Present and Future Commercial Applications of Carbon Nanotubes: A Review

Madiha Mazhar
Dept. of Chemistry and chemical Engineering
Lahore University of Management Sciences
Lahore , Pakistan
14130007@lums.edu.pk

Abstract

The production capacity for carbon nanotubes (CNTs) already reaches a few thousand tons per year, reflecting the global commercial interest in CNTs. Today, bulk CNT powders are used in a variety of commercial items, including rechargeable batteries, automobile components, recreational goods, boat hulls, and water filters. CNTs can now be included into thin-film electronics and large-area coatings due to advances in CNT manufacturing, purification, and chemical modification. CNT yarns and sheets already exhibit promise performance for applications such as supercapacitors, actuators, and lightweight electromagnetic shields, while not yet offering compelling mechanical strength or electrical or thermal conductivities for many applications.

Keywords

Carbon nanotube, boat hulls, thermal conductivity, mechanical strength, and electrical properties.

1. Introduction

Carbon nanotubes, also known as CNTs, are seamless cylinders made up of one or more layers of graphene and can have either open or closed ends. They are designated as single-wall or multiwall carbon nanotubes, respectively (Shabir et al. 2022). All of the carbons in perfect CNTs are bonded together in a hexagonal lattice, with the exception of the carbons at the ends of the CNT. However, defects in mass-produced CNTs introduce pentagons, heptagons, and other imperfections in the sidewalls, which generally result in a degradation of the properties that are desired. SWNTs normally have diameters ranging from 0.8 to 2 nm, and MWNTs typically have diameters ranging from 5 to 20 nm, despite the fact that MWNT diameters can surpass 100 nm. The lengths of CNTs can range from less than 100 nm to several centimeters, which allows them to bridge the gap between the molecular and macroscopic scales.

When only the cross-sectional area of the CNT walls is taken into consideration, the elastic modulus of individual MWNTs has been measured to be close to 1 TPa, and their tensile strength has been determined to be 100 GPa (Shabir et al,. 2022). Its strength surpasses that of any industrial fiber by more than a factor of ten. MWNTs are primarily made of metal and have the ability to transport currents of up to 109 A cm–2 (Shabir et al,. 2023). The orientation of the graphene lattice with respect to the tube axis is what is referred to as the chirality. Individual CNT walls can either be metallic or semiconducting, depending on which orientation they have. The thermal conductivity of individual SWNTs can be as high as 3500 W m1 K1 at ambient temperature, which is higher than the thermal conductivity of diamond. This is determined by the wall area of the SWNT.

The earliest documented observations of hollow carbon nanofibers were made as early as the 1950s, which predates the beginning of widespread CNT research in the early 1990s. This study was preceded by the first industrial synthesis of what are now known as MWNTs, which occurred in the 1980s. However, the most significant increase in economic activity related to CNT has occurred over the course of the last ten years (Ullah H et al ., 2014). Since 2006, the global capacity for CNT manufacture has expanded by at least a factor of ten, and the number of journal articles and patents relating to CNTs that are issued each year continues to increase as well (Fig. 1).

The vast majority of the carbon nanotubes produced today are destined for use in bulk composite materials and thin films. These applications rely on disorganized CNT structures, which have restricted property sets. Organized CNT architectures (fig. S1) such as vertically aligned forests, yarns, and sheets have the potential to scale up the properties of individual CNTs and realize new functionalities. Some of these new functionalities include shape recovery , dry adhesion , high damping , terahertz polarization , large-stroke actuation , near-ideal black-body absorption (13), and thermoacoustic sound emission (Shabir et al,. 2023).

However, the currently realized mechanical, thermal, and electrical properties of CNT macrostructures such as yarns and sheets remain much lower than those of individual CNTs. These differences can be attributed to the fact that CNT macrostructures are more complex.

CNT powders, on the other hand, have already found their way into a variety of commercial applications and are about to enter the expansion phase of their product life cycle as a result of the large-scale bulk production that has been going on. This review focuses on the most potential present and future commercial applications of carbon nanotubes (CNTs), along with related problems that will drive continued research and development. In light of these trends, we have chosen to focus on these areas. Section 1 is Introduction to the work, Section II explains synthesis of CNTs , While Section III presents Composites Materials , Section IV gives a brief idea of General Methods and Coating Process, Section V and VI explains applications of CNTs in Microelectronics and Biotechnology and Section VII concludes and gives a future perspective of the work.

1.1 Objectives

This research is focused on Carbon nanotubes synthesis, applications and properties.

2. Synthesis of CNTs

2.1 Methodology

The most common method for the manufacture of massive volumes of carbon nanotubes is known as chemical vapor deposition, or CVD. CVD commonly makes use of fluidized bed reactors, which allow for uniform gas flow and heat transfer to metal catalyst nanoparticles. MWNT prices have dramatically dropped as a result of scale-up, the utilization of feedstocks with low costs, increases in yield, and reductions in both energy usage and waste output . Unfortunately, large-scale CVD procedures produce impurities that can have an effect on the characteristics of CNTs and frequently call for expensive thermal annealing and/or chemical treatment in order to eliminate them (Moyzhes G. *et al ., 2005*). These processes have the potential to reduce the length of CNTs and introduce flaws into the sidewalls of CNTs. At the moment, bulk pure MWNTs can be purchased for less than $100 per kilogram, which is between one and ten times more expensive than carbon fiber that is already on the market. Due to a better understanding of the parameters under which the CVD process occurs, it is now possible to preferentially synthesize metallic or semiconducting SWNTs with a selectivity of 90 to 95%, as well as dope CNTs with boron or nitrogen and flow-directed growth of isolated SWNTs up to 18.5 cm long have all been made possible thanks to an understanding of the conditions under which the CVD process occurs (Krebs F., 2009). Yet, there is an immediate need for increased awareness of how CNT works. chirality, diameter, length, and purity are all related to the composition of the catalyst as well as the parameters of the process. In-situ monitoring of carbon nanotube (CNT) nucleation and molecular. In order to make progress in chirality-selective synthesis, modeling the CNT-catalyst interface is going to be absolutely necessary (Shabir et al.,2022).

