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CARBON NANOTUBES: A REVIEW OF THE CURRENT STATE-OF-THE-ART MATERIAL SCIENCE AND TECHNOLOGY TOWARDS ACHIEVING LARGE-SCALE INDUSTRIAL PRODUCTIONS AND COMMERCIALIZATION

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ABSTRACT

We reviewed state of the art and science towards achieving large-scale industrial productions and commercialization of Carbon nanotubes' (CNTs). It transcends their physical and chemical structure to the identification of the need for large-scale production of carbon nanotubes in enhancing manufacturing industrial processes, and potential frame work for commercialization. Solution potential with reference to the research and manufacturing industry, particularly in electronic device was x-rayed and evaluated estimating production capacity of the CNT process plant and the processes involved. The cost of manufacturing Nano-emission display (NED) device with CNTs was highlighted showing great commercial potential in this specified area. Furthermore, the viability of CNTs for possible large-scale industrial productions and commercialization was critically examined using PEST analysis. Finally, it was concluded that, there are huge potentials for large scale industrial productions of CNTs investment both by the governments or private sectors.

Key Words: Carbon nanotubes' (CNT's), Large scale industrial production, Flat panel display devices

INTRODUCTION

Carbon nanotubes are novel material that holds huge potential in the electronics, biomedical sensor, pharmaceuticals, aerospace and photolithography manufacturing (with direct or indirect applications in domestic, commercial and industrial products) if mass production and commercialization is done[1-5]. They form a major building blocks of nanotechnology possessing100 times the tensile strength of steel, higher thermal conductivity than pure diamond with higher electrical conductivity with copper. These properties make them outstanding engineering materials and hence they spring research interest amongst industrialist, academics, government and investors as captured in [1].

Origin of Carbon Nanotube

Carbon nanotube (CNT), discovered by Sumio Iijima in 1991 [2] in the soot of an arc discharge apparatus. The discovery of CNT ignited research on growth, characterization and application development has exploded due to the amazing electronics and extraordinary mechanical properties[3]. Thus CNT can be metallic or semi-conducting, and hence provides the potential to create semiconductor to semiconductor and semiconductor to metal junctions, useful in electronics devices. The high-tensile strength and Young's Modulus, and other mechanical properties assured for the production of high-strength composites for structures application[3].

Siochi, et al (2003) also identified that the revolutionary design concept in future aerospace vehicles would basically rely on novel materials with extraordinary structural properties which enables significant reduction of mass and size of components to be achieved while imparting intelligence. Hence, Carbon Nanotubes (CNTs) are expected to allow this paradigm shift in design concepts. However, Siochi et al [4], pointed out that significant challenges still exist in translating these CNT properties

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into macrostructures needed for future aerospace vehicles.

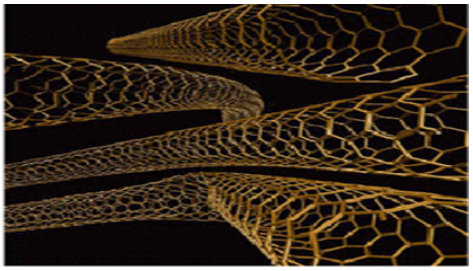

Figure 1: A typical carbon nanotubes [1].

Meyyappan and Srivastave[5], identified that researchers have been exploring CNT in the area of nanoelectronics, sensors, field-emission base displays, batteries, polymer matrix composites, re-enforce materials, electrodes, etc.

Carbon Nanotubes Structures and Properties

Basically they are two chemical structures of CNTs with the same properties; the single-wall carbon nanotubes, SWCNT and the multiple-wall Carbon nanotubes, MWCNT as shown in Figure 2. Both interesting nano-materials can either be metallic or semiconductor, depending on its chiral vector (n, m) where n and m are two integers [3].

