Editorial: Entering into nanotechnology era

Vladimir Pokropivny

Nanotechnology (NT) can be defined as the complex of fundamental and engineering sciences that integrates the chemistry, physics and biology of nanostructures with a materials science, electronics, and processes technologies focused on a comprehensive research of nanostructures, on a development of atomistic physico-chemical processes, self- and automatic-assembling of nanomaterials and workpieces using complex probe microscopes combined with other tools, resulting in a fabrication and manufacturing of nanodevices, nanomachines, ultra-low integrated circuits, micro-opto-electro-mechanical systems, nanobiorobots, etc.

In reality NT appeared in the early 1980s, when scanning tunnelling microscopy, the atomic force and other probe microscopies were invented. These have given the opportunity to realise the main concept of NT formulated by Richard Feynman, namely, to assemble artificially nanoworkpieces and nanodevices from single atoms and molecules.

The huge advantages of Pentium-4 over IBM-360 have been achieved by a miniaturising of integrated circuits and fabricating of microchips containing $\sim 10^9$ units/sm^2 of ~200 nm in size. And this is not a limit, the size of individual units may be decreased at least on the orders of magnitudes.

In the nanoworld a natural question arises, "where are its boundaries?"

Formally it is confined by the size of nanoparticles, $d < 100$ nm. Physically it is determined by a variety of size effects. Based on the decreasing of the size the physico-chemical properties of particles and materials change dramatically and sometimes cordially. It is possible to divide the size effects into two types, the internal and external, as well as the classical and quantum ones. Internal or intrinsic size effects are determined as a change of the properties peculiar to particles (the lattice parameters, melting temperature, hardness, band gap, luminescence, diffusion coefficients, chemical activity, sorption, etc.) irrespective of external disturbances. External size effects arise inevitably and always in the processes of interaction between different physical fields and matter as the size of its building units decreases (particles, grains, domains) down to a crucial value, when this size becomes comparable with the length of physical phenomena (the free length of electrons, phonons, coherent length, screening length, irradiative wavelength, etc.). In turn, the classical size effects become apparent in variation of lattice parameters, hardness, plasticity, thermal conductivity, diffusion, etc. The quantum size effects manifest themselves in a blue shift of luminescence, in the rise of peculiar low-dimensional quantum states, in the quantisation of electroconductivity in magnetic field, in the oscillation of the superconductivity critical temperature, magnetoresistance and other physical characteristics, in the generation of hypersound, etc. Hence just when studying the size effects in novel nanostructured materials activated by different external fields it is possible to hope for the discovery of novel effects and phenomena and for the development of novel nanotechnology on this base.

Nanotechnology is therefore a complex interdisciplinary science which includes:

- nanochemistry (nanocolloid, sol–gel and quantum chemistry) destined for self-assembling and synthesis of nanoparticles as well as for research of their intrinsic size effects
- nanophysics (quantum physics, spintronics, photonics) destined for artificial assembling and fabrication of nanostructures as well as for research of their external size effects
- nanomaterials science (nanopowder technology, nanoceramics compounds, nanotribology, nanosintering and other nanoprocesses) destined for research, development and production of novel nanostructured architectures, functional nanomaterials and smart nanocomponents with unique properties
- nanoelectronics, optoelectronics and nanoengineering destined for development of novel technological processes, nanomotors, nanoactuators, nanodevices, micro-opto-electro-mechanical systems (MEMS, MOEMS), ultra-large integrated circuits (ULCI), nanorobots, etc.
- nanobionics destined for the development of novel biomachine complexes, such as nanobiochips, nanobiorobots, etc.
- nanometrology, nanodevice-building and nano-hand-craft destined for the development of special nanotools, instrumentations, information and computational systems for support of NT itself.

The association of these sciences in nanotechnology reflects both their inherent interconnection around the nanoobjects and the change in technology paradigm, namely, the nanomaterial, nanodevice or nanosystem seem to be fabricated by the automatic artificial assembling or self-assembling from molecules or clusters *in whole*, in situ, *in place*, in the single technological process incorporating them then in microdevices, rather than by aggregating different components as at present. The novel atomistic nanotechnology processes (nanomanipulation, artificial- and self-assembling, nanolithography, membrane-templating synthesis, sol–gel synthesis, molecular-beam epitaxy, etc.) are expected to replace the traditional processes of thermomechanical treatment (rolling, cutting, welding, soldering, moulding, etc.) and microelectronics processes (chemical and physical vapour depositions, lithography, etc.)

