Nanotechnology Innovation System – Strategic Perspective

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ABSTRACT

A strategic approach is necessary to stimulate learning and awareness of nanotechnology innovation which is the new growth innovator of 21^{st} century. This paper offers a perspective view on nanotechnology innovation strategy that will radically affect most of current industries in both the near and long term. In this paper, the proposed strategic frameworks provide nanotech innovation scenario in identifying opportunities within existing and emerging markets. Technology categorization and comparative strategies are also discussed to address nanotechnological development worldwide.

Keywords: Innovation system, Innovation strategy, Nanotechnology, Technology transfer

1. INTRODUCTION

Nanotechnology has been recognized as a promising new growth innovator which leads to a shift from the exploration of nanotechnology knowledge towards a phase of exploitation by throwing challenges to solve major societal problem, to energize the economy for decades and to incrementally change the silicon technology base. However, this technology crosscuts the traditional disciplines of materials science, chemistry, physics, biology, computational science and engineering by occupying the frontiers of these fields and creates the basis of the next industrial revolution. From the *scientific* point of view, Nanotechnology refers briefly to the design, characterization, production and application of structures, devices, and systems by controlling shape and size at nanometer scale and from the *management and policy* point of view Nanotechnology is a socio-economic process that seamlessly integrates a series of specific activities.

Innovation system can be featured in several dimensions: National, Regional and Sectoral [1] [2] [3] [4] [5]. As a sector, nanotechnology innovation system is the flow of nano based technology and information among people, enterprises and institutions which is a key to an innovation process. This system contains the interaction between the actors who are needed to turn an idea into a process, product or service on the market. Technological based innovations are often envisioned as the introduction into the economy of new knowledge which are looked upon mainly as the result of interactive learning processes [6]. Nanotechnology has been regarded as a breakthrough technology that requires new core competencies and potentially bring about a wave of radical innovation and industrial restructuring [7]. This paper focuses on Nanotechnology knowledge and market dynamics based on innovation strategies as well as nanotech knowledge networks that are born with scientific discovery and shape the paths of societal problem solving by nano-application.

1. 1. Why nanotechnology

Nanotechnology is the useful application of knowledge that we generate in nano-research. As nanotech evolves, two important things happen. First, there is an integration of existing technologies as well as incremental advances. Second, there are new applications based on chance discoveries, or serendipity. These are transformational in the way of manufacturing, health care, and information technologies. Because of its potential to change fundamentally whole fields of technology, nanotech is expected to lead to innovations that can contribute towards addressing many of the problems facing today's society as well as regarded as a key technology which is not only influence technological development in the near future, but also have decisive economic, ecological and social implications.

1. 2. Nanotechnology innovation characteristics

Nanotechnology developed from its humble beginnings in the mid 1980's to an important sector of the high-tech industries. It has been also described as a cluster of scientific and technological activities where functional structures with dimensions and tolerances at the nanometer level play a critical role and allow a much better use of the social capital of actors involved in nanotechnology [9]. Nanotechnology is the most interdisciplinary field so far. This interdisciplinarity is naturally enhanced by the fact that at the nanolevel the differences between very different disciplines, such as mechanics and chemistry, begin to blur to a large extent and leads to an acceleration of the knowledge production and transfer. One striking character of nanotechnology is that its achievements flow seamlessly from discoveries in nanoscience, which is not only toward miniaturization; but also a convergence of quantum physics, molecular biology, computer science, chemistry and engineering [10] [11]. It appears that nanotechnology is essentially a techno-science and, more specifically, a techno-sci-engineering discipline. Other character of nanotech is certainly disruptive for manufacturing by contributing with new materials and new markets, but equally pervasive which forces rapid change and dramatically transforming the market.

