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A review on Carbon nano-tubes - A new era of nanotechnology

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Abstract- Carbon nanotubes, which consist of rolled graphene sheets built from sp^2 hybridized carbon atoms, were reported to be discovered in 1991, and are now attracting researchers from various disciplines due to their alluring physico-chemical properties. The special nature of carbon combines with the molecular perfection of buckytubes to endow them with exceptionally high material properties such as electrical and thermal conductivity, strength, stiffness, and toughness. The delocalised π -electron donated by each atom is free to move about the entire structure, rather than stay home with its donor atom, giving rise to the first molecule with metallic-type electrical conductivity. The high-frequency C-C bond vibrations provide an intrinsic thermal conductivity higher than even diamond. CNTs open incredible applications in diverse aspects of engineering like materials, electronics, chemical processing and energy management and some of these applications are now realized in products. Others are demonstrated in early to advanced devices, and one, hydrogen storage, is clouded by controversy. The purpose of this review report is to provide the reader some insight in the wide range of aspects of chemistry and applications of CNT and, ultimately, some support and guidance for the reader's own research.

Keywords—Nanotechnology, Carbon nanotubes, Properties of CNTs, Applications of CNTs, Functionalization schemes.

I. INTRODUCTION

Carbon nanotubes (CNTs), the walls of which are made up of a hexagonal lattice of carbon atoms analogous to that of graphite, are cylinder-shaped macromolecules (radius of a few nanometers, which can be grown up to 20 cm in length) [1] and are capped at their ends by one half of a fullerene-like molecule. In the most general case, a CNT is composed of a concentric arrangement of many cylinders (see Fig.1). Such multi-walled nanotubes (MWCNTs) can reach diameters of up to 100 nm. Single-walled nanotubes (SWCNTs) have the simplest geometry, and have been observed with diameters ranging from 0.4 to 3 nm. The formation of a SWCNT can be visualized through the rolling of a graphene sheet. Based on the orientation of the tube axis with respect to the hexagonal lattice, the structure of a nanotube can be completely specified through its chiral vector (see Fig.2(a) and Fig.2(b)), which is denoted by the chiral indices (n, m). The classification of the nanotubes as armchair (n=m) or zigzag (m=0) has its origin from the geometric arrangement of the carbon atoms at the seam of the cylinders.

While both these types of tubes possess mirror symmetry, nanotubes with $m\neq n$ are chiral. The latter kind of tubes exists as two enantiomers with right- and left-handed helicity. Historically the multi-walled nanotubes were the first to be discovered (1991) [2], followed by the single-walled counterparts (1993) [3]. In the meantime, CNTs have emerged to be one of the most intensively investigated nanostructured materials [4].



Fig.1. Structure of a multi-walled carbon nanotube made up of 3 shells.

The observation of the longest carbon nanotubes (18.5 cm long), which were grown on Si substrates using an improved chemical vapour deposition (CVD) method and represent electrically uniform arrays of single-walled carbon nanotubes [5] and was reported in 2009. The shortest carbon nanotube is the organic compound cycloparaphenylene, which was synthesized in early 2009 [6][7][8]. The thinnest carbon nanotube is armchair (2,2) CNT with a diameter of 3 Å. This nanotube was grown inside a multi-walled carbon nanotube. Assigning of carbon nanotube type was done by combination of HRTEM, Raman spectroscopy and density functional theory (DFT) calculations [9]. The thinnest freestanding single-walled carbon nanotube is about 4.3 Å in diameter. Researchers suggested that it can be either (5,1) or (4,2) SWCNT, but exact type of CNT remains questionable [10]. (3.3), (4.3) and (5,1) carbon nanotubes (all about 4 Å in diameter) were unambiguously identified using more precise aberrationcorrected high-resolution transmission electron microscopy and they were found inside of double-walled carbon nanotubes [11].



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Fig.2(a). CNT is configurationally equivalent to a two dimensional graphene sheet rolled into a tube (three different types are shown)



Fig.2(b). A CNT is characterized by its Chiral Vector: $C_h = n \hat{a}_1 + m \hat{a}_2$, where, $\theta \rightarrow$ Chiral Angle with respect to the zigzag axis.

However, different nanostructures of carbon, their properties, functionalization schemes, and the potential applications are discussed in this review work.