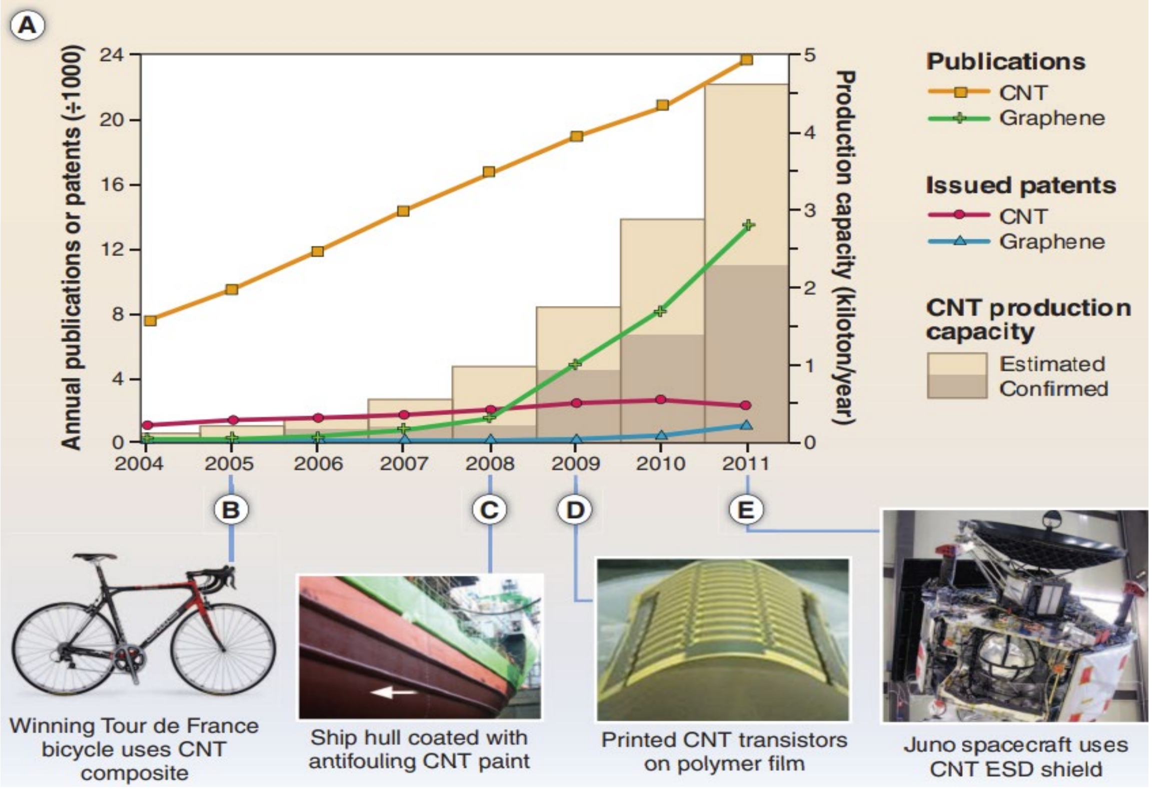

Figure 1. Recent developments in CNT research and commercialization are discussed. (A) The number of journal publications and global patents that are granted each year, in addition to the expected annual production capacity (see supplementary materials). (B to E) A selection of goods that contain carbon nanotubes, including antifouling coatings (courtesy of NanoCyl), printed electronics (courtesy of NEC Corporation; unauthorized usage not permitted), and electrostatic discharge shielding (courtesy of NanoComp Technologies, Incorporated).

Gel chromatography is another method that may be used to separate high-purity SWNT powders according to their chirality. This method can be used in conjunction with density-gradient centrifugation to achieve selective surfactant wrapping . The manufacture of stable CNT suspensions necessitates either the chemical modification of the CNT surface or the addition of surfactants, despite the fact that various CNT powders and suspensions are available for purchase on the market. After depositing the solution in some manner, such as via spin-coating or printing, it is customarily necessary to do a washing or thermal treatment in order to eliminate any remaining surfactants(Shabir et al.,2022).Moreover, bulk SWNT pricing are still orders of magnitude higher than prices for MWNTs. This is due to the fact that SWNT synthesis by CVD requires considerably more stringent process control than MWNT synthesis does. Also, this is due to the legacy expenses of research and process development(Shabir et al.,2023).

Hence, the use of MWNTs is preferred for applications in which the CNT diameter or bandgap does not play a crucial role; nonetheless, the majority of developing applications that require chirality-specific SWNTs require further price reductions for them to become commercially viable(Shabir et al.,2023).

Instead, the synthesis of long CNTs that are aligned and can be treated without the requirement of dispersion in a liquid shows promise for the cost-effective realization of appealing bulk characteristics. Self-aligned development of horizontal and vertical CNTs on substrates covered with catalyst particles is one example of these approaches. Another example is the manufacture of CNT sheets and yarns straight from floating-catalyst CVD systems.CNT forests are capable of being manipulated into thick solids , aligned thin films , and complicated three-dimensional (3D) microarchitectures , and they are also capable of being directly spun or dragged into long yarns and sheets (Shakil et al.,2022).

3. Composites Materials

Deep learning techniques are being used in the work as Composite Products Utilizing their high aspect ratio to form a percolation network at concentrations as low as 0.01 weight percent (wt%), MWNTs were initially utilized as electrically conductive additives in plastics. At 10 wt% deposition, disordered MWNT-polymer composites exhibit conductivities as high as 10,000 S m–1(Parsian K., et al 2013) . Conductive CNT plastics have enabled the electrostatic-assisted painting of mirror housings, gasoline lines, and filters that dissipate electrostatic charge in the automotive industry. Other products for the microelectronics industry include electromagnetic interference (EMI) shielding packages and wafer carriers.CNT powders mixed with polymers or precursor resins can increase stiffness, rigidity, and toughness for load-bearing applications(Shabir et al.,2022) . Adding 1% MWNT to epoxy resin increases stiffness and fracture durability by 6% and 23%, respectively, without affecting other mechanical properties . These enhancements are dependent on CNT diameter, aspect ratio, alignment, dispersion, and matrix interfacial interaction.Numerous CNT manufacturers offer pre-mixed resins and master batches with CNT loadings ranging from 0.1% to 20% by weight(Amin et al.,2022).