2. NANOTECHNOLOGY TIMEFRAME AND INNOVATION CHAIN

It was Richard Feynman of the California Insitute of Technology who first suggested the concept nanotechnology to the world by delivering his famous lecture “There is Plenty of Room at the Bottom” in 1959 in which he offered the vision of exciting new discoveries if one could fabricate materials and devices at the atomic and molecular scale. Also he argued that judging by their potential impact and practical usefulness to society, nanotech fields assume a greater importance than other areas as a subject of research. Although the term “Nanotechnology” was not used until 1974, when Norio Taniguchi, a researcher at the University of Tokyo, used it to refer to the ability to engineer materials precisely at the nanometer level (figure 1).

There is a background factor behind the emergence of nanotechnology is the development of analyzing techniques that can be used to observe nanoscale structures and have opened the way to a new world of atomic image observation. An important event was the invention of the scanning tunnel microscope (STM) in 1981 by Drs. Gerd Binnig and Heinrich Rohrer of IBM’s Zurich Research Laboratory. Since nanostructures cannot be observed by the use of optical tools, the scanning probe microscope (SPM) and transmission electron microscope (TEM) were developed as alternative techniques to directly observe and measure nanostructures. The scanning probe and electron beam techniques are now essential research tools in nanotechnology. The development of these new tools has resulted in the discovery of new nanostructures with unique functions. A simple example of such new nanostructure is seen in the fellerene C60 soccer-ball-shaped molecule which is the fourth type of carbon molecule (as carbon molecules are three basic shapes: diamond-type, graphite-type and amorphous-type) discovered by Richard E. Smalley and Robert F. Curl of Rice University, and Harold W. Kroto of the University of Sussex. Public attention was captured by discovering the new type of carbon molecule that exhibited properties unlike anything seen before. This discovery led to a flurry of excitement over the potential use of the molecule in applications in markets ranging from healthcare to construction and manufacturing.

In the meantime Dr. Eric Drexler of MIT proposed molecular nanotechnology in his 1986 book *“Engines of Creation: The Coming Era of Nanotechnology”* by developing the idea of a molecule machine. As the 1990s came upon us, the flurry of activity and the pace of significant discoveries increased. In 1991 NEC Japan researcher Sumio Iijima discovered carbon nanotubes, a close relative to the fullerene exhibiting exciting (about 1/6th the weight and nearly 100 times stronger than steel) and diverse properties as a metal, semiconductor or superconductor, leading to wide variety of applications. This discovery created the base for most of all the nano-products. Researchers enthusiasm for nanotechnology advances was contagious. In 2000 US goernment announced the National Nanotechnology Initiative (NNI), the first formal government program to

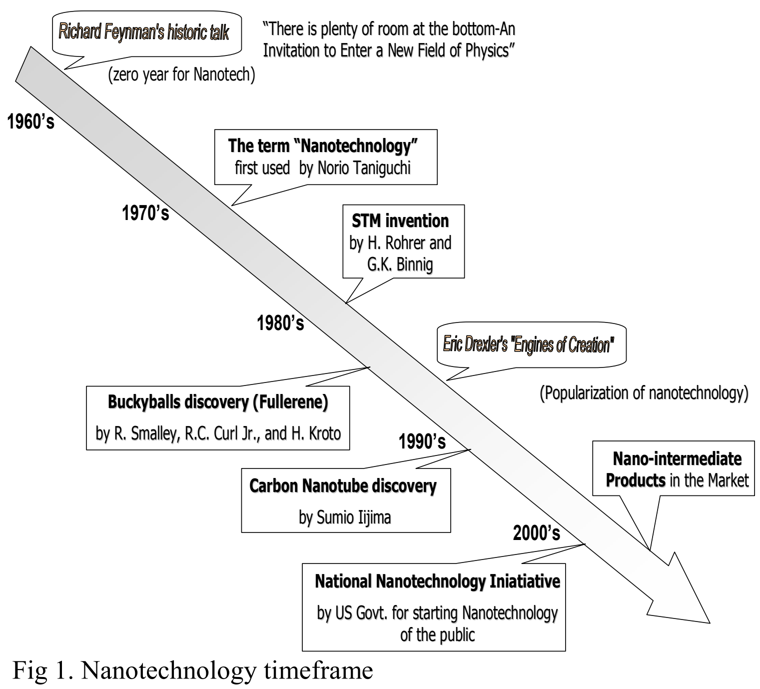

Fig 1. Nanotechnology timeframe

accelerate the pace of research, development and commercialization of nanoscale applications. Other countries quickly followed suit like EU, Japan, Taiwan, Korea have all begun similar measures in shaping up the first truly global race of the 21st century. And afterwards the nano-intermediate products enter into the market followed by nano-enabled products in near future.

