NANOTECHNOLOGY IN GENERAL AND QUANTUM DOTS AS AN INTERESTING EXAMPLE

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Abstract

This lecture - as the name suggests - is composed of two parts. An attempt of definition of nanotechnology, its importance, interdisciplinary overlap and fields of application will be given in the first part. The second part will be devoted to examples of our concrete contributions to nanotechnology and nanocharacterisation. We have been preparing semiconductor nanostructures, starting from quantum wells to quantum dots (QDs) for more than twenty years.

QD preparation and characterisation are described in detail using six selected papers concentrating on our measurements of photoluminescence, magnetophotoluminescence, electroluminescence and ballistic electron emission microscopy and spectroscopy of QDs.

The lecture is based on the results of more than thirty of papers published in scientific journals. Other important sources were invited and contributed lectures at many international conferences, Universities and Institutes, as well as experiences obtained during organising of many international conferences namely: IC MOVPE, EW MOVPE, MIOMD, Crystal Growth Conferences, ENF, NANOCON, etc.

The metal nanoparticles and metal based nanotechnology will be mentioned only marginally, because many conference participants know about this subject more than me.

Keywords: Nanotechnology, nanomaterials, nanocharacterisation, nanostructures, quantum wells and dots

1. ON NANOTECHNOLOGIES AND NANOSTRUCTURES IN GENERAL

1.1. Definition of nanotechnologies and nanostructures

The Wikipedia [1] states that nanotechnology is the manipulation of matter on an atomic or molecular scale. Nanotechnology deals in general with structures of size 100 nanometres or smaller, in at least one dimension (direction) and includes also development of materials of this magnitude. We can also consider for nanotechnology something that matches the following three criteria:

The first criterion: Nanotechnology is a research activity or technological development conducted on atomic, molecular or macromolecular level in scale of single or hundreds of nanometres. In certain cases we do consider as a nanotechnology also activity which manipulates with objects of scale of up to several micrometers.

The second criterion: Structures, facilities or systems which have new properties or functions resulting i.a. from their tiny size must be made or used by these activities. Therefore we have to accept the fact that on nanoscale do the particles and their structures behave differently than in macroworld. This is given i.a. by the fact that the main factors influencing behaviour of nanoparticles are atomic forces, properties of chemical bonds and especially the quantum phenomena.

The third criterion: Only such methodic, which allows creation of functioning systems and complexes from nanoparticles can be called a nanotechnology procedure. We also have to be able to set, control and regulate the functioning of these complexes by objective procedures, i.e. be able to manipulate with them.
This definition and criteria are quite general, but correct in principle. We can even use them on the old Chinese techniques of colouring with golden nanoparticles or on Lycurgos chalice from ancient Rome. It can be objected that then nothing was known about quantum physics, but even we do not really understand it at it isn’t even fully included in the body of knowledge of physics (the connection with relativistic, gravitation or brain biology). It is necessary to inform the students also on this deep history as the nanotechnology doesn’t really begin with Feynmans quote or quantum physics from early 20th century.

For example the discovery of glass colouring with tiny amount of golden nanodust was attributed to German glassmaker Johann Künckel, who lived in 17th century, but it obviously is much older technique, which is a textbook example of use of nanotechnology: “The changing coloration of the chalices is connected with unusual property of gold (as well as silver and copper), by which it is different from most other metals. Electrons in the atomic lattice are move freely and create waves similar to waterwaves on the surface of the metal which create the light. For alkali metals and Cu, Ag or Au they are partly in the visible part of spectrum. Metal nanoparticles gently spread in glass or in solution or metal nanofoils have bright colours – brown (Ag), green (Cu) to ruby (Au). Electrons on the surface of these atoms transmit electromagnetic field similarly as photons light. These waves are named surface plasmons [2].

It is very important to stress that e.g. nanoelectronics will be not only simple miniaturisation of microelectronics, but also its fundamental change caused by new effects (quantum physics) and thus new applications. Very interesting view on this subject is “Miniaturisation of solid state devices” – see Fig. 1.

![Fig. 1 Nanostructures and Moore law [3].](image)

1.2. History and development of nanotechnologies

The beginning of nanotechnology is usually dated in 1950s and connected with the American physicist Richard Feynman. He has asked the scientific world: „Why can’t we write all twenty-four volumes on Encyclopaedia Britannica on a pinhead yet?” Feynman lectured: „There’s Always (or Plenty) Room at the Bottom,” [4] at an American Physical Society meeting at Caltech on December 29, 1959. He has described a vision that later became reality and new field of physics – the nanotechnology vision. He has described a conception by which the ability to create new materials by manipulation with individual atoms and molecules might be developer. Later development in 1980s proved him right. The Scanning Tunnelling Microscope was
invented 1981, the Atomic Forces Microscope in 1986 and the IBM engineers have written the logo of their company by thirty-five isolated xenon atoms thanks to STM in 1989.

The first to use the term of “nano-technology” was Japanese scientist Norio Tamaguchi from University of Tokyo in 1974 [5]. His definition for separation of thin semiconductor films was: „Nanotechnology is chiefly creation, separation, composition and deformation of materials on the atomic or molecular level.” It is rather obsolete today, but still valid for many fields.

The current imagine on classification and development of nanosystems is in Fig. 2:

![Fig. 2. Classification and possible development of the nanosystems][1]

1.3. Importance and financing of nanotechnologies

The US National Nanotechnology Initiative launched by president Bill Clinton was funded by 500 million US dollars in 2000 [7, 8], during George W. Bush presidency it was 3.63 billion for 2003-2007 and by 2009 the support was 1.5 billion dollar per year [9].

