Nigerian Research Journal of Engineering and Environmental Sciences 4(1) 2019 pp. 468-478

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

Effective Control of Auger Recombination in Silicon Solar Cell

Oduah, U.I.
Department of Physics, Faculty of Science, University of Lagos, Lagos, Nigeria.
uoduah@unilag.edu.ng

ARTICLE INFORMATION

Article history:
Received 30 January, 2019
Revised 13 May, 2019
Accepted 15 May, 2019
Available online 30 June, 2019

Keywords:
Auger recombination
Auger ionization
Auger parameterization
Solar cell
Exciton

ABSTRACT

The efficiency of silicon solar cells is hindered by Auger recombination wherein the exciton recombination energy is transferred to a third charge carrier. Consequently, the lifetime of the circulating carriers and fill factor of the device are severely limited. This research explores the oscillatory theoretical dependence of the rate of Auger ionization on the shape of the nanocrystals and the value of the potential well surrounding it, to control the Auger recombination by modifying the nanocrystal surface and size. Numerical modeling and simulation were used to analyze recombination losses with due consideration to the generated carrier concentration, carrier transport and conservation. Optical and carrier recombination losses in all back-surface field and all local back surface field silicon wafer cells were investigated using various Auger parameterizations namely Altermatt, Kerr and Richter, with each implemented in Sentaurus TCAD. The overall efficiency of the silicon wafer solar cell improved from 18.7% to 20.25% at 315 K. This signifies an enhancement in the efficiency of the device by 8.3% of its initial value.

1. INTRODUCTION

Photovoltaic cells have evolved over many years in a bid to improve on incident photon conversion efficiency and optimizing cost of production in an environmentally safe manner (Takuya *et al.*, 2018). Previous studies reveal that there is a direct relationship between the auger recombination and the efficiency of silicon solar cell (Vinnichenko *et al.,* 2016; Vinnichenko *et al.*, 2017). In tropical locations like Nigeria, high carrier injection in silicon solar cells as a result of high intensity of sun causes droop in the efficiency of the device (Hongliang *et al.*, 2019). Contrary to the much-expected increase in the efficiency of the silicon solar cell, the Auger recombination affects the performance of the device adversely during high carrier injections (Fiacre *et al.*, 2018). This created the need to understand the principles of occurrence of Auger recombination and possible ways of suppressing it.

An evaluation of silicon wafers reveals variations in the amount of crystal defects and grain boundaries. A reduced minority carrier lifetime is observed for both bulk and surface recombination process that occur through these defects (Seiji, 2012). Among other factors, recombination is associated with the lifetime of the material, and thus of the solar cell. A previous study revealed that auger recombination is a reverse ionization process which involves three carriers (Cuevas, 2014). An electron and a hole recombine, but rather than emitting the energy as phonon or as a photon, the energy is given to a third carrier, an electron in the conduction band or a hole in the valence band. In the case of an electron, the electron then thermalizes back down to the conduction band edge. Consequently, in silicon based solar cells, auger recombination limits the lifetime and its efficiency (Satyal *et al.*, 2014). Also, these recombination losses affect both the current and voltage parameters of the solar cell such as the short-circuit current (I_{SC}) and the open-circuit voltage (V_{OC}).

In the investigation of the contribution of Auger effect to the overall efficiency of the silicon solar cell, the various aggregates of carrier recombination are classified according to the region of the cell in which it occurs. The following components of the solar cell total carrier recombination were evaluated. The surface termed surface recombination, the recombination at the bulk of the solar cell described as bulk recombination, and the recombination which occurs at the depletion region termed depletion region recombination. In order to maximize the efficiency of this device, the processes that promotes the generation of electron-hole pairs while minimizing the recombination of electron-hole pairs were considered. Previous report on the statistics of carrier recombination in relation to Auger recombination has established the guiding principles of this research. Auger recombination process is directly dependent upon the strength of carrier-carrier coulomb coupling and the degree of spatial overlap between the electron and hole wave functions involved in the auger transition (Zebrev and Zemtsoy, 2016). Also, auger decay rate is directly related to the steepness of the interfacial potential of a material.

It is therefore the focus of this research to leverage on these factors that relate directly to auger recombination process to improve the chemical and photostability of silicon solar cell against ionization.

2. MATERIALS AND METHODS

2.1. Materials

Pure silicon crystals were grown using Czochralski method in an epitaxial junction. Nanocrystals of cadmium zinc selenium synthesized through colloidal technique in aqueous medium applying intermediates selenium source were characterized using scanned electron microscope (SEM) transmission electron microscope (TEM) and X-ray diffraction (XRD). Nanoparticles of sizes below 10 nm were derived and used in the solar cell fabrication process.