A revolution in analytical instruments which always preceded discovery and subsequent technological advancement [8] made possible the ongoing revolution in nanotechnology and begin the exploration of nanoscale structures that has led to the development of nanoscale technologies. Nanotechnology innovation chain thus occupy a value starting with production and test equipments and analytical equipments for fabrication and characterization of nanostructures, followed by nanoscale structures discovery like CNTs, fullerene, nanofilms, and then intermediate nano-products by nanomaterials like nano-coatings, nano-fibres, memory and logic chips, optical components,

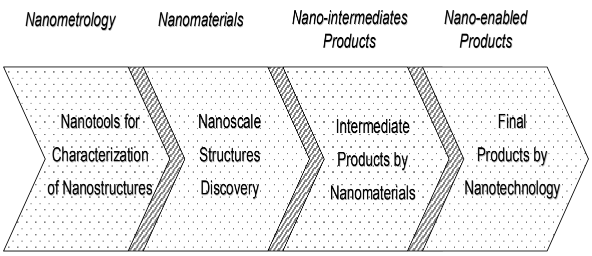

Fig 2. Nanotech innovation chain

orthopaedic materials, superconducting wire, etc. and ending with finished goods by nanotechnology like Clothing, computers, consumer electronics devices, pharmaceuticals, processed food, plastic containers, appliances, cancer therapies etc. (figure 2).

3. STRATEGIC FRAMEWORK FOR NANOTECH INNOVATION

Nanotechnology presents a tremendous opportunity to introduce a host of new products that could energize economy, solve major societal problems, revitalize existing industries, and create entirely new businesses. Therefore a strategic framework is necessary to stimulate learning and awareness of nanotechnology innovation which is the new growth innovator of 21st century. This framework requires a robust understanding of the fundamental scientific principles operating at the nanoscale, including interdependent structure-property relationships. Such an understanding enables cost-effective design, synthesis, and scale-up of nanomaterials that deliver selected properties, allowing material producers to focus on the requirements for specific applications as the primary drivers of the manufacturing process. The capability will accelerate nanotechnology development, moving the field from today's discovery-based science and product development to application-based problem solving in the future (figure 3).

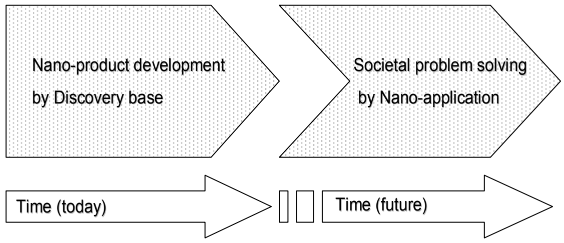

Fig 3. Strategic approach for nanotech innovation

Once the capability becomes available, large numbers of diverse products could rapidly enter global markets to solve long-standing problems and stimulate economic growth for decades to come. To date, understanding of nanotechnology has been achieved primarily through empirical research. While this approach continues to make important contributions, the development of this technology is likely to be accelerated by a systematic understanding of fundamentals by discovery base. In addition, the broadest and most efficient commercialization of nano-products can be realized by taking nanotechnology to the next level: deliberate, predictive design and manufacturing capability based on the application and end-use functions by creating materials with functions and properties needed to solve specific societal problems. In the discovery base innovation, nanomaterials are manufactured by exploratory research in the broad range. After identifying properties, potential and commercial validities, nano-products can enter into the market. On the other hand, in the application base innovation after clarifying the social problems, scale-up nano-based materials are designed, produced in the large numbers to enter in multiple markets (figure 4).