II. DIFFERENT NANOSTRUCTURES OF CARBON

There is no consensus on some terms describing carbon nanotubes in scientific literature: both "-wall" and "walled" are being used in combination with "single", "double", "triple" or "multi", and the letter C is often omitted in the abbreviation; for example, multi-walled carbon nanotube (MWNT) instead of multi-walled carbon nanotube (MWCNT). Different nanostructures are reported and illustrated in the following table (see **Table.I**). In this particular work, though our objective is to emphasise on the nanotubes, but gathering the ideas of other nanostructures are very significant as they are either modification of CNTs or CNTs are coupled with other nanostructures.



Fig.3(a). HRTEM image of SWCNT (b). HRTEM image of a bundle of nanotubes



Fig.4. A nanobud over the wall of a SWCNT.

III. PROPERTIES OF CNT

Certain Properties of CNTs have attracted the attention of researchers around the globe. CNTs have very interesting mechanical, optical, thermal, electrical properties that made CNTs unique and these unique identities of CNTs are exploited by the researchers in many aspects. Some of the properties are listed in **Table.II**. Properties of CNTs can be manipulated via grafting or functionalization (grafting of chemical functions at the surface of the nanotubes) as per the requirement.

IV. FUNCTIONALIZATION OF CNT

Modification, better known as functionalization, of CNTs via doping it by some specific functions is a very interesting phenomena. The properties of CNTs are observed to be changed after modification. The chemical modification is done via 3 different methods, namely,

(a) Thermally Activated Chemical Functionalization (see **Fig.5(a)** and **5(b)**) [39] [40] [41][42]

(b) Electrochemical Modification (see **Fig.6(a)** and **6(b)**) [43][44][45]

(c) Photochemical Functionalization (see **Fig.7**.) [46][47][48]



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Table.I. Different nanostructures of carbon

Nano-	Comments
structure	
Single walled	Most single-walled nanotubes (SWNT) (see Fig.3(a)) have a diameter of close to 1 nm, with a tube length that can be many millions of times longer. The structure of a SWNT can be conceptualized by wrapping a one-atom-thick layer of graphite called graphene into a seamless cylinder. The way the graphene sheet is wrapped is represented by a pair of indices (n,m). The integer n and m denote the number of unit vectors along two directions in the honeycomb crystal lattice of graphene. SWNTs are an important variety of carbon nanotube because most of their properties change significantly with the (n,m) values, and this dependence is non-monotonic. In particular, their band gap can vary from zero to about 2 eV and their electrical conductivity can show metallic or semiconducting behavior. Single-walled nanotubes are likely candidates for miniaturizing electronics. The most basic building block of these systems is the electric wire, and SWNTs with diameters of an order of a nanometer can be excellent conductors [12][13]. One useful application of SWNTs is in the development of the first intermolecular field-effect transistors (FET). The first
	intermolecular logic gate using SWCNT FETs was made in 2001 [14].
Multi walled	Multi-walled nanotubes (MWNT) (see Fig.3(b)) consist of multiple rolled layers (concentric tubes) of graphene (see Fig.1). There are two models that can be used to describe the structures of multi-walled nanotubes. In the Russian Doll model, sheets of graphite are arranged in concentric cylinders, e.g., a (0,8) single-walled nanotube (SWNT) within a larger (0,17) single-walled nanotube. In the Parchment model, a single sheet of graphite is rolled in around itself, resembling a scroll of parchment or a rolled newspaper. The interlayer distance in multi-walled nanotubes is close to the distance between graphene layers in graphite, approximately 3.4 Å. The Russian Doll structure is observed more commonly. Its individual shells can be described as SWNTs, which can be metallic or semiconducting. Because of statistical probability and restrictions on the relative diameters of the individual tubes, one of the shells, and thus the whole MWNT, is usually a zero-gap metal.
	In the case of SWNT, covalent functionalization will break some C=C double bonds, leaving "holes" in the structure on the nanotube and, thus, modifying both its mechanical and electrical properties. In the case of DWNT, only the outer wall is modified. DWNT synthesis on the gram-scale was first proposed in 2003 [15] by the CCVD technique, from the selective reduction of oxide solutions in methane and hydrogen
Torus	In theory, a nanotorus is a carbon nanotube bent into a torus (doughnut shape). Nanotori are predicted to have many unique properties, such as magnetic moments 1000 times larger than previously expected for certain specific radii [16]. Properties such as magnetic moment, thermal stability, etc. vary widely depending on radius of the torus and radius of the tube [16][17].
Nanobud	Carbon nanobuds (see Fig.4) are a newly created material combining two previously discovered allotropes of carbon, carbon nanotubes and fullerenes. In this new material, fullerene-like "buds" are covalently bonded to the outer sidewalls of the underlying carbon nanotube. This hybrid material has useful properties of both fullerenes and carbon nanotubes. In particular, they have been found to be exceptionally good field emitters. In composite materials, the attached fullerene molecules may function as molecular anchors preventing slipping of the nanotubes, thus improving the composite's mechanical properties.
g-CNTs	Graphenated CNTs (g-CNTs) are a relatively new hybrid that combines graphitic foliates grown along the sidewalls of multiwalled or bamboo style CNTs. Yu et al. [18] reported on "chemically bonded graphene leaves" growing along the sidewalls of CNTs. Stoner et al. [19] described these structures as "graphenated CNTs" and reported in their use for enhanced supercapacitor performance. Hsu et al. further reported on similar structures formed on carbon fiber paper, also for use in supercapacitor applications [20]. The foliate density can vary as a function of deposition conditions (e.g. temperature and time) with their structure ranging from few layers of graphene (< 10) to thicker, more graphite-like [21].



