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## A Carbon Nanotube (CNT)-based SiGe Thin Film Solar Cell Structure

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(Received 23 Dec. 2020; Revised 10 Jan. 2021; Accepted 17 Feb. 2021; Published 15 Mar. 2021)

**Abstract:** In this paper, a structure of thin film SiGe solar cell based on carbon nanotube (CNT) is proposed. We present the design and simulation of the device using Silvaco TCAD. The modeling of the CNT-based SiGe thin film solar cell structure is performed and then compared with conventional SiGe thin film solar cell structure. Results from numerical simulation show that the CNT- based SiGe thin film solar cell has better parameters such as short circuit current, open circuit voltage, fill factor, maximum power and efficiency in comparison with pervious structures. The simulation results also prove that the efficiency increases by 40.36%.

**Keywords:** Solar Cell, Thin Film, SiGe, Carbon Nanotube (CNT), Efficiency.

### 1. INTRODUCTION

Lack of energy and global warming are considered to be the major challenges in the world right now. The solution to these risks is to replace fossil fuels with renewable energy. Solar cell technology is one of the most interesting types of renewable energy. It is believed that the share of photo electric systems (PESs) in power consumption would increase to 25–30% by 2030 [1]. Among many types of solar cells, Amorphous Silicon-based thin-film solar cell (TFSC) is regarded as one of the best choices that can be produced at a low cost.

In the present study, we show the effect of some good properties of a-SiGe as compared to Si on higher short circuit current. These properties include: higher

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absorption coefficient in higher wavelength and the higher number of free electrons, it then leads on to higher conductivity. SiGe found to be a good alternative because: the energy of the visible part of the spectrum used by the solar cell is less than 50%; a low band gap material ( $E_g < 1.1$  eV) is required for increasing the absorption of sun power; and the ability for modifying band gap and its electrical properties by varying Ge content ( $1.08 < E_g < 0.67$ ). SiGe has a higher mechanical strength and suppresses the high-intensity degradation of the solar cell under illumination [2, 3].

Silicon germanium amorphous alloys are widely used in multipurpose solar cells. This is because their optical band gap shifts to lower energies as germanium concentration increases and with the enhancement of optical absorption for longer wavelength photons.

SiGe and GaAs-SiGe dual junction solar cells are promising candidates to act as the bottom cell in a tandem and multi-junction structures, due to its high mobility, good process compatibility, adjustable lattice constant, and capability of absorbing light of wavelengths up to 1800 nm [4-6].

The SiGe layers were successfully used as end cells in the solar cells until 1982. Improving solar cell efficiency and reducing the thickness of the active layer are both economically and technologically important. In order to prevent a dramatic decrease in short-circuit current ( $J_{SC}$ ) in a low-thickness cell, it is essential to increase material uptake and optimization of cell structure [7].

It is possible to use a material with a smaller band gap, such as SiGe, in the active base region of the cell. This approach is consistent with the determination of its compatibility with the complete Si-based cell process. A noticeable increase in photonic current in SiGe material is expected because the absorption of photons has increased. On the other hand, the reduction in open circuit voltage ( $V_{OC}$ ), due to the decrease in SiGe band gap with increasing concentration, should be considered and prevented in optimizing cell behavior. Consequently, a compromise between cell parameters is necessary in the optimization procedure [8]. Optimizing band offset between SiGe and GaAs on the Valence band or conduction band can help design the back surface field (BSF) more effectively. The recombination rate is greatly reduced due to a potential barrier against carriers. The offset of the  $E_V$  and  $E_C$  bands in the interface depends on the concentration of Ge in the layer. In addition to lower surface recombination velocities, the smaller band gap ( $E_g$ ) at higher concentrations of Ge in the SiGe has a higher light absorption coefficient, which can lead to higher electron-hole pairs and higher  $J_{SC}$ . Both can increase the efficiency of SiGe-based solar cells [9].

## 2. APPLICATION of CNTs IN SOLAR CELL STRUCTURS

In recent years, new development in carbon nanotubes technology has made Nanotechnology more popular and also has encouraged many researchers to focus on this subject. The use of CNTs in solar cell is one of interesting fields. This is because of their especial properties such as semi-transparent conductor, anti reflect coating, self cleaning and as emitter or p-layer in Si- based solar cells [10- 12]. The use of CNTs in many other types of solar cell also reported [13-17]. The reported efficiency for CNT-based solar cell structures listed in Table I.

