Carbon Nanotubes.... A Better Interconnection!

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Abstract

Nanotechnology is a growing field. There has been lot of development & research going on in this field. Discovery of carbon nanotube in 1991 has brought remarkable changes in the field of electronics. Their remarkable electronic properties has led to the usage of carbon nanotubes (CNTs) as interconnection in complex wiring schemes. This article deals with the basic structure of carbon nanotubes, their various properties & the strategies followed during their synthesis for their proper positioning as interconnect at nanoscale regime.

Keywords: Carbon nanotubes, Electromigration, Directed, Non-directed strategies, Inter nanotube contacts & Junctions.

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1. Introduction

Nanoscience encompasses all scientific phenomena that transpire in dimensions spanning the range atom clusters, molecular aggregates, super molecular structures, polymers & biomolecules. Nanoscience is a science of nanoscale. Nanotechnology, the technological use of these properties & phenomena has the potential to revolutionize the breathtaking Range of fields across practically all domains of human activity. After discovery of soccer ball structure of C-60,76,77 representing a new form of elemental carbon further varieties of unusual forms of carbon have been elucidated, of these a particularly fascinating & potentially useful form is "nanotube". Carbon nanotubes, long, thin cylinders of carbon, were discovered in 1991 by S. Iijima. Nanotube structures are made of graphite like carbon (mainly C6 ring fusions) possessing enough C5 – ring fusions to allow curvature into cylinders. These cylinders or tubes can be single walled (SWNT) or multi walled nanotubes & can be closed at one end or both ends. They are really nanofibers.

2. Structure of carbon nanotubes:

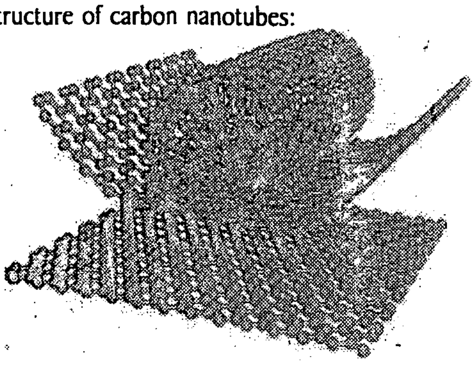

Figure 1: Schematic diagram of individual carbon layer in the honey comb graphite lattice called Graphene layer

Graphite consists of 3D stacking ordering of large graphite layers (where an individual carbon layer in the honeycomb graphite lattice is called graphene layer) of planar hexagonal networks of carbon atoms based on sp^2 bonding. Carbon nanotubes are seamless cylindrical forms of such graphene layers of nanometer size diameter, consisting of single or concentric multilayer.

The diameter of central hollow core is basically fullerene size (around 1 nm) & minimum size diameter that has been observed 0.34 nm. The basic shape of CNT wall is a cylinder which can be identified by indices (n,m). The rolling of single graphene layer which is honeycomb network of carbon atoms to form CNT is well reviewed in papers & books. CNT can either be metallic or semi conducting. There remarkable electrical properties follow from electrical structure of 2D graphite under constraints of quantum confinement in the circumferential direction.

2.1 Single and multiwall carbon nanotubes

CNTs can be visualized as rolled sheets of graphene that are sometimes capped (by fullerene like hemisphere) on each end. They can be single walled with diameter as small about 0.4 nm or multi walled (2 to 30 concentric tubes positioned within one another) with outer diameter ranging from 5 nm to 100 nm. The typical structures of SWNTs have been confirmed by Scanning Tunneling Microscopy (STM) & electrical diffraction studies.

If the C60 molecule is bisected normally to fivefold axis the cap of an "armchair" nanotube is formed, if C60 molecule is bisected normal to threefold axis, the cap for "zigzag" nanotube is formed. In addition to armchair & zigzag nanotubes large number of chiral CNTs can be formed with a screw axis along axis of nanotube.

The constituent shells of MWNTs can possess many different helical structures & variation in the radii & helical structures have been predicted to affect the nanotube's electronic transport which can vary from metallic to semiconducting as shown in fig 3 the band gap estimated by an empirical high binding method as a function of nanotube radius suggests that a nanotube diameter can get larger thus decreasing pronounced curvature of graphene layer , the value of band gap corresponds to that of graphene sheet.