2.2. The Fabrication Process

The first approach was to engineer the interfacial potential of the silicon wafer. Nanocrystals of CdZnSe/ZnSe (Cadmium Zinc Selenium/Zinc Selenium) were used to achieve a smooth confining potential by applying a smooth confining potential in a graded composition of the nanocrystal interfacial layer. The steepness of the interfacial potential leads to decreased exciton-exciton coulomb coupling which in turn suppressed the auger recombination (Tuan *et al*, 2013; Timothy *et al.*, 2019). Another approach was to manipulate the degree of spatial overlap between the electron and hole wave functions of the generated carriers. This was achieved by changing the particle surface stoichiometry and hence the magnitude of surface charges. Also, by inducing a piezoelectric field through the deposition of a lattice-mismatched shell material the Auger recombination process was suppressed. The nanocrystal can be Auger auto-ionized only if the band offset in the conduction or valence band is smaller than the nanocrystal band gap energy. But by removing the photoexcited hole from the nanocrystal to the nanocrystal surface, the rate of electron thermalization is reduced. Also removing the hole from the nanocrystal decreases the probability of energy transfer from the electron to the hole which again reduces Auger-like thermalization processes. Consequently, the magnitude of the auger recombination at high carrier injection density was controlled. The partial spatial separation between electrons and holes reduces electron-hole overlap integral which decreases the rate of auger decay therefore extended the auger lifetime by approximately -2nS. The process of controlling the Auger recombination is elucidated in Figure 1.

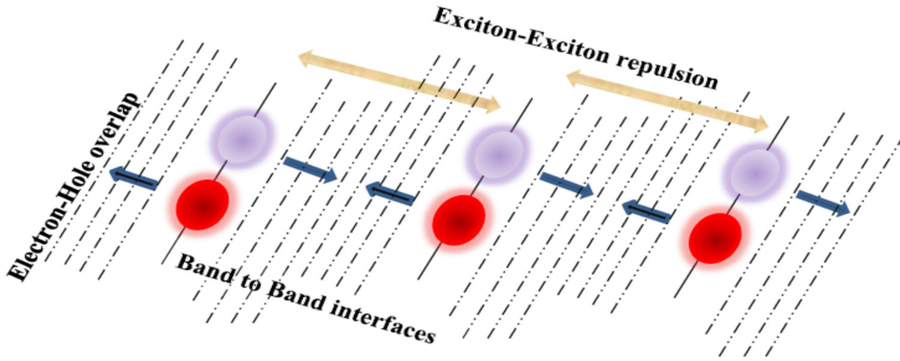

Figure 1: Suppression of Auger recombination in a silicon solar cell achieved through manipulation of the effective spatial extent of electronic wave functions.

2.3. Theory

2.3.1. Auger recombination process

Basically, auger recombination involves a three-particle interaction where a conduction band electron and a valence band hole recombine, with the excess energy being transferred to a third free electron or hole. In this recombination process, the charge carriers involved are assumed to be non-interacting quasi-free particles. If the excess energy is transferred to another electron, it is denoted as eeh (electron, electron-hole) with recombination rate given by:

$$U_{eeh} = C_n n^2 p \tag{1}$$

Where C_n is the auger coefficient; n and p are the concentration of free electrons and free holes respectively.

Similarly, the ehh (electron-hole, hole) is considered when the excess energy is transferred to another hole with recombination rate given by:

$$U_{ehh} = C_p n p^2 \tag{2}$$

Where C_p is the auger coefficient.

The total auger recombination rate, U_{Auger} is given by:

$$U_{Auger} = C_n n^2 p + C_p n p^2 \tag{3}$$

Auger recombination lifetime in n-type silicon under low injection ($\tau_{Auger} l_i$) and high injection ($\tau_{Auger}\, h_i$) is given by:

$$\tau_{Auger}\, l_{iD} = \frac{1}{C_p N_D^2} \tag{4}$$

$$\tau_{Auger}\ h_{ip} = \frac{1}{(C_n + C_p)\,\Delta p^2} \quad (5)$$

$$\tau_{Auger}\ l_{iA} = \frac{1}{C_p N_A^2} \quad (6)$$

$$\tau_{Auger}\ h_{in} = \frac{1}{(C_n + C_p)\,\Delta n^2} \quad (7)$$

where N_D and N_A are the net donor and net acceptor concentrations respectively; Δn and Δp are the excess electron density and excess hole density respectively.

