PART 1

Concepts, Discoveries and the Rapid Development of Nanotechnologies

Chapter 1

Nanotechnologies in Context: Social and Scientific Awareness of their Impact

1.1. Feynman, the visionary

The term "nanotechnology" was coined in the 1970s by the Japanese professor Norio Taniguchi [TAN 74] to design "infinitesimal" technologies; however, interest in such technologies had already been around well before that time.

Richard Feynman (a physicist famous for his developments in quantum electrodynamics, Nobel Prize awarded 1965) was the first to anticipate the future interest in studying and using properties of objects or systems composed of only a small number of atoms or molecules (atomic or molecular aggregates) to develop new fields of applications based on the practice of a new physical chemistry [FEY 59].

In a lecture given in 1959 at the American Society of Physics congress at the California Institute of Technology (Caltech), he defined a new type of chemistry in which atoms are individually manipulated with the prospect of developing devices at the nanometer scale (a billionth of a meter).

The title of his lecture “There’s Plenty of Room at the Bottom” became famous. It was a real incentive for scientists to explore the world of the infinitesimal that he presented as a new El Dorado for science and technology, and for the benefit of society.

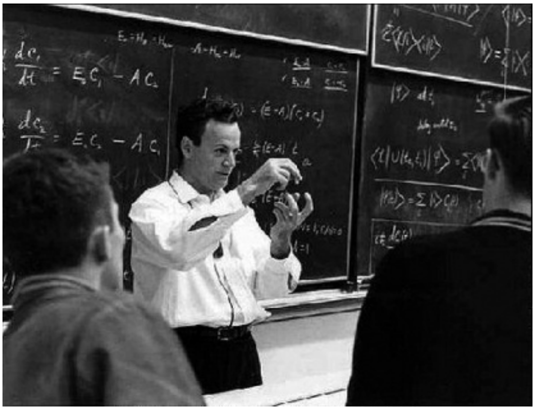

Figure 1.1. *Feynman with his students in the 1950s (courtesy of Caltech)*

To illustrate his point and to stir the imagination of the audience, he showed, after a simple computation, that the 25 volumes of *Encyclopedia Brittanica* could be inscribed onto the head of a pin.

Speaking in the context of the 1950s could be somewhat perplexing, considering the advancing state of technology in the field of miniaturization in general, especially that of electronics.

Indeed, we must remember that the invention of the transistor by the American scientists, Shockley, Bardeen and Brattain in Bell laboratories (Nobel Prize awarded 1957) dates back to 1947 [SHO 56], and that the first integrated circuit (an important simplification of electronic circuits) invented by Kilby (Nobel Prize awarded 2000) in Texas Instruments laboratories in the United States, only appeared a decade later, and was far from miniature [KIL 00].

It was not until the early 1970s that the first processors appeared; devices including a very large number of transistors arranged in thin layers on the same base of silicon. We can rightly consider this to have marked the actual beginning of the miniaturization of electronic circuits.

This miniaturization of circuits arranged in thin layers could not have been carried out if it was not for the considerable progress made in the chemistry and physics of surfaces and without the development of instruments for analyzing and controlling them at the microscopic scale.

Figure 1.2. *Shockley, Bardeen and Brattain (from left to right), Bell Labs, 1947*

Yet this is still far from manipulations at the nanometer scale. As a guide, the first microprocessors built in 1971 by Intel® (4004-86 Processor) already containing a decent number of transistors (2,300), of miniscule sizes (approximately 10 µm), are in no way comparable to the most recent processors made in 2010, involving about a billion transistors, and a hundred times smaller in size [INT 2011].

This nicely shows how in the 1960s technology was deeply rooted in the micrometer scale, and that Feynman's premonition could appear more futuristic to some and somewhat utopic to others.

1.2. Nanotechnologies and their definition

After numerous discussions, a consensus emerged in the scientific community around 2000; the field of nanotechnology was rather generally defined as the manipulation of objects with dimensions between 1 and 100 nm. The term "nanotechnologies" is intentionally recommended rather than "nanosciences" in order to emphasize all the social implications that nanotechnologies might be able to bring in the near future.

This definition, *a priori* restrictive, implies that all manipulations of objects with dimensions of nanometers (groups of atoms or molecules) translate as an insertion or a link to macroscopic systems (objects with dimensions of micrometers or millimeters) that are also a part of nanosciences.

So, any modification made to a material, by grafting atoms or molecules onto its surface, or even by incorporating nanosized particles into the core of the material is still found under this definition. In a more general fashion, this comes back to defining these modifications as a restructuring of matter at the nanometer scale. This definition also applies to manipulating complex macroscopic objects to which nanosized active components are associated.

From a practical point of view, defining nanotechnologies according to units in nanometers is rather allusive if we do not have some indications of known objects.

The nanometer, equal to a billionth of a meter (one millionth of a millimeter or one thousandth of a micron) is not a common unit of measurement. This is why, in order to better appreciate this dimension, we have placed (Figure 1.3) some more familiar objects (atoms, molecules, living cells, wavelengths of visible light, transistors and microprocessors from the previous generation, etc.) on to a logarithmic scale.