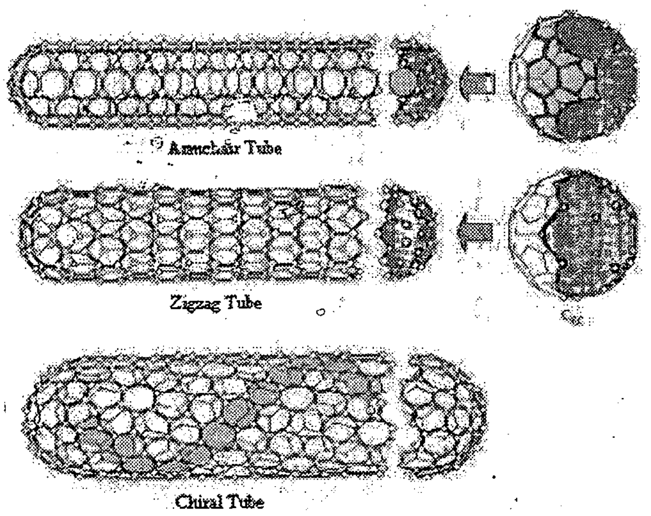

Figure 2: Models of SWNTs

3. Why CNT as an Interconnection?

Copper was used 5 years ago as an interconnection. It was found that Cu interconnects suffer from an effect of electromigration (It's a phenomenon in which transport of material occurs by gradual movement of ions in a conductor due to momentum transfer between conducting electrons & diffusing metal atoms). As current density increases this effect is more prominent. This is not a favorable effect for integrated circuits. CNTs don't show this effect even if current densities are as high as $10^{6} - 10^{7}$ A/cm^2.

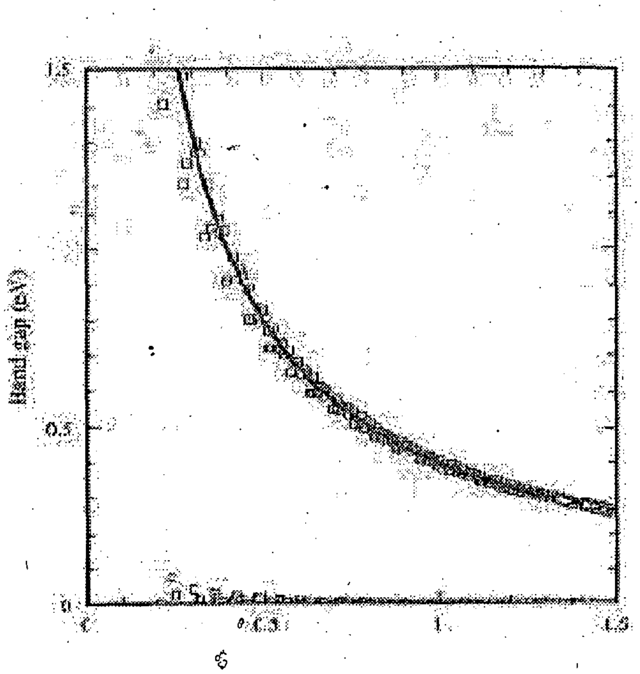

Figure 3: Band gap as a function of nanotube radius

4. Properties of Carbon Nanotubes

With graphene tubes parallel to the filament axis, nanotubes would inherit several important properties of 'intra-plane' graphite. This imparts a very unique combination of properties on this material, namely:

1. High aspect ratio structures with diameters in nanometers, lengths in microns,High mechanical strength (tensile strength 60GPa) and modulus (Young's modulus 1TPa),
2. High electrical conductivity (10^{-6} ohm m typically), and for well crystallized nanotubes ballistic transport is observed,
3. High thermal conductivity (1750-58 00 W/mK),
4. Being covalently bonded, as electrical conductors they do not suffer from electron migration or atomic diffusion and thus can carry high current densities (10^{7} -10^{9} A/cm^2),
5. Single wall nanotubes can be metallic or semi-conducting,
6. Chemically inert, not attacked by strong acids or alkali,
7. *Collectively, nanotubes can exhibit extremely high surface area.*

5. Carbon Nanotubes Interconnects

Various strategies followed during synthesis of nanotubes for interconnect technologies are discussed below:

CNTs could provide critical performance enhancements in a gigascale device & interconnect architectures. The challenge in implementation of CNTs into interconnect technologies is the ability to position the nanotubes controllably & reproducing at prespecified locations with nanometer scale precision.

Non directed strategies & directed strategies share common challenges including tailoring the electrical properties (metallic vs semiconductor) of the nanotubes establishing reliable ohmic contacts between nanotubes & metallic leads & forming tightly controlled internanotube connections in complex wiring architectures.

5.1 Non directed synthesis

Non directed synthesis requires post growth positioning a method that is time consuming, highly inefficient, not amenable to scale up procedures for manufacturing & inconsistent with prevailing Silicon fabrication protocols. Directed synthesis of tubes at predetermined loacations basically through direct patterning of a solid catalyst on the substrate offers significantly a better option. Directed synthesis is highly surface sensitive, nanotube orientation is determined at least in part by substrate controlled growth. The various approaches for synthesizing tubes in large quantities are arc discharge, laser ablation & Chemical Vapour Deposition (CVD). These approaches require a two step fabrication process wherein the nanotubes are grown first then individually transported to the substrate & manipulated into the desired location. The synthesis produced impurities as well as any carbon over-coated on the grown tubes can be removed by oxidation purification either in an oxygen environment at elevated temperatures or by refluxing nanotubes in HNO_3 solution to oxidize amorphous C & metal catalyst particles. The grown tubes generally stack into a hexagonal lattice with parallel alignment of individual tube axes. The bundled tubes are referred as "rope" resembling along pile.

