International Journal of Scientific and Technical Advancements

ISSN: 2454-1532

Role of Carbon Nanotube as a Main Hole Transport Layer In Hybrid Solar Cell: A Review

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Abstract**—**CNT being darkest material in the world capable of absorbing nearly all wavelengths, to efficiently grasp solar light energy permitting its use well in Photovoltaics (PV). This paper deals with the literature review on the CNT-Silicon based hybrid solar cell elaborating its different fabrication methods, properties, applications etc., finally leading to the utilization of CNT as a main hole transport layer in hybrid solar cell.

Keywords**—** CNT; Solar Cell; SWCNT; MWCNT; Photovoltaic (PV).

I. INTRODUCTION

The energy requirements of the world are increasing day-by-day laying pressure on the conventional energy sources which are limited and also cause environmental pollution. The prominent choice is the sun's energy which is clean, abundant, free, everlasting and renewable causing no potential damage to the environment can be converted to electricity by photovoltaic effect. First operational Si-solar cell was determined almost five decades ago and an efficiency of ≈ 24% has been confirmed over the last 20 years [1]. Solar cells consist of thin silicon disks and when number of these cells are connected together either in series/parallel fashion, solar modules are formed. These modules are therefore, used to power satellites and provide electricity for power plants [2]. It has been found that efficiency and output power of Photovoltaic module is inversely proportional to its temp. [3], [4]. In order to avoid drop in electrical efficiency, water and air are to be used as the cooling fluid to cool the PV module [5].

Solar cells can be categorized into three different classes:1) Crystalline solar cell 2) Amorphous solar cell and 3) Thin film solar cell. To enhance the overall conductivity of solar cells, emergence of CNT's came into play. CNT's are reported to be the darkest material in the world being capable of absorbing nearly all of the solar energy with only few reflection suggesting its use as photovoltaic materials to capture solar light energy. Heterojunction solar cell employing CNT's are constructed with inorganic semiconductor such as n-Si and n-Ga As, where CNT's play major roles including charge separation, collector and transport. By adding electrolyte like HNO_3 to the CNT-Si interface, the efficiency of CNT-Si cells was improved to 6-12% [6].

II. CNT STRUCTURE

Carbon nanotubes (CNTs) are allotropes of carbon with a cylindrical nanostructure. Nanotubes have been constructed with length-to-diameter ratio of up to 132,000,000:1, significantly larger than for any other material [7]. Nanotubes are members of the fullerene structural family. Their name is derived from their long, hollow structure with the walls formed by one-atom-thick sheets of carbon, called graphene. At specific and discrete chiral angles these sheets are rolled and the combination of the rolling angle and radius decides the nanotube properties; for example, whether the individual nanotube shell is a metal or semiconductor.

The chemical bonding of nanotubes is composed entirely of sp^2 bonds, similar to those of graphite being stronger than the sp^3 bonds found in alkanes and diamond, provide nanotubes with their unique strength. Nanotubes can be categorized into single-walled nanotubes (SWNTs) and multi-walled nanotubes (MWNTs) [8]. SWNTs properties significantly changes with the (n,m) values. In particular, their band gap can vary from zero to about 2 eV and their electrical conductivity define whether it is metallic or semiconducting [9], [10]. Most single-walled nanotubes (SWNTs) have a diameter lies in the vicinity of 1 nanometre, with a tube length that can be many millions of times longer. The diameter of an ideal nanotube can be calculated from its (n, m) indices [8] as follows.

$$d = \frac{a}{\pi}\sqrt{(n^2+nm+m^2)} = 78.3\sqrt{((n+m)^2-nm)}\text{pm}$$

Where a = 0.246 nm

By wrapping a one-atom-thick layer of graphite called graphene into a seamless cylinder, the structure of a SWCNT can be analysed. The way the graphene sheet is wrapped is represented by a pair of indices (n,m). The integer's n and m denote the number of unit vectors along two directions in the honeycomb crystal lattice of graphene. If m = 0, the nanotubes are called zigzag nanotubes, and if n = m, the nanotubes are called armchair nanotubes. Otherwise, they are called chiral [8]. The electronic structure of armchair, zigzag and chiral SWCNT are shown below.