Moreover, engineering nanoscale stick-slip between CNTs and CNT-polymer contacts can improve material damping , which is used to improve sporting products such as tennis racquets, baseball bats, and bicycle frames (Fig. 1C).CNT compounds are also utilized to improve the performance of fiber composites. Recent examples include composite wind turbine blades and hulls for maritime security vessels made from carbon fiber composite with CNT-enhanced resin (Fig. 2A) (Parsian K., et al 2014). CNTs can also be utilized as additives in carbon fiber-forming organic precursors (Shabir et al.,2022). The CNTs influence the arrangement of carbon in the pyrolyzed fiber, allowing the fabrication of 1-mm-diameter carbon fibers with greater than a 35% increase in strength (4.5 GPa) and rigidity (463 GPa) compared to control samples lacking CNTs .Hierarchical fiber composites have been produced by growing aligned CNT forests onto glass, SiC, alumina, and carbon fibers , thereby producing so-called "fuzzy" fibers. Fuzzy CNT-SiC fabric impregnated with epoxy demonstrated improved crack-opening (mode I) and in-plane shear

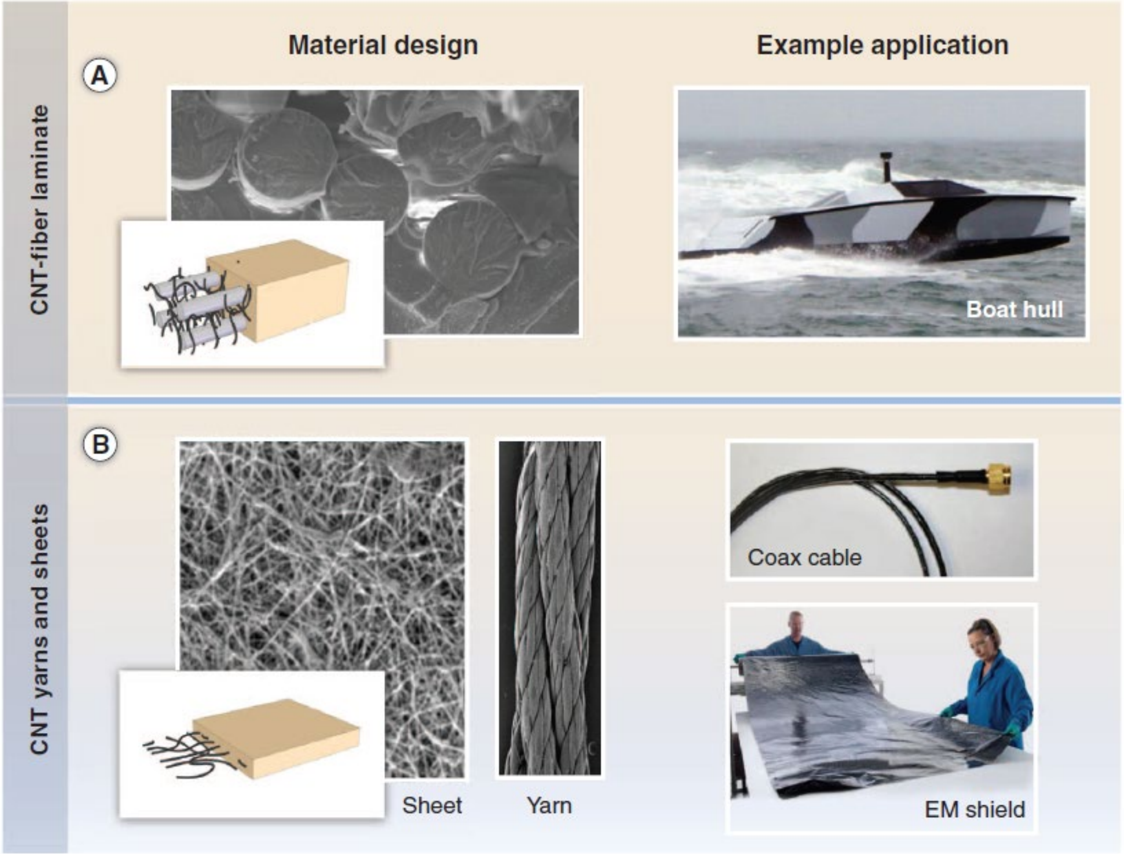

Figure 2: New CNT macrostructures and composites. Lightweight CNT-fiber composite boat hulls are being developed for use in maritime security vessels, as seen in (A) this micrograph of a carbon fiber laminate with CNTs scattered in the epoxy resin. These pictures were provided by Zyvex Technologies. (B) lightweight data cables and electromagnetic (EM) shielding material made from CNT sheets and yarns. [Photographs provided by Nano comp Technologies, Inc.]

interlaminar (mode II) toughnesses compared to control specimens (40), while CNT-alumina fabric demonstrated improved mode II toughness by 69%. Multifunctional aircraft applications being researched include lightning protection, deicing, and structural health monitoring (Koster L., *et al* ., 2006*)* .

CNTyarns and laminated sheets made by direct CVD or forest spinning or drawing methods may eventually compete with carbon fiber for high-end applications, particularly weight-sensitive applications requiring combined electrical and mechanical functionality (Figures 1E and Figure 2B). According to scientific reports, yarns made from high-quality few-walled CNTs have achieved a rigidity of 357 GPa and a strength of 8.8 GPa, but only for a gauge length comparable to the millimeter-long CNTs contained within the yarn (28). Centimeter-scale gauge lengths demonstrated a 2-GPa strength, which corresponds to the gravimetric strength of commercially available Kevlar (DuPont)(Zervos H, 2007).Due to the fact that the probability of a critical flaw increases with volume, macroscale CNT strands may never attain the same strength as their constituent CNTs. However, the high surface area of CNTs may provide interfacial coupling that mitigates these shortcomings, and unlike carbon fibers, CNT filaments can be knotted without compromising their strength (Deshmukh M., et al 2021).Moreover, by coating forest-drawn CNT sheets with functional powder prior to inserting a twist, weave, braidable, and sew able fibers containing up to 95 wt% powder have been produced, which have been demonstrated as superconducting wires, battery and fuel cell electrodes, and self-cleaning textiles.Through coagulation-based spinning of CNT suspensions , aligned SWNT fibers with high performance can be produced (Zaidi B., et al 2006). This is attractive for scalability if the price of high-quality SWNTs drops significantly or if spinning can be extended to low-cost MWNTs. Thousands of spinnerets could operate in parallel, and CNT orientation could be achieved through the formation of liquid crystals, similar to the spinning of Kevlar (Shabir A., et al 2023).