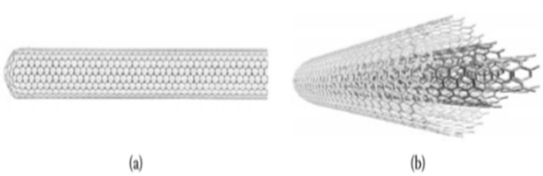

Figure 2: Schematic of a SWCNT (a) and a MWCNT (b) [6].

Doudero and Gorge [6], that carbon nanotube can be synthesized in two structural forms single-wall and multiple-wall. Iijima[2] first discovered the first tubules exhibiting a multiwall structure of concentric nanotubes forming into a tube (MWCNT) and the single-wall structure by observing a single-shell structure believed to be precursor to the MWCNT. The single-wall CNT (SWCNT) can be best described as a rolled-up tubular shell of graphitic sheet shown in figure 2 which is capped at both ends by half dome-shaped half-fullerene molecules with a diameter of 1 nm which are made of benzene-type hexagonal rings of carbon atoms [5].

The multi-wall CNT (MWCNT) is a rolled-up stack sheet in graphitic and concentric cylinders, ends either capped by half fullerenes or kept open. An arrangement (*n,m*) used to identify each SWCNT, refers to integer indices of two grapheme unite pattern vector corresponding to chiral vector for nanotubes[4-5].

Furthermore, nanotubes are described by using one of the three morphologies: armchair, zigzag and chiral. Figure 3 shows the assembly of the carbon hexagon of the graphitic sheet with distinct chiral vectors and angles [6]. The indices of the vector determine the morphology of the nanotubes[6].

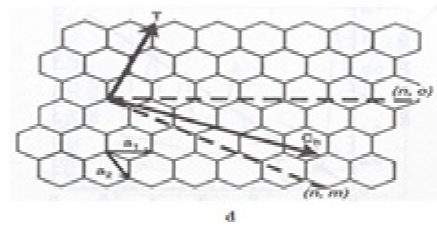

Figure 3: Schematic of nanotube morphologies: (a) armchair, (b) zigzag, (c) chiral [6], (d) Structureorientation and properties[20].

Srivavastava et al [7], in their explanation of the morphologies of nanotubes structures suggested that nanotubes of type (n,m), (in figure 3(b)), are commonly called armchair because of their shape, which is perpendicular to the tube axis and a symmetry along the axis of short unit cell (0.25nm) that can be repeated to make the entire section of long nanotubes. The nanotubes type (n,0) are known as the zigzag nanotubes, figure 3(c), because of the zigzag shape perpendicular to the axis, and they also have a short unit cell (0.43 nm) along their axes. Dresselhaus [8]argued that the variance of morphology of the nanotubes can lead to change of the properties of the nanotubes; for example, the electronic properties of an armchair are metallic. On the other hand, the electric properties of the zigzag nanotubes are semiconducting. Lau and Hui[9]believed that the behavior of nanotube structure morphologies is determined based on a mathematical model developed using the chiral vector indices.

Advantages of Carbon Nanotubes

Iijima, Mayyappan, and Siegel investigated the physical properties of carbon nanotubes and the potential to drive research and adapted the use of vibration of nanotubes as a function of temperature in calculating Young's modulus at 1Tpa [10]. Figure 4 shows a chart comparing the tensile strength of CNT to other materials. Methods commonly used to measure elastic properties of individual carbon nanotubes include the micro Raman spectroscope [11], thermal oscillation by transmission microscope [10, 12] and application of force on a nanotube rope suspended across a pit using an atomic force microscope cantilever [13 - 15]. However, Pan et al [16] also shows that the results of tensile test experiments of the CNT rope properties and obtained an average value for each tube based on the numbers of nanotubes on the rope. The values measured have tensile modulus and strength for single-wall (SWCNTs) and multi-wall CNTs

(MWCNTs), ranging from 270GPa to 1TPa and 11GPa to 200GPa respectively [9].