Multi-walled nanotubes (MWNTs) consist of multiple rolled layers (concentric tubes) of graphene. It has high electrical conductivity, mechanical strength and thermal and chemical stability [11-14].The interlayer distance in multi-walled nanotubes is close to the distance between graphene layers in graphite, approximately 3.4 Å. Double-walled carbon nanotubes (DWNTs) form a special class of nanotubes because their morphology and properties are similar to those of SWNTs but their resistance to chemicals is significantly improved [8].

III. CNT: SYNTHESIS, PROPERTIES AND APPLICATIONS

In this section, various methods of CNT fabrication defining pros and corn of each, its properties and finally applications are explained as follows

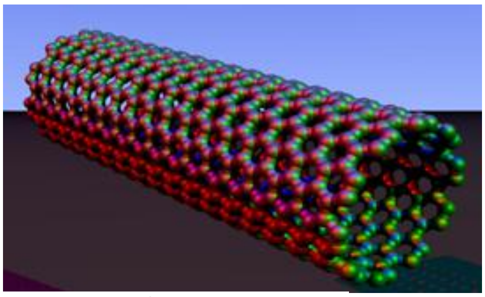

Fig 1. Electronic structure of armchair SWCNT [8].

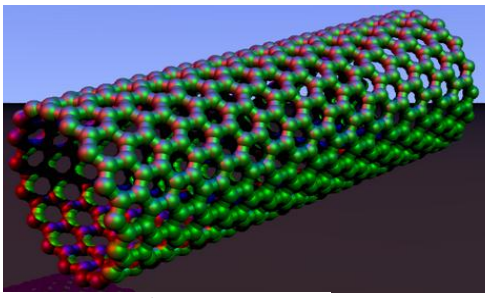

Fig 2. Electronic structure of zigzag SWCNT [8].

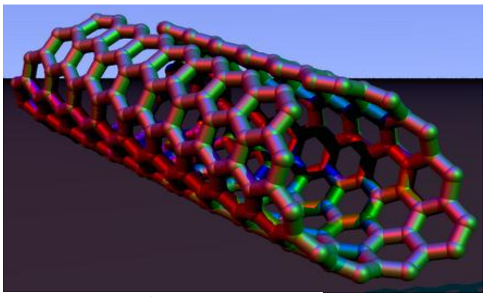

Fig 3. Electronic structure of chiral SWCNT [8].

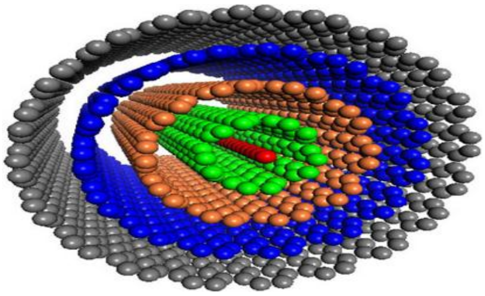

Fig 4. Electronic structure of MWCNT [15].

A. *CNT Synthesis*

Thin film formation of CNTs is necessary step to their fundamental study and use in applications. It is necessary to understand how to control the tube density, the overall spatial layouts, their lengths and their orientations for different fabrication techniques, because these parameters significantly influence the collective electrical, optical and mechanical properties [16]. CNT can be synthesized by different methods.

1) CVD (Chemical vapour deposition) which is a direct method to obtain CNT films on solid substrates. Several other growth methods were developed to synthesize different forms of CNTs in a controlled manner, such as arc discharge [17], pulse laser deposition [18], and catalytic CVD (CCVD) [19]. Further for CCVD, there are several specialized versions, such as hot wire [20], plasma-enhanced [21] and template CCVD [22] which are the most commonly utilized techniques today. Among the methods described now, CCVD techniques shows the great advantage that well-aligned CNT films similar to the prepatterned template can be made when applied on prepatterned substrates or catalyst particles, [23], [24]. Through the development of floating catalyst CVD (FCCVD) technique [25], large area transparent, strong and highly conducting SWCNT films can be synthesized. The next method for obtaining a vertically aligned CNT is a plasma enhanced CVD (PECVD) technique [26], [27].

