

Nanomaterials and Nanotechnology

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Abstract: Nanoscience primarily deals with synthesis, characterization, exploration, and exploitation of nanostructured materials. These materials are characterized by at least one dimension in the nanometer range. A nanometer (nm) is one billionth of a meter, or 10^{-9} m. One nanometer is approximately the length equivalent to 10 hydrogen or 5 silicon atoms aligned in a line. The processing, structure and properties of materials with grain size in the tens to several hundreds of nanometer range are research areas of considerable interest over the past years. A revolution in materials science and engineering is taking place as researchers find ways to pattern and characterize materials at the nanometer length scale. New materials with outstanding electrical, optical, magnetic and mechanical properties are rapidly being developed for use in information technology, bioengineering, and energy and environmental applications. On nanoscale, some physical and chemical material properties can differ significantly from those of the bulk structured materials of the same composition; for example, the theoretical strength of nanomaterials can be reached or quantum effects may appear; crystals in the nanometer scale have a low melting point (the difference can be as large as 1000°C) and reduced lattice constants, since the number of surface atoms or ions becomes a significant fraction of the total number of atoms or ions and the surface energy plays a significant role in the thermal stability. Therefore, many material properties must now be revisited in light of the fact that a considerable increase in surface-to-volume ratio is associated with the reduction in material size to the nanoscale, often having a prominent effect on material performance. Historically, fundamental material properties such as elastic modulus have been characterized in bulk specimens using macroscopic, and more recently microscopic, techniques. However, as nanofabrication advances continue, these bulk properties are no longer sufficient to predict performance when devices are fabricated with small critical dimensions.

1. Introduction

Nanotechnology is a new area of research, nanomaterials are known to be used for centuries. For example, the Chinese used gold nanoparticles as an inorganic dye to introduce red color into their ceramic porcelains more than thousand years ago. Roman glass artifacts contained metal nanoparticles, which provided beautiful colours. In medieval times, nanoparticles were used for decoration of cathedral windows. What really new about nanoscience is the combination of our ability to see and manipulate matter on the nanoscale and our understanding of atomic scale interactions. Advances in the materials processing along with the precipitous rise in the sophistication of routine, commonly available tools capable for characterization of materials with force, displacement and spatial resolutions as

small as picoNewtons ($\text{pN} = 10^{-12}$ N), nanometer ($\text{nm} = 10^{-9}$ m) and Angstrom ($\text{\AA} = 10^{-10}$ m), respectively, have provided unprecedented opportunities to probe the structure and mechanical response of materials on nanoscale. In addition, major improvements in computer support have allowed the simulations of material structures and behavior with a degree of accuracy unimaginable as recently as a decade ago. Although study on materials in the nanometer scale can be traced back for centuries, the current fever of nanotechnology is at least partly driven by the ever shrinking of devices in the semiconductor industry. The continued decrease in device dimensions has followed the well-known Moore's law predicted in 1965 and illustrated in Fig. 1. The trend line illustrates the fact that the transistor size has decreased by a factor of 2 every 18 months since 1950.

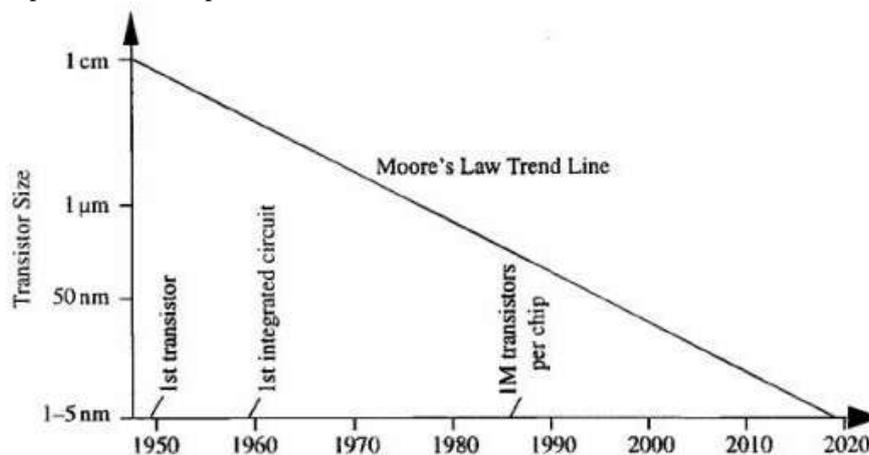


Fig. 1. "Moore's Law" plot of transistor size versus year.

