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Review Article

Carbon Nano Tubes and Copper Indium Gallium Selenide (CIGS) Based Solar Cell

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Abstract

The exorbitant cost of silicon photovoltaics has led to a growing interest in alternate semiconductor materials for light gathering. Single-walled carbon nanotubes possess unique electrical and optical characteristics, making them a viable material for photovoltaic applications. Exploring ways to utilize these capabilities in photovoltaic devices is crucial. Carbon nanotubes have undergone extensive research in organic photovoltaics and photoelectrochemical cells. However, they may also be combined with a well-known semiconductor, such as Copper Indium Gallium Selenide (CIGS). Nanotube-silicon heterojunction solar cells have shown up to 33 % power conversion efficiency, potentially due to the photoactivity of carbon nanotubes.

Keyword: Nanotubes, Single-Walled, Semiconductor, Photoactivity, Heterojunction.

1. INTRODUCTION

There is currently a lot of interest in finding alternative semiconductor materials and/or alternative methods of fabricating current generation solar cells in order to get around the high production costs of silicon solar cells as well as the toxicity and/or scarcity issues of other solid-state semiconductors. Carbon, in the form of carbon nanotubes, is one material that has a lot of potential in various fields. There is undoubtedly no shortage of carbon, and industrial economies of scale might make this material quite affordable. Carbon nanotubes have potential as photovoltaic components for the reasons described later in this paper. Since Iijima's initial findings on carbon nanotubes [1], as well as those of Iijima and Ichihashi [2], and Bethune *et al.*, [3], about single-walled carbon nanotubes.

Because of its exceptional and frequently unique electrical [3, 4], and optical [5], capabilities, carbon nanotube research has continued to grow tremendously since the early 1990s. An allotrope of carbon, carbon nanotubes are hollow cylinders made of graphene sheets that have been coiled up. Single-walled (SWNTs), double-walled (DWNTs), and multi-walled (MWNTs) carbon nanotubes are the three different types. Apart from its length, a SWNT may be fully defined by an intrinsic geometric characteristic called the chiral vector, or Ch [10].

C h = na 1 + ma 2 is the equation that defines the chiral vector [11], where a1 and a 2 are the graphene lattice basis vectors in real space, and the integers (n, m) represent the number of steps along the zigzag carbon bonds. The chiral vector forms an angle, θ, also referred to as the chiral angle, with the zigzag or a 1 direction, as shown in Figure 1a. [12]. The amount of "twist" in the nanotube is determined by the chiral angle, and there are two limiting examples where the chiral angle is at 0° and 30° [13]. These limiting situations are referred to as armchair (30°) and zig-zag (0°) depending on the shape of the carbon bonds surrounding the nanotube's perimeter [14]. All other conformations in which the C–C bonds are positioned at angles ranging from 0 ° to less than 30 ° are classified as chiral [15].

The numbers n and m define nanotube chirality and consequently the electrical band structure. Chirality significantly affects the optical, mechanical, and electrical characteristics of carbon nanotubes [16]. Changing the chiral angle allows for switching between

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metallic, low band gap, and high band gap semiconducting carbon nanotubes [6-8]. Nanotubes are metallic when $n - m = 3p$ (p is an integer), and semiconducting when $n - m \neq 3p$ [17]. The band gap energy, E_g, is determined by the nanotube diameter, d_t, the C-C nearest neighbor potential overlap integral, $V_{pp\pi}$, and the C-C bond distance, Acc.

$$Eg = \frac{2V_{pp\pi}A_{cc}}{d_t} \qquad (1)$$

Armchair carbon nanotubes are the solely intrinsically metallic type with no bandgap. However, one-third of all zigzag nanotubes are also considered ' metallic' at room temperature due to a smaller energy gap than thermal energy ($k_B T$), which allows carriers to be excited into the conduction band. The term "metallic" might be confusing if used interchangeably with "bulk metals." Metallic nanotubes have a different color than nanoparticulate metals due to their excitonic characteristics [18].

All chiral nanotubes and two-thirds of zigzag nanotubes have semiconductor band gaps, as specified by Equation 1. About 60% of nanotube chirality's are semiconducting, whereas the remaining 40% are metallic [19]. Carbon nanotubes show quasi-one-dimensional characteristics, resulting in van Hove singularities in the electrical density of states (DOS) (Figure 1b, c). The energy gap between valance and conduction bands in bulk semiconducting materials determines the absorption onset wavelength of optical spectra. If nanotubes are viewed as single particles, their discrete electronic transitions in the DOS should result in characteristic peaks in the UV-Vis-NIR absorption spectra of SWNTs at wavelengths that correspond to their transition energies. Nanotubes' optical absorption spectra are totally excitonic, requiring careful consideration of many-body processes to accurately describe their optical features [20]. The light energy required for a "v_i -c_i " transition is (E_{ci} - E_{vi}) + binding energy (eh) - self energy (ee). Experiments show that E_{22}/E_{11} tends to 1.8 with decreasing tube diameter, rather than the expected value of 2 based on density functional theory calculations [21].