Using CNT layer as the charge collector and semitransparent layer help us to provide a low resistance path for carrier and could decrease series resistance. This will eventually lead us to reduce the number of front electrodes and shadowing effect. These all together could improve the cell efficiency [16, 18].

**TABLE I**  
Reported efficiency for CNT-based solar cell structures

Structure	Efficiency%	Reference
CNT/Si	14.5-17%	10,11
CNT/n-Si	7.4%	10
CZTS&CNT	11.31%	13
PVP/CZTS&CNT	15.21%	13
CNT/Provskite base	12.9%	14
CNT/DSSC based	1.98%	15
CNT/GaAs	29.18%	16
CNT/InGaP/GaAs	41.95%	17

CNT are promising candidates for a variety of nano-scale electronic and photonic applications. Presence of nanotubes leads to increase of charge carrier's mobility and respectively conductivity for a few orders of magnitude [19].

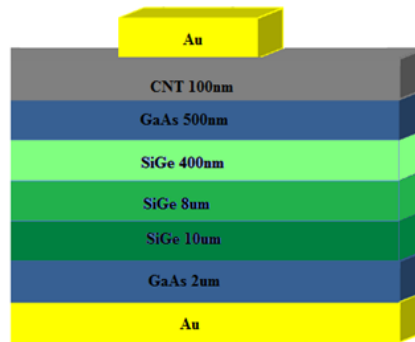
In this study, we design and simulated a CNT-based SiGe thin film solar cell structure using Silvaco TCAD. We investigate different performance parameters of the device such as: short circuit current, open circuit voltage, maximum power, and fill factor and compare to a conventional SiGe solar cell structure.

This paper is structured as follows: In section 2, the CNTs in solar cell application is described, Section 3 describes the CNT-based SiGe thin film solar cell structure. In section 4, we present the employed theoretical model for simulation of the device. Section 5 covers the simulation results obtained for the

characteristics of the proposed CNT-based SiGe solar cell structure. Finally, the conclusion is given in Section 6.

### 3. THE PROPOSED CNT-BASED SiGe THIN FILM SOLAR CELL STRUCTURE

The schematic structure of CNT-based SiGe thin film solar cell is shown in Fig.1. The structure consists of several layers, including GaAs with a thickness of  $2\mu\text{m}$  as the back surface field (BSF), SiGe with a thickness of  $10\mu\text{m}$  as the substrate, SiGe with a thickness of  $8\mu\text{m}$  as the base layer, SiGe with a thickness of  $0.4\mu\text{m}$  as the emitter layer, GaAs with a thickness of  $0.5\mu\text{m}$  as the window layer, and a thin layer of carbon nanotube (CNT) with a thickness of  $100\text{nm}$  as the semi-transparent charge collector. We used the Au ( $0.1\mu\text{m}$ ) as the electrodes of the solar cell. The layer parameters such as thickness and doping are summarized in Table II.



**Fig. 1.** Schematic structure of the proposed solar cell

**TABLE II**  
Layers parameters

Layer	Material	Thickness ( $\mu\text{m}$ )	Doping ( $\text{cm}^{-3}$ )
Electrode	Au	0.1	-
Semi-transparent	CNT	0.1	-
Window	GaAs	0.5	P type- $1\text{e}18$
Emitter	SiGe	0.4	P type- $1\text{e}18$
Base	SiGe	8	N type- $1\text{e}17$
Substrate	SiGe	10	N type- $5\text{e}17$
Substrate (BSF)	GaAs	2	N type- $1\text{e}18$

Carbon nanotubes are tubular structures that are typically of nanometer diameter and many micrometers in length. This fascinating new class of materials was first observed by Endo in 1975, and later by Iijima in 1991 in the soot produced in the arc-discharge synthesis of fullerenes [20].

