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Nanotechnology: Principles and Applications

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Abstract — Nanotechnology is one of the leading scientific fields today since it combines knowledge from the fields of Physics, Chemistry, Biology, Medicine, Informatics, and Engineering. It is an emerging technological field with great potential to lead in great breakthroughs that can be applied in real life. Novel Nano and biomaterials, and Nano devices are fabricated and controlled by nanotechnology tools and techniques, which investigate and tune the properties, responses, and functions of living and non-living matter, at sizes below100 nm. The application and use of nanomaterial's in electronic and mechanical devices, in optical and magnetic components, quantum computing, tissue engineering, and other biotechnologies, with smallest features, widths well below 100 nm, are the economically most important parts of the nanotechnology nowadays and presumably in the near future. The number of Nano products is rapidly growing since more and more Nano engineered materials are reaching the global market The continuous revolution in nanotechnology will result in the fabrication of nanomaterial with properties and functionalities which are going to have positive changes in the lives of our citizens, be it in health, environment, electronics or any other field. In the energy generation challenge where the conventional fuel resources cannot remain the dominant energy source, taking into account the increasing consumption demand and the CO_2 emissions alternative renewable energy sources based on new technologies have to be promoted. Innovative solar cell technologies that utilize nanostructured materials and composite systems such as organic photovoltaic offer great technological potential due to their attractive properties such as the potential of large-scale and low-cost roll-to-roll manufacturing processes The advances in nanomaterial's necessitate parallel progress of the Nano metrology tools and techniques to characterize and manipulate nanostructures. Revolutionary new approaches in Nano metrology.

I. INTRODUCTION

The term nanotechnology comes from the combination of two words: the Greek numerical prefix nano referring to a billionth and the word technology. As an outcome, Nanotechnology or Nano scaled Technology is generally considered to be at a size below 0:1 _m or 100 nm (a nanometer is one billionth of a meter, 10_{-9} m). Nano scale science (or Nano science) studies the phenomena, properties, and responses of materials at atomic, molecular, and macromolecular scales, and in general at sizes between 1 and 100 nm. In this scale, and especially below 5 nm, the properties of matter differ significantly (i.e., quantum-scale effects play an important role) from that at a larger particulate scale. Nanotechnology is then the design, the manipulation, the building, the production and application, by controlling the shape and size, the properties-responses and functionality of structures, and devices and systems of the order or less than 100 nm .Nanotechnology is considered an emerging technology due to the possibility to advance well-established products and to create new products with totally new characteristics and functions with enormous potential in a wide range of applications. In addition to various industrial uses, great innovations are foreseen in information and communication technology, in biology and biotechnology, in medicine and medical technology, in metrology, etc. Significant applications of Nano sciences and Nano engineering lie in the fields of pharmaceutics, cosmetics, processed food, chemical engineering, high-performance materials, electronics, precision mechanics, optics, energy production, and environmental sciences. Nanotechnology is an emerging and dynamic field where over 50,000 nanotechnology articles have been published annually worldwide in recent years, and more than 2,500 patents are filed at major patent office's such as the European Patent Office. Nanotechnology can help in solving serious humanity problems such as energy adequacy, climate change or fatal diseases: "Nanotechnology" Alcatel-Lucent is an area which has highly promising prospects for turning fundamental research into successful innovations. Not only to boost the competitiveness of our industry but also to create new products that will make positive changes in the lives of our citizens, be it in medicine, environment, electronics or any other field. Nano sciences and nanotechnologies open up new avenues of research and lead to new, useful, and sometimes unexpected applications. Novel materials and new-engineered surfaces allow making products that perform better. New medical treatments are emerging for fatal diseases, such as brain tum ours and Alzheimer's disease. Computers are built with nano scale components and improving their performance depends upon shrinking these dimensions yet further". Nano materials with unique properties such as: nanoparticles carbon nanotubes,