According to fundamental photovoltaic physics, optimal efficiency requires matching the semiconductor's optical band gap to the sun spectrum [22]. Approximately 12-15 distinct semiconducting nanotube chirality with fundamental optical gaps ranging from 1.0-1.2 eV can achieve an optimum band gap of ~ 1.1 eV [15]. Calculations for the optimum band gap criterion are applicable to bulk semiconductors with a smooth continuum of states above and below the gap, but not for SWNTs with discontinuous DOS characteristics [23].

Semiconducting nanotubes, like undoped silicon, contain a Fermi level in the center of their band gap and are considered 'intrinsic'. When exposed to air, they exhibit p-type characteristics due to the electron-withdrawing properties of adsorbed oxygen molecules. Adsorbed oxygen is difficult to remove even at ultra-high vacuum, potentially skewing previous study results [25].

SWNTs can be chemically doped with p-type electron-withdrawing species (e.g., strong oxidizers or oxidizing acids) or n-type electron-donating species (e.g., alkali metals, hydrazine, nitrogen-rich polymers, and aromatic compounds) [17–20]. Substitutional doping has been shown for boron (p-type) and nitrogen (n-type) [21-23]. The potential for all-nanotube photovoltaics using p-n or p-i-n heterojunctions is enticing. However, such designs have not yet been documented for devices other than single tubes [26].

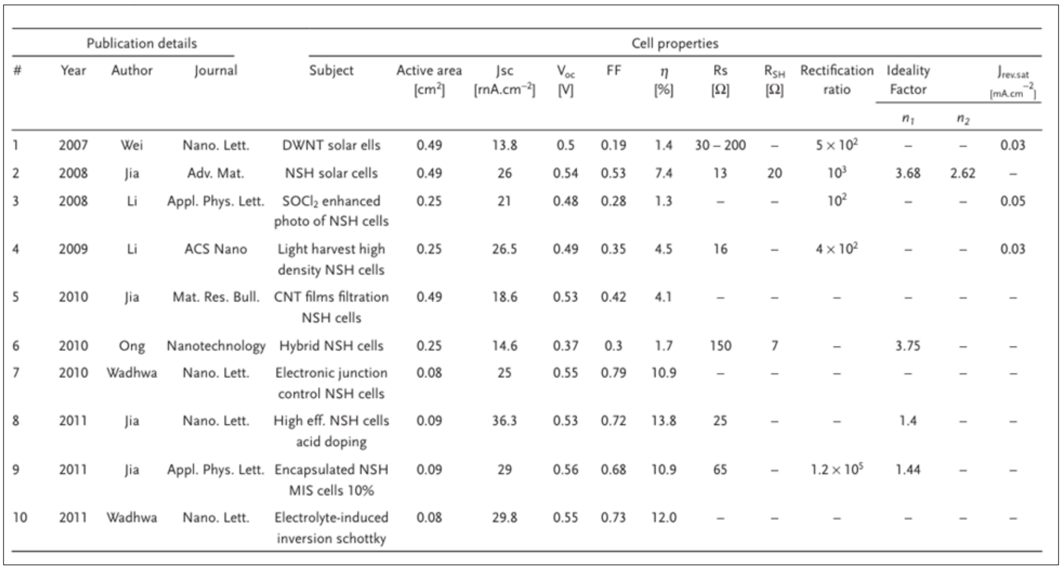
At first, SWNTs were held in high esteem as the prototypical nanostructure. Unfortunately, the poly chirality of both as-produced and purified SWNTs has hindered their effective incorporation into better and newer devices. The chirality of the nanotubes has a significant impact on the electrical, optical, and physical characteristics of single-walled carbon nanotubes (SWNTs) [24]. Despite several reports of SWNT sorting and characterization in the literature, these samples are often too tiny to be used for device development [27-30]. Due to the dominance of edge effects, the performance of thin film and other solar cell devices does not scale up well from very small research cells. Therefore, in order to fabricate devices large enough to provide meaningful, scalable performance data, significant quantities of sorted nanotubes are required [26]. Until recently, it was not possible to sort nanotubes into populations with individual chirality in such large quantities [31].