There are many nanoscale electronic devices available now: tunneling junctions; devices with negative differential electrically configurable switches; carbon nanotube transistor; and single molecular transistor; ultrahigh density nanowires lattices and circuits with metal and semiconductor nanowires; etc. Devices have also been connected together to form circuits capable of performing single functions such

as basic memory and logic function. Computer architecture based on nanoelectronics (also known as nanocomputers) has also been intensively studied. Various processing techniques have been applied in the fabrication of nanoelectronics such as focused ion beam (FIB), electron beam lithography, and imprint lithography. Major obstacles preventing the development of such devices include addressing nanometer-

sized objects such as nanoparticles and molecules, molecular vibrations, robustness and the poor electrical conductivity. Certainly, nanomaterials play an important role not only in semiconductor – based electronics. Nano-sized materials currently are used in numerous industries, e.g., carbon black particles make rubber tires wear resistant; nanofibers are used for insulation and reinforcement of composites; iron oxide creates the magnetic material used in disk drives and audio-video tapes; nano-zinc oxides and titania are used as sunblocks for UV rays; etc. Nanoscale particles and nanoscale layers of materials are being used, among other things, to make products lighter, stronger or more conductive. Some of the products on the market using nanotechnology are: magnetic recording tapes; computer hard drivers; bumpers on cars; solid – state compasses; protective and glare – reducing coatings for eyeglasses and windows; automobile catalytic converters; metal – cutting tools; dental bonding agents; longer – lasting tennis ball; burn and wound dressing; ink; etc. Promising applications of nanotechnology in medicine and/or biology have attracted a lot of attention and have become a fast growing field. One of the attractive applications in nanomedicine is the creation of nanoscale devices for improved therapy and diagnostics. Such nanoscale devices or nanorobots serve as vehicles for delivery of therapeutic agents, detectors or guardians against early disease and perhaps repair of metabolic or genetic defects. For applications in medicine, the major challenge is “miniaturization”: new instruments to analyze tissues literally down to the molecular level, sensors smaller than a cell allowing to look at ongoing functions, and small machines that literally circulate within a human body pursuing pathogens and neutralizing chemical toxins.

2. Classification of Nanostructures

2.1 Gleiter's classification of nanostructured materials

The materials and/or devices sintered by means of the controlled manipulation of their microstructure on the atomic level may be divided into three categories. The first category comprises materials and/or devices with reduced dimensions and/or dimensionality in the form of isolated, substrate-supported or embedded nanometer-sized particles, thin wires or thin films. The techniques that are most frequently used to produce this type of microstructure are chemical vapor deposition (CVD), physical vapor deposition (PVD), various aerosol techniques, and precipitation from the vapor, supersaturated liquids or solids. Well-known examples of technological applications of materials the properties of which depend on this type of microstructure are catalysts and semiconductor devices utilizing single or multilayer quantum well structures. The second category comprises materials and/or devices in which the nanometersized microstructure is limited to a thin (nanometer-sized) surface region of a bulk material. PVD, CVD, ion implantation and laser beam treatments are the most widely applied procedures to modify the chemical composition and/or atomic structure of solid surfaces on a nanometer scale. Surfaces with enhanced corrosion resistance, hardness, wear resistance or protective coatings are examples taken from today's technology in which the properties of a thin surface layer are improved by means of creating a nanometer-sized microstructure in a thin surface region. For example, patterns

in the form of an array of nanometer-sized islands (e.g. quantum dots) connected by thin (nanometer scale) wires. Patterns of this type may be synthesized by lithography, by means of local probes (e.g. the tip of a tunneling microscope, near-field methods, focused electron or ion beams) and/or surface precipitation processes. Such kind of processes and/or devices are expected to play a key role in the production of the next generation of electronic devices such as highly integrated circuits, terabit memories, single electron transistors, quantum computers, etc. The third category comprises bulk solids with a nanometer-scale microstructure. Those are solids in which the chemical composition, the atomic arrangement and/or the size of the building blocks (e.g. crystallites or atomic/molecular groups) forming the solid varies on a length scale of a few nanometers throughout the bulk.

2.2 Classification of nanostructures by dimensionality

Nanostructures (NSs) should be separated from NSMs because the former (NSs) are characterized by a form and dimensionality while the last (NSMs) by a composition in addition. Hence NSs should be classified accurately upon one of these sign, namely, dimensionality, as being the general natural attribute, integrated a size and shape or form. Abundance of forms for bulk 3D materials is infinite. Under transition into nanoworld an atomic difference between some shapes can be neglected regarding these forms as the same due to their low dimension. Hence one can conclude that a number of NS-classes becomes to be finite. This brings up the problem of modern NSs classification. Under a nanostructure we understand the structure the one size of which d at least is less or equal to a critical one d^* , $2d \leq d^* \approx 10$ nm. The value of d^* have not certain meanings because it is dictated by a critical characteristic of some physical phenomena (free path length of electrons, phonons, length of de Broglie wave, length of external electromagnetic and acoustical waves, correlation length, penetration length, diffusion length, etc.) giving rise to the size effects. We constitute our classification of NSs on their dimensionality. It may be one of the four, namely, 0D, 1D, 2D or 3D. All NSs can be build from elementary units (blocks) having low dimensionality 0D, 1D, and 2D. The 3D units are excluded because they can't be used to build low dimensional NSs except 3D matrix. However 3D structures can be considered as NSMs if they involve the 0D, 1D, 2D NSs. This is just the case that Gleiter considered in his classification of NSMs. Let us introduce the notation of NSs