The carrier lifetime indicates the quality of silicon material. This quality depends primarily on the growth process such as float zone (FZ) and Czochralski method (CZ). Previous reports show that lifetime can change when wafers are processed at high temperature or subjected to certain treatments. In this research, the Czochralski method was applied with some modifications (Rens *et al.*, 2018). The usual Auger recombination which is the dominant mode of recombination in silicon for high injection levels and for high dopant densities as occurs in heavily doped emitter regions of silicon solar cells were effectively controlled (Zhu *et al0*, 2016; Haug and Greulich, 2016; Ngo *et al.*, 2017).

2.3.2. Effect of auger parameterization on surface passivation

In order to reduce the impact of surface recombination in the silicon solar cell, a special passivation technique was deployed. Generally, highly efficient silicon wafer solar cells are developed using improved surface passivation schemes. The local back surface field solar cells (LBSF) sometimes referred to as passivated emitter rear contact (PERC) are examples of highly efficient silicon wafer solar cells previously used. These device structures are achieved through effective engineering of auger parameterization on the surface passivation of the solar cells. The target is therefore to use improved surface passivation to suppress surface recombination. A lower surface recombination is achieved by reducing the metallized area fraction. An advanced surface passivation using field effect passivation is applied on non-metallized surfaces. Field effect passivation was achieved using dielectric thin films of SiN. This provided an excellent surface passivation due to strong field-effect passivation in combination with chemical passivation. Both strategies applied accordingly reduced the impact of surface recombination according to the reports of (Rein, 2004; Benick *et al*, 2019; Schmidt *et al.*, 2009; Luder *et al.*, 2011).

In order to accurately calculate the carrier lateral transport in the silicon wafer cell, auger parameterizations were implemented into Sentaurus TCAD via a physical model interface. Three auger parameterizations are implemented namely the Altermatt, Kerr, and Richter parameterizations. The difference between the three auger parameterizations for various doping densities and injection levels was compared and used as basis to evaluate the performance efficiency of the solar cell. The applied parameterization model for the complete intrinsic recombination is shown in Equations (8) and (9) in line with the previous study (Richter *et al.*, 2012).

$$T_{intr.adv} = \frac{\Delta n}{\left(np - n_{i.eff}^2\right)\left(2.5\times10^{-31} g_{eeh}\, n_o + 8.5\times10^{-32}\, g_{ehh}\, p_o + 3.0\times10^{-29}\,\Delta n^{0.92} + B_{rel}\, B_{low}\right)} \quad (8)$$

The enhancement factors described by Equations (9) and (10).

$$g_{eeh}(n_o) = 1 + 13\left\{1 - \tanh\left[\left(\frac{n_o}{N_{o.eeh}}\right)^{0.66}\right]\right\} \quad (9)$$

$$g_{ehh}(p_o) = 1 + 7.5\left\{1 - \tanh\left[\left(\frac{p_o}{N_{o.ehh}}\right)^{0.63}\right]\right\} \quad (10)$$

All the variables are described in Table 1.

Table 1: Description of parameters for Equations (8), (9), and (10) (Fa-juan *et al*, 2014)

Parameter	Description
n	Electron density (cm^{-3})
p	Hole density (cm^{-3})
n_o	Equilibrium electron density (cm^{-3})
p_o	Equilibrium hole density (cm^{-3})
Δn	Excess carrier density (cm^{-3})
n_i	Lowly doped and lowly injected silicon, 9.7 x 10^9 cm^{-1} at 300 K
n_{ieff}	Effective intrinsic carrier concentration (cm^{-3})
B_{low}	Radiative recombination coefficient for lowly doped and lowly injected silicon, 4.73 x 10^{15} cm^{-3} S^{-1} at 300 K
B_{rel}	Relative radiative recombination coefficient for lowly doped and lowly injected silicon.
No_{eeh}	3.3 x 10^{17} cm^{-3}
No_{ehh}	7.0 x 10^{17} cm^{-3}

2.3.3. Impact of temperature on auger recombination

The influence of temperature on auger recombination was investigated. Theoretically, increase in temperature will lead to increase in the population of thermally generated carriers. The increase in the number of thermally generated carriers will translate to more chances of auger recombination and therefore more energy losses in the device.

2.3.4. Impact of size and shape of the microscopic confinement potential to auger recombination

The impact of size and shape of microscopic confinement potential was investigated with reference to their influence on auger recombination. The oscillatory theoretical dependence of the rate of auger ionization on the shape and size of the nanocrystals forms the basis for this study. In accordance with the report of (Xiaoyong *et al*, 2009), the size and shape of the microscopic confinement potential affects the non-radiative auger decay rate of confined carriers.