These days, you may sort nanotubes using a variety of techniques, including Di electrophoresis, density-gradient ultracentrifugation (DGU), selective polymer wrapping, and liquid-phase chromatography, among others [32]. The intended use case and the consequent requirement to sort tubes according to metallicity, diameter, and/or chiral angle dictate the approach to be used. It would be great to employ quantities of single-chirality semiconducting nanotubes for solar cells since their electrical and optical characteristics are homogeneous [33]. Methods such as selective polymer wrapping, differential gradient chromatography (DGC), and liquid-phase chromatography can separate small-diameter nanotubes (< 1.1 nm) into fractions according on their spirality. But the yield in getting a specific (n, m) proportion might be rather low depending on the raw material's diameter and chirality dispersion [34]. Extracting (n, m)-tubes from a raw material with an extremely narrow diameter distribution must thus be the plan of action [35].

Shockley and Queisser determined a basic upper bound on the photovoltaic conversion efficiency (PCE) of a single junction solar cell by employing rigorous balancing calculations [36]. Since then, calculations have been refined, resulting in a limit of around 33%; nevertheless, this assumes that one photon produces one exciton. It has been demonstrated that one photon may generate multiple exciton generations (MEG) in SWNTs [37]. This procedure generates n excitons by absorbing a photon with an energy equal to n times the band gap. It has not yet been possible to realize a fully functional solar cell device that takes use of this characteristic and allows for the breach of the Shockley Quiesser limit.

There have been several reports of studies that have used carbon nanotubes in solar cell devices recently. Many organic photovoltaics (OPVs) now include nanotubes as one example [38]. Though carbon nanotubes do have a role in exciton formation in these systems when light is absorbed, their primary function is to improve electron transport or exciton dissociation in polymeric systems. Incorporating carbon nanotubes into photoelectrochemical cells (PECs) has also been the subject of extensive research in recent years. This research has focused on PECs that use carbon nanotubes alone [31] or in donor-acceptor hybrids with fullerenes/P3HT, fullerenes/porphyrin, porphyrins, pyrenes, polythiophenes, phthalocyanines, PAMAM dendrons, quantum dots, and many more [40, 41]. There is a wealth of foundational research on photoinduced charge transfer processes including carbon nanotubes and other species. It should be mentioned that the boundary between organic photovoltaics (OPVs) and photo electrochemistry (PECs) is not clearly defined, as photo electrochemistry is also used to characterize novel OPV systems. Carbon nanotubes have also been used in dye-sensitized solar cells (DSCs) to improve the electrical characteristics of titania, substitute the titania scaffold, or even replace the platinum catalyst counter electrode [42, 13]. Sections 31c and 44 if you would want to learn more about how these light harvesting systems and structures utilize nanotubes, we recommend reading the evaluations written by Shakil *et al*., [39].

Table 1: Literature review of the CNT based solar cells



Publication details				Cell properties												
#	Year	Author	Journal	Subject	Active area [cm^2]	Jsc [$rnA.cm^{-2}$]	V_{oc} [V]	FF	η [%]	Rs [Ω]	R_{SH} [Ω]	Rectification ratio	Ideality Factor		$J_{rev.sat}$ [$mA.cm^{-2}$]
													n_1	n_2	
1	2007	Wei	Nano. Lett.	DWNT solar ells	0.49	13.8	0.5	0.19	1.4	30 – 200	–	5×10^2	–	–	0.03
2	2008	Jia	Adv. Mat.	NSH solar cells	0.49	26	0.54	0.53	7.4	13	20	10^3	3.68	2.62	–
3	2008	Li	Appl. Phys. Lett.	$SOCl_2$ enhanced photo of NSH cells	0.25	21	0.48	0.28	1.3	–	–	10^2	–	–	0.05
4	2009	Li	ACS Nano	Light harvest high density NSH cells	0.25	26.5	0.49	0.35	4.5	16	–	4×10^2	–	–	0.03
5	2010	Jia	Mat. Res. Bull.	CNT films filtration NSH cells	0.49	18.6	0.53	0.42	4.1	–	–	–	–	–	–
6	2010	Ong	Nanotechnology	Hybrid NSH cells	0.25	14.6	0.37	0.3	1.7	150	7	–	3.75	–	–
7	2010	Wadhwa	Nano. Lett.	Electronic junction control NSH cells	0.08	25	0.55	0.79	10.9	–	–	–	–	–	–
8	2011	Jia	Nano. Lett.	High eff. NSH cells acid doping	0.09	36.3	0.53	0.72	13.8	25	–	–	1.4	–	–
9	2011	Jia	Appl. Phys. Lett.	Encapsulated NSH MIS cells 10%	0.09	29	0.56	0.68	10.9	65	–	1.2×10^5	1.44	–	–
10	2011	Wadhwa	Nano. Lett.	Electrolyte-induced inversion schottky	0.08	29.8	0.55	0.73	12.0	–	–	–	–	–	–