Small amounts of carbon nanotubes (CNTs) added to metals have enhanced their tensile strength and modulus, which could be useful in aerospace and automotive structures. Stronger than stainless steel (0.7 to 1 GPa) but just a third as dense (2.6 g cm-3) are commercial Al-MWNTcomposites. Al-MWNT composites are said to be less expensive yet having comparable strength to Al-Li alloys (Shabir et al., 2022).

As a last use, MWNTs can be added to plastics to make them less flammable; this effect is mostly related to alterations in rheology caused by nanotube loading. As an alternative to halogenated flame retardants, whose use is limited by environmental restrictions, these nanotube additions have economic appeal (Wu et al 2016).

4. General Methods and Coating Process

Utilizing CNT dispersion, functionalization, and large-area deposition techniques, CNTs are becoming a coating material with multiple functions.For instance, MWNT-containing coatings inhibit the attachment of algae and barnacles to ship hulls (Figure 1C).They are an alternative to coatings containing environmentally hazardous biocides. The incorporation of carbon nanotubes (CNTs) into anticorrosion coatings for metals can increase coating stiffness and strength while also providing an electric pathway for cathodic protection (Zaidi, B 2020).

As an alternative to indium tin oxide (ITO), CNT-based transparent conducting films (47) continue to undergo extensive research and development. ITO is becoming more expensive due to the scarcity of indium, which is exacerbated by the increasing demand for displays, touch-screen devices, and photovoltaics (Suh H., et al 2014).

In addition to cost, the flexibility of CNT transparent conductors over brittle ITO coatings is a significant advantage for flexible displays. In addition, transparent CNT-conductors can be deposited from solution (e.g., slot-die coating, ultrasonic sprinkling) and patterned using low-cost nonlithographic techniques (e.g., screen printing, microplotting). Recent commercial development efforts have produced SWNT films with 90% transparency and 100 ohm per square sheet resistivity(Zaidi, B 2021). This surface resistivity is adequate for some applications, but it is significantly higher than that of optimally doped, equally transparent ITO coatings . CNT thin-film heaters are used in applications with less stringent requirements, such as defrosting windows or pavements. All of the aforementioned coatings are pursued commercially(Zaidi, B 2020) .

5. Microelectronics

Low electron scattering and a bandgap dependent on diameter and chiral angle make high-quality SWNTs attractive for use in transistors. SWNTs are also compatible with FET architectures and high-k dielectrics. After the introduction of the first CNT transistor in 1998 (50), the first SWNTtunneling FET with a subthreshold oscillation of 60mV decade–1 in 2004 (49, 51) and CNT-based radios in 2007 (52) are notable achievements. SWNT FETs with sub-10 nanometer channel lengths demonstrated a higher normalized current density (2.41 mA mm–1 at 0.5 V) in 2012 than silicon devices (Shakil S. and Ullah. M,. 2022).

In spite of the optimistic performance of individual SWNT devices, the control of CNT diameter, chirality, density, and placement is insufficient for microelectronics production, particularly over large areas. Therefore, devices containing patterned coatings of tens to thousands of SWNTs, such as transistors, are more immediately applicable. Using CNT arrays improves device uniformity and reproducibility by increasing output current and compensating for defects and chirality differences (Shakil S. and Ullah. M,. 2023). Using horizontally aligned CNT arrays, transistors were able to obtain mobilities of 80 cm2 V1 s1, subthreshold slopes of 140 mV decade–1, and on/off ratios of up to 105 . Recent methods for precise high-density CNT film deposition support these developments, allowing conventional semiconductor fabrication of more than 10,000 CNT devices on a single chip (Shakil S et al ., 2023).

CNT thin-film transistors (TFTs) are especially attractive for operating organic light-emitting diode (OLED) displays due to their higher mobility than amorphous silicon (1 cm2 Vs1) and the fact that they can be deposited using low-temperature, non-vacuum methods. Recent research has demonstrated flexible CNT TFTs with a mobility of 35 cm2 V–1 s–1 and an on/off ratio of 6 106 (Fig. 3A) . A vertical CNT FET demonstrated sufficient current output to operate OLEDs at low voltage , allowing OLEDs to emit red, green, and blue through a transparent CNT network.

CNTelectronics' promising commercial development involves low-cost printing of TFTs and radiofrequency identification tags . For the commercialization of CNT thin-film electronics, a better understanding of CNT surface chemistry is essential; recent developments, for example, enable selective retention of semiconducting SWNTs during spin-coating and reduction of sensitivity to adsorbates (Shabir A. et al., 2023).

The International Technology Roadmap for Semiconductors suggests that due to their minimal scattering, high current-carrying capacity, and resistance to electromigration, CNTs could replace Cu in microelectronic interconnects. This requires vias composed of metallic CNTs densely packed (>1013 per cm2) with low defect density and low contact resistance. On full 200-mm-diameter substrates, recently demonstrated 150-nm-diameter CMOS-compatible interconnects (Figure 4) with a single CNT–contact hole resistance of 2.8 kohm . CNTs can also serve as electrical conductors and heat dissipators in high-power amplifiers as a replacement for solder bumps (Figure 3D).