$$kDl_{lmn} \dots (1)$$

where k is a dimensionality of NS as a whole, while the integers l, m, n denotes the dimensionality of the NS's building units of different types. Each integer l, m, n refers to different type unit, so the number of these integers must be equal to the number of the different constituting units. From the definition of NSs the condition leads, namely, $k \geq l, m, n$, and $k, l, m, n = 0, 1, 2, 3$. It follows from this conditions that restricted number of NSs classes exists, namely, 3 sorts of elementary units (0D, 1D, 2D), 9 single classes of kDl type built of 1 sort units, 19 binary classes of $kDlm$ type built of 2 sort units, and variety of ternary, quaternary, etc., classes. Restricting the classification by 5 main ternary structures of $kDlmn$ type built of 3 sort units, we obtain in the result $3+9+19+5=36$ classes of NSs.

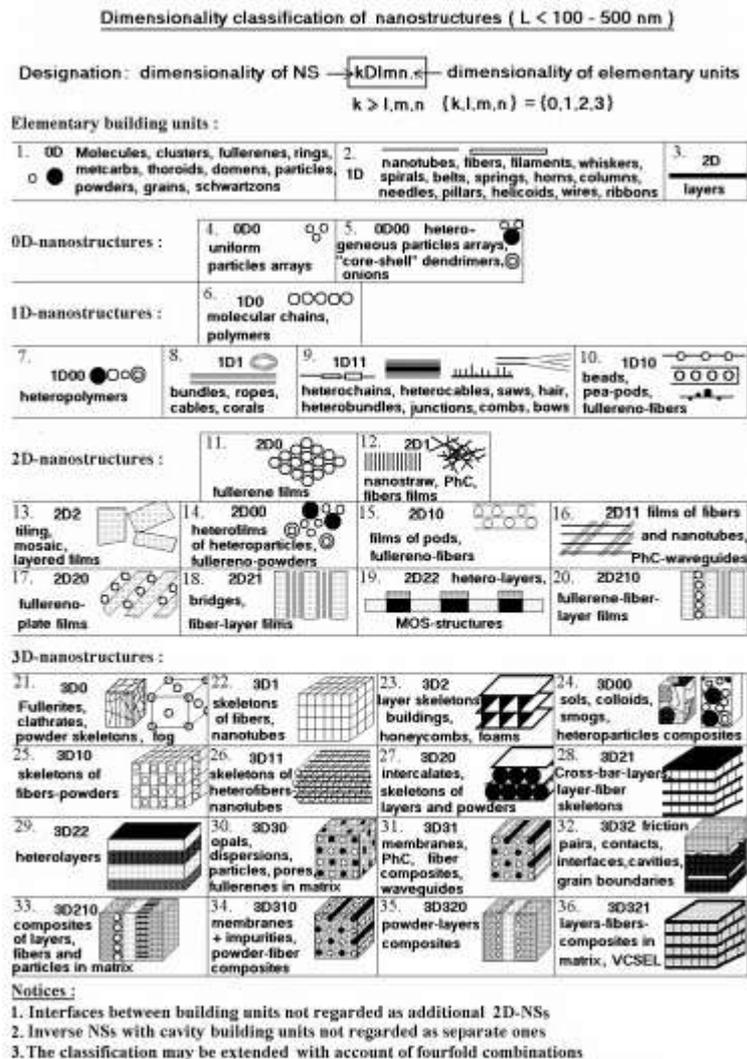


Fig. 6. Dimensionality classification of nanostructures.