The CNTs are made by rolling a sheet of graphene and placing hemispheric carbon based caps on both of the tube ends. Based upon the orientation of the rolling of the graphene sheet, CNTs is divided in two types with different properties, semiconducting or metallic properties. The CNTs factors that have been studied recently include; processing techniques and parameters, length of the CNT, doping and metallic amount of the CNT in the mixture, transparency and conductivity.

In addition to its flexibility, CNT films also show high transparency in a large range of solar spectrum as compared to ITO which has excellent transparency in the visible range. Most notably, CNTs were found to have maximum current densities two to three times greater than metals commonly used as conductors.

CNTs can be deposited onto materials in random arrays to create a heterogeneous conducting network which only absorbs and reflects a small portion of the light shined upon it based on the density of tubes in the network. Recently, transparent CNT thin films have been studied and tested in a variety of optoelectronic devices [12]. The use of CNTs in the structure of solar cells has been considered by researchers due to its ability to increase efficiency.

#### 4. THEORETICAL MODELING

The dynamics of the carrier in the solar cell can be described by the one-dimensional equations of drift-diffusion, the current continuity equations, and the Poisson equation. The Poisson equation is shown below:

$$\nabla^2 V = \frac{q}{\epsilon_r \epsilon_0} (n - p - N) \quad (1)$$

Where  $\epsilon_r$  and  $\epsilon_0$  are the relative dielectric constant and the vacuum dielectric constant, respectively.  $V$  is the potential and  $q$  is the initial charge.  $n$  and  $p$  are the electron and hole position dependent density, respectively.

The drift-diffusion equation and the current continuity equation are expressed as follows [21-23]:

$$\begin{aligned} J_n &= -qn\mu_n \nabla V + qD_n \nabla n \\ J_p &= -qp\mu_p \nabla V - qD_p \nabla p \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{1}{q} \nabla \cdot J_n - R_n + G_n &= 0 \\ -\frac{1}{q} \nabla \cdot J_p - R_p + G_p &= 0 \end{aligned} \quad (3)$$

where  $J_n$  and  $J_p$  are the electron and hole current density, respectively.  $\mu_n$  and  $\mu_p$ , are electron and holes mobility and  $D_n$  and  $D_p$  are electron and hole diffusion coefficient, respectively. Also  $G_n$  and  $G_p$  are the electron and hole generation rate because of light illumination.  $R_n$  and  $R_p$  are defined as the recombination rate of electrons and holes, respectively.

Due to the structure of the CNT electronic band, the carrier statistics in CNT can be described as follows [16]:

$$p - n = \text{sign}(E_D - E_F) \frac{1}{\pi \hbar^2 v_F^2} (E_F - E_D)^2 \quad (4)$$

where  $p$  and  $n$  are the hole and the electron density in the CNT layer, respectively.  $E_D$  and  $E_F$  are the Dirac point and the Fermi level of the CNT sheet, respectively. Also  $\hbar$  is the reduced Planck's constant and  $v_F$  is the Fermi velocity in the CNT.

The height of the junction barrier in the CNT/SiGe can be inferred by matching the JV curves (in the dark state) in the Schottcky CNT/SiGe diode:

$$J = J_0 \left( \exp \frac{qV}{N_{IF} KT} - 1 \right) \quad (5)$$

where  $K$  is Boltzmann's constant,  $N_{IF}$  are the ideal factor of the junction, and  $T$  is temperature. Based on the on thermionic-emission theory, the density of saturation current  $J_0$  can be described as follows:

$$J_0 = A^* T^2 \exp \left( -\frac{q \Phi_{\text{barrier}}}{KT} \right) \quad (6)$$

where  $A^*$  is the effective Richardson constant and is equal to  $127A/\text{cm}^2\text{K}^2$  for n-type SiGe [16, 24].