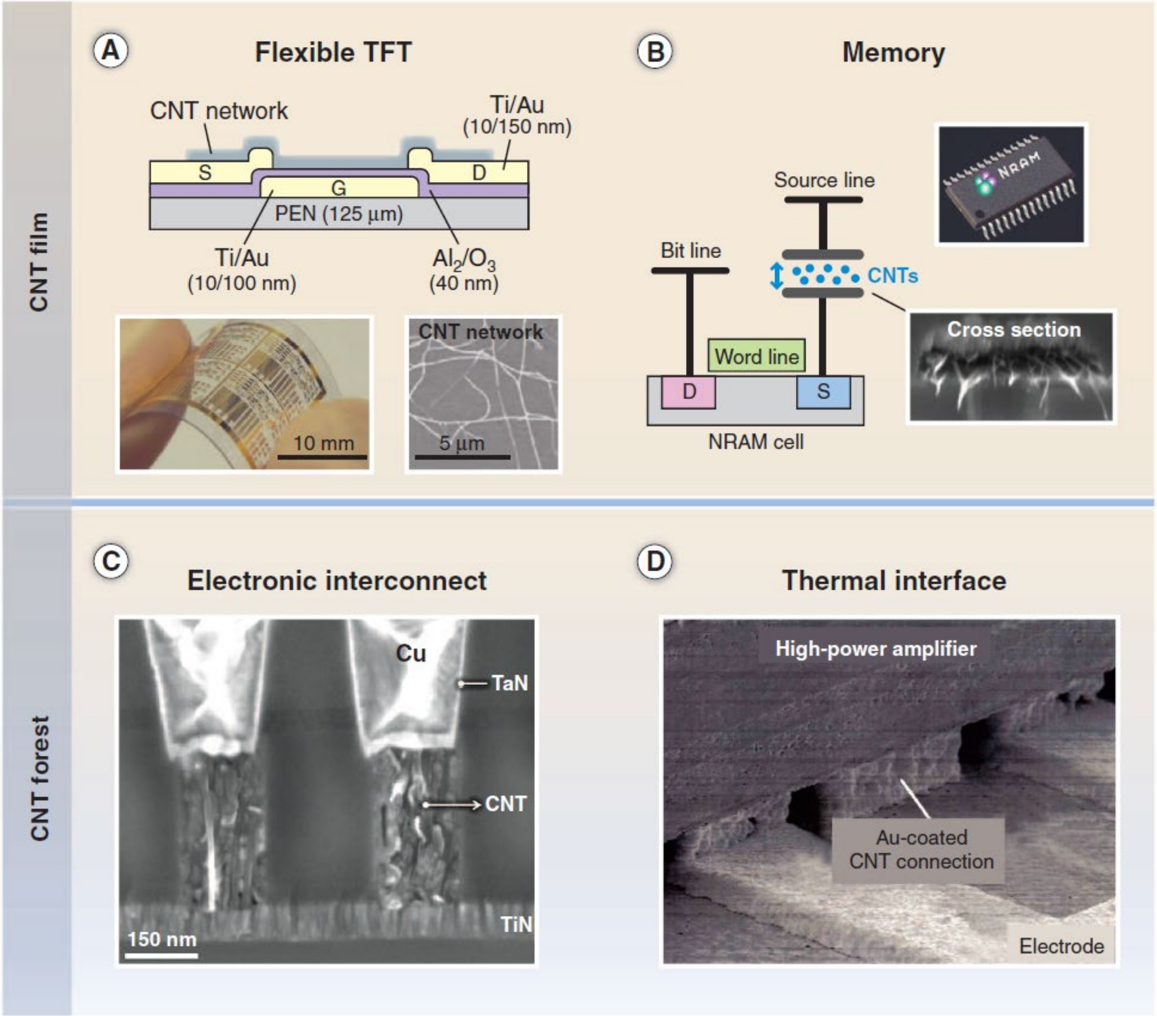

Figure 3: Selected applications of CNTs in microelectronics. Aerosol CVD-deposited flexible TFTs containing CNT networks. [Schematic and photograph reproduced with permission from Macmillan Publishers Limited; scanning electron micrograph courtesy of Y. Ohno] Nonvolatile random-access memory (NRAM) cell fabricated using spin-coating and patterning of a CMOS-compatible CNT solution. [Photographs courtesy of Nantero, Inc.] (C) 150-nm vertical interconnects compatible with CMOS, developed by imec and Tokyo Electron Limited. [Image provided by imec] CNT spikes used in high power amplifiers to improve thermal dissipation. [Photograph provided by Fujitsu Limited]