2.3 Concept of “surface form engineering” in nanomaterial science

Concept of a “grain boundary engineering” is apparent from Gleiter's classification stated that the properties of NSMs strongly depend on the grain boundaries. In a similar manner the new concept of a “surface form engineering” follows from the classification proposed. In this classification the NSs properties strongly depend on free surface shape. It is based on the essential difference between intercrystalline grain boundaries and free surfaces. The boundaries give rise to the inner classical (IC) size effects, such as diffusion enhancement, decrease in melting point, lattice parameter, etc. The surfaces determine the form, shape, dimensionality, and thereby class of NSs. Sharp thin free surface can serve as a mirror for reflection of the electromagnetic, acoustic and de Broglie waves, in contrast to thickened diffusive grain boundaries, that only transmit and scatter these waves. This puts on forefront the indexes of refraction, absorption, and transmission of all the waves as main peculiar characteristics of NSs. Value of any classification is determined by an ability to predict some general properties. With the aim for any mesh, for each NS-class in our case, the general properties should be related to representative for this NS-class. Then, determining a class of NS, we are capable to predict its general properties. However at the present time the properties of NSs are

studied insufficiently with rare exception. In particular, a general dependence of density of electron states (DOS) on the NS-dimensionality is well known, namely, $\rho(\epsilon) \sim \epsilon^2$, $\rho(\epsilon) \sim \epsilon$, $\rho(\epsilon) \sim \epsilon^0$, and $\rho(\epsilon) \sim \epsilon^{-1}$ for the 3D, 2D, 1D, and 0D nanostructures, respectively. Hence we can predict the general behavior of DOS for each class of NSs combining the DOS of their building units and NS as whole. For instance, the DOS of 2D1 NS-class may predicted to be $\rho(\epsilon) \sim \epsilon^2 \ln \epsilon$.

In addition to dimensionality a size of NSs becomes to be the main factor determining their properties. In extreme case of nanoparticle external $d \ll \lambda$ a size and form have not affect its interaction with external electromagnetic field. In opposite extreme case of bulk 3D material of internal $d \gg \lambda$ a size and form have not affect its interaction with internal waves due to their intense scattering and vigorous attenuation. Only in case of $d \sim \lambda$ the size restriction of NSs leads to quantum confinement and causes the inner quantum (IQ) size effects manifested itself in optical spectra. Electron reflection from NS-surface when electron free path length becomes greater than NSsize, $l_{e} \geq d$, may lead to decrease in electroconductivity, etc. Phonon reflection from NS-surface when the phonon free path length stands out NS-size, $l_{ph} \geq d$, may lead to cut of a long wave phonon spectrum, and to decrease of thermal conductivity, heat capacity, Debye temperature, hypersound generation, and

other IQ size effects. Variety of external size effects, both classical (EC) and quantum (EQ) type, may arise under interaction of NSs with external field, when its wave length becomes to be compatible with NS-size, $em \lambda \approx d$. In this case a condition of total internal reflection or Bragg reflection $\sin / 2 em d n \cdot = \theta \lambda$ may be fulfilled. For instance, the NSs of 2D11 class such as photonic crystals can act as light waveguide and left-handed media, in which unusual unique phenomena were predicted, namely, negative refraction index, inverse Doppler and Cherenkov effects. Beside size effects the variety of resonance effects was shown to be possible in NSs, in particular, Aaronov-Bohm, magneto-acoustic, photogalvanic effects, in which NS serves as resonator for acoustic, electronic, electromagnetic waves. In special nanotubular crystals on special sole super-frequency an unique photo-acousto-electronic super-resonance between microwave, hypersound, and matter waves was suggested to be possible. The state can be regarded as novel nanostructured state of matter, in which a lossless repumping and converting of the electromagnetic, acoustic and electronic energies, one to each other, was suggested to be possible. One can conclude that in accordance with suggested "surface form engineering" a geometry shape becomes to be a principal factor determining the properties of NSMs. In comparison with our 36 classes in fig. 6 there are only 4 classes in Gleiter's scheme in fig. 5 where more than 32 classes are absent, though there are just the new precise classes that belong to new excited field of nanotechnology. Geometry always plays an exceptional role in physics. Generalizing Einstein principle of general relative theory one can say that "physics is geometry plus physical laws". This is in Universe. Applied to nanoworld this principle can be reformulated as follows: "nanophysics is geometry of surface and size of NSs plus critical characteristics of physical phenomena in materials". Geometric forms can be designed theoretically in couple with prediction of novel size effects and resonance phenomena. Excited idea arises of a theoretical design of novel size effects and resonance phenomena combining diversity of NSs-forms with the critical characteristics of materials. Suggesting their meaning is 36 and 10 respectively, one can obtain limited number (360) of the size effects and resonance phenomena. In the result nanoworld one can image as "multi-room (~ 360) house" of size effects and resonance phenomena. Paraphrasing the well known Feynman's aphorism we can say

"There are plenty rooms of restricted classes at a bottom". Hence, the principally new result of the proposed classification is an opportunity of a priori prediction and theoretical design of novel NSMs with unique properties. Attention should be focused on engineering of surface forms of NSs in addition to grain boundaries extending paradigm of nanostructured materials science and nanotechnology.