2) EPD (Electrophoretic deposition) fundamentally is a combination of two processes, electrophoresis and deposition. In the first step, particles suspended in a liquid are forced to move toward an electrode by applying an electric field. In the second step, the particles collect at the electrode and form a coherent deposited film [28-30].

3) CNTs can also be synthesized from the (LB) Langmuir-Blodgett technique where deposition can be performed by layer-by-layer method for more layers either by horizontal lifting or vertical dipping, which allows ready control of the film thickness exhibiting greater feasibility. SWCNTs in these films are found to be highly oriented in a specific rotation. Polarized absorption spectroscopy and atomic force microscope (AFM) observations demonstrate that the tubes are oriented in the direction of the trough barrier in the case of horizontal lifting or in the dipping direction in the case of vertical dipping [16].

4) The next possibility for CNT preparation lies with the SAM (Self-assembling method) which reduces the phase segregation and makes different components highly homogeneous, well dispersed, and interpenetrated by the means of electrostatic and vander-waals interactions [31].

5) Electropolymerization is also another method for CNT preparation provided CNTs were correctly modified by some polymerizable groups such as phenyl amine. The oxidized multiwalled nanotube was functionalized with p-phenylenediamine, which gave functional groups on the surface [16].

6) Last but not the least is Vacuum-filtering method, regarded as the simplest process for the fabrication of ultrathin, transparent, optically homogeneous, electrically conducting films composed of pure CNTs [32]. This process is quite simple, containing three steps: vacuum filtering a dilute, surfactant-based suspension of purified nanotubes onto a

filtration membrane to form a homogeneous film on the membrane, then washing away the surfactant with purified water to allow film formation of pure CNT, followed by dissolving the filtration membrane in solvent [16].

B. CNT Properties

The properties of CNTs can be listed as follows.

1) *Mechanical strength*: A 200-nm-thick film exhibits high tensile strength and good toughness. The tensile strength is 360 MPa, which is 30 and 10 times higher than typical bulky paper and sheets from oleum,[33] respectively; the density-normalized stress is 280 MPa/(g/cm3). The Young's modulus is about 5 GPa. Compared with the theoretical strength of individual SWNTs (37 GPa), the film strength is two orders lower.

2) *Thermal response*: As a transparent conducting coating, thin films of CNTs have outstanding performance as a thermal interface layer for heat dissipation in high-density electronic packaging. Because CNT film is composed of a network of individual CNTs and CNT bundles, the thermal and electrical resistances are dominated by the intertube junctions which depend strongly on chemical modification of the SWNTs and the film-preparation technology [16].

3) *Electrical conductivity*: Although the axial conductivity of an SWNT rope can reach 10000–30000 S/cm, conductivity in films or networks is usually one or two orders lower. For CNT films, sheet resistance is the result of three distinct contributions. The first is from the CNTs themselves. Many inherent factors have an effect on the electronic properties of nanotubes, including diameter, chirality, defect, curvature, and local environment [34]. As a result, their inhomogeneous distribution complicates the conductivity of the films. The second component is the existence of some barriers at intertube junctions [35] Electron transport via the hopping mechanism through the intertube junctions is predominant in the conductivity of CNT films. Finally, the additional resistances introduced during the fabrication process of CNT films also contribute to sheet resistance, such as residual surfactant [16].

C. CNT Applications

In CNT applications include vast area viz: Temperature and humidity sensor, Gas sensor, Biosensor, Energy conversion and storage, Photocatalytic applications, Antimicrobial and antifouling applications, Solar energy storage [36] etc.