Living in a macroworld a human being comes into controllable tunable contact with the nanoworld mainly by means of a tip of probe microscope so the contact 'tip-surface' is the contact 'macroworld–nanoworld'. Therefore the key problem of present-day nanotechnology is a comprehensive research of atomistic mechanisms of the nanocontact phenomena (adhesion, indentation, friction, wear, etc.) in dependence of a type of interatomic intermolecular bonds, a type and structure of contact materials, a size of tip and nanostructure, a value of load, a width of gap, a content of atmosphere, a temperature, an external electric and magnetic field, a frequency and intensity of electromagnetic waves, and so on. These researches have to be expressed in the development of techniques for tunable manipulation, characterisation, control, and position assembling of nanostructures, in particular seizure, gripping, restraining, turning, moving, breaking, reset and adhesion of a molecular building block onto a prescribed place. Such operations at atomic and molecular level are principal to nanotechnology.

It should be emphasised that NT has not intended to replace the existing microtechnologies, but on the contrary in close connection with them to complement them in deeper advanced studies and control of the nanoworld.

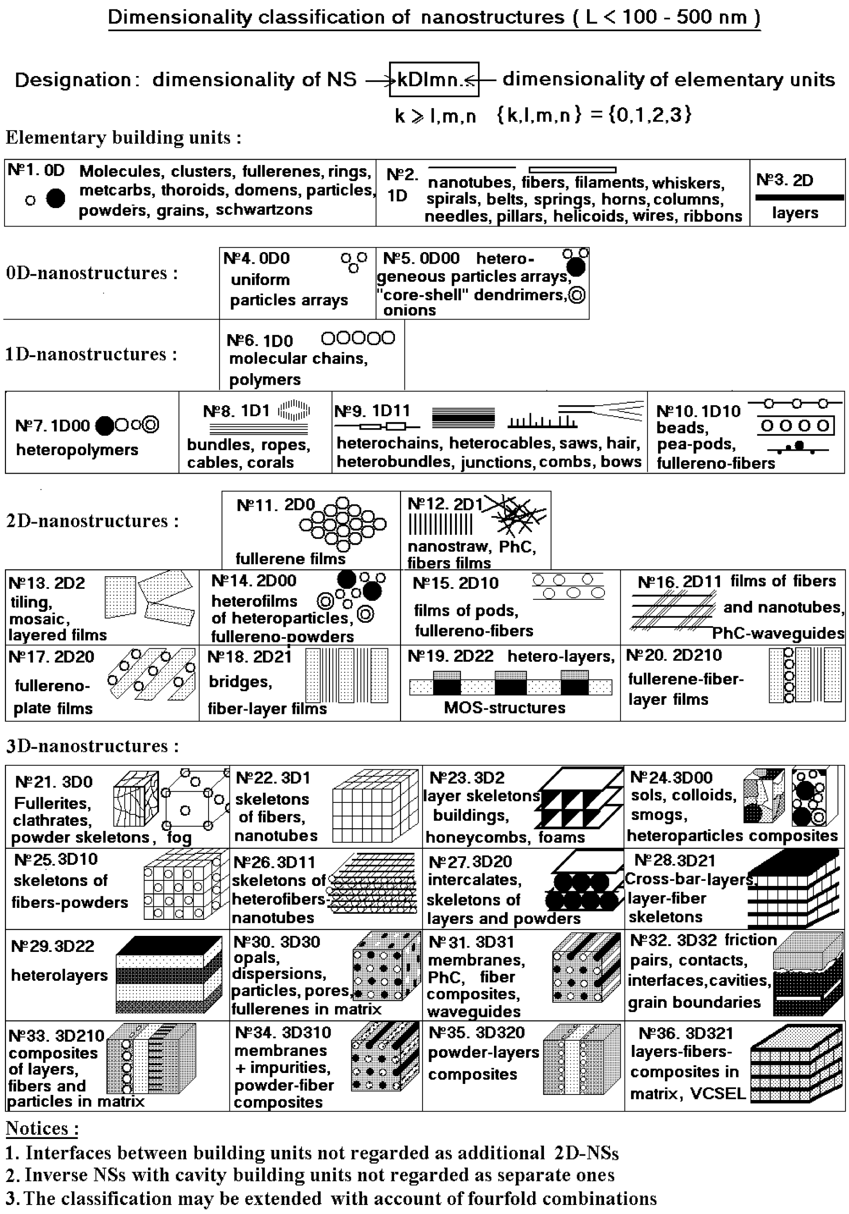
Atoms, molecules, clusters, fullerenes, supramolecular structures, their crystals, nanotubes, nanowires, nanorods, their arrays and photonic crystals offer as NT objectives.

Fullerenes and atomic clusters are the extremely smallest zero-dimensional (0D) nanostructures called quantum dots, that possess properties inherent in nanomaterial rather than in a single atom. Note that under fullerenes it should mean not only the buckyball C_{60}, but also a multitude of other carbon C_n and noncarbon clusters and metcarbes Me_2C_n. Presently based on this a number of experimental nanodevices have been developed, such as the switchers, diodes, transistors, amplifiers, sensors, optical filters, solar cells, magneto-optical recorders, etc.