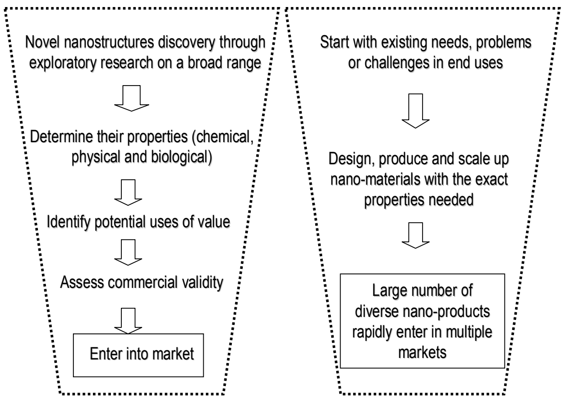

Fig 4. NI by discovery and application base

In the nanomaterial manufacturing there are two fundamental strategies: 'top-down' and 'bottom-up' (figure 5). Starting from microtechnology, structures and components are more and more miniaturized in the top-dowm approach by using techniques such as precision engineering and lithography which is predominant particularly in physics and physical technology. On the other hand there is bottom-up approach in which increasingly complex structures are specifically assembled from atomic or molecular

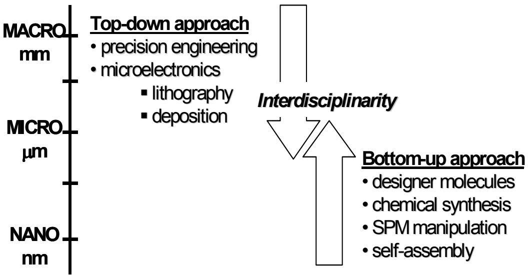

Fig 5. Nano-manufacturing strategy

components. This approach is primarily featured in chemistry and biology and involves the building of structures atom-by-atom or molecule-by-molecule.

4. COMPARATIVE NANOTECH INNOVATION STRATEGIES

The level of economic development, the level of education of the workforce, and specific industrial strengths of different countries greatly shape their strategy towards the development and maintaining the leading edge in nanotechnology which emerge naturally because of the optimum mix of economic and societal factors. In today's global market, economic growth demands innovation which is in turn dependent upon research.

In the US, nanotechnology is recognized as an emerging and critical technology for the 21st century and considered to be at the early stage of scientific exploration, research fund have been channeled into the creation of academic centers of excellence rather than university-industry collaborations [12]. Gevernment funding is traditionally spent on fundamental or applied basic research and research infrastructure. The U.S. nanotechnology strategy's (figure 6) intention to focus (i) support on interdisciplinary research teams, long-term fundamental nanoscale science and engineering research; (ii) supports research in nine grand challenge areas to the translation of nanoscale research into useful applications. The challenge areas are nanostructured materials by design, manufacturing at the nanoscale,

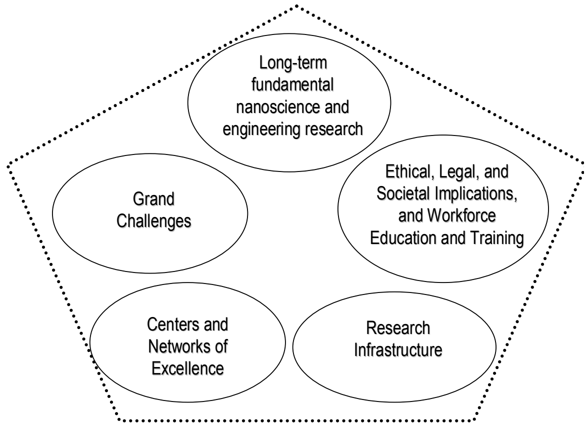

Fig 6. U.S. nanotech innovation strategy

chemical-biological-radiological-explosive detection and protection, nanoscale instrumentation, nano-electronics and photonics, healthcare therapeutics and diagnostics, energy conversion and storage, microcraft and robotics, and nanoscale processes for environmental improvement; (iii) supports 'centers of excellence' or multi-year research center grants in developing and utilizing specific nanoscale research tools and in promoting research partnerships; (iv) supports research infrastructure, including a nationwide network of shared use facilities called the National nanotechnology Infrastructure Network (NNIN); (v) supports research relevant to workforce and the social implications of nanotechnology. Outside the NNI, various public and private funding agencies are involved such as large companies in chemical, materials, computer, semiconductors and other areas.