In order for carbon nanotubes to be a viable alternative to silicon in solar cells, it is imperative to comprehend the mechanisms of photogeneration, transport, and dissociation of excitons and charge carriers in large ensembles. Combining them with a well-understood, model semiconductor material, such as silicon, is one of the numerous routes to achieving this objective. Carbon nanotubes are purportedly utilized in the generation of photocurrent by nanotube-silicon heterojunction (NSH) solar cells, a recent photovoltaic method. The architecture of a typical device is comparable to that of a single junction crystalline silicon solar cell, with the exception of the emitter layer being replaced by a thin film of single, double, or multi-walled carbon nanotubes (SWNTs, DWNTs, or MWNTs). However, the precise mechanism of operation of these cells is not well established. The operation mechanisms that have been mentioned in the literature can be categorized into two groups: 1) the mechanism is that of a p-n heterojunction solar cell (Figure 2 a and Figure 2 c), with the nanotubes serving as the p-type emitter material. Photons are primarily absorbed in the n-type silicon base region, and the resulting excitons diffuse to the space-charge region. There, they are separated into free charge carriers by the built-in potential caused by Fermi level equilibration at the junction. In the p-type nanotube region, photons can also be absorbed; however, this is due to the fact that the nanotube films typically have a transmittance of 85 and above comparison can be seen in table 1.

The process resembles that of a Schottky junction solar cell or the closely associated metal insulator semiconductor (MIS) solar cell. A Schottky junction is a device utilized as a solar cell, formed by the amalgamation of a semiconductor and a metal. Fifty-two in this design, the nanotubes function as the metal, the insulator (for MIS) is a thin SiOx passivation layer on the silicon surface, and the semiconductor base area is n-type silicon. Excitons are produced in the base area by photon absorption, then diffusing to an inversion layer next to the Si/SiOx or Si/metal junction in the silicon. The intrinsic potential between the metal or SiOx (which has a Fermi level aligned with that of the neighboring metal) and the silicon segregates charges. Tunneling is the process by which minority carriers traverse the thin insulating oxide layer of the MIS solar cell following charge separation.

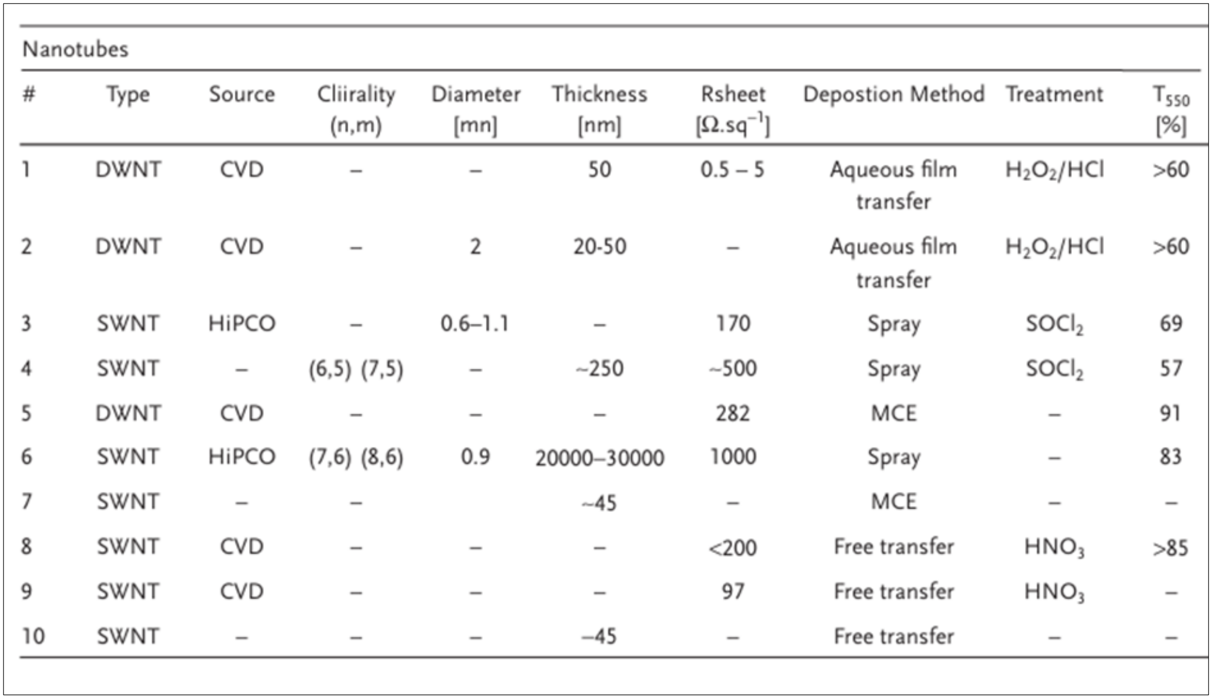
In contrast to a bulk silicon p-n homojunction, there exists a vast array of diminutive nanotube-silicon heterojunctions, which are further complicated by a range of nanotube chirality's. Currently, the majority of NSH solar cells utilize inhomogeneous mixes of metallic and semiconducting nanotubes, allowing for a potential combination of operational processes [14-16]. One could be inclined to assume that a device composed only of semiconducting nanotubes would function as a p-n junction sun cell, whereas a device made exclusively of metallic nanotubes would operate as either a Schottky or MIS solar cell, contingent upon the existence of an intermediate insulating layer.