fullerenes, quantum dots, quantum wires, nano fibers, and Nano composites allow completely new applications to be found. Products containing engineered nanomaterial's are already in the market. The range of commercial products available today is very broad, including metals, ceramics, polymers, smart textiles, cosmetics, sunscreens, electronics, paints and varnishes. However new methodologies and instrumentation have to be developed in order to increase our knowledge and information on their properties. Nanomaterial's must be examined for potential effects on health as a matter of precaution, and their possible environmental impacts. The development of specific guidance documents at a global level for the safety evaluation of nanotechnology products is strongly recommended. Ethical and moral concerns also need to be addressed in parallel with the new developments. Huge aspirations are coupled to nan technological developments in modern medicine. The potential medical applications are predominantly in diagnostics (disease diagnosis and imaging), monitoring, the availability of more durable and better prosthetics, and new drug-delivery systems for potentially harmful drugs. While products based on nanotechnology are actually reaching the market, sufficient knowledge on the associated toxicological risks is still lacking. Reducing the size of structures to Nano level results in distinctly different properties. As well as the chemical composition, which largely dictates the intrinsic toxic properties, very small size appears to be a dominant indicator for drastic or toxic effects of particles. From a regulatory point of view, a risk management strategy is already a requirement for all medical technology applications .
In order to discuss the advances of nanotechnology in nanostructured materials, we presented first in Sect. 1.2 the methods and principles of Nano scale and nanotechnology, and the relevant processes. The impact of nanotechnology in the field of electronics is presented in Sect. 1.3. Energy harvesting and clean solar energy are presented in Sect. 1.4 focusing in a new emerging technology of plastic photovoltaic which is based on nanostructured materials. The techniques and the tools which are currently used to characterize and manipulate nanostructures are presented in Sect. 1.5. In Sect. 1.6, the future perspectives as well as the increasing instrumentation demands are discussed.

II. Methods and Principles of Nanotechnology

1.What Makes Nanostructures Unique

The use of nanostructured materials is not a recently discovered era. It dates back at the fourth century AD when Romans were using nanosized metals to decorate glasses and cups. One of the first known, and most famous example, is the Lycurgus