Certain ropes can self assemble into periodic cross bar structures.

Once purified tube bundles are separated in a surfactant such as sodium dodecyl sulfate, often through sonication.

The surfactant overcomes the Van Der Waals attraction between the tubes allowing dispersion on surface. After separation individual tubes are dispersed on a substrate & then manipulated into place to form the desired circuit elements.

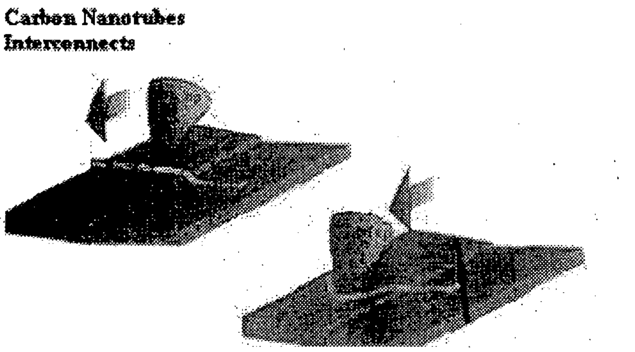

Figure 4: Schematic diagram depicting the manipulation of single CNT by the tip of atomic force microscope

5.2 Directed Synthesis

It could result in the controlled & selective growth of CNTs in a one step process on predetermined locations on a substrate. Three principle methods have been employed in this.

1. Template directed synthesis.
2. Solid catalyst controlled synthesis in which tube growth occurs exclusively in catalyst rich locations.
3. Pattern substrate driven synthesis in case of a gaseous catalyst in which selective growth occurs only on specific surfaces e.g. on SiO_2 but not as Si or native oxide.

5.2.1 Template Directed Synthesis

It uses pre existing nano pores to constrain the growth of NT. The template material is anodized to form nanopores. Individual pore diameter & length are controlled by anodisation processing parameters such as applied voltage, duration & chemistry of solution to which Al_2O_3 is exposed. Tube thickness is controlled by the concentration of reaction gases.

5.2.2 Catalyst Controlled Synthesis

The directed growth of nanotubes can be controlled through the predeposition patterning of catalyst particles. A subsequent chemical mechanical polishing step is used to remove the surface of the SiO_2 to expose tips of the NTs. Electrical contacts could then be patterned to engage individual tubes or rows of tubes depending on the spacing between tubes as determined by spacing within patterned catalyst matrix. Sometimes, if the catalayst is metallic it can act as one of the electrical contacts to the underlying device layers. Ropes of single walled nanotubes (SWNT) self align in a cross bar pattern on the surface.

5.2.3 Pattern Substrate Driven Synthesis

In this case the catalyst is introduced as gaseous precursor such as ferrocene into the CVD reactant mixture. Such growth often leads to encapsulated catalyst material with the core of nanotube. Selective nanotube growth is driven primarily by the identity of substrate surface; eg: in case of patterned surface consisting of SiO_2 substrate growth takes place .No growth occurs on exposed Si surfaces. In another embodiment of this technique vertically aligned nanotube structures were grown under patterned Nickel (Ni) films actually lifting the Ni off the underlying Si substrate. A key advantage of this method is that it not only controls location of nanotube growth but also provides metallic (ohmic) contacts to the nanotube. In short advantages of directed synthesis include controlled growth of nanotube structures selectivity & reproducibility directly over large area substrate in a one step process. Its disadvantages are it lacks flexibilities in formation of complex wiring schemes given that nanotube grew only in one specific location.