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Peapod	A Carbon peapod [22] is a novel hybrid carbon material which traps fullerene inside a carbon nanotube. It can possess interesting magnetic properties with heating and irradiating. It can also be applied as an oscillator during theoretical investigations and predictions [23].
Cup- stacked CNTs	Cup-stacked carbon nanotubes (CSCNTs) differ from other quasi-1D carbon structures, which normally behave as quasi-metallic conductors of electrons. CSCNTs exhibit semiconducting behaviors due to the stacking microstructure of graphene layers [24].

V. POTENTIAL APPLICATIONS OF CNTS

The recently developed chemical methods for chemical functionalization of carbon nanotubes have opened up a broad range of novel application perspectives. In this Section, four major and diversely practiced applications of CNTs are described in detail.

A. FETs

For many electronic applications it is of great importance to have nanotube ensembles that exhibit uniform electrical properties. While metallic nanotubes are desirable for nanoscale electrical interconnects, the fabrication of transistor devices requires exclusively semiconducting nanotubes. At present there exists no synthesis method that allows for a reliable control over the electrical properties of the produced nanotubes. The raw nanotube material thus constitutes a mixture of metallic and semiconducting nanotubes.

Various methods for the separation of the two types of nanotubes have been devised. One such procedure is based upon alternating current dielectrophoresis of surfactantstabilized SWCNTs, [48] which takes advantage of the differing concentrations of freely movable charge carriers in nanotubes: Metallic nanotubes possess a high density of such carriers, which gives them a large electronic polarizability. Hence, when a suitable alternating electric field is applied, they are attracted to the regions of highest field strength, whereas the semiconducting tubes are repelled. An important disadvantage of this method is that it is limited to very small material quantities. On the other hand, chemical separation methods exploiting differences in the solubility of the two types of tubes upon doping with an electron acceptor offer an easier scalability [49]. However, all currently available chemical methods are still. far from enabling an exclusive enrichment of one type of tube.

An alternative technique for the separation of the tubes is based on the selective destruction/functionalization of the metallic nanotubes in a tube ensemble. As one possibility, this can be achieved by applying an increasing electrical voltage across the tube ensemble until the metallic tubes are burnt off as a consequence of Joule heating arising from the high current densities [50].



Fig.5(a). Chemical modification of nanotubes through thermal oxidation, followed by subsequent esterification or amidization of the carboxyl groups



Fig.5(b). Overview of possible addition reactions for the functionalization of the nanotube sidewall

The procedure is performed by simultaneous application of a gate voltage to deplete the semiconducting nanotubes of charge carriers, so that exclusively the metallic nanotubes remain conductive.



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Fig.6(a). Reaction scheme for reductive ECM with an aromatic diazonium salt



Fig.6(b). Reaction scheme for oxidative ECM with a substituted aromatic amine



Fig.7. Reaction scheme for sidewall osmylation of a SWCNT using UV light

While this method has proven effective for the separation of single tubes, its application to samples composed mainly of bundles faces limitations. This is due to the close proximity of the metallic and semiconducting nanotubes within the bundles, which leads to a high risk of damage for the latter type of tubes. Electrochemical methods offer an elegant solution to this problem. Upon switching off the semiconducting tubes under appropriate gate control, the metallic tubes are exclusively provided with a high density of covalently coupled phenyl radicals reductively generated from aromatic diazonium salts. As a consequence, the modified metallic tubes become insulating, and the resulting ensemble shows purely semiconducting behavior. The conductance of such devices can be varied over many orders of magnitude through the voltage at the gate electrode [51]. The key concept of this approach is the creation of highly reactive radicals exclusively at the locations where the reaction is desired, that is, at the interface between the electrolyte and the metallic nanotubes.