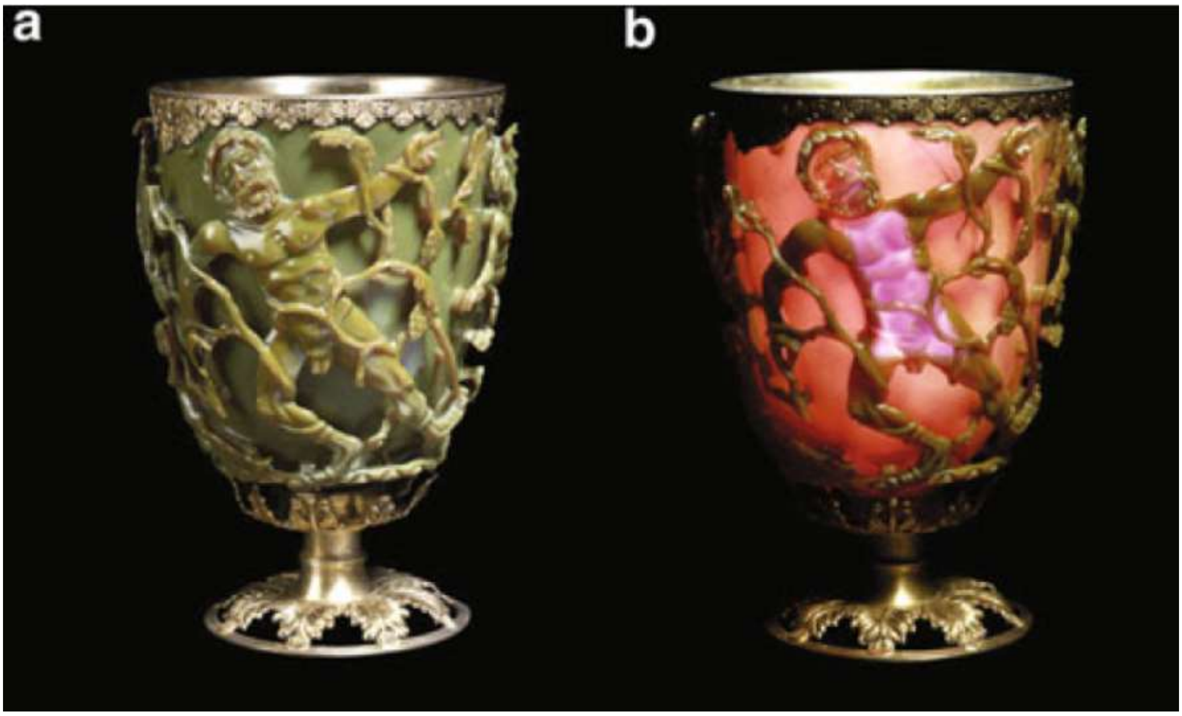

Fig. :The Lycurgus cup in reflected (a) and transmitted (b) light. Scene showing Lycurgus being enmeshed by Ambrosia, now transformed into a vine-shoot. Department of Prehistory and Europe, The British Museum. Height: 16.5 cm (with modern metal mounts), diameter: 13.2 cm. The Trustees of the British Museum cup , that was fabricated from nanoparticles (NPs) from gold and silver that were embedded in the glass. The cup depicts King Lycurgus of Thrace being dragged to the underworld. Under normal lighting, the cup appears green. However, when illuminated from within, it becomes vibrant red in color. In that cup, as well as in the famous stain glass windows from the tenth, eleventh, and twelfth centuries, metal NPs account for the visual appearance. To shed light to the changes in visual appearance of gold, from the usual yellowish color to the reddish one that appears in the Lycurgus cup a comparison between differences of absorption spectra from a bulk gold metal film and a gold colloidal film . The thin, bulk gold metal film absorbs across most of the visible part of the electromagnetic spectrum and very strongly in the IR and at all longer wavelengths. It dips slightly around 400–500nm, and when held up to the light, such a thin film appears blue due to the weak transmission of light in this wavelength regime. On the contrary, the dilute gold colloid film displays total transparency at low photon energies (below 1.8 eV). Its absorption becomes intense in a sharp band around 2.3 eV (520 nm) This sharp absorption band is known as surface plasmon absorption band. Metals support SPs that are collective oscillations of excited free electrons and characterized by a resonant frequency. They can be either localized as for metal NPs or propagating as in the case of planar metal surfaces. Through manipulation of the geometry of the metallic structure, the SPR can be tuned depending on the application. The resonances of noble metals are mostly in the visible or near infrared region of the electromagnetic spectrum, which is of interest for decorative applications. Because of the plasmonic excitation of electrons in the metallic particles suspended within the glass matrix, the cup absorbs and scatters blue and green light – the relatively short wavelengths of the visible spectrum. When viewed in reflected light, the plasmonic scattering gives the cup a greenish hue, but if a white light source is placed within the goblet, the glass.

Size Dependence:

The aforementioned ability of gold as well as of other noble metals and semiconductors relies on quantum confinement which is a very successful model for describing the size dependent electronic structure of nanometer sized materials According to this theory electrons are confined in all three dimensions causing matter to behave completely different in terms of its optical and electronic properties. When the dimension of a material approaches the electron wavelength in one or more dimensions, quantum mechanical characteristics of the electrons that are not manifest in the bulk material can start to contribute to or even dominate the physical properties of the material .Besides quantum size effects, the nanomaterial's behavior is different due to surface effects which dominate as Nano crystal size decreases. Reducing the size of a crystal from 30 to 3 nm, the number of atoms on its surface increases from 5% to 50% beginning to perturb the periodicity of the "infinite" lattice. In that sense, atoms at the surface have fewer direct neighbors than atoms in the bulk and as a result they are less stabilized than bulk atoms. The origin of the quantum size effects strongly depends on the type of bonding in the crystal.

Metal NPs:

For metals, the electron mean free path (MFP) determines the thermal and electrical conductivity and affects the color of the metal. For most of the metals, MFP is of the order of 5–50 nm. Reducing further this threshold, the electrons begin to scatter off the crystal surface, and the resistivity of the particles increases. For very small metal particles, the conduction and valence bands begin to break down into discrete levels. For gold particles, this causes a change in color from red to orange at sizes around 1.5 nm.

Quantum Dots:

In a bulk semiconductor electrons can freely move within an area from a few nanometers to a few hundred of nanometers as defined by the Bohr radius. Thus continuous conduction and valence energy bands exist which are separated by an energy gap. Contrary, in a quantum dot, where exactions cannot move freely, discrete atomic like states with energies that are determined by the quantum dot radius appear.

III. Future Perspectives

Nanotechnology is distinguished by its interdisciplinary nature. As investigations at the nano level are occurring in a variety of fields, it is expected that the results of this research are going to have a significant impact on a broad range of applications Nanomaterial's with tailored unique properties have limitless possibilities in materials science Products where the addition of a relatively small amount of functionalized nanoparticles or carbon nanotubes leads to a major change in the properties are going to revolutionize many commercial technologies. It is believed that nanotechnology can greatly contribute to the evolution of modern medical approaches and practices. Nano scale constructs are already used in therapeutically applications against cancer and pathogens mostly by acting as drug carriers. Also either in-vivo or ex-vivo engineered scaffolds and tissues are implanted in patients whose own organs and tissues are damaged or lost. Furthermore, specific nanostructures are widely used as imaging and detection agents in diagnostic procedures. The ideal goal is to improve health by enhancing the efficacy and safety of Nano systems and Nano devices while at the same time use Nano medicine in order to cure diseases that remain incurable or the conventional therapeutically approaches against

