and properties of these nanostructures which are dominated by grain boundaries and interfaces. In understanding the behavior and the properties of these nanostructures the potential for technological applications will be considered.

Many other unpredictable advances resulting from nanotechnology are inevitable. Thus, the future prospects for nanotechnology actually represents a revolutionary super-cutting-edge field that is expected to eventually become the foundation for such currently disparate areas as, and many others that we cannot even foresee at this time. It is then no wonder that it is considered to lead the humanity to the next industrial revolution.

Conclusions and Recommendations

A scientific and technological revolution has begun which is the ability of the human beings to systematically organize and manipulate matter on a bottom-up fashion starting from atomic level. Significant accomplishments in performance and changes of manufacturing paradigms are predicted to lead to several break troughs in the present, 21st, century.

The answer to the question of how soon will this next industrial revolution arrive depends a great deal on the intensity of activities of the scientific communities in academic disciplines, national laboratories, or even entire industries all around the world. That certainly depends on the efforts by the research and development funding agencies which are mostly powered by government funds. There is also the question of who will benefit the most, and who will be in the position to control and counter the negative aspects of this revolution.

Nanotechnology revolution will change the nature of almost every human-made object and activities. The ultimate societal impact of this revolution is expected to be as dramatic as the first industrial revolution and greater than the combined influences that aerospace, nuclear energy, transistors, computers, and polymers have had in this century.

Because of that we recommend development of an international initiative sponsored by the United Nations in order to advance this activity among the governments all around the world. Through the avenues of the United Nations we can effectively embrace and facilitate the new industrial revolution to maximize its benefit to the human race and other inhabitants of the earth. Breakthroughs and developments in nanotechnology will be quite frequent in the coming years. To be up to date with the latest information one has to refer to Internet resources.

Below is a list of the important Internet sites related to nanotechnology:

i. APEC on Nanotechnology
http://www.apectf.nstda.or.th/html/nano.html

ii. Foresight Institute
http://www.foresight.org/

iii. Nanoscale Data on the Web
http://tigger.uic.edu/~mansoori/Thermodynamic.Data.and.Property_html

iv. U.S. National Nanotechnology Initiative
http://www.nano.gov

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