In contrast with the US, the view in Japan is that nanotechnology is close to being made commercially available across many industries and areas of application. Japan is the uncontested leader in nanotechnology among Asian countries and provides, the opposite example to the U.S. with regard to development policies. Japanese strategy for nanotechnology innovation (figure 7) have the following characteristics: (i) strengthen existing technology and advances towards nanotech level; (ii) challenges for companies in producing its own unique products; (iii) creating new business in parallel with the existing business. The national effort consists of the involvement of both the public and the private sector, as opposed to the U.S. effort, where the industry makes most of the decisions in the later stages. Japan emphasizes development of a knowledge base and industrial capabilities of traditional Japanese areas such as semiconductors and electroceramics; stresses being internationally competitive and export oriented [11].

transferring to industry; innovation for emphasizing the benefit of a coordinated approach to produce wealth; and the societal dimension to devote due attention to the societal aspects of nanotechnology. A further step in support of a high level of public health, safety, environmental risks and after all internatiuonal cooperation associated with nanotechnology needed to advance R&D and technological progress.

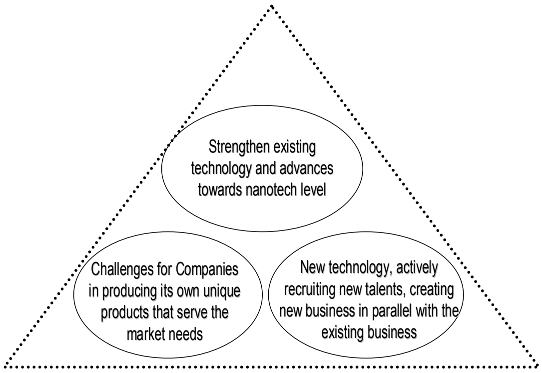

Fig 7. Japan nanotech innovation strategy

E.U. nanotechnology innovation strategy (figure 8) starts from differentiating various sectors of nanotechnology from their respective "mother" academic fields. The European version of nanotechnology empathically preserves the "biodiversity" of the fields involved in a

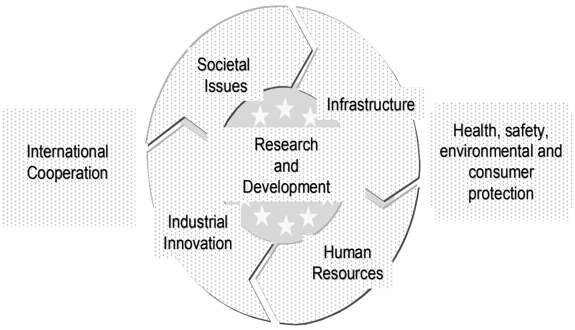

Fig 8. EU nanotech innovation strategy

nanotechnology ecosystem [13]. Another related characteristic of E.U. approach in the development of nanotechnology is the emphasis on the right balance between centralized coordination and nurturing of informal scientific networks. The centralized coordination policy line translates into programs at the community level, national forecasting activities to identify priorities for technology policies, and practical proposals for coordinated research at the European level, including a new European program. EU communication proposes actions as part of an integrated strategy to maintain and strengthen European R&D in nanosciences and nanotechnologies. It considers the issues that are important to ensure the creation and exploitation of the knowledge generated via R&D for the benefit of society. In this context, five dynamic strategyies are identified: R&D to ensure that Europe can remain competitive in the long-term; infrastructure to provide essential services to the research community; education and training to realise the potential of nanotechnology in generating knowledge and