B. Electrochemical sensors

Carbon nanotubes exhibit high electron transfer rates for different redox couples in various media [52], which has stimulated an increasing amount of research into CNT based amperometric sensors for the detection of specific analytes in solution. The length scales of CNTs are similar to that of typical biological molecules, which gives CNTs an edge over other materials in functioning as effective electrodes in bioelectrochemical sensing [53]. In particular, their high aspect ratio and their diameter in the nanometer range make CNTs particularly well suited for direct electrochemical communication with the redox site of a protein, without requiring any mediator. When properly arranged, a nano-tube should have the capability to act as a 1D channel that guides electrons towards the redox center.

Direct electron transfer has been achieved with various types of CNT electrodes for cytochrome [54] horseradish peroxidase,[55] myoglobin,[56] as well as glucose oxidase [53]. It is noteworthy that in the latter case, the redoxactive center is deeply embedded within the protein. In some cases, an oxidative pre-treatment that introduces negatively charged surface groups on the CNTs was necessary to achieve high electron transfer rates. In a strategy to optimize the accessibility of the redox center, aligned CNT arrays have been fabricated using self assembly techniques, followed by the covalent attachment of micro-peroxidase to the tube ends [57]. On this basis, various types of amperometric biosensors have been fabricated [58]. Fig.8. schematically illustrates the working principle of a glucose sensor obtained by immobilizing glucose oxidase onto SWCNTs deposited on a glassy carbon surface [59].

C. Heterogeneous catalysis

For a long time, active carbon has found widespread application as a support material in heterogeneous catalysis. Compared to this form of carbon, carbon nanotubes offer the advantage of a more defined morphology and chemical composition as well as the possibility to attach catalysts onto their surface through covalent bonds. The applicability of SWCNTs as carriers for catalytically active molecular functional units has recently been demonstrated through the covalent coupling of an organic vanadyl complex [60]. The nanotubes modified in this manner (see **Fig.9**) permit the catalytic cyanosilylation of aldehydes.

E. Mechanicaly reinforced composites

Carbon nanotubes possess extraordinarily high tensile strength, which outreaches that of a steel wire of specific thickness by around one order of magnitude.



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Table.II. Properties of CNTs

Property	Comment	
Material	A. Strength	
properties	Carbon nanotubes are the strongest and stiffest materials yet discovered in terms of tensile strength and elastic modulus respectively. This strength results from the covalent sp ² bonds formed between the individual carbon atoms. In 2000, a multi-walled carbon nanotube was tested to have a tensile strength of 63 gigapascals (GPa) [25]. (For illustration, this translates into the ability to endure tension of a weight equivalent to 6422 kg on a cable with cross-section of 1 mm ² .) Further studies, conducted in 2008, revealed that individual CNT shells have strengths of up to ~100 GPa, which is in good agreement with quantum/atomistic models [26]. Since carbon nanotubes have a low density for a solid of 1.3 to 1.4 g/cm ³ [27], its specific strength of up to 48,000 kN·m·kg ⁻¹ is the best of known materials, compared to high-carbon steel's 154 kN·m·kg ⁻¹ .	
	Although the strength of individual CNT shells is extremely high, weak shear interactions between adjacent shells and tubes leads to significant reductions in the effective strength of multi-walled carbon nanotubes and carbon nanotube bundles down to only a few GPa's [28]. This limitation has been recently addressed by applying high-energy electron irradiation, which crosslinks inner shells and tubes, and effectively increases the strength of these materials to ~60 GPa for multi-walled carbon nanotubes [26] and ~17 GPa for double-walled carbon nanotube bundles [28].	
	CNTs are not nearly as strong under compression. Because of their hollow structure and high aspect ratio, they tend to undergo buckling when placed under compressive, torsional, or bending stress [29].	
	TEM observation of radial elasticity suggested that even the van-der-Waals forces can deform two adjacent nanotubes [30]. Nano-indentation experiments, performed by several groups on multiwalled carbon nanotubes [31][32] and tapping/contact mode atomic force microscope measurement performed on single-walled carbon nanotube [33], indicated Young's modulus of the order of several GPa confirming that CNTs are indeed rather soft in the radial direction.	
	B. Hardness	
	Standard single-walled carbon nanotubes can withstand a pressure up to 24 GPa without deformation. They then undergo a transformation to super-hard phase nanotubes. Maximum pressures measured using current experimental techniques are around 55 GPa. However, these new super-hard phase nanotubes collapse at an even higher, albeit unknown, pressure.	
	The bulk modulus of super-hard phase nanotubes is 462 to 546 GPa, even higher than that of diamond (420 GPa for single diamond crystal) [34].	
	C. Kinetic properties	
	Multi-walled nanotubes are multiple concentric nanotubes precisely nested within one another. These exhibit a striking telescoping property whereby an inner nanotube core may slide, almost without friction, within its outer nanotube shell, thus creating an atomically perfect linear or rotational bearing. This is one of the first true examples of molecular nanotechnology, the precise positioning of atoms to create useful machines. Already, this property has been utilized to create the world's smallest rotational motor [35]. Future applications such as a GHz mechanical oscillator are also envisaged.	
Electrical properties	Because of the symmetry and unique electronic structure of graphene, the structure of a nanotube strongly affects its electrical properties. For a given (n,m) nanotube, if $n=m$, the nanotube is metallic; if $(n-m)$ is a multiple of 3, then the nanotube is semiconducting with a very small band gap, otherwise the nanotube is a moderate semiconductor. Thus all armchair $(n = m)$ nanotubes are metallic, and nanotubes $(6,4)$, $(9,1)$, etc. are semiconducting [36].	
	However, this rule has exceptions, because curvature effects in small diameter carbon nanotubes can strongly influence electrical properties. Thus, a (5,0) SWCNT that should be semiconducting in fact is metallic according to the calculations. Likewise, vice versa, i.e, zigzag and chiral SWCNTs with small diameters that should be metallic have	