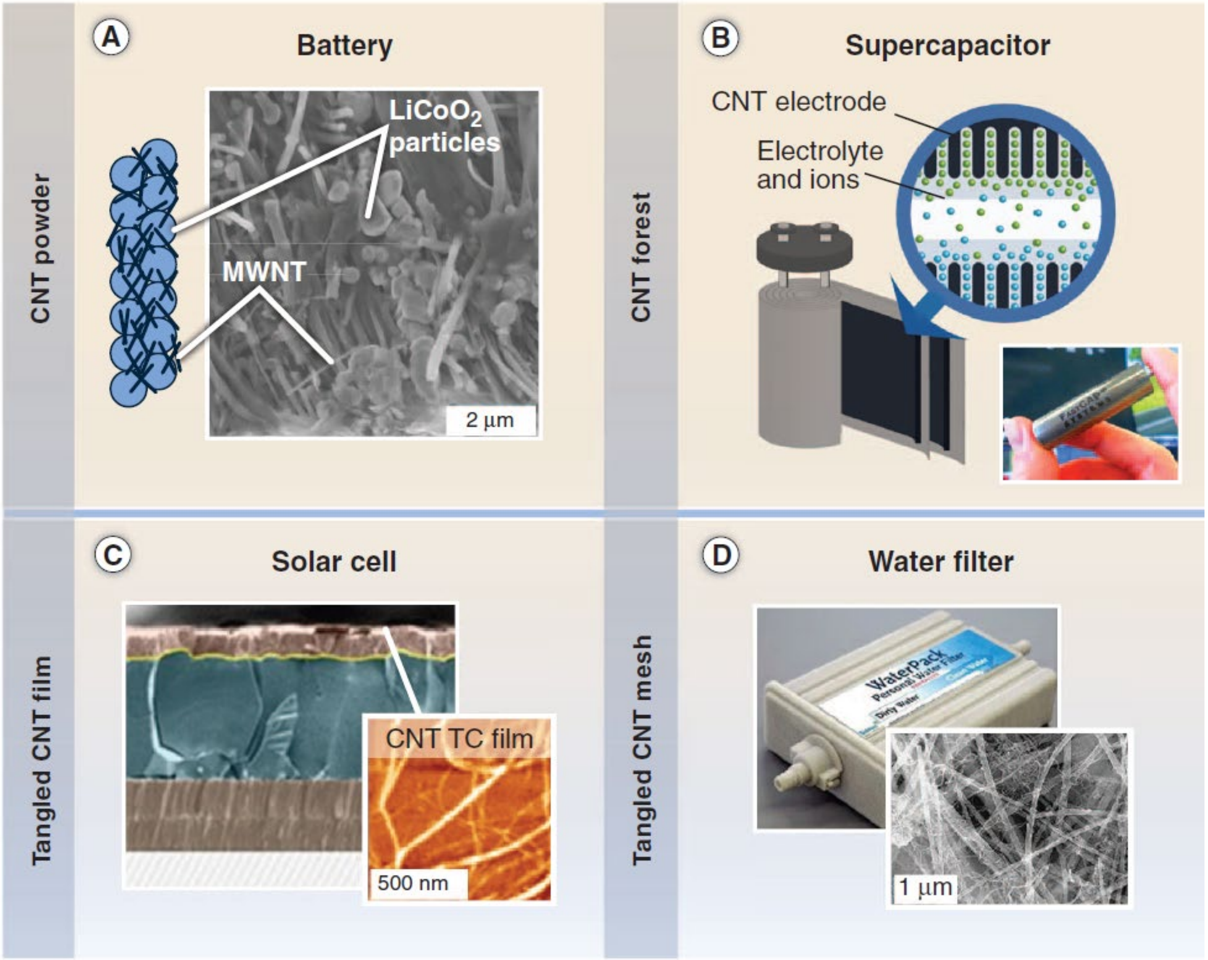

Figure 4. CNT applications related to energy. (A) MWNTs and active granular mixture for battery electrode. [Images reproduced with the permission of John Wiley and Sons] (B) A supercapacitor concept based on CNT forests. [Photographs provided by FastCap Systems Corporation] (C) Solar cell with a transparent SWNT-based conductor. [Photographs courtesy of Eikos Corporation] The most advanced prototype of a portable water filter utilizing a functionalized tangled CNT lattice. [Photographs curtsey by Seldon Technologies]

Finally, patterned tangled CNT thin films have been implemented as the functional elements of a commercially viable nonvolatile memory idea based on individual CNT crossbar electromechanical switches (Figure 3B). To achieve this, ultrapure CNT suspensions consistent with CMOS processing standards had to be developed so they could be spin-coated and processed in industrial clean rooms (Bernek 2005).

5.1 Environment and Energy Storage

The widespread adoption of MWNTs in lithium ion batteries for portable electronics is a major commercial success . One wt% CNT loading in LiCoO2 cathodes and graphite anodes are examples of how MWNT powder is used in conjunction with active materials and a polymer binder to create these batteries. CNTs improve rate capability and cycle life due to their enhanced electrical connection and mechanical integrity .

For unpackaged batteries and supercapacitors, many sources report gravimetric energy storage and power densities, normalized with regard to the weight of active electrode materials. High performance based on total cell weight or volume requires high areal energy storage and power densities, but the frequent use of low areal densities for active materials makes it difficult to assess how these gravimetric performance metrics relate to those for packaged cells. One of the few recent studies on packaged cells found that supercapacitors using binder- and additive-free, forestgrown SWNTs (62) achieved remarkable performance, with a 40-F supercapacitor reaching a maximum voltage of 3.5 V and a power density of 16 Wh kg1(Zaidi B., 2019). A 16-year lifespan was estimated based on accelerated testing at temperatures of up to 105 degrees Celsius. Despite these promising results, the high price of SWNTs at the moment remains a significant barrier to widespread use (Shabir et al. 2023).

Doped CNTs may enable Pt-free fuel cells, and using CNTs as a catalyst support could cut Pt usage in fuel cells by as much as 60% compared to carbon black. Ongoing studies are utilizing the characteristics of CNTs to decrease unwanted carrier recombination and improve resistance to photooxidation in organic solar cells. Long-term, CNT-Si heterojunctions could be included into solar technology to take advantage of efficient multiple-exciton production at p-n junctions generated within individual CNTs , among other benefits (Wu. et al., 2001).

In the not-too-distant future, transparent SWNT electrodes may find their way into commercial photovoltaics (Fig. 4C). CNTs have promising future uses in water purification technology(Leschkies ,R et al 2007). Mechanically and electrochemically robust networks with regulated nanoscale porosity can be provided by tangled CNT sheets. Electrochemical oxidation has been utilized to eliminate organic pollutants , bacteria , and viruses . Commercialized portable filters using CNT meshes can clean contaminated water on the go (Fig. 4D).In addition, membranes made of aligned encapsulated CNTs with open ends allow flow into the interior of the CNTs, resulting in extremely low flow resistance for both gases and liquids . Water desalination by reverse osmosis may require less energy than with conventional polycarbonate membranes thanks to this improved permeability. To repel salt at seawater concentrations, however, extremely small-diameter SWNTs are required (Debnath et al 2023).

6. Biotechnology

Because of their structural and chemical compatibility with biomolecules like DNA and proteins, CNTs continue to attract attention as potential components of biosensors and medical devices.Additionally, CNTs allow for near-infrared radiation-based local heating , fluorescence imaging , and photoacoustic imaging (Zaidi B., 2019).

Adsorption of a target on the CNTsurface is a common method for modulating the electrical impedance and optical characteristics of SWNT biosensors in response to their surroundings. Engineering the CNT surface (e.g., functional groups and coatings) and proper sensor design (e.g., field effects, capacitance, Raman spectrum shifts, and photoluminescence) are required for low detection limits and excellent selectivity. Inkjet-printed test strips for estrogen and progesterone detection, DNA and protein detection microarrays, and NO2 and cardiac troponin sensors are among the products now in development (84). In the food industry, the military, and environmental applications, similar CNTsensors have been utilized to detect gases and toxins (Shabir A., et al 2023).

CNTs can be internalized by cells for use in vivo once their tips attach to membrane-bound receptors . Because of this, molecular cargo linked to or encapsulated inside CNTwalls or CNTs can be transfected (Shakil S., et al 2022). Up to 60 weight percent of the cancer medication doxorubicin was loaded onto CNTs, while only 8 to 10 weight percent was placed onto liposomes . Near-infrared light can be used to liberate cargo. Controlling CNT retention within the body and preventing undesired buildup, which may come from altering CNTsurface chemistry (89), will be crucial for free-floating CNT usage (Kymakis E. *et al*., 2007).

Although CNT toxicity is still an issue, it is becoming clear that CNT shape and surface chemistry have a significant impact on biocompatibility, suggesting that CNT biocompatibility may be modifiable through engineering (89). Asbestos-like pathogenicity was found early on after injecting significant doses of MWNTs into the lungs of mice. A later investigation, however, found that when compared to asbestos and the particulate matter found in DC air samples, the lung inflammation generated by injecting well-dispersed SWNTs was negligible . A better understanding of the immune response is necessary for the eventual medical adoption of CNTs, as is the determination of exposure guidelines for various use scenarios such as inhalation, injection, ingestion, and skin contact (Shabir A., et al 2023).
CNT trees immobilized in a polymer were examined for potential application in implants by implanting them into rats reaction compared to the control group. This bodes well for the application of CNTs as coatings for catheters to minimize thrombosis, and as low-impedance brain interface electrodes (Kumar U., 2016).