5. NANOTECHNOLOGY RESEARCH MANAGEMENT

For sustainable economic development and comfortable and safe life of the people, the Japanese government is committed to providing strong support for nanotechnology research based on the Second Science and Technology Basic Plan (2001–2005) prepared by Council for Science and Technology Policy (CSTP). Nanotechnology creates one of the strategic priority in R&D to basic research in the Basic Plan by exemplified five different areas: nano-devices & materials for next-generation communication systems (information technology), materials for the environment & energy-saving (environment), nano-biology for new medical care technologies & biomaterials (biotechnology), underlying technologies such as fabrication and analysis/simulation technologies (generic technology), and novel materials with innovative functions (materials). The plan also calls for prioritized promotion of nanotechnology for both basic and advanced R&D and for future industrialization, notes the importance of building research networks that promote joint efforts and information exchanges between different research areas and researchers, and also of developing personnel for new interdisciplinary areas [10] [11].

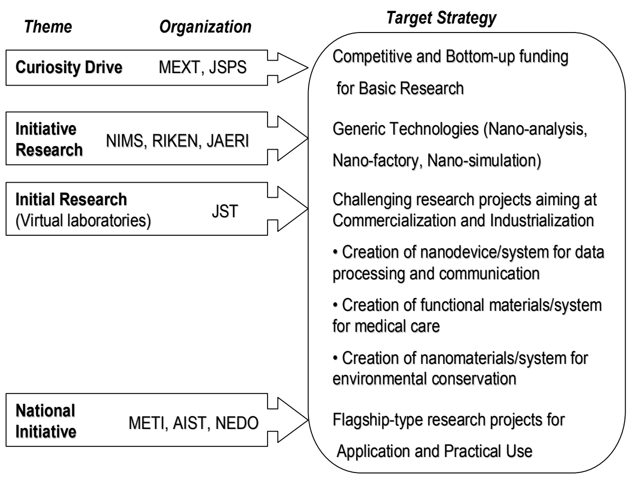

Fig 9. Nanotech research management in Japan

There are four themes for nanotechnology research management in Japan: *curiosity drive* by MEXT and JSPS in competitive and bottom-up funding for nanotech basic research; *initiative research* by NIMS, RIKEN, JAERI in generic technologies; *initial research* by JST in challenging research projects aimed at commercialization and industrialization; *national initiative* by METI, AIST, NEDO in flagship type research projects for application and practical use (figure 9). Furthermore, Nanotechnology Support Project (Nanonet) started by MEXT and Nanotechnology Business Creation Initiative (NBCI), a consortium of more than 300 private companies, was founded with a help of METI. Both MEXT and METI have several highlights of nanotechnology research programs such as 'Leading Projects' by MEXT, 'Nanotechnology Virtual Laboratories' by JST, 'Focus 21' by METI, and 'Nanomaterials and Processing Sub-Program' by NEDO and these are parts of research and development projects for economic revitalization in Japan.

6. IMPACT AND MARKET APPLICATIONS BY NANOTECH INNOVATION

The potential for nanotech products applications are vast, spanning across a wide range of industries and