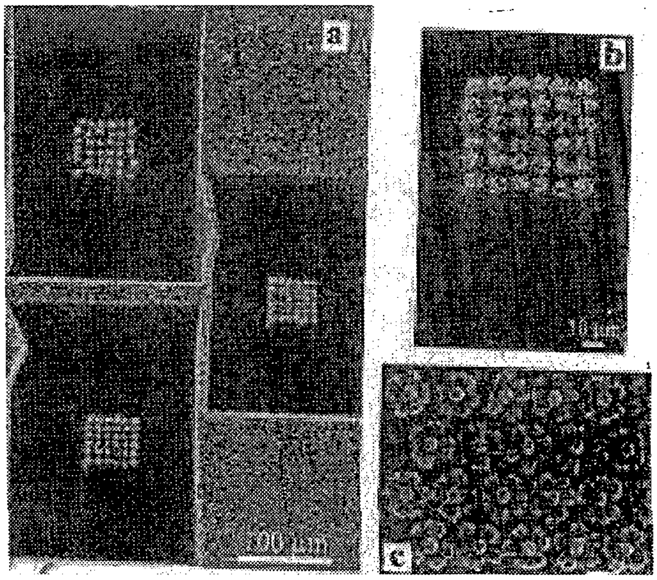

Figure 5: a) Columns consisting of tens of nanotubes grown vertically on patterned SiO_2 substrates. b) Magnified image of one set of columns. c) Repeating patterns of nanotubes demonstrating growth perpendicular to orthogonal silica surfaces. Vertical growth occurs on top of SiO_2.

5.3 Internanotube Contacts Junctions & Connections

Synthesis separation & alignment highlighted opportunities & challenges in the fabrication of CNT interconnects for incorporation in complex metallization schemes. This section presents associated challenges in formation of actual intertube contacts, junctions & connections. Intertube connections can be formed during growth e.g. Y shaped tubes can be made using Y shaped nanopores during template based synthesis. Similarly nanotube grown on metallic catalyst or patterned metal sites are already coupled to a metallic contact & that could be used to input or extract signal from the nanotube.

Tube – tube junctions fall in two categories.

1. **Cross Tube Junction** wherein physical contacts between two tubes forms basis of connection.
2. **On Tube Connections** wherein chemical bonding provides basis of connection with interfacial chemical bonds within individual tubes being rearranged to join the constituent tubes.

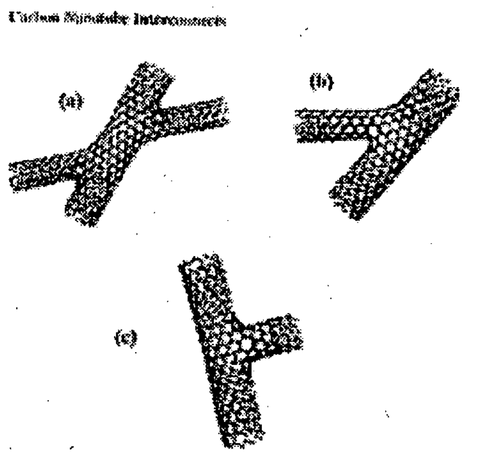

Figure 6: On tube junction a) X-like b) Y-like c) T-like junctions

6. Applications of this Interconnect Technology

1. As candidate materials for future wiring technologies, carbon nanotubes possess extraordinary physical and electrical characteristics. Carbon nanotubes have high current carrying capacity, excellent thermal conductivity, low thermal expansion coefficients, and are less susceptible to electro migration than conventional interconnect materials such as copper, tungsten and aluminum
2. An example of such a technology is the use of carbon nanotubes as interconnects for computer chips.
3. NASA needs high-performance computing in small packages for future autonomous spacecraft. The use of tiny carbon nanotubes to replace copper to interconnect network layers on silicon chips, which are 10,000 times smaller than a human hair. One advantage of using carbon nanotube interconnects within integrated circuits is that these interconnects have the ability to conduct very high currents, more than million amperes of current in a one square centimeter area without any deterioration, which seems to be a problem with today's copper interconnects.
4. Poly(vinylpyrralidone) modified graphite carbon nanofibers or nanotubes as promising supports for Pt, Ru catalyst in direct methanol fuel cells. The direct methanol fuel cells (DMFC) are used in portable electronic devices such as cellphones, personal computer etc. The performance of DMFC is strongly affected by many factors such as sizes, amount & dispersion of catalyst nanoparticles & total surface area of carbon supports. Since Pt or Pt-Ru are costly materials the cost of DMFC is very high. So as to reduce the cost the amount of Pt-Ru nanoparticles should be reduced but it should not affect the performance of fuel cells. It was found that PVP grafted carbon nanomaterials have much less loss in electrical conductivity & thus better electrolytic performance.
5. In electrical engineering, brushes conduct current between stationary wires and moving parts, most commonly in a rotating shaft. Conductive carbon nanotubes have been used for several years in brushes for commercial electric motors. They replace traditional carbon black, which is mostly impure spherical carbon fullerenes. The nanotubes improve electrical and thermal conductivity because they stretch through the plastic matrix of the brush. This permits the carbon filler to be reduced from 30% down to 3.6%, so that more matrix is present in the brush.

7. Conclusion

Carbon nanotubes will be main material in use when it comes to complex wiring schemes at nano level in the future. It can act as a boon to the world of computer and electronics. Articles on carbon nanotubes is well received in various research papers & books. CNTs have the potential to become one of the most useful & prominent nano materials of tomorrow.

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