7. Future Perspectives

Integration of CNT processing into current production procedures was crucial for the commercialization of products that use CNT powders distributed in polymer matrix or deposited as thin films. The gap between the nanoscale characteristics of CNTs and the length scales of bulk engineering materials is beginning to be bridged by organized CNT materials such as forests and threads. But it's important to figure out why CNT yarns and sheets don't have the same thermal conductivity and mechanical strength as single CNTs. The opposite extreme would be a breakthrough for electrical devices and scanning probe tips if individual CNTs with the desired structure could be placed with lithographic precision over vast substrates.

Many businesses are reportedly investing in CNTs for use in a wide variety of products, including transparent conductors, thermal interfaces, antiballistic jackets, and wind turbine blades, as reported in the media. To make matters more complicated, firms tend to keep technological data secret for a long period after commercialization, making it hard to foresee how well a product will do in the market.

Since CNT applications are still in their infancy, the growth in nanotube production and sales is a particularly relevant indicator.
Improved quantitative characterization methods that may be incorporated into production processes, as well as health and safety regulations for CNT fabrication and use, are essential for the sector's continued industrial development. Standards for characterization and management of MWNTs were released in 2010 by the Chinese government , and in 2011 the National Institute of Standards and Technology (NIST) created a SWNT reference material. Bayer took precautions by setting an occupational exposure limit for its CNTs at 0.05 mg m-3 (95). These initiatives stress the importance of proceeding cautiously, particularly in industries like CNT fabrication that may release airborne particulate matter.

It will be important to establish disposal and/or reuse protocols when more CNT materials enter the consumer market. Cross-contamination during recycling can occur , unless CNTs are burned before entering municipal waste streams. There has to be more collaboration between businesses, universities, and government to fully understand the environmental and social effects of CNTs.

Finally, the meteoric rise of graphene will be complemented by ongoing CNT research and development.
CNT research has been used to inform rapid developments in graphene synthesis and characterization, including CVD methods and Raman spectroscopic techniques. 3D carbon nanotube (CNT)-graphene networks for thermal interfaces and fatigue-resistant graphene-coated CNT aerogels are two examples of promising materials integrating carbon allotropes. CNT research and development will continue to advance the state of the art in nanotechnology and related commercial goods in areas as diverse as surface chemistry and industrial production.

References

Shabir A., and Ullah M., “Heat transfer characteristics of CNT with chirality engineering for solar cell application,” *In 2022 IEEE International Semiconductor Conference (CAS 2022),* Barsov, Romania, 12-14., pp. 159 -162. 2022.

Shabir A., and Ullah M., “Investigation of the emerging materials based high-efficiency cdte solar cell,” *Proceedings of the 7th North American International Conference on Industrial Engineering and Operations Management (IEOM 2022)*, Orlando, USA, 11 -14 pp. 2698-2706. 2022.

Shabir A., and Ullah M., Chirality Engineering on CNTs - A New Approach to Boost the Solar Cell Efficiency,” *Proceedings of the 7th North American International Conference on Industrial Engineering and Operations Management (IEOM 2022)*, Orlando, USA, 11 -14, pp. 1705-1706. 2022.

Shabir, A., Cao, J., Fouad, E., & Ullah, M. W.,“Prospects of solar cell technology from silicon to carbon nanotube," *In 2022 IEEE 9th International Conference on Sciences of Electronics, Technologies of Information and Telecommunications (SETIT 2022)*, Genoa, Italy, 19 -21, pp. 385-391.2022.

Shabir A., Zaidi B., Ullah M., Carrier Generation Ability of CNTs to Harvest Maximum Energy from Solar Spectrum, In *IEEE SoutheastCon 2023*, Orlando, USA, 14-16, 2023, In Press.

Shabir, A., & Ullah, M., “Explore the chirality engineering of carbon nanotubes for solar cell”. *Florida Scientist, vol.85, no.*2, pp. 68, 2022.

Ullah H., Marí B., Cui H., “Investigation on the effect of Gallium on the efficiency of CIGS solar cells through dedicated software”, Applied Mechanics and Materials, Vol. 448, pp. 1497- 150, 2014.

Wu X., Keane J., et al, “16.5%-efficient CdS/CdTe polycrystalline thin-film solar cell,” in Proc. 17th Eur. Photovoltaic Sol. Energy Conf., , pp. 995–1000. 2001.

Zaidi, B., Shekhar C., K. Kamli, Z. Hadef, S. Belghit, and Ullah S, "Junction Configuration Effect on the Performance of In2S3/CZTS Solar Cells." Sumy State University, 2020.

Zaidi, B., M. S. Ullah, S. Zahra, S. Gagui, and C. Shekhar. "Analysis of I-V-T Characteristics of CH3NH3PbBr3 Perovskite Based Solar Cells." Journal of Nano- & Electronic Physics . Vol. 13 Issue 5, p05016-1-05016-4. 4p, 2021.

Shakil S. and Ullah. M., "Effects of NBTI On PMOS Device With Technology Scaling." *2022 IEEE 13th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON 2022)*, NY, USA, 26 - , pp. 0402 - 0406. 2022

Zaidi, B., Ullah M., et al" Role of TCO Films in Improving the Efficiency of CdS/MoS2 Heterojunction Solar Cells." Journal of nano-and electronic physics, vol.11, no. 2, pp. 02030-1, 2019.

Shakil S., and Rashid M., The Potential Impacts of Wireless Power Transfer on the Global Economy, Society, and Environment," in *IEEE 14th Power Electronics, Drive Systems, and Technology Conference (PEDSTC)* 31 january – 02 Feb. 2023,In press.

Shakil M., and Ullah M., "Analysis of HCD Effects for NMOS Transistor with Technology Scaling," In IEEE SoutheastCon 2023-Engineering the Magic. Orlando, USA, In Press.

Amin A., S. M. Shakil and M. S. Ullah, "A Theoretical Modeling of Adaptive Mixed CNT Bundles for High-Speed VLSI Interconnect Design," *Crystals*, vol. 12, no. 2, pp. 186-201, 2022

Moyzhes G. *et al*., "The thermionic energy converter as a topping cycle for more efficient heat engines-New triode designs with a longitudinal magnetic field," *J. Phys. D. Appl. Phys*, vol. 38, no. 56, pp. 782–786, 2005.