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	finite gap (armchair nanotubes remain metallic) [36]. In theory, metallic nanotubes can carry an electric current density of 4×109 A/cm ² , which is more than 1,000 times greater than those of metals such as copper [37], where for copper interconnects current densities are limited by electro-migration. Because of their nanoscale cross-section, electrons propagate only along the tube's axis and electron transport involves quantum effects. As a result, carbon nanotubes are frequently referred to as one-dimensional conductors. The maximum electrical conductance of a single-walled carbon nanotube is $2G_0$, where $G_0 = 2e^2/h$ is the conductance of a single ballistic quantum channel [38]. There have been reports of intrinsic superconductivity in carbon nanotubes [39][40].
Optical property	One of the more recently researched properties of multi-walled carbon nanotubes (MWNTs) is their wave absorption characteristics, specifically microwave absorption. Interest in this research is due to the current military push for radar absorbing materials (RAM) to better the stealth characteristics of aircraft and other military vehicles. There has been some research on filling MWNTs with metals, such as Fe, Ni, Co, etc., to increase the absorption effectiveness of MWNTs in the microwave regime. Thus far, this research has shown improvements in both maximum absorption and bandwidth of adequate absorption. The reason the absorptive properties changed when filled is that the complex permeability (μ_r) and complex permitivity (ε_r), shown in the equations below, have been shown to vary depending on how the MWNTs are called and what medium they are suspended in. The direct relationship between μ_r , ε_r , and the other system parameters that affect the absorption sample thickness, d, and frequency, f, is shown in the equations below, where Z_{in} is the normalized input impedance. As shown in the equation below, these characteristics vary by frequency. Because of this, it is convenient to set a baseline reflection loss. A common R.L. to use for this bandwidth determination is -10 dB, which corresponds to a loss of over 90% of the incoming wave. This bandwidth of $Z_{in} = 1$. Moreover it was found that Fe filled MWNTs exhibited a maximum reflection loss of -22.73 dB and had a bandwidth of 4.22 GHz for a reflection loss of -10 dB [41].
	$R.L.(dB) = 20log_{10}[(Z_m-1)/(Z_m+1)]$ Where, $Z_m = (\mu_r/\varepsilon_r)^{0.5} tanh[j \ \mu_r^{0.5} \ \varepsilon_r^{0.5}(2fdn/c)]$
Thermal properties	All nanotubes are expected to be very good thermal conductors along the tube, exhibiting a property known as "ballistic conduction", but good insulators laterally to the tube axis. Measurements show that a SWNT has a room-temperature thermal conductivity along its axis of about 3500 W·m ⁻¹ ·K ⁻¹ ;[61] compare this to copper, a metal well known for its good thermal conductivity, which transmits 385 W·m ⁻¹ ·K ⁻¹ . A SWNT has a room-temperature thermal conductivity across its axis (in the radial direction) of about 1.52 W·m ⁻¹ ·K ⁻¹ ,[42] which is about as thermally conductive as soil. The temperature stability of carbon nanotubes is estimated to be up to 2800 °C in vacuum and about 750 °C in air [43].
Defects	Crystallographic defects also affect the tube's electrical properties. A common result is lowered conductivity through the defective region of the tube. A defect in armchair-type tubes (which can conduct electricity) can cause the surrounding region to become semiconducting, and single monoatomic vacancies induce magnetic properties [44]. Crystallographic defects strongly affect the tube's thermal properties too [45].