So, at the lower limits of the scale, between 0.1 and 1 nm, we find atoms (made up of a nucleus and an electron cloud); next come molecules made up of assemblies of atoms whose size clearly reflects the number of atoms.

In the case where the number of atoms making up a molecule is very large, the diameter of the molecule is still less than 1 nm, but its length can vary from several nanometers to tens of nanometers (macromolecule).

In extreme cases such as deoxyribonucleic acid (DNA), a molecule made up of an assembly of two strands of DNA (two macromolecules of complementary structures that spontaneously combine as a result of weak forces), the diameter is less than 1 nm, but the length of the molecule is considerable and can reach up to several hundred nanometers, or even several tens of centimeters (Stryer [STR 95]).

The electronics industry, where remarkable developments have been made in terms of miniaturization, is also at the heart of nanotechnology.

For instance, the last generation of Intel® field-effect transistors (the FET "Tri Gate" is approximately 100 nm), which intervenes in the operating of microprocessors (cm dimensions), could only be carried out thanks to advances in vacuum-deposition techniques, which now allow extremely complex circuits to be made from diverse materials with layers of only a few nanometers thick.

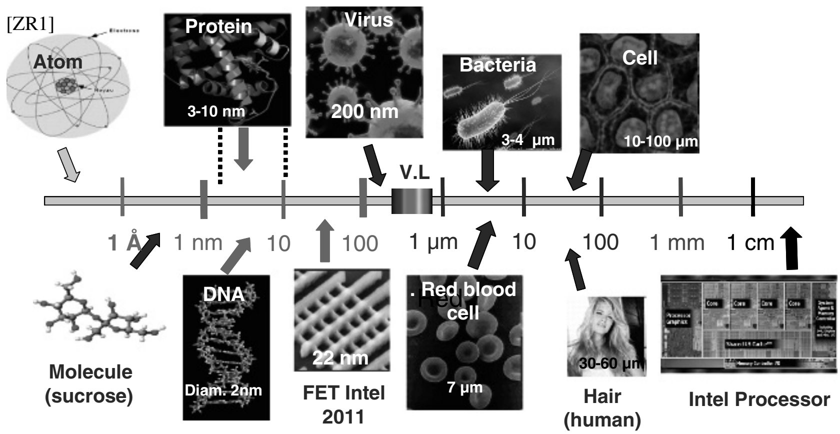

Figure 1.3. *Scale of dimensions of several familiar objects positioned on a logarithmic scale (each interval corresponds to a multiple of 10). The Angström (Å), generally used to define dimensions of atoms, is equal to 0.1 nm. For a color version of this figure see www.iste.co.uk/lacaze/nano.zip*

Beyond 100 nm, the visible light spectrum (VL) is also a familiar dimension, with bands of wavelengths λ extending from 400 nm (violet) to 700 nm (red).

It is also within this range of dimensions that viruses are found (between 200 and 400 nm), whereas bacteria, red blood cells and living cells are found within the micrometer domain, with sizes ranging from several microns to several tens of microns (1 µm = 1,000 nm = 0.001 mm).

Much further in this same range of dimensions, we find the human hair, with thicknesses varying according to the individual between 30 and 80 µm (i.e. 30,000 and 80,000 nm).

Finally, in the centimeter range, microprocessors, comprising an assembly of a considerable number of transistors (around one billion in 2010), which can be regarded as pure products of nanotechnology, presented in the form of a small circuit board of several centimeters.

1.3. The consideration of nanotechnologies by scientific organizations

In the 1960s and the 1970s, a large portion of experiments in physics, chemistry and biology could be considered retrospectively as being within the field of nanoscience, even though this term had not yet been coined.

Given the importance of new applications related to the discovery and study of new materials of nanometric dimensions such as aggregates of atoms or nanoparticles (NPs) or carbon nanomaterials (fullerenes in 1980, nanotubes of carbon in 1985) and also, after new observation instruments in the nanometric scale were invented (near-field scanning microscopy), it was not until the 1990s that public research organizations began to realize the importance of the domain and encouraged the majority of governments to financially support R&D initiatives within nanosciences. It was in the United States that the incentive was greatest. At the initiative of the NSF (National Science Foundation), there was a considerable mobilization among the main components of society, in order to formalize the launch of a vast research program dedicated to all forms of nanotechnologies.

This is the famous National Nanotechnology Initiative (NNI) developed at the beginning of 2000 under the auspices of societies' major scientists and with the support of federal departments.

This NNI establishes a strategic preliminary plan of 10 years for the intensive development of nanotechnologies.

Among the main actions of R&D to be undertaken, there are nine key themes:

1) the nanostructuration of materials;

2) industrial production at the nanoscale;

3) chemical, biological and radiological detection and protection against explosives;

4) instrumentation and metrology;

5) nanoelectronics, nanophotonics and nanomagnetics;

6) health: diagnosis and therapies;

7) conversion of energy and its storage;

8) micromechanics and robotics;

9) upgrading and developing chemical processes at the nanoscale for improving environmental conditions (Roco [ROC 11]).