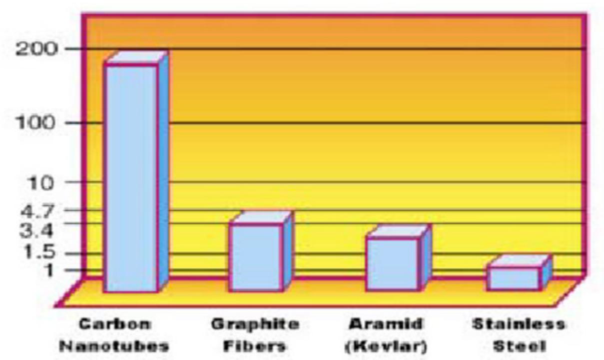

Figure 4: Chart comparing SWCNTs with other common high tensile Materials [20].

Yu and Lieber[17] research potentials of nanoscience and nanotechnology in chemistry, physics, materials science, engineering, and life sciences.

The Needs Analysis for Carbon Nanotubes

Carbon nanotubes have been promising for applications in large areas on consumer and non-consumer products. Consumers products such as electronics, temperature sensors, biomedical devices amongst others, non-consumers products such as in aerospace industry, lightweight manufacturing industry, research, business etc. The substantial increase of the demand of CNTs has presented major challenges of the need for industrial scale productions. Mass productions of CNT are still insignificant because of the lack of raw materials. Currently bulk production rate of SWCNTs is hovering around few kilograms per day, large-scale composite effort are nonexistent at present [5]. Table 1 show the present approximate amount produced worldwide per day.

The Need for Carbon Nanotubes in Flat Panel Display

Nanotubes have been promising in the manufacturing of flat panel display products such as flat TV screen, computer monitors, smart phones display etc. The use of carbon nanotubes in display technology has posed a new challenge to other display product such as LCD, plasma and OLED display[17]. Nano- emission display (NED) based on carbon nanotubes is basically a thin, flat cathode ray tube with thousands of electron guns at each pixel and it shows that NEDs have a promising future for use in flat panel displays [17]. However the manufacturing of NED for commercialization still faces the major challenge of availability of raw materials of CNTs to meet the lager areas of application of display panels and other products for commercial demands in the long term. Figure 11 shows the continuous rise of demand for flat panel display.

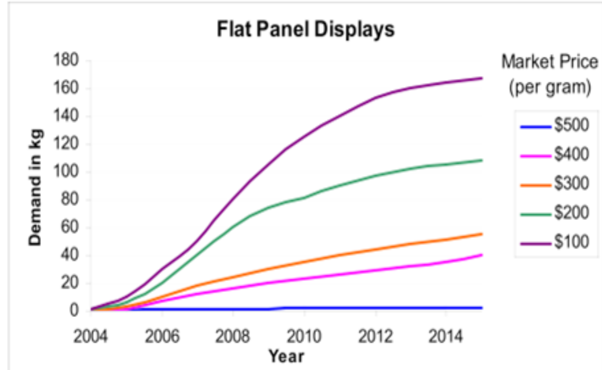

Figure 5: Demand of Flat panel displays [20].

Table1 below shows approximated figures in grams per day of carbon nanotubes produced worldwide while Table 2 shows the common areas of applications and desire form of functionalization of carbon nanotubes, especially SWCNTs. The information obtained from both tables indicates that the quantity of CNTs produce per day cannot be compared to the quantity needed for large areas of applications in terms of large-scale production. Clearly there is huge demand for the manufacturing of CNTs.

Table 1: Present amount of CNTs produced [20].

Company	Production (g/day)
Carbolex	35
Carbon Solutions Inc.	50
CNI	500
IIJIN	200
MER	10
Nanocarblab	3
Nanocyl	20
Nanolab	50
NanoLedge	120
NanoAmor	50
Shenzhen Nanotech	200
SouthWest	500
AVERAGE	145
TOTAL	1738

However the concerns of large-scale productions of CNTs have been observed by researchers in this field. Agboola et al, Do et al[18, 20] has presented conceptual designs of CNTs process plants if implemented may be a possible solution for large-scale production of CNTs for commercialization.