2. Nanotube- Copper Indium Gallium Selenide (CIGS) Heterojunction Photovoltaic Cells

While not comprehensive, the work outlined below encompasses significant and fascinating discoveries in the discipline, summarized in Tables 1, 2, and 3. The documentation of NSH solar cells started in 2007 with Wei *et al*., [32], who exhibited a device with high efficiency [34]. designed a process in which MWNTs were formed on n-silicon substrates using H2O expansion and subsequent aqueous film transfer of an as-grown chemical vapor deposition (CVD) film, as seen in Figure 3a [37]. Further illustrated the significance of proper electrical contact to the base of the n-Si substrate, a clear component contributing to series resistance. The deposition of a Ti/Pd/Ag layer, which exhibits strong adhesion and establishes effective ohmic contacts with silicon, resulted in a tenfold increase in the observed short circuit current density (J SC) compared to the application of silver paint as a contact. Nonetheless, the total PCE was diminished due to an inadequate fill factor (FF) of 0.19, as seen in Figure 3b. Benham *et al*., [8, 9], investigated the intrinsic characteristics of nanotube-silicon junctions, demonstrating that tunneling is the primary charge transport mechanism in untreated nanotube films at ambient temperature, but thermionic emission prevails at temperatures beyond about 240 K.

Jia *et al.,* announced a notable advancement from their 2007 study by establishing a 7.4% efficient DWNT/n-Si device [56]. The DWNT film was produced and submitted as in the previous study. The increased efficiency compared to previous work can be ascribed to a reduced series resistance. This was achieved partially by substituting the comparatively.

Table 2: Different chirality harvesting of CNTs



Nanotubes

#	Type	Source	Cliirality (n,m)	Diameter [mn]	Thickness [nm]	Rsheet [Ω.sq^{-1}]	Depostion Method	Treatment	T_{550} [%]
1	DWNT	CVD	–	–	50	0.5 – 5	Aqueous film transfer	H_2O_2/HCl	>60
2	DWNT	CVD	–	2	20-50	–	Aqueous film transfer	H_2O_2/HCl	>60
3	SWNT	HiPCO	–	0.6–1.1	–	170	Spray	$SOCl_2$	69
4	SWNT	–	(6,5) (7,5)	–	~250	~500	Spray	$SOCl_2$	57
5	DWNT	CVD	–	–	–	282	MCE	–	91
6	SWNT	HiPCO	(7,6) (8,6)	0.9	20000–30000	1000	Spray	–	83
7	SWNT	–	–		~45	–	MCE	–	–
8	SWNT	CVD	–	–	–	<200	Free transfer	HNO_3	>85
9	SWNT	CVD	–	–	–	97	Free transfer	HNO_3	–
10	SWNT	–	–	–	–45	–	Free transfer	–	–