IV. CNT AS A MAIN TRANSPORT LAYER

In a paper [37], authors elaborated that due to the unique electrical, optical and optoelectronic properties, Carbon nanotube (CNTs) have promising applications in photovoltaic devices. It is the darkest material in the world being capable of absorbing nearly all of the solar energy with only very low reflection, which suggests that CNTs can be used as photovoltaic materials to capture solar light energy. By adding small amount of CNTs, the performances of organic solar cells were improved significantly. Recently, CNTs were also used to construct heterojunction solar cells with inorganic semiconductor, such as n-Si and n- GaAs, where CNTs play multiple roles, including charge separation, collector and transport. By adding electrolyte to the CNT-Si interface, the efficiency of CNT-Si cells was improved to 6-12%. By doping with corrosive HNO_3 acid, the efficiency of the CNT-Si solar cells was steadily above 10%.

In a paper [38], authors described Carbon nanotube (CNT)/silicon (Si) hybrid solar cells a new class of photovoltaic devices which benefits from the superior opto-electronic properties of CNTs coupled with well-established Si photovoltaic technologies. A transparent CNT film deposited on a Si wafer functions as a charge carrier collecting conductive electrode and establishes a built-in voltage for separating photo carriers. In this regard, single-walled carbon nanotubes (SWNTs) are more suitable than double- (or multi-) walled carbon nanotubes owing to their tunable/direct band gap energies matching with a wide range of the solar spectrum and better charge carrier transport properties. They further stated that maximum PCE of SWNT/Si solar cells reported so far remains below 11%, and their device ideality factors are significantly greater than unity, indicating that carrier transport is limited by recombination. Some alternative approaches have been developed to achieve higher efficiency (>12%) by "wetting" SWNT/Si interfaces, which rely on the in situ infiltration of acid solutions or the control of electronic junctions via an ionic liquid electrolyte.

In a paper [39], authors revealed that Carbon nanotubes (CNTs) have high carrier mobility and can be interconnected into two-dimensional networks with tunable electrical and optical properties. They have demonstrated that coating a CNT film on n-type Si results in Si-CNT heterojunction solar cells with efficiencies upto7%. Compared with p-n junction Si modules and devices incorporating other nanomaterials on Si, their Si-CNT structure holds several advantages and potentially could lead to low-cost and high-efficiency solar cells. First, the CNT film acts as the p-type layer to form heterojunction with n-type Si and enable charge separation, removing the high-temperature diffusion and element doping steps in traditional Si cell fabrication. Second, the two-dimensional conductive CNT network also serves as the transparent electrode for charge collection and transport, therefore metal wiring from the device surface that usually blocks a portion of incident light is no longer necessary. Third, the efficiency of their Si-CNT cells can be further improved by tailoring the composition and thickness of the CNT film to optimize the electronic and optical properties, as well as by chemical functionalization of CNTs.

In another paper [40], authors found that an interesting application for doped SWNTs lies is in hybrid SWNT/silicon (Si) Photovoltaics. Recently a number of efficient p-type carbon nanotubes (CNT)/Si devices have been reported, where the p-type behaviour of the CNTs is obtained by doping with HNO_3, $SOCl_2$, or $HAuCl_4$. The main advantage of these hybrid solar cells is that the intrinsically high photovoltaic efficiency of Si can be realized in a cost-effectively manner owing to the low- temperature solution process ability inherent to the

Deepika Jamwal and Rakesh Vaid, "Role of carbon nanotube as a main hole transport layer in hybrid solar cell: a review", *Journal of Scientific and Technical Advancements*, Volume 1, Issue 3, pp. 135-138, 2015.

fabrication of SWNT/Si junctions. Despite the progress on p-SWNT/n-Si solar cells, there are relatively few examples of n-SWNT/p-Si solar cells due to the difficulty in obtaining highly transparent n-type SWNTs with a suitable doping level.

V. CONCLUSION

At this juncture we can say that no other material rather than CNT offers enhanced efficiency up to 13% by acting as a main hole transport layer in inorganic Silicon based hybrid solar cells. In order to study how it act as a transport layer, we have to get through the basics of CNT synthesis methods, its properties, applications etc. what was done in this paper. At last, various papers concerning CNTs are presented which justify its existence being employed as transport layer in Photovoltaics.

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