Framework Solutions for CNT Large-scale Production

Possible framework solutions of the needs for large-scale production have been initiated and conceptual design delivered by Agboola et al, Do. [18, 20], and in different occasion, they both presented a conceptual design of carbon nanotubes process plant that will have the capability of producing hundreds kilograms per year. The growth technique used by both researchers is the Chemical Vapor Discharge (CVD) method which is a novel development of the CVD growth technique which establish the one (CNT-PFR process) used the high pressure carbon monoxide disproportional reaction iron over catalytic particle clusters (HiPOC reactor), and the other (CNT-FBR process) used catalytic disproportional carbon monoxide over a silica supported cobalt- molybdenum catalyst (CoMoCAT reactor). The tables below show the capability of both HiPOC and CoMoCAT process plants of CNTs [18].

Research on Commercial and Demand forecast of Carbon Nanotubes

The outcome of the research on commercial and demand of carbon nanotubes shows realistic market potentials of the state-of-art material and economic viability its products.

Forecast Demand Curves

The information obtained from the demand graph in Figure 14is as follows: Demand for research and commercial sectors in short and long term; the demand curves to the right with time; indicated that demand becomes less inelastic with time and at lower price, this, indicates market potential in future.

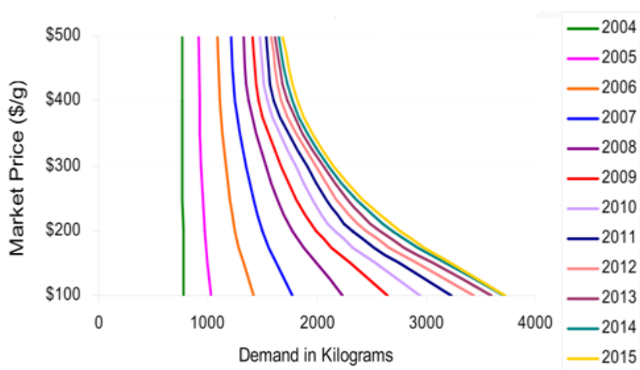

Figure 6: The demand curve of research and commercial sectors [20].

However, figure 15 below shows an approximate forecast of the numbers of companies into the market and it was estimated base on the past trends and the average production rate is determined from the market research.

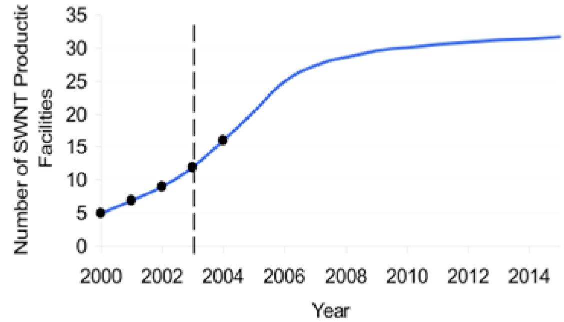

Figure 7: Projected entry of companies into the market [20].

Supply Forecast and Market Equilibrium

Figure 16 and 17, graphically illustrates the forecast of supply curves, quantity of large-scale production of carbon nanotube to market price.

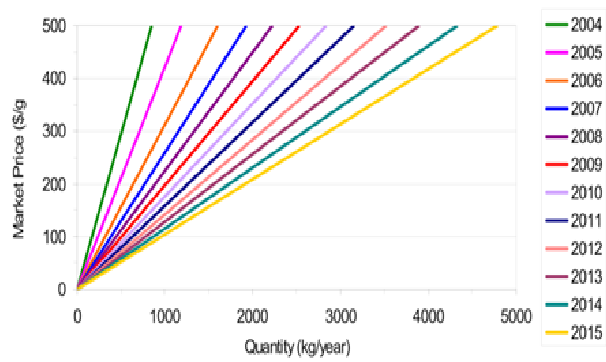

Figure 8: Forecast of supply curves [20].