3. Peculiarities of Nanostructured Materials

3.1 Introduction

Nanostructured materials (NSM) have their own peculiar characteristic distinguished them from the bulk macroscopic 3D materials. Relative to microstructural (MSM) metals and alloys, the NSM contain a higher fraction of grain boundary

volume (for example, for a grain size of 10 nm, between 14 and 27% of all atoms reside in a region within 0.5–1.0 nm of a grain boundary); therefore, grain boundaries play a significant role in the materials properties. Changes in the grain size result in a high density of incoherent interfaces or other lattice defects such as dislocations, vacancies, etc. As the grain size d of the solid decreases, the proportion of atoms located at or near grain boundaries relative to those within the interior of a crystalline grain, scales as $1/d$. This has important implications for properties in ultra-fine-grained materials which will be principally controlled by interfacial properties rather than those of the bulk. The misfit between adjacent crystallites in the grain boundaries changes the atomic structure (e.g. the average atomic density, the nearest-neighbor coordination, etc.) of materials. At high defect densities the volume fraction of defects becomes comparable with the volume fraction of the crystalline regions. In fact, this is the case if the crystal diameter becomes comparable with the thickness of the interfaces. From the courses of physics and mechanics, the role of structural defects in material properties is well established. Vacancies are point defects in the crystalline structure of a solid that may control many physical properties in materials such as conductivity and reactivity. However, nanocrystals are predicted to be essentially vacancy-free; their small size precludes any significant vacancy concentration. This result has important consequences for all thermo mechanical properties and processes (such as creep and precipitation) which are based on the presence and migration of vacancies in the lattice. Planar defects, such as dislocations, in the crystalline structure of a solid are extremely important in determining the mechanical properties of a material. It is expected that dislocations would have a less dominant role to play in the description of the properties of nanocrystals than in the description of the properties of microcrystals (mc), owing to the dominance of crystal surfaces and interfaces. The free energy of a dislocation is made up of a number of terms: (i) the core energy (within a radius of about three lattice planes from the dislocation core); (ii) the elastic strain energy outside the core and extending to the boundaries of the crystal, and (iii) the free energy arising from the entropy contributions. In mc the first and second terms increase the free energy and are by far the most dominant terms. Hence dislocations, unlike vacancies, do not exist in thermal equilibrium. In nanocrystals, the elastic strain energy is reduced. The forces on dislocations due to externally applied stresses are reduced by a factor of about three and the interactive forces between dislocations are reduced by a factor of about 10. Hence re-recovery rates and the annealing out of dislocations to free surfaces are expected to be reduced, as well. Dislocations are positioned closer together and dislocations movement in the net is hindered by interaction between them. Together with the reduced elastic strain energy, this fact results in dislocations that are relatively immobile and the imposed stress necessary to deform a material increases with decrease in grain size. Moreover, nanostructures allow alloying of components that are commonly immiscible in the solid and/or molten state. For example, Fig. 4 schematically represents a model of the 21 nanostructured copper – bismuth (Cu – Bi) alloy. Bismuth atoms are incorporated in the boundaries at sites of enhanced local free volume. In nanocrystalline alloy of silver – iron (Ag – Fe), there exist a mixture of nanometer-sized Ag and

Fe crystals. In the (strained) interfacial regions between Ag and Fe crystals, solid solutions of Fe atoms in Ag crystallites and Ag atoms in the Fe crystallites are formed although both components are immiscible in the liquid as well as in the solid state. Similar effects may occur in the grain boundaries between adjacent Fe and Ag crystals. From the point of view of physics, size effects are important if the characteristic size of the building blocks of the microstructure is reduced to the point where critical length scales of physical phenomena (e.g. the mean free paths of electrons or phonons, a coherency length, a screening length, etc.) become comparable with the characteristic size of the crystallites. From basic courses of physics and chemistry, the wave – particle duality of electron, the architecture of atom and the Schrodinger equation, which is the basic nonrelativistic wave equation used in one version of quantum mechanics to describe the behavior of a particle in a field of force, are well-known. The Schrodinger equation is used to find the allowed energy levels of quantum mechanical systems (such as atoms, or transistors). The associated wave function gives the probability of finding the particle at a certain position. The solution to this equation is a wave that describes the quantum aspects of a system. Or, in other words, the Schrodinger equation is the representation of the wave function which yields the probability of the physical variables in the terms of expectation values. It was shown that electron band structure of solids considers the electron waves in a periodic crystalline potential. One of the approaches is to treat the free electrons in metals quantum mechanically and consider their wave-like properties. The free valence electrons are assumed to be constrained within a potential well which essentially stops them from leaving the metal (the ‘particle-in-a-box’ model). The box boundary conditions require the wave functions to vanish at the edges of the crystal (or ‘box’). The allowed wave functions given by the Schrodinger equation then correspond to certain wavelengths. For a one-dimensional box of length L , the permitted wavelengths are $\lambda_n = 2L/n$, where $n = 1, 2, 3 \dots$ is the quantum number of the state; the permitted wave vectors $kn = 2\pi/\lambda$ are given by $kn = n\pi/L$. In the free electron model, the energies of the electronic states depend on $1/L^2$ where L is the dimension of the system in that particular direction; the spacing between successive energy levels also varies as $1/L^2$. This behavior is also clear from the description of a solid as a giant molecule: as the number of atoms in the molecule increases, the molecular orbitals gradually move closer together. Thus if the number of atoms in a system, hence the length scale, is substantially different to that in a normal bulk material, the energies and energy separations of the individual electronic states will be very different. As the system size decreases, the allowed energy bands become substantially narrower than in an infinite solid. The delocalized electronic properties of a solid become severely distorted and the electrons in a reduced-dimensional system tend to behave more like the ‘particle in a box’ description; this is the phenomenon of quantum confinement. In other words, the electronic states are more like those found in localized molecular bonds rather than those in a macroscopic solid. The main effect of these alterations to the bulk electronic structure is to change the total energy and hence, ignoring entropy considerations and the thermodynamic stability of the reduced length scale system relative to that of a normal bulk crystal. This can have a number of important implications. It may change the