Nanotubes, nanorods, nanowires, nanofibres manifest more advanced and promising properties as the 1D quantum wires nanoscopic in diameter but microscopic in length. Their unique properties stem from an opportunity of the ring and cylindrical types of acoustic and electromagnetic waves to propagate that made them a unique nanolaboratory for research of quantum resonance phenomena. All the above-mentioned concern with noncarbon 1D nanowires and nanotubes based on the boron-nitride, oxides, chalcogenides, dichalcogenides, chalogenides, and some other III–V and II–VI compounds possessing of most manifold physico-chemical characteristics.

Reduced 2D heterostructures, nanolayers and nanodisks being the well-known 2D quantum wells are believed to migrate from micro- to nano-electronics. In addition the 2D arrays of nanowires and nanotubes ordered as 2D ‘forest’ arrays and 2D crystals form the very perspective core of NT. Their unique properties are known to be determined by novel principles of electromagnetic waves propagation based on the Bragg diffraction law rather than total internal reflection. The quantum and the macroscopic 2D crystals in which the various quantum states and resonance effects are expected exist. Actually in such resonance states it is possible for one to recognise as a novel state of matter, a research that tends to become advanced in nanophysics. On this basis the waveguides, laser emitting diodes, infrared sensors and other nanodevices were developed earlier. We propose to classify all possible nanostructures as shown in figure, that focus researcher attention on wide range of novel kinds of nanostructured materials, rather then their grain boundaries, extending the paradigm of nanostructured materials science.

The design and assembly of such artificial media, a search for novel effects and phenomena in them, as well as the development of novel nanodevices on this base seems to be the most promising road to the nearest NT. One example is the discovery of ‘left’ matter, in which an unconventional inverse refraction law as well as inverse Doppler and inverse Cherenkov effects were observed. In nanomaterials science the structure-form engineering is emphasised in addition to the impurity engineering. Material at once gets transformed into a nanoworkpiece. Note that the advantage of nanomaterials is hoped to proclaim itself in the development of nanodevices, the electronic gnat for example, rather than in largescale industry.



The peculiarity of the nanoworld is the blurring of distinctions between live and inorganic matter. The exchange of substance as being the indication of life manifests itself on the supramolecular level rather than a molecular one. Proteins, membranes, and nucleic acids refer to giant natural nanostructures built as a result of self-assembling. The analogy opens a fantastic opportunity for nanomaterials and nanodevices fabrication by such biomimicry. Artificial growth of pearls inside mussels, as well as the ordering of nonequilibrium defects into 2D nanostructures on a surface of semiconductors under the ion bombardment and implantation are examples.

The question arises as to what features inherent to atomic and molecular physics, chemical synthesis technologies, microelectronics, etc., did not exist before the NT era. The novelties include:

- artificial manipulating by nanoobjects and manual or automatic assembling of the nanodevices designed beforehand using a 'bottom-up' approach
- deliberate intervention in processes and mechanisms with the comprehensive control of chemical self-assembly at the molecular level
- invention, design and production of nanodevices of sub-micrometre size followed by their integration into micro-, meso-, and macro-systems.

When venturing into NT, one must beware of some illusions and problems.

- There is a lower limit on the size of particles because this does not always result in the improvement of properties. For instance, the optimal size of disperse inclusions in oxide ceramics ca. ~10–20 μk was shown to exist at which the optimal combination of hardness and durability is achieved.
- When the size of particles decreases, the processes of thermal instability and phase transitions were shown to take place resulting in nondurability of nanosystems. For instance, the well-known words IBM, NANO, and corals drown on substrate by atomic-force microscopy which turned out to be unstable due to fast surface diffusion of building addatoms. Since the covalent bonded semiconductors and ceramics preferably appear to be stable and durable, the nanomaterials for NT looks as nonmetallic.
- Cosmic irradiation and background radiation are capable of knocking atoms out of nanostructures leading to degradation of their properties and in to worsening of nanodevice operation.
- Thermal noise and vibrations will always restrict the properties and characteristics of nanodevices. In particular, it limits knowledge of the position of the microscopic probe, which can never be less than a half-amplitude of thermal vibrations.
- Even the smallest concentrations of inherent impurities and unremovable contamination are capable of destroying the assembling processes, so super-high-purity feed reagents and clean-room processes are required.

In conclusion, all physical discoveries in vacuum have been made already, not counting the further discovery of the vacuum itself. Novel discoveries, laws, phenomena, technical decisions, solutions, and inventions would be made only in specially designed and assembled artificial nanostructures to be fabricated by future nanotechnology.

At present we meet NT in its childhood. The announcement of grand projects, such as biochips and nanobiorobots for medicine, smart dust for space research, etc., have become a motivation for its intense development, which may influence the development of civilisation. In USA, EU, Japan, Russia and other leading countries great funding has been made available for NT projects. The perspectives of NT at the beginning of the twenty-first century look very optimistic, although a severe reality is capable of darkening this somewhat naive prospect. But in any case the development of NT is unavoidable and appears assured of success.