This forecast supply curves is assume to be linear and it is estimated base on the projected numbers of companies' entry into the market by 2015, with average production increase by 10% per year. This indicates potential of steady increase in supply in future market.

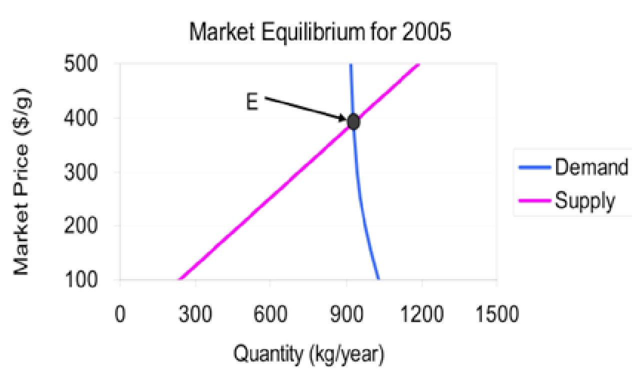

Figure 9: Market Equilibrium[20].

Nano Emission Display Flat Panel

According to Motorola's "*Motorola's Nano Emission Display (NED) technology is demonstrating full colour video with good response time,"* Barry Young, the CFO of Display Search, states that "*According to a detailed cost model analysis conducted by our firm, we estimate the manufactured cost for a 40-inch NED panel could be under $400*" [21].If compared to other flat panel display products such as plasma and light-emitting diode (LED) on the market today's. Nano-emission displays (NED) based carbon nanotube would be significantly cheap to manufacture. The low costs of manufacturing NED will have potential low market price as well and perhaps dominate the market segment of flat display panels.

Figure 10: Nanotubes Display [19].

Therefore, Presumably Nano-emission display (NED) will have very large market segment in display components such as smart phones, computer monitors, large display screens, and related display applications due to its outstanding features and opportunities of the product and as well the superior electron properties of the material carbon nanotube.

DISCUSSION

It is obvious that research carried out on this novel material since itsfirst discovery [2] has opened new era of exploration of carbon and its isotopes and materials sciences in general due to its composites. Thus, critical appraisal of nanotechnology and carbon nanotubes arises, it will be appropriate to employ the school of thought 'PEST' an acronym for the following words: Politics, Ecology, Sociology/Economic and Technology respectively for appraisal.

Politics of CNTs Large-Scale Production

Carbon nanotubes have not only caught the interest of scientists, researchers, investors, engineers but also governments [24]. The government of some western countries, especially the United States of America (USA) have invested billions of dollars in research and development (R&D) program of Nano-science, Nano-technology and the buildings blocks (carbon nanotubes and carbon nanowires) through governmental R&D agencies like National Aeronautic Space Administration (NASA), National Nanotechnology Initiatives (NNI) and a host of other governmental and private research agencies.

According to the NNI Nano-science, Technology and Engineering Handbook 2007, it states that. The American Government believes that significant breakthrough of nanotechnology will enhances economic creativities and democratization in the present time and more in the future. This positive attitude of the USA in this regards will no doubt inspire more developed countries to key into, and developing countries to be abreast with the carbon nanotubes development challenges in order for them to contribute their quota as well.

Ecology (Environment) of CNTs Large-Scale production

This emerging technology and the production and manufacturing of carbon nanotubes could be relatively eco-friendly. The environment must be carefully considered due to climate change (global warming) experienced on the Earth, probably caused by human activities such as indiscriminate burning of large amounts of hydro-carbons into the atmosphere. Agboola et al[18] stated that, in the conceptual design of the carbon nanotube process using two CVD methods to product CNTs for industrial scale, these processes are energy intensive and emits significant amounts of carbon dioxides of about 2700kg/h. This will definitely increases the greenhouse gases in the atmosphere. Thus, Xu et al[22], claims that *"sustainable development in the concept should be developed to meet the needs in the present without compromising the future to meet the needs"* therefore, a sustainable solution was devised, ensuring that the carbon dioxides produced from the industrial processes could be utilized as a raw material in other carbon dioxide processes, for example production of urea and methanol, amongst others reported [22].