Categories	Functions	Examples of Materials	Examples of Applications
One dimensional nanomaterials	***Mechanical Functions*** Highly hydrophobicity, elasticity, controlled porosity Tailored properties (e.g, large surface area)	**Thin films and layers** **Engineered surfaces**	Breathable, waterproof fabrics, electronic devices, vehicles Fuel cells, catalysts
Two dimensional nanomaterials	***Mechanical Functions*** Very strong as stiff as diamond, flexible on the axis ***Electrical Functions*** Conduct electricity extremely well	**Carbon nanotubes**	Reinforced composites, antistatic packaging, sensors Nanoelectronics, display devices
	Physical and Chemical Functions Tribological properties, resistance to shockwave impact, catalytic reactivity, high capacity for hydrogen and lithium storage	**Inorganic** (fullerene like) **nanotubes** (molybdenum disulphide, titanium dioxide)	Catalysis, photo-catalysis, energy storage
	Optical Functions Bent light around very tight corners ***Electrical Functions*** Superconductivity ***Magnetic Functions*** High magnetism	**Semiconductor nowires** (made of silicon, gallium nitride, indium phosphide)	High-density data storage Electronic and opto-electronic nanodevics Quantum devices
Three dimensional nanomaterials	***Mechanical Functions*** Act as construction materials, fillers in a matrix ***Optical Functions*** Transparent to visible light and able to absorb and reflect UV light ***Chemical Functions*** Enhanced reactivity due to large surface area, biocompatible	**Nanoparticles** • Natural (photochemical, volcanic, flakes of clay) • Pollutant (combustion, food cooking, vehicle exhausts) • Manufactured (Ti & Zn oxides)	Car bumpers and tyres Sunscreens, cosmetics, textiles, aircraft paint coatings Targeted drug delivery, catalysts, water remediation
	Magnetic Functions Unusual magnetism ***Mechanical Functions*** Wear-resistant, bio-compatible, High strength, inertness	**Nanocrystalline materials** • Yttrium-samarium-cobalt grains • zirconium oxide • silicon carbide	Magnetic resonance imaging (MRI), motors, microsensors, Orthopaedic implants Artificial heart valves
	Mechanical Functions Very strong	**Fullerenes** (spherical C60 carbon materials)	Ball bearings to lubricate surfaces, drug delivery vehicles
	Chemical Functions Act as carrier molecules, can trap metal ions	**Dendrimers** (spherical polimeric molecules)	Drug delivery, environmental clean-up, coatings, inks
	Optical Functions Emit or absorb specific wavelengths (colors) of light	**Quantum dots** (nanoparticles of semiconductors)	Solar cells, composites, fluorescent biological labels)

Fig 10. Impact by nanomaterials

disciplines. The most important areas for nanotechnology innovation are considered to include materials and manufacturing; nano-instumentation; nanoelectronics and ICT; biotechnology and medicine.

Categories	Examples of Techniques	Functions	Examples of Applications
Electron beam techniques	**Transmission electron microscopy (TEM)**	Passing electrons through the sample and using magnetic lenses to focus the image of the structure	Investigate the internal structure of micro- and nanostructures, chaacterize the fabrication
	High-resolution TEM	Exploiting interactions of the electrons with the atoms in the sample	Chemical analysis
	Scanning electron microscope (SEM)	A beam of electrons is focused and scanned back and forth across the surface	Visual imaging
Scanning probe techniques	**Scanning probe microscopy (SPM)**	Uses interaction between a sharp tip and a suface to obtain an immage and scanned back and forth	Can image clusters of individual atoms and molecules
	Scanning tunnelling microscope (STM)	Electrons tunnel across the gap of sharp conducting tip and surface	Surface structural and electronic information with atomic resolution
	Atomic force microscope (AFM)	Uses a sharp tip on the end of a flexible beam or cantilever	Can image insulating materials
Optical tweezers	**Single beam gradient trap (laser beam, laser scalpels)**	The radiation pressure and gradient forces create an optical trap	Measure interatomic forces and displacements of single atoms, strands of DNA and living cells

Fig 11. Impact by Nano-instrumentation

Nanomaterials exhibit new and/or certain properties that will act as building blocks upon which complex two- and three-dimensional functional nanoscale systems with the built, enabling new devices and new functionalities (figure 10). Benefits of nanostructuring can result in lighter, stronger and programmable materials, enabling unique applications such as high-speed integrated circuits, and the use of molecular/cluster manufacturing to develop structures and architectures that did not exist previously in nature. Inorganic nanomaterials such as nanotubes, ceramic, powers, nanocrystals are being intensely developed. Moreover, hybrid materials such as carbon nanotubes are considered as advance nanomaterials that exerts particular qualities that make these structures suited for a variety of applications ranging from replacing current TV and computer monitors, computer memory devices, conductivity and storage, and are also being considered for the storage of hydrogen.