By solving the above equations, the different performance parameters of the solar cell can be determined. The I-V curve of the solar cell is the superposition of the IV curve of the solar cell diode (in the dark mode) with the current generated by light [16].

$$I = I_0 \left[ \exp\left(\frac{qV}{nKT}\right) - 1 \right] - I_L \quad (7)$$

where  $I_L$  is the light output,  $n$  is ideality factor of junction. The equation of curve IV in the first quarter is:

$$I = I_0 \left[ \exp\left(\frac{qV}{nKT}\right) - 1 \right] \quad (8)$$

The open circuit voltage of the solar cell is as follows:

$$V_{OC} = \frac{nKT}{q} \ln\left(\frac{I_L}{I_0} + 1\right) \quad (9)$$

In general the power delivered from a power source can be  $P = IV$ . If we use the current density of  $J$  instead, the power density ( $P_d = JV$ ) is obtained. The maximum power density occurs somewhere between  $V = 0$  (short circuit) and  $V = V_{oc}$  (open circuit) at  $V_m$  voltage. The corresponding current density is called  $J_m$ , so the maximum power density is  $P_m = J_m V_m$ . The efficiency of a solar cell is as follows [16, 25]:

$$P_{max} = V_{OC} I_{SC} FF \quad (10)$$

where  $FF$  is fill factor that used to describe a solar cell performance. The fill factor can be defined as follows:

$$FF = \frac{V_{OC} - \ln(V_{OC} + 0.72)}{V_{OC} + 1} = \frac{I_m V_m}{I_{SC} V_{OC}} \quad (11)$$

Using  $FF$  we can write the efficiency as follow:

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}} = \frac{P_{max} [W] \times 100}{1000 [Wm^{-2}] \times CellArea [m^2]} \quad (12)$$

Where  $V_{OC}$  and  $I_{SC}$  are open circuit voltage and short circuit current respectively and  $P_m$  the input light power density, which is assumed to be  $1000 \text{ Wm}^{-2}$  in our simulation.

## 5. SIMULATION AND RESULTS

The present study aimed to design and simulate the CNT-based SiGe thin film solar cell structure using Silvaco TCAD, and then comparing characteristics of the CNT-based SiGe thin film solar cell structure with conventional SiGe thin film solar cell structure.

The CNT layer that is used in the proposed structure was fabricated by the Institute for Micro Structural Science of Canada with sheet resistance of  $128\Omega/\square$ . In this CNT heterogeneous structure,  $1/3$  of the nanotubes are metallic and  $2/3$  of them are semiconductors. This layer is used as a charge collector in our thin film structure and makes a low resistance pathway for carriers to the top contact. The CNT layer was modeled as completely transparent, low band gap semiconductor material with sheet resistance based on experimental data [18].

Selecting 4H-SiC as a basic material for modeling CNT layer has advantages because this material is supported by software library and just some of the material properties should.

According to the relation given below, the  $\mu_n$  and  $\mu_p$  modified to achieve desired value of  $128\Omega/\square$  sheet resistance.

$$\rho = \frac{1}{q(n\mu_n + p\mu_p)} \quad (13)$$

$$R_S = \frac{\rho}{t} \quad (14)$$

where  $\mu_n$  and  $\mu_p$  are electron and hole mobility and  $q$  is the initial charge,  $n$  and  $p$  are the electron and hole density and  $t$  is the thickness of the material, respectively [16,26]. The other parameters that have been used in model layers in our simulation are presented in Table III.

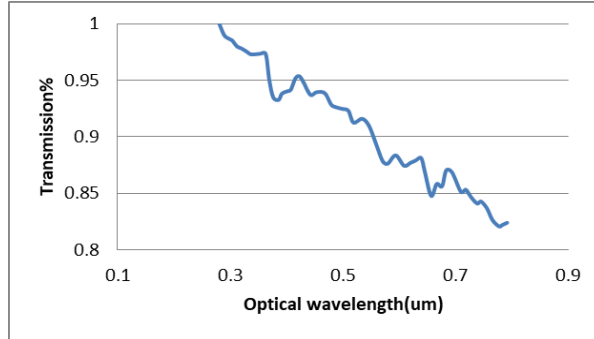
ATLAS simulator has a different physical model for calculating carrier mobility and recombination rate that should be selected by the user. In this work we use conmob, fldmob (concentration and electric field dependent mobility) models and consrh (concentration dependent Shockley-Read-Hall) model for utilizing recombination.