Krebs F., "Fabrication and Processing of Polymer Solar Cells: A Review of Printing and Coating Techniques," *Sol. Energy Mater. and Sol. Cells*, vol. 93, no. 178, pp. 394 - 412, 2009.

Koster L., Ultimate Efficiency of Polymer/Fullerene Bulk Heterojunction Solar Cells, *Appl. Phys. Lett*., vol. 88, no.103, pp. 093511-093520, 2006.

Deshmukh M., S. J. Park and S. Bhavna, Recent progress in solar cells based on carbon nanomaterials," *Solar Energy*, vol. 27, no. 42, pp.6549-6574, 2021.

Parsian K., K. Mohseni and A. Behnam *et al*, "Monolithic III-V Nanowire Solar Cells on Graphene via Direct van der Waals Epitaxy," *Advanced Materials*, vol. 26, no. 22, pp. 3755-3760, 2014.

Parsian K, K. Mohseni and A. Behnam, *et al,*"InxGa1–xAs Nanowire Growth on Graphene: van der Waals Epitaxy Induced Phase Segregation", *Nano Letters*. vol.13, no.3, pp.1153-1161, 2013.

Suh H., H. S. Jung, V. Nosang. Myung, K. Hong, "Bamboo-like Te Nanotubes with Tailored Dimensions Synthesized from Segmental NiFe Nanowires as Sacrificial Templates," *Bulletin of the Korean Chemical Society*, vol.35, no. 11, pp. 3227-3231, 2014.

Zervos H., "Properties and tailoring of the ubiquitous core-shell p-n junction in semiconductor nanowires by δ-doping", *physica status solidi (RRL) - Rapid Research Letters*, vol.7, no.10, pp. 894-897, 2013.

Bitam H., B. Zaidi, B. Hadjoudja, C. Shekhar, S. Gagui and M. S. Ullah, "Junction Configuration Effects on the Photovoltaic Parameters of a-Si/Cu_2ZnSnS_4 Solar Cells," *Applied Solar Energy*, Springer, vol. 58, pp. 198-202, 2022.

Shakil S M., and Ullah M. S., "Analyzing the Operational Parameters of a Single Walled Carbon Nanotube Field Effect Transistor (SWCNT-FET)," Proceedings of the 8th North American International Conference on Industrial Engineering and Operations Management (IEOM 2023), Houston, Texas, USA, 13 -15, 2023, Accepted.

Shakil S M., and Ullah M. S., "Reliability Issues in Current MOSFET and Beyond Silicon Technology," Proceedings of the 8th North American International Conference on Industrial Engineering and Operations Management (IEOM 2023), Houston, Texas, USA, 13 -15, 2023, Accepted.

Zaidi B., M. S. Ullah, S. Zahra, S. Gagui and C. Shekhar, "Analysis of I-V-T Characteristics of $CH_3NH_3PbBr_3$ Perovskite Based Solar Cells," *Journal of Nano and Electronics Physics*, vol. 13, no. 5, pp. 05016-1 – 05016-4, 2021.

Debnath Atanu., Uddin MN., et al "Underwater Surveillance Autonomous Boat," Proceedings of the 8th North American International Conference on Industrial Engineering and Operations Management (IEOM 2023), Houston, Texas, USA, 13 -15, 2023.

Debnath Atanu., Uddin MN., et al "Current Scenario of Solar Home Systems and Future Utilization in Bangladesh," Proceedings of the 8th North American International Conference on Industrial Engineering and Operations Management (IEOM 2023), Houston, Texas, USA, 13 -15, 2023.

Bakiri A., B. Zaidi, K. Aouadj, S. Gagui and M. S. Ullah, "Design and Simulation of $In_xGa_{1-x}N$ Based Solar Cells," *Acta Physica Polonica A*, vol. 139, no. 1, pp. 46 – 50, 2021.

Zaidi B., C. Shekhar, K. Kamli, Z. Hadef, S. Belghit and M. S. Ullah, "Junction Configuration Effect on the Performance of In2S3/CZTS Solar Cells," *Journal of Nano- and Electronic Physics*, vol. 12, no. 1, pp. 01024 - 1 – 01024 - 3, 2020.

Zaidi B., and M. S. Ullah *et al*., "Role of TCO Films in Improving the Efficiency of CdS/MoS2 Heterojunction Solar Cells," *Journal of Nano-and Electronic Physics*, vol. 11, no. 2, pp. 02030-1 - 02030-4, 2019.

Kymakis E. *et al*., "Carbon Nanotube Doping of P3HT: PCBM Photovoltaic Devices", *J. Phys. D: Appl. Phys.,* vol. 41, no.16, pp. 165110-165114, 2008.

Leschkies ,R. Divakar and J. Basu et al. " Photosensitization of ZnO nanowire with with CdSe quantum dots for photovoltaic devices." Nono Lett. Vol, 7. Issue 6, pp. 1793-8. 2007.

Roest A., and J. J. Kelly et al "Staircase in Electron Mobility of a ZnO Dot Assembly due to shell Filling" , phys. Rev. Lett , vol, 83,issue 3, pp. 036801-4, 2002.

Shabir A. "Design of MR Damper for Automobile suspension with Finite Element method" 8th North American Conference on industrial Engineering and Operational Management ; Houston Taxas, USA . 13-15. 2023. Manuscript.

Bernek R., H. Tsuchiya et al. "Enhancement and limits of the photoelectrochemical response from anodic TiO2 TiO2 nanotubes," Appl. Phys. Lett. Vol. 87, issue 24, pp. 243114-1 to 243114-3, 2005.

Kumar U., *et al.,* "Carbon Nanotube: Synthesis and Application in Solar Cell," *Journal of Inorgnic and Organometallic Polymers and Materials,* vol. 26, no. 6, pp. 1231–1242, 2016.

Biography

Madiha Mazhar received her bachelor's degree in chemistry from Pakistan's prestigious Government College University Lahore. Many articles detailing this study appeared in the field of organic chemistry. Materials, such as carbon emissions and their reduction, were the main topics of research. Lahore University of Management Sciences, among the greatest schools in South Asia, was where I earned my Master of Philosophy in chemistry. My Master's thesis work was in physical chemistry, and I hope to pursue doctoral studies in the field at the University of Florida USA in the near future.