most energetically stable 22 form of a particular material; for example, small nanoparticles or nano-dimensional layers may adopt a different crystal structure from that of the normal bulk material. For example, some metals which normally adopt a hexagonal close-packed atomic arrangement have been reported to adopt a face-centered cubic structure in confined systems such as metallic multilayers. If a different crystallographic structure is adopted below some particular critical length scale, then this arises from the corresponding change in the electronic density of states, which often results in a reduced total energy for the system. Reduction of system size may change the chemical reactivity, which will be a function of the structure and occupation of the outermost electronic energy levels. Correspondingly, physical properties such as electrical, thermal, optical and magnetic characteristics, which also depend on the arrangement of the outermost electronic energy levels, may be changed. For example, metallic systems can undergo metal – insulator transitions as the system size decreases, resulting from the formation of a forbidden energy band gap. Other properties such as mechanical strength that, to a first approximation, depends on the change in electronic structure as a function of applied stress, and hence interatomic spacing, may also be affected. Transport properties may also change in that they may now exhibit a quantized rather than continuous behavior, owing to the changing nature and separation of the electron energy levels.

3.2 Nanoscale

The nanoscale refers to structures with a length scale applicable to nanotechnology, usually cited as 1–100 nanometers. A nanometer is a billionth of a meter. The nanoscale is sometimes marked as the point where the properties of a material change. Above this point, the properties of a material are caused by ‘bulk’ or ‘volume’ effects. Below this point, ‘surface area effects’ (also referred to as quantum effects) become more apparent. These effects are due to the geometry of the material and can have a drastic effect on quantized states, and thus the properties of a material. Consider a spherical object of radius r . The surface area to volume ratio is inversely proportional to r . That is, there is more of surface area for a given volume when we move from bulk to nanoscale.

3.3 Quantum Confinement

The quantum confinement effect can be observed once the diameter of the material is of the same magnitude as the de Broglie wavelength of the electron. When materials are of this size, their electronic and optical properties deviate substantially from those of bulk materials. A particle behaves as if it were free when the confining dimension is large compared to the de Broglie wavelength of the particle. During this state, the bandgap remains at its original energy due to a continuous energy state. However, as the confining dimension decreases and reaches a certain limit, typically in nanoscale, the energy spectrum turns to discrete. As a result, the bandgap becomes size dependent. This ultimately results in a blue shift in optical illumination as the size of the particles decreases. Specifically, the effect describes the phenomenon resulting from electrons and holes being

confined into a dimension that approaches a critical quantum measurement, called the exciton Bohr radius. In current application, a quantum dot such as a small sphere confines in three dimensions, a quantum wire confines in two dimensions, and a quantum well confines only in one dimension. These are also known as zero-, one- and two-dimensional potential wells, respectively. In these cases they refer to the number of dimensions in which a confined particle can act as a free carrier. The electronic and optical properties of materials are affected by size and shape. A rather good approximation of an exciton's [the electron-hole pair formed after the excitation of electron from valence band to conduction band, leaving a hole behind] behaviour is the 3-D model of a particle in a box. The solution of this problem provides mathematical connection between energy states and the dimension of space

3.4 Moore's Laws

Moore's law is the observation that over the history of computing hardware, the number of transistors in a dense integrated circuit doubles approximately every two years. The period is often quoted as 18 months because of Intel executive David House, who predicted that chip performance would double every 18 months (being a combination of the effect of more transistors and their being faster). Moore's second law states that the capital cost of a semiconductor fabrication unit also increases exponentially over time.