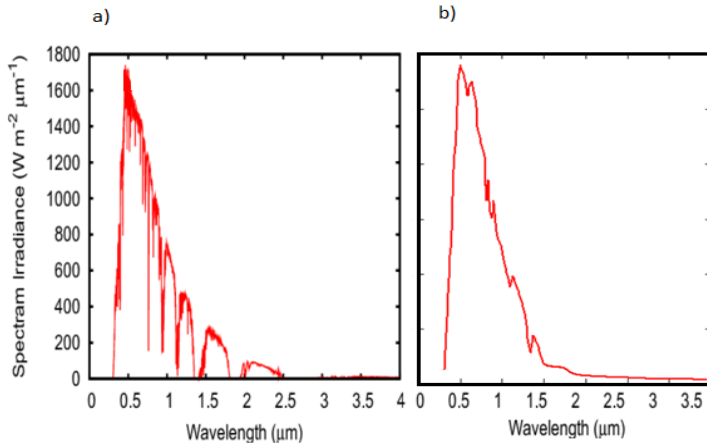
**TABLE III**  
Material parameters for numerical simulation [2, 24, 27, 16]

Atlas identifier	CNT	Window	Absorber
	4H-SiC	GaAs	SiGe(x=0.1)
$E_g$ (eV)	0.026	1.42	1.08
Affinity (eV)	5.8	4.07	4.045
Permittivity $\epsilon_r$ (Fcm-1)	5.4	13.1	12.15
MUN $\mu_n$ (cm <sup>2</sup> /vs)	8138.2	8000	1000
MUP $\mu_p$ (cm <sup>2</sup> /vs)	8138.2	400	500
NC300 (cm <sup>-3</sup> )	$3 \times 10^{17}$	$4.7 \times 10^{17}$	$2.62 \times 10^{19}$
NV300 (cm <sup>-3</sup> )	$3 \times 10^{17}$	$7 \times 10^{18}$	$0.996 \times 10^{19}$

In order to simulate a solar cell structure, it is illuminated with a complex spectrum such as massless air AM0 or AM1.5 spectrum or a constant wavelength of light. In this simulation, the CNT layer is considered completely transparent and using the information of the transmission CNT layer with sheet resistance  $128 \Omega/\square$  and its spectrum led us to achieve the input power at each wavelength. It is modeled by reducing the power loss at each wavelength from the standard spectrum. The modified spectrum is obtained as shown in Fig. 3 [16]. Fig. 3 shows the altered AM1.5 spectrum used in the simulation of CNT networks versus the standard AM1.5 spectrum.