To confirm the operation of new nanomaterials and specially to characterize all the steps of fabrication and modification, nanoscale characterization tools are absolutely critical. So, we categorizes the nanotools impact and ultimately the development of the necessary tools and instrumentation helps the successful advancement in the ability to understand, create and manipulate objects and processes on the nanoscale (figure 11).

Categories	Functions	Examples of Materials	Examples of Applications
Information sorage	***Magnetic Functions*** Storing data and images in magnetic hard drives	**Solid-state memory(DRAM), Flash memory, Disk-based memory**	Digital camera, Personal computer, video camera etc.
	Electro-mechanical Functions Data and images in magnetic hard drives	**Hard disk drive**	Personal computer, DVD player, CD player
Optoelectronics	***Electro-optical Functions*** Converting electrical signals to and from light, ability to transmit light at any wavelength	**Photonic crystals**	Displays, optical sensing, optical computing
	Able to detect the presence of a single molecule in a drop of blood	**Optical devices(spectroscopy)**	Point-of-care health screening, constant monitoring of diabetes or critical care
Sensors	***Electrical Functions*** Detected property is converted into an electrical signal and the transmission of the sensing signal to a remote detector	**Sensors with increasing selectivity**	Monitoring the quality of drinking water, state and performance of products and materials to give early warning. Detecting and tracking pollutants, checking food for edibility

Fig 12. Impact by nanoelectronics & ICT

The continuing development in the field of Integrated Circuits (IC) and semiconductors has been inching closer to maturity with currently available technologies. There has been increasing demand for greater precision and more advanced materials other than silicon to be developed to

Categories	Functions	Examples of Materials	Examples of Applications
Bio-mimetic structures	***Biological Functions*** Behave as rotary or linear molecular motors ***Antimicrobial Functions*** Release ionic silver to provide a antimicrobial spectrum of pathogens	**Catenanes and rotaxanes** **Nanocrystalline silver**	Disease diagnosis, drug delivery, molecular imaging Wound dressing
Array technologies	***Biological Functions*** Carries an array of DNA molecules on an inert carrier Integrated nanoscale system	**DNA chip** **Lab-on-a-chip**	Gene and protein analysis Sensing and supporting disease diagnosis
Self-assembly	***Mechanical Functions*** Construction, incorporation, fabrication	**DNA-based structure (artificial crystals)**	Hybrid nanomachine
Drug delivery	***Mechanical Functions*** Capable of targeting specific deseased cells containing therapeutic agents	**Functinalised nanoparticle (polymer conjugates)**	Drug therapies, gene therapies, cystic fibrosis

Fig 13. Impact by nanobiotechnology and medicine

improve capabilities, size and performance. Nanoelectronics advances could potentially open future markets for nanotechnology semiconductors or microprocessors, as carbon nanotubes are being seriously considered to replace silicon in transistors (figure 12).

The most exciting speculation on nanotechnology development has been attributed to the potential benefits and applications to life sciences and biotechnology. The ability to manipulate molecular behavior and structures at nanometer scales has revolutionary implications for the disciplines of chemistry, physics and biology. Using nanobiotechnology to master techniques to manipulate biological and non-biological elements at the molecular and atomic level will increase the speed and quality of genome sequencing for gene tracking and diagnostics and therapeutics. Consequently, nanotechnology can facilitate the development of tools for diagnostic and biochemical research and early detection and treatment of diseases, such as the detection of cancerous cells/tumors, for medical and surgical equipments and technologies, and new formulations for drug discovery, design and delivery (figure 13).

7. CONCLUSION

This paper constructed the strategic frameworks that creates nanotechnology innovation scenario for stimulating business opportunity awareness. Since nanotech is a general purpose technology on which the disciplinary background and the working environment have a heavy impact. The key factors were identified in a variety of segments: developments in nanotechnology and nanotech-influenced industries and markets, specific developments in industries related to linkages with biotechnology and IT, comparative strategies and research management on nanotechnology innovation.

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