European Commission has prepared a proposal on financing research of nanotechnologies in 2010-2015 by 4 billion EUR [6] for the European Parliament's approval. Projects in a very wide spectrum of nanotechnology fields should be funded, nevertheless a major selection was made given to European possibilities, competitiveness and impact for European economy. Very strong support for nanotechnologies is in single European countries, esp. in Germany, United Kingdom and France.

Even stronger support and development of nanotechnologies is in all countries of eastern Asia, where vast majority of nanoproduction is realised - and most of the profits from this production goes to further research, which thus receives much bigger funding than elsewhere. Even Saudi Arabia does bet on nanotechnologies, as on a perspective successor of oil.

Czech national program "Nanotechnologies for the society", on the preparation of which I have participated, brings to nanotechnology research approx. 1 billion crowns in 2008-2013. Very small part is given to basic research, most of the funding goes to applied research and minor part is for companies, on which support and co-financing is bounded most of the projects. It is a pity that joint project of the Academy of Sciences

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[1]: http://example.com/fig2.png
and Czech Technical University to establishment of Institute of applied sciences, which should very much focus on research of nanostructures and nanotechnologies failed in 2010.

1.4. Fields of nanotechnology and applications of nanostructures

I am afraid that nanotechnology can’t be described as independent field (which is happening in many cases when new scientific (and teaching) disciplines split from established scientific fields, spin off their subject of study and create their own terminology. Nanotechnology was created by pooling several areas of science, or rather by deepening or widening of their objects of study. Nanotechnology also tends to take over even terminology. The basic tool of description and explanation is (there, where nanotechnology isn’t mere miniaturization) already established quantum physics.

Nanotechnology as well as nanoparticles and nanostructures goes across virtually all natural and technical sciences as a tool, scope of business or subject of study today. It is in basic foundations of physics, chemistry, biology, and engineering of materials. Machine- and house-building, electronics, medicine, energetic, automobile industry and other areas use its products.

The “horizontal issue”, of nano- which would connect all nanofields is looked for frequently. I fear it is neither:

**physics**: quantum mechanics is fundamental for understanding of most events on the nanolevel, nevertheless it is too complicated for use in nanobiology or nanomedicine and too complicated for other fields like nanomachinery or nanomaterials for building;

**nor nanorisk, nanosafety or nanoethics**: it is a highly important discipline – although some nanoparticles can be deadly dangerous (asbestos, diesel engine fumes etc.), other nanostructures or nanoparticles aren’t, even can’t be dangerous as nanoparticles per se, and neither can the elements from which they are formed. Regulation on informing on nanoparticles inclusion in various products can seem proper, but I found it nonsensical due to the fact that all material is most probably composed from nanoparticles (atoms). There is a risk of nanomaterials, and it can’t be underestimated, but it also shouldn’t be generalized;

**nor nanoeducation**: teaching on nanotechnologies in their total scope is impossible due to limited capacities of teachers and students. Single fields have and must have different approaches to cognition and a unifying theory isn’t even on a horizon. Nanotechnology education grows on bases of single fields.

Only nanocharacterisation could be unifying: Everyone needs to know how big is and how looks like a nanostructure or nanoparticle which is object of his interest. This corresponds with rapid development of nanocharacterisation methods and techniques. There are probing (tipping), electron, x-ray, and optical (despite relative big size of photons) methods. In one study are described dozens of varieties of probing characterisation techniques.

Application of nanostructures intervenes probably in all areas of human activity. I include at least small overview according to [6], where many pages are filled only with description of fields where are nanotechnologies and nanostructures used in Europe. Incomplete and not current overview of workplaces, disciplines and projects in Czech Republic is included in publication [11]. I will only limit myself on description, explanation of function and introduction of applications from area of semiconductor nanostructures called quantum dots.

2. SEMICONDUCTOR QUANTUM DOTS

There are two types of quantum dots (QD) – free and embedded. Both have similar structure – inside is material with narrower forbidden gap, surrounded by wider e.g. semiconductor material. Free QDs have wide field of application in the medicine (diagnostics as well as therapy). QDs crystallographically perfectly fixed in the heterostructures are used mainly for optoelectronic devices (LED, lasers, detectors, …).
Some of our results are briefly summarised here:

Lateral shape of InAs/GaAs QDs in vertically correlated structures

Elongation of InAs/GaAs QDs determined from magnetophotoluminescence measurements

Influence of strain reducing layers on electroluminescence and photoluminescence of InAs/GaAs QD structures
QDs are prepared by epitaxial techniques – Molecular Beam Epitaxy or Metalorganic Vapour Phase Epitaxy. Short description of our QD preparation and our new results will be presented.

CONCLUSIONS

We can conclude that nanodevices and nano technology can be in principle divided to the three fields:

Simple miniaturisation – semiconductor memories, small particles with large surface, small fibres or pores.

Miniaturisation with additional value – better surface properties, more efficient LED and LD structures, …

Quite new properties – tunnelling diodes, quantum cascade lasers, quantum well and dot devices, …

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LITERATURE

[7] President Clinton’s speech: My budget supports a major new National Nanotechnology Initiative, worth $500 million. Over 40 years ago, Caltech’s own Richard Feynman asked, "What would happen if we could arrange the atoms one by one the way we want them?". President George W. Bush further increased funding for nanotechnology. In 2003 Bush signed into law the 21st Century Nanotechnology Research and Development Act, which authorizes expenditures for five of the participating agencies totaling US$3.63 billion over four years. The NNI budget supplement for Fiscal Year 2009 provides $1.5 billion dollars to the NNI.