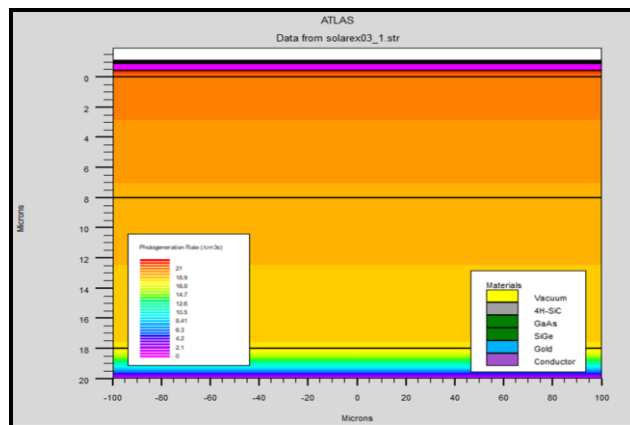


**Fig. 2.** Transmission spectrum of CNT [16]

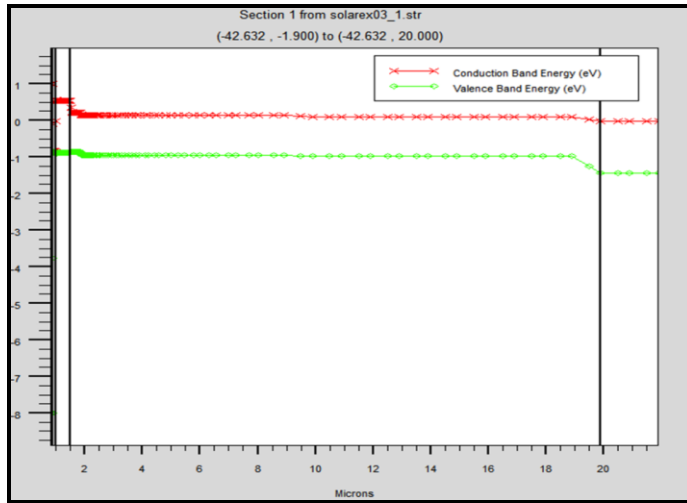


**Fig. 3.** a) The standard AM1.5 spectrum. b) The altered AM1.5 spectrum used in simulation of CNT networks

Simulation of devices starts by designing CNT-based SiGe thin film and conventional SiGe thin film solar cell structures using ATLAS. There are several steps in devices simulation in order to obtain the characteristics of the solar cell for further analysis. Fig. 4 shows the designed CNT-based SiGe thin film solar cell structure using ATLAS simulator. The conduction and valence band energy of this solar cell structure are illustrated in Fig. 5.

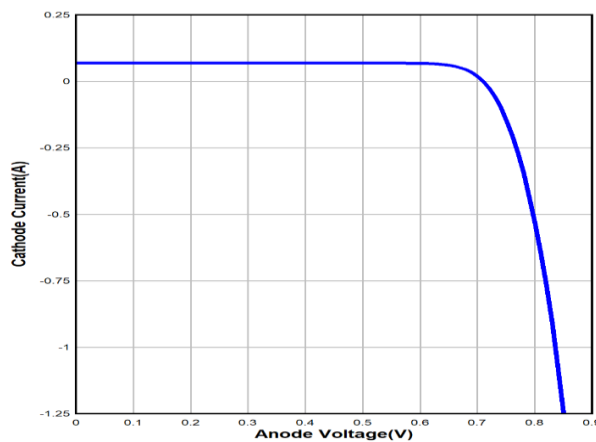


**Fig. 4.** The designed CNT-based SiGe thin film solar cell structure.



**Fig. 5.** Energy band diagram of the designed CNT-based SiGe thin film solar cell structure.

The I-V characteristic of CNT-based SiGe thin film solar cell is shown in Fig. 6. The extracted performance parameters for both CNT-based SiGe thin film and conventional SiGe thin film solar cell structures are presented in Table IV.



**Fig. 6.** The cathode current versus anode voltage curve for CNT-based SiGe thin film solar cell

**TABLE IV**

Comparison performance parameters of the CNT-based SiGe and conventional SiGe structures

Solar cell	$I_{sc}$	$V_{oc}$	$V_m$	$I_m$	$P_m$	$FF$	$E_{ff}$
Conventional SiGe	0.061	0.6732	0.59	0.061	0.3854	85.65	34.67
CNT-based SiGe	0.069	0.7121	0.62	0.06721	0.04167	83.9574	40.3633

As can be seen from table IV, the efficiency of the CNT-based SiGe solar cell structure increased to 40.36%. Indeed, CNT layer used to reduce the problems of internal resistance and shadowing in solar cells. By reducing the net resistance of the CNT layer as a charge collector and reducing the percentage of the surface of the solar cell covered by the top metal grid, the efficiency of solar cell can be easily increased. Improved conduction on the surface of a solar cell provided by a CNT layer can increase the distance between the lines of metal grid. Therefore, these lines can be thickened to reduce losses due to resistance in network lines and increase the efficiency of a solar cell.

For comparison other SiGe solar cells performance with our design, according other literatures SiGe solar cells could achieve conversion efficiency around 28% by changing Ge mole fraction [28].

## 6. CONCLUSION

In this paper, a structure of thin film SiGe solar cell based on carbon nanotube (CNT) has been proposed. We designed and simulated the CNT-based SiGe thin film solar cell structure using Silvaco TCAD. We compared the simulated performance parameters of the CNT-based SiGe thin film solar cell structure with conventional SiGe structure.

Results from numerical simulation show that the CNT-based SiGe thin film solar cell has better parameters such as short circuit current, open circuit voltage, fill factor, maximum power and efficiency in comparison with previous structures. In the CNT-based SiGe thin film solar cell structure, the CNT layer provided a low resistance path for moving charge carriers to the top electrode of solar cell. Therefore, it can be said that the conversion efficiency of the proposed structure would increase by 40.36%.

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