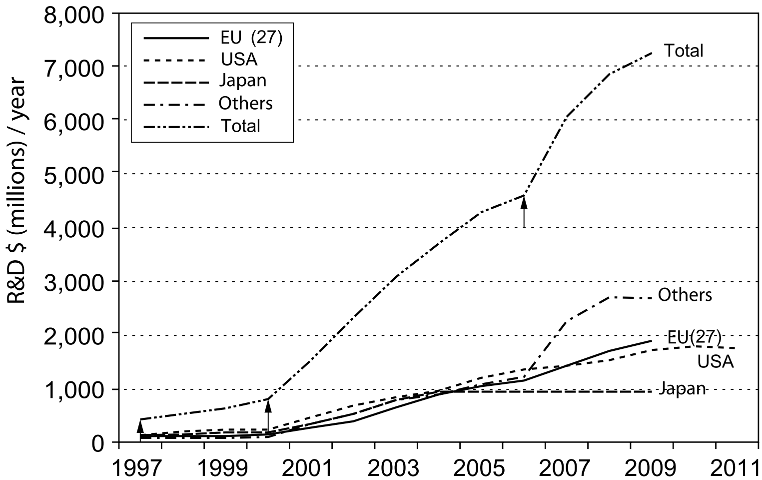

Figure 1.4. *Annual evolution of credits dedicated to R&D in different parts of the world. Notice the acceleration of financing after 2000 and 2006, with a global amount of more than $7 billion in 2009. (China, Korea and Taiwan represent the countries in the category "Others".) (adapted from Roco [ROC 11]). For a color version of this figure see www.iste.co.uk/lacaze/nano.zip*

To highlight how important this plan is, President Clinton personally offered his support in a speech that he gave on January 21, 2000, at Caltech, more than 40 years after that of Feynman [CLI 00].

Very rapidly, similar plans were also implemented in other countries, with similar priorities to those of the NNI. Accompanied by important financial support, they contributed to induce a strong inclination in science toward all types of nanotechnology. The growth in loans, granted by diverse states or regions of the world, shows rather brilliantly the growing interest in their development (Figure 1.4).

Just as significantly, the increase in scientific publications within this sector also demonstrates a generalized tendency toward the study of nanosciences; quite remarkably, China has now overtaken the United States in terms of publications (Figure 1.5).

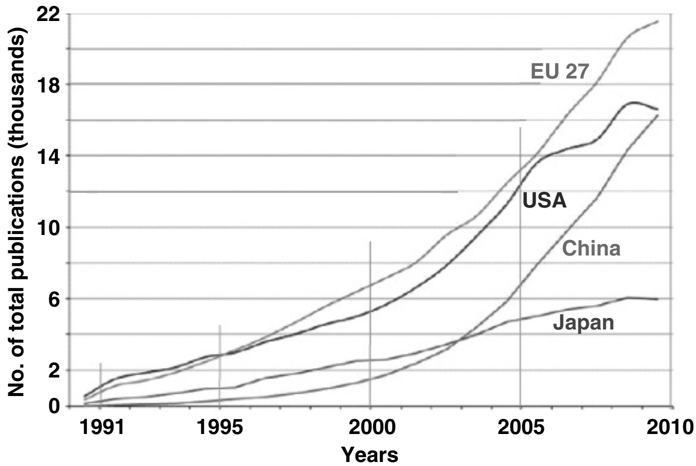

Figure 1.5. *Evolution of the number of total publications within the field of nanotechnology between 1990 and 2009, calculated by studying the keywords in the SCI database (Science Citation Index, Thomson Reuters) (adapted from Roco [ROC 11])*

At the European level, the overall activity in the field of nanotechnology is equally as great. In 2010, it surpassed the United States, China and Japan in terms of total publications, with a distribution according to the 27 members (countries) in the EU, approximately proportional to the size of populations of each one.

Economically, this is a huge market; in 2010, it was given a value of approximately $250 billion.

In terms of research activities, there were 400,000 researchers in 2008 (150,000 of whom are in the United States) within the field of nanotechnology, a number that is constantly increasing and is expected to reach two million (800,000 of whom are in the United States) by 2015 [ROC 11].

In France, since 2005, there has been a major reorganization in research, with the purpose of encouraging the development of nanotechnologies. The MINATEC (Mini and Nano Technologies) center, inaugurated in 2006 at the scientific polygon in Grenoble, currently has more than 2,000 researchers and includes the most significant center of research in Europe dedicated to nanotechnologies; the ultimate aim being the collaboration of international research projects with industry. Academic research was also restructured under the auspices of the French National Centre of Scientific Research (CNRS) with the creation of six regional centers of expertise from 2006 onward (C'Nano) joining together more than 6,000 researchers in the nanosciences and with inclination of favoring exchanges and collaborations between laboratories.

Undoubtedly, society can expect beneficial outcomes to be manifested, especially in the field of medicine as we will see later on; the introduction of nanotechnologies represents a major event in the 21st Century, the same as seen with computing at the end of the 20th Century.

1.4. Bibliography

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