Thick isinglass (mica) front window with a thin SiOx window fabricated by photolithography. Decreasing the thickness of the front window diminishes the bending and stretching of the nanotube film. Different results can be seen in Table 2 the interval that lies between the front window and the silicon active region. The reduced series resistance resulted in an enhancement in J SC from 13.8 to 26 mA cm − 2 and an improvement in FF from 0.29 to 0.53 relative to previous research. Subsequently, other groups have employed various techniques to create thin films of carbon nanotubes on n-type silicon. Li *et al*., developed an NSH solar cell with a SWNT film applied via an airbrushing process from a dimethylformamide (DMF) solution. The final devices demonstrated an efficiency of 1.3%. Li *et al*., examined post-treatment techniques for carbon nanotube films to enhance device efficiency. Hall Effect tests indicated that the treatment of SWNT films with SOCl2 results in an increase in carrier density and effective mobility from 3.1 × 10^15 to 4.6 × 10^17 cm^−2 and from 0.23 to 1.02 cm^2 V^−1 s^−1, respectively. According to the author network transitioned from variable range hopping to tunneling following the SOCl2 therapy. The treatment of SWNT films with SOCl2 results in a modest elevation of the open-circuit voltage and a substantial augmentation of the short-circuit current by readjusting the Fermi level and improving carrier density mobility. Li *et al*., later released a research indicating a threefold increase in efficiency for identically designed SOCl2 posts. Processed apparatus [34], and further characterized the performance of devices created by transplanting an as-grown nanotube 'spider web' onto silicon [39]. SOCl2 has been extensively examined about its impact on SWNTs, demonstrating its efficacy as a p-type dopant that enhances conductivity by elevating the nanotube Fermi level into the valence band. Therefore, SOCl2 treatment diminishes the S11 transition in semiconducting nanotubes, and the implications of this on the operational mechanism of NSH devices remain ambiguous. Some devices may initially operate as p-n junctions prior to post-treatment, but then transition to Schottky junction devices, which exhibit superior performance after the treatment imparts metallic properties to the nanotubes. Thors, "The primary conduction mechanism of the SWNT coating" [14], described a nanotube deposition technique utilizing vacuum filtration over mixed cellulose ester (MCE) membranes, followed by the dissolution of the MCE in acetone for removal.

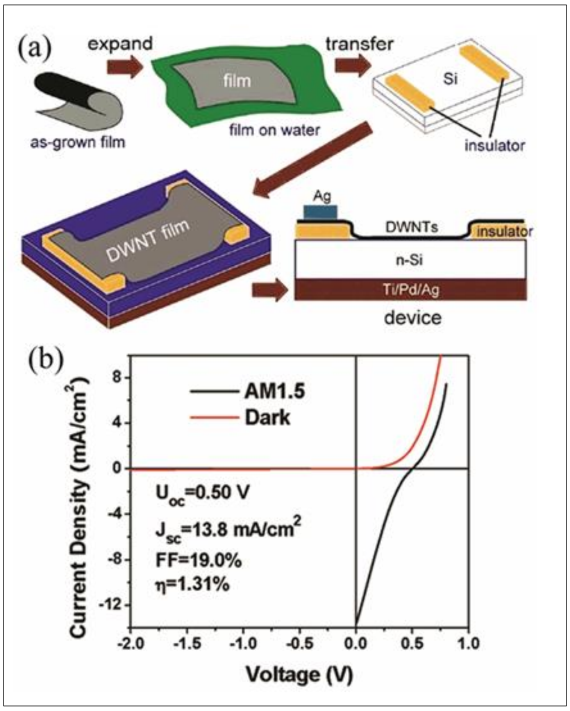


Figure 1: Function of Si based cell [a], Shows the Parameters of solar cells [b]

The MCE deposition technique was employed for SWNTs and MWNTs, whereas aqueous film transfer of a self-assembled film was utilized for DWNTs, in accordance with their previous research [5-17]. Given the sensitivity of the electrical properties of nanotube films to their morphology, this complicates the comparison of the performance of these three films in NSH solar cells, particularly if MCE deposition were also employed for DWNTs. The paper examines the impact of altering the area density of nanotubes on performance. SWNT films exhibit superior performance compared to MWNTs just at low densities, suggesting that optical transmittance is the primary factor in the comparison between SWNTs and MWNTs. The authors link a figure of merit (FM) for transparent conductive films with the power conversion efficiency (PCE) of NSH solar cells. The FM is defined in Equation 2 as follows:

$$FM = \frac{T_{550}(\%)}{R_s\left(\frac{\Omega}{sq}\right)} \tag{2}$$

T 550 denotes the optical transmittance at λ = 550 nm, whereas RS represents the sheet resistance, distinct from the series resistance that bears the same designation. The findings indicate that the figure of merit

(FM) is directly linked to the power conversion efficiency (PCE), wherein enhanced film transparency or reduced sheet resistance results in improved device efficiency. Optical transparency is enhanced in thinner films, whereas sheet resistance diminishes in larger films [5-15]. Consequently, there must be a trade-off between these two factors, with the ideal thickness presumably limited by the optimization of other cellular characteristics. It is noteworthy that $T \sim e - \alpha d$, where α represents the attenuation coefficient and d denotes the film thickness, and $R \sim 1/d$. Consequently, the free energy is evidently governed by the exponential relationship of T to d, and only in the case of extremely thin films does Rs prevail. Despite the extreme thinness of nanotube films, the observed reliance of the power conversion efficiency on the film morphology implies that the function of the nanotubes is primarily that of a transparent conducting film rather than a photoactive material. Castrucci *et al*., [61], examined the influence of nanotube film thickness and similarly determined that the density of the nanotube film (the number of nanotube-silicon connections) is a crucial factor in optimizing performance.