Properties of Nanomaterials [or] Property changes at nanoscale

- 1) Electrical: Due to the increase in the number of grain boundaries, there is increased resistance to the electron flow.
- 2) Optical: Due to the increase in bandgap at nanoscale, the emission spectra shift to shorter wavelengths.
- 3) Mechanical: Due to the increased grain boundaries, the resistance to the motion of dislocations increase, increasing the yield strength.
- 4) Thermal: With the increase in grain boundary area, as the disorder is already large, it needs less thermal energy to melt nanomaterials. That is, their melting points are low.
- 5) Magnetic: At reduced grain sizes, due to the nature of quantum mechanical exchange forces, it is difficult to form ferromagnetic domains. Therefore, a ferromagnet in bulk state reduces to a paramagnet at the nanoscale.
- 6) Chemical: Reaction rates increase as the available surface area for the reactions increase.

3.5 Quantum Dots

A quantum dot is a nanocrystal made of semiconductor materials that are small enough to exhibit quantum mechanical properties. Specifically, its excitons are confined in all three spatial dimensions. The electronic properties of these materials are intermediate between those of bulk semiconductors and of discrete molecules. In a semiconductor crystallite whose diameter is smaller than the size of its exciton Bohr radius, the excitons are squeezed, leading to quantum confinement. The energy levels can then be modeled using the particle in a box model in which the energy of different states is dependent on the length of the box. Quantum dots are said to be in the 'weak confinement

regime' if their radii are on the order of the exciton Bohr radius; quantum dots are said to be in the 'strong confinement regime' if their radii are smaller than the exciton Bohr radius. If the size of the quantum dot is small enough that the quantum confinement effects dominate (typically less than 10 nm), the electronic and optical properties are highly tunable. Fluorescence occurs when an excited electron relaxes to the ground state and combines with the hole. In a simplified model, the energy of the emitted photon can be understood as the sum of the band gap energy between the occupied level and the unoccupied energy level, the confinement energies of the hole and the excited electron, and the bound energy of the exciton. Although these are simplifying assumptions, the implications are clear: the energy of the quantum dots is dependent on their size due to the quantum confinement effects, which dominate below the critical size leading to changes in the optical properties. This effect of quantum confinement on the quantum dots has been experimentally verified and is a key feature of many emerging electronic structures.

4. Applications of Quantum Dots

- 1) The ability to tune the size of quantum dots is advantageous for many applications. For instance, larger quantum dots have a greater spectrum-shift towards red compared to smaller dots, and exhibit less pronounced quantum properties. Conversely, the smaller particles allow one to take advantage of more subtle quantum effects.
- 2) Being zero-dimensional, quantum dots have a sharper density of states [number of available states per unit volume in the interval E and $E+dE$] than higher-dimensional structures. As a result, they have superior transport and optical properties, and are being researched for use in diode lasers, amplifiers, and biological sensors.
- 3) Quantum dot technology is one of the most promising candidates for use in solid-state quantum computation. By applying small voltages to the leads, the flow of electrons through the quantum dot can be controlled and thereby precise measurements of the spin and other properties therein can be made. With several entangled quantum dots, or qubits, plus a way of performing operations, quantum calculations and the computers that would perform them might be possible.
- 4) In modern biological analysis, various kinds of organic dyes are used. However, with each passing year, more flexibility is being required of these dyes, and the traditional dyes are often unable to meet the expectations. To this end, quantum dots have quickly filled in the role, being found to be superior to traditional organic dyes on several counts, one of the most immediately obvious being brightness as well as their stability. It has been estimated that quantum dots are 20 times brighter and 100 times more stable than traditional fluorescent sources.
- 5) The usage of quantum dots for highly sensitive cellular imaging has seen major advances over the past decade. Another application that takes advantage of the extraordinary photostability of quantum dot probes is the realtime tracking of molecules and cells over extended periods of time. Researchers were able to observe quantum dots in lymph nodes of mice for more than 4 months.

- 6) Semiconductor quantum dots have also been employed for in vitro imaging of pre-labeled cells. The ability to image single-cell migration in real time is expected to be important to several research areas such as embryogenesis, cancer metastasis, stem cell therapeutics, and lymphocyte immunology.
- 7) First attempts have been made to use quantum dots for tumor targeting under in vivo conditions. There exist two basic targeting schemes: active targeting and passive targeting. In the case of active targeting, quantum dots are functionalized with tumor-specific binding sites to selectively bind to tumor cells. Passive targeting uses the enhanced permeation and retention of tumor cells for the delivery of quantum dot probes. Fast-growing tumor cells typically have more permeable membranes than healthy cells, allowing the leakage of small nanoparticles into the cell body. Moreover, tumor cells lack an effective lymphatic drainage system, which leads to subsequent nanoparticle-accumulation.
- 8) Quantum dots may be able to increase the efficiency and reduce the cost of today's typical silicon photovoltaic cells. Quantum dot photovoltaics would theoretically be cheaper to manufacture, as they can be made using simple chemical reactions.
- 9) Quantum dots are valued for displays, because they emit light in very specific gaussian distributions. This can result in a display that more accurately renders the colors that the human eye can perceive. Quantum dots also require very little power since they are not color filtered.