them are either expensive or inefficient. The advances in fundamental Nano sciences, the design of new nanomaterial's, and ultimately the manufacturing of new Nano scale products and devices all depend to some degree on the ability to accurately and reproducibly measure their properties and performance at the Nano scale. Therefore, Nano metrology tools and techniques are both integral to the emerging nanotechnology enterprise and are two of the main areas critical to the success of nanotechnology. Decades of Nano science research have led to remarkable progress in nanotechnology as well as an evolution of instrumentation and metrology suitable for some Nano scale measurements. Consequently, today's suite of metrology tools has been designed to meet the needs of exploratory Nano scale research. New techniques, tools, instruments and infrastructure will be needed to support a successful nonmanufacturing industry.
The currently available metrology tools are also beginning to reach the limits of resolution and accuracy and are not expected to meet future requirements for nanotechnology or nonmanufacturing. Novel methods and combinations, such as the TERS technique, achieve much higher resolution values since they provide a significant increase in the Raman signal and in the lateral resolution by up to nine orders of magnitude. This combination overcomes the difficulties that originate from low signal since the Raman systems have limit in lateral resolution of 300 _m and require high laser power for surface investigation because the measured Raman intensity is six orders of magnitude lower than the excitation power. Thus, TERS is a promising technique and we can see it in the near future to be used for probing
the chemical analysis of very small areas and for the imaging of nanostructures and biomolecules such as proteins. New approaches have to be developed and existing ones based on XPS, X-ray absorption spectroscopy, SPM and SIMS have to be improved in terms of better spectral and spatial resolution, better contrast and better sensitivity for elements and molecular species. Ideally new methods should have capabilities to work in situ, at ambient air and/or in liquid surroundings. However, clever new approaches need to be developed. For this, it is required to understand the fundamental mechanisms by which the probes of the Nano metrology measuring systems interact with the materials and objects that are being measured. Also, it is important to develop standard samples and to construct standardized procedures for measurements in nanometer scale, which enable the transfer of the properties and response of the unit from the nanometer to macroscopic scale without any appreciable loss of accuracy, for certifying, calibrating, and checking Nano metrology instruments. Finally, even with the vast array of current tools available, the important question is whether or not they are providing the required information or reams of inconsequential data. Revolutionary approaches to the Nano metrology needed may be required in the near future and therefore, revolutionary and not just evolutionary instrumentation and metrology are needed.

IV. Summary

Nanotechnology is an emerging technology with applications in several scientific and research fields, such as information and communication technology, electronics, energy, biology, medical technology, etc. Novel nano- and biomaterials, and Nano devices are fabricated and controlled by nanotechnology tools and techniques, which investigate and tune the properties, responses and functions of living and non-living matter, at sizes below 100 nm. Nanotechnology is a science with huge potential and great expectations. The daily announcements of new discoveries and breakthroughs are going to influence all aspects of human society. Nanomaterial's bring new possibilities by tailoring the optical, the electronic the mechanical, the chemical, and the magnetic properties. In the last few years there was a rapid progress in the fabrication and processing of nanostructures. As a result anaphase materials and applications are already in the market and a large volume of new applications is expected over the next several years. However, the development and commercialization of products containing nanomaterial's raises many of the same issues as with introduction of any new technology, including concerns about the toxicity and environmental impact of nanomaterial exposures. Despite the extensive research of the last decade the literature on toxicological risks of the application of nanotechnology in medical technology is scarce.
In order to investigate in depth the complex Nano systems, highly sophisticated Nano scale precision metrology tools are required. The advances in nanomaterial's necessitate parallel progress of the Nano metrology tools and techniques. Examples of important Nano metrology tools as they have been discussed above include: ellipsometry, highly focused X-ray sources and related techniques, Nano indentation and scanning probe microscopies. The above described Nano metrology methods contribute towards the understanding of several aspects of the state-of-the-art nanomaterial's in terms of their optical, structural, and Nano mechanical properties. The Nano scale precision and the detailed investigation that these Nano metrology techniques offer, give them an enormous potential for even more advanced applications
for the improvement of the quality of research and of the everyday life.

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