This attribute combined with their high length-todiameter ratio and low density (one-sixth that of steel) makes CNTs valuable components for mechanically reinforced composite materials. A critical issue here is the attainment of good adhesion between the matrix and the individual tubes, which is required for an effective transfer of the mechanical load onto the nanotubes. To this end, covalent coupling between the matrix and the nanotubes is currently under extensive investigation. An optimal density of covalently bonded groups on the nanotubes would ensure that sufficient linkages to the matrix are provided without impeding too much the mechanical stability of the nanotubes.

A promising approach for the reinforcement of organic polymers comprises of polymer synthesis from covalently attached initiator sites. In this manner, the radical polymerization of methacrylate esters on the nanotubes has been realized (see **Fig.10**) [61]. This flexible "graftingfrom" approach has recently been extended to ring-opening metathesis polymerization reactions, in which SWCNTs were functionalized with ruthenium based catalysts [62].

In this particular work only four major applications of CNT were discussed. Yet, the domain of applications of CNT is much more versatile (see **Table. III**) in many aspects of engineering and applied science.



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VI. CONCLUSIONS

This account has mainly described the possible routes to large-scale synthesis of carbon nanotubes (single and multiwalled), with emphasis on their applications in electrochemical systems and polymer nanocomposites. The unique electronic properties of nanotubes also make them good candidates in the electronics industry for replacing silicon-based technologies with those based on nanocarbons. At present, researchers are working on the following areas in order to apply carbon nanotubes in emerging technologies.

- i. Production of defect-free and high-purity carbon nanotubes.
- ii. Establishment of useful techniques for quantifying the number of defects (their types, where they are, etc.) in the nanotube structure.
- iii. Development of effective purification techniques (below the parts per million level) for the metal particles within carbon nanotubes, especially for biological and electronic applications.
- iv. Achievement of homogeneous CNT dispersion in polymer composites.



Fig.8. Bio-electrochemical sensing with carbon nanotubes: Schematic showing the operation mechanism of a SWCNT-based amperometric glucose sensor. The presence of glucose is sensed by SWCNTs modified with glucose oxidase [60]



Fig.9. SWCNT with a covalently bonded vanadyl complex for applications in catalysis



Fig.10. Polymerization of a methacrylate ester from an initiator site that is covalently attached to the nanotube sidewall

The possible applications of carbon nanotubes range from electronics to field emission displays, energy-storage devices and functional fillers in composites. These have attracted both industrial and academic interest. Therefore, it is important that some of the basic knowledge is transferred to industry very shortly so that real and novel technologies appear commercially.

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Table.III. Some novel applications of modified CNTs in 21st century

Potential Application	Function of the covalently bonded structure
→Nanostructured electronic devices,	\rightarrow Local modification of the electronic band structure
\rightarrow (Bio-) chemical sensors	\rightarrow Selective recognition of analyte molecules
→Catalyst supports	\rightarrow Anchoring of molecules or metal nanoparticles
→Mechanically reinforced composites	\rightarrow Chemical coupling with a matrix
\rightarrow Chemically sensitive tips for scanning	\rightarrow Selective chemical interaction with surfaces
probe Microscopy	
→Field emission	\rightarrow Reduction of the work function for electrons at the tube ends
→Nanofiltration	→Control of the passage of molecules or ions through steric effects or Coulombic interactions
\rightarrow Artificial muscles	\rightarrow Mechanical stabilization of nanotube films through
→Controlled drug release	→Covalent cross-linking
→Pharmacology	→Biocompatibility; recognition of biological fingerprints
\rightarrow Directed cell growth on surfaces	→Enzyme inhibition or blocking of ionic channels in the cell membrane and specific interactions with cell surfaces

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