Regarding the subject of how these devices work [15], made a significant contribution by stating that when it comes to their NSH cells, "comparison of the photocurrent with the near infrared (NIR) absorption spectra clearly indicates an excellent matching of the S11 band (corresponding to the fi rest interbond transition for SWNTs with (7,6) and (8,6) chirality) with the photocurrent band located at 1150 nm." So, "the SWNT film works as a light absorber in addition to a charge separator, transporter, and collector in the photoconversion process ". This is a crucial difference between a Schottky cell, in which the metal component cannot absorb photons, and a heterojunction solar cell, which has two active components that can absorb light. A slight shoulder, about 50 nm below the relevant peak in the nanotube absorption spectrum (Figure 2 a), can be seen on the low energy side of the silicon photo response in Figure 2 b. An increase in photon energy results in a rapid decrease in the photocurrent induced by silicon. The authors of the study [17], note a lesser but comparable decrease in the photocurrent spectra's high energy area; yet, when compared to a silicon-only cell, there is a little enhancement in the UV response that corresponds to the nanotubes' π - π∏ transitions. The presence of nanotube filaments in Figure 4b suggests that the nanotube-silicon architecture may not be a Schottky junction, but rather a p-n junction, because it is known that nanotube filaments can generate photocurrents when deposited on semiconductor substrates [16]. More information might be gleaned from a thorough investigation of the capacitance of nanotube-silicon junctions.

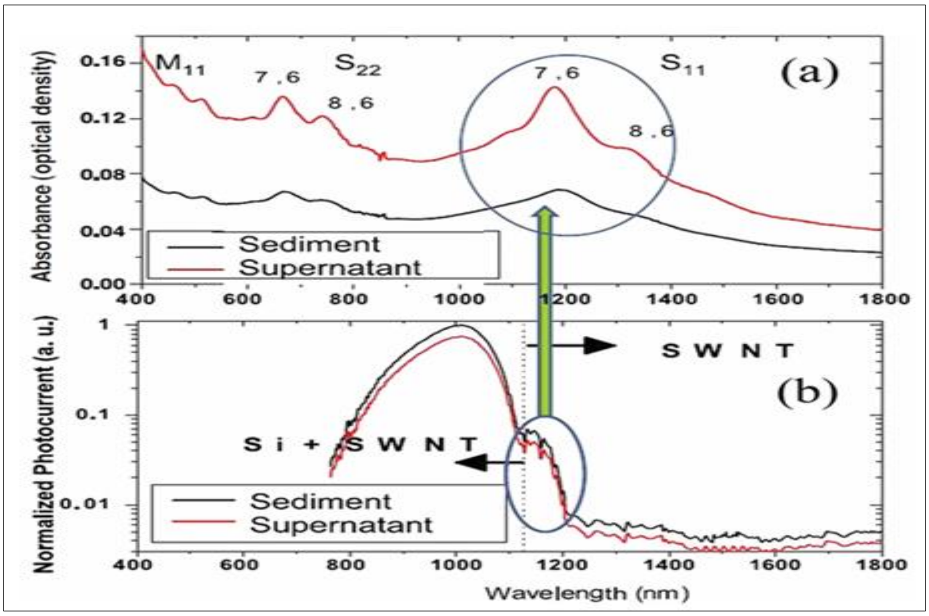


Fig. 2: a) UV NIR spectra of SWNT film. b) Photocurrent spectra showing current peak

A related study by Tsolov *et al.,* described the mid-IR response of a photodiode made of silicon-carbon nanotubes that was grown by CVD on phosphorous-doped n-type silicon using an anodized aluminum oxide (AAO) template technique (Figure 3 a). The assertion is made that the wide photocurrent response, spanning around 1.5-10 μm, is caused by the nanotubes themselves absorbing photons and creating excitons, even though using a template is shown to be an easy way to create aligned nanotube arrays on silicon. But Spitzer and Schroder have shown that free carrier absorption in silicon might be the cause of this photocurrent spectral characteristic [39]. By comparing Figure 5 a and b, we can see that (a) displays three characteristics at about 0.75 eV, 0.9 eV, and 0.95 eV, but (b) does not. These characteristics may have originated in the nanotubes rather than the silicon, as they are located too far from the silicon's absorption band edge (1.12 eV). Unfortunately, there is no evidence that MWNTs like the ones employed have such well-defined absorption properties. In contrast, MWNTs are known for their characteristically wide, featureless absorption spectra, which are the consequence of complicated state mixing caused by interactions between walls that are chirally different. On the low energy side of silicon absorption, a comparable characteristic is discovered, as in Ong's subsequent work, which is equally noteworthy [39]. But neither Tsolov's nor Ong's research shows that the nanotubes are responsible for the devices' photocurrent. An experiment that is comparable to Ong's might perhaps provide an answer to this question.