Carbon Nanotubes [CNTs]

Carbon nanotubes (CNTs) are allotropes of carbon with a cylindrical nanostructure. Nanotubes have been constructed with length-to-diameter ratio of up to 132,000,000:1 significantly larger than for any other material. These cylindrical carbon molecules have unusual properties, which are valuable for nanotechnology, electronics, optics and other fields of materials science and technology.

In particular, owing to their extraordinary thermal conductivity and mechanical and electrical properties, carbon nanotubes find applications as additives to various structural materials. For instance, nanotubes form a tiny portion of the material(s) in some (primarily carbon fiber) baseball bats, golf clubs, or car parts. Nanotubes are members of the fullerene structural family. Their name is derived from their long, hollow structure with the walls formed by one-atom-thick sheets of carbon, called graphene. These sheets are rolled at specific and discrete ("chiral") angles, and the combination of the rolling angle and radius decides the nanotube properties; for example, whether the individual nanotube shell is a metal or semiconductor. Nanotubes are categorized as singlewalled nanotubes (SWNTs) and multi-walled nanotubes (MWNTs). Individual nanotubes naturally align themselves into "ropes" held together by van der Waals forces. There are other categories too. Applied quantum chemistry, specifically, orbital hybridization best describes chemical bonding in nanotubes. The chemical bonding of nanotubes is composed entirely of sp² bonds, similar to those of graphite. These bonds, which are stronger than the sp³ bonds found in alkanes and diamond, provide nanotubes with their unique strength.

Single Walled Nanotubes

Most single-walled nanotubes (SWNT) have a diameter of close to 1 nanometer, with a tube length that can be many millions of times longer. The structure of a SWNT can be conceptualized by wrapping a one-atom-thick layer of graphite called graphene into a seamless cylinder. The way the graphene sheet is wrapped is represented by a pair of indices (n,m). The integers n and m denote the number of unit vectors along two directions in the honeycomb crystal lattice of graphene. If m = 0, the nanotubes are called zigzag nanotubes, and if n = m, the nanotubes are called armchair nanotubes. Otherwise, they are called chiral.

A logic gate requires both a p-FET and an n-FET. Because SWNTs are p-FETs when exposed to oxygen and n-FETs otherwise, it is possible to protect half of an SWNT from oxygen exposure, while exposing the other half to oxygen. This results in a single SWNT that acts as a NOT logic gate with both p and n-type FETs within the same molecule.

Applications of CNTs

Current use and application of nanotubes has mostly been limited to the use of bulk nanotubes, which is a mass of rather unorganized fragments of nanotubes. Bulk nanotube materials may never achieve a tensile strength similar to that of individual tubes, but such composites may, nevertheless, yield strengths sufficient for many applications. Bulk carbon nanotubes have already been used as composite fibers in polymers to improve the mechanical, thermal and electrical properties of the bulk product.

- 1) CNT technology is used in a number of bicycle components—including flat and riser handlebars, cranks, forks, seatposts, stems and aero bars.
- 2) CNT can be used to build maritime vessel. CNTs help improve the structural performance of the vessel, resulting in a lightweight 8,000 lb boat that can carry a payload of 15,000 lb over a range of 2,500 miles.
- 3) Hybtonite carbon nanoepoxy resins where carbon nanotubes have been chemically activated to bond to epoxy, results in a composite material that is 20% to 30% stronger than other composite materials. It has been used for wind turbines, marine paints and variety of sports gear such as skis, ice hockey sticks, baseball bats, hunting arrows, and surfboards.
- 4) CNT is used to build tips for atomic force microscope probes. 5. CNT is used in tissue engineering, carbon nanotubes can act as scaffolding for bone growth

5. Conclusion

Nanomaterials are here now—in some cases as incremental but significant improvements of development efforts before the nanotechnology label was applied—and are finding application in a wide range of markets. Substantial funding along with intense government, business, and media attention promises to accelerate R&D and implementation, although significant challenges exist for large-scale nanomaterials for structural applications. While the emergence of nanotechnologies has greatly broadened the disciplines involved, the structure-processing-property framework that materials science and engineering brings will be a vital component in ultimate technical and commercial success.

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