In effect, the utilization of carbon dioxides emission from the CNTs processing will not only make carbon nanotube processes significantly eco-friendly but reduce the costs of production, because the resources needed to control the carbon dioxides released into the atmosphere by the industrial processes of CNT production can be utilized by re-investment into the industrial processes for continuous improvement of the processes and technology.

Sociology/Economic of CNTs Large-Scale production

Nanotechnology and carbon nanotubes have demonstrated flexibility and integration into multiple disciplines from science, technology and economics. This can be justified by the high numbers of application areas such as Nano-science, Nano-biomedical, Nano-electronic, Nano-super computer etc. [23]. The formulation of NNI is basically to create a platform of an interdisciplinary nanotechnology community to facilitate R&D infrastructures that will constitute significant growth. This initiative will attract thousands of professional and NGOs contributors that will constitute wide participation thereof. So it has become an alternative to the centralized approach in the United States. But apart from Japan and United Kingdom which have contributed little to in this respect. Other nations of the world probably have not done significant campaign on the state-of-the-art material [24].The major economic issue with CNTs is the costs of manufacturing for various applications for commercialization; therefore, the potential for batch productions of CNTs may significantly reduce the manufacturing costs for carbon nanotubes commercialization initiatives.

Technology of CNTs Large-Scale production

Nano-technology is a novel technology which revives the study of matters of atoms and molecules in their nanoscale state, and thus the manipulating of carbon atoms and molecules in nano-scales, defining its functionality for useful macro applications. According to the American National Science Foundation (NSF) and the National Nanotechnology Initiative (NNI), the definition of nanotechnology *"is the ability to understand, control and manipulate matters at the level of individual atoms and molecules, as well as 'supermolecular' the level involving clusters of molecules (in the range of 0.1 to 100nm), in order to create materials, devices, and systems with fundamental properties and functions because of their small structure"*.

or the case of flat panel display, nano-emission display (NED) technology based on carbon nanotubes has presumably fulfilling the anticipated future of nano-based electronics applications with the feature of lager size components but lighter weight, smaller components but smarter, low energy consumptions and probably cheaper. Motorola has successful design and built a prototype of NED that *"outperform today's flat-panel televisions are ready to move out of the lab and into factories"* [19].

CONCLUSION

This study carried out a critical review on the current state-of –art material science and technology towards achieving large-scale industrial productions and commercialization of Carbon nanotubes (CNTs). The following conclusions were being drawn:

- A promising engineering material for modern technological devices, which have shown significant level of progress in the past decade. Following the continuous development of their extraordinary mechanical and unique electronic properties, provides the opportunities for state-of-the-art applications that will break the jinx for large-scale production for commercialization that will amount to wealth creation.
- Initial breakthrough for large-scale production for commercialization has been achieved. For example, the developed consumer's product like Motorola's Nano emission displays technology of full colour flat display panel prototype and with the developed detail design of CNTs production process plant.
- For private investors, there is high potential for returns on investment (ROI) in short term and long term. And also, governments have nothing to lose by investing significantly into the developmental strategies that would results into large-scale production. Hence, huge investment by governments shall be beneficiary overall. This will definitely contribute to the reduction of unemployment, improvement of nation's defense strategies, and facilitating robust research and development (R&D) communities of Nano science and Nanotechnology locally and internationally.

Finally, it would be safe to end this conclusion section, in recognition of the huge potentials for large-scale industrial productions and commercialization of CNTs. Tangible investment both by governments or private sectors will change the status quo of production challenges and take advantage of Nano-science and Nano-technology trend.

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