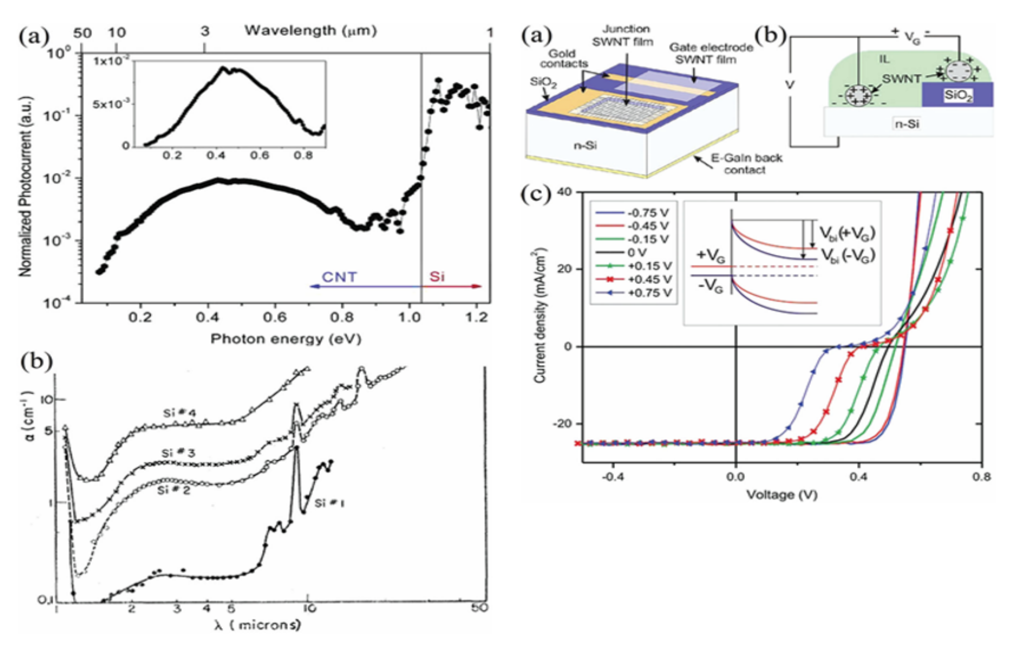


Figure 3: (a) Photons energy (b) Microns energy

In this experiment, cells with bigger diameter nanotubes are used to detect the spectrum response and the energy of the first excitonic transition, which occurs at the absorption onset of silicon (for example, at 1400 nm). It should be easy to resolve any contribution from the nanotubes in this scenario.

3. CONCLUSION

Potentially useful components of future inexpensive solar technologies, carbon nanotubes have several desirable properties. Performance gains of up to approximately 11% for 'dry' cells and cells using electrolyte assisted junction control, and up to about 14% for cells doped in situ with nitric acid, have been rapidly observed in the field of nanotube-silicon heterojunction solar cells, which started with early reports of 1% power conversion efficiency. Results like the figure of merit from Jia *et al.,* point to Schottky/MIS, whereas the photocurrent spectra from Ong *et al.,* could indicate p-n characteristics; nevertheless, the exact mechanism of action is still not obvious. As chirality-sorted material becomes more accessible to the nanotube research community, we expect measurements on devices using purely metallic or semiconducting nanotubes. This is because the poly chirality of the nanotubes used in many of the devices reported thus far complicates the matter. There is evidence that reducing film resistivity and adjusting the nanotube Fermi level after treating nanotube films with powerful oxidizers and oxidizing acids significantly improves device performance. Implementing ionic using liquid electrolytes to regulate electronic junctions has been shown to be a very successful strategy. Making solar cells that use a nanotube-silicon heterojunction work better, even if this probably won't be used in commercial products anytime soon. Adding nanotubes to silicon solar cells that currently have efficiencies over around 24% could be seen as counterproductive. It is important to highlight that this is still a relatively tiny and new area of research, especially when compared to the decades of intense study into silicon solar cells. Consequently, it is desirable to delve more into these devices. There is probably a lot of untapped potential in the field, given how quickly and easily a small group of academics has achieved good efficiencies. The functionality of carbon nanotube films has been amply proven. It is now obvious that carbon nanotube films can increase the performance of silicon solar cells by reducing optical shadowing. This is because they act effectively as transparent, conducting front electrodes. While it is shown that carbon nanotubes paired with silicon nanocrystals or C 60 may harvest light in solid state devices, the question of whether this holds true when combined with planar monocrystalline silicon is still up for debate.

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