2.3.5. Effective carrier lifetime

The evaluation of the effective carrier lifetime is a factor of the rate of recombination of the generated carriers. It has been shown that recombination greatly reduces the effective carrier lifetime, which therefore reduces the performance of the solar cells, particularly the cell voltage and efficiency. This research therefore describes processes that will extend the effective carrier lifetime in the solar cell. The overall recombination rate is given by the sum of the individual recombination rates resulting in an effective lifetime τ_{eff}.

$$\frac{1}{\tau_{eff}} = \left[\frac{1}{\tau_{SRH}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{rad}}\right] + \frac{1}{\tau_{Surface}} \quad (11)$$

Where τ_{SRH} is the Shockley-read-hall recombination lifetime

τ_{Auger} is the Auger recombination lifetime

τ_{rad} is the radiative recombination lifetime

$\tau_{Surface}$ is the surface recombination lifetime

3. RESULTS AND DISCUSSION

The variation of the effective rear recombination velocities with maximum power point recombination current density is presented in Figure 2. It can be deduced that with decreasing effective rear surface recombination velocity, $S_{eff.rear}$ the contribution of the Auger recombination increases significantly, reaching about 35% of the total maximum power point recombination current density, $J_{rec.mpp}$ at $S_{eff.rear}$ equals 12cm/s (represented by the ratio of the area covered by the Auger recombination in Figure 2). However, by reducing $S_{eff.rear}$ from 1000 cm/s to 10 cm/s, the minority carrier density in the bulk and in the emitter region (represented by the sum of the extrinsic recombination) increased by more than one order of magnitude.

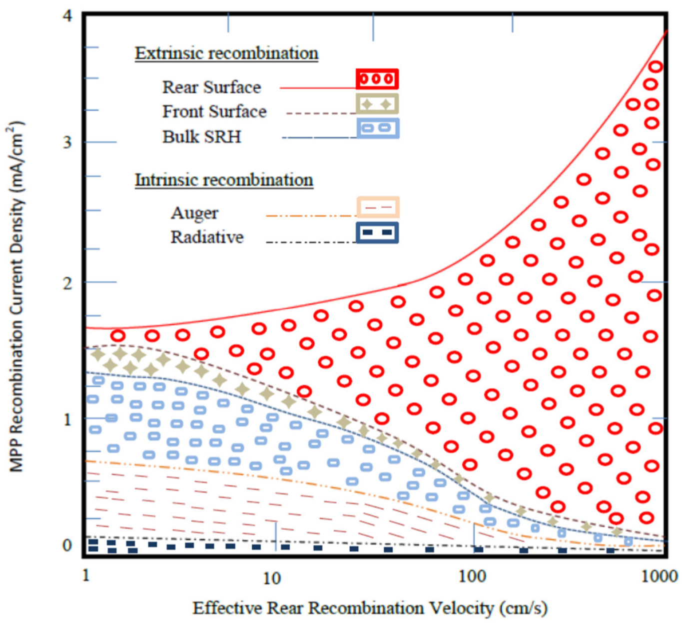

Figure 2: Comparison of the various recombination mechanisms

The ratio of the area covered by auger recombination compared to the entire area of the total intrinsic recombination confirms the influence of auger recombination on the mpp recombination current density.

Also, the auger lifetime in crystalline silicon was measured under high carrier injection conditions using an injection and temperature dependent photoconductance apparatus, across a temperature range from 240 K to 475 K. The corresponding ambipolar auger coefficient was found to have a value of 1.62 x 10^{-30} cm^3/s at 300 K at an injection level of 5 x 10^{15} cm^{-3}. The Auger coefficient was found to decrease between the ranges of 240 K to 300 K, and remain approximately constant up to about 475 K.

Calculations conducted in the two-band effective mass Kane model show that smoothing out the confinement potential reduced the rate of Auger recombination by more than 3 orders of magnitude relative to the rate in structures with abruptly terminating boundaries. It was observed that as the confinement potential width is increased, the calculated rate of Auger recombination decreases overall, exhibiting very deep minima at regular widths. Consequently, by manipulating the nanocrystal sizes, the non-radiative auger processes are strongly suppressed.

The resulting effective lifetime is dominated by SRH recombination at low injection and Auger recombination at high injection level in line with previous studies by (Kerr and Cuevas, 2002; Trupke and Bardos, 2004; Plebaniak and Wibig, 2016).

The control of the abruptness of the interfaces modified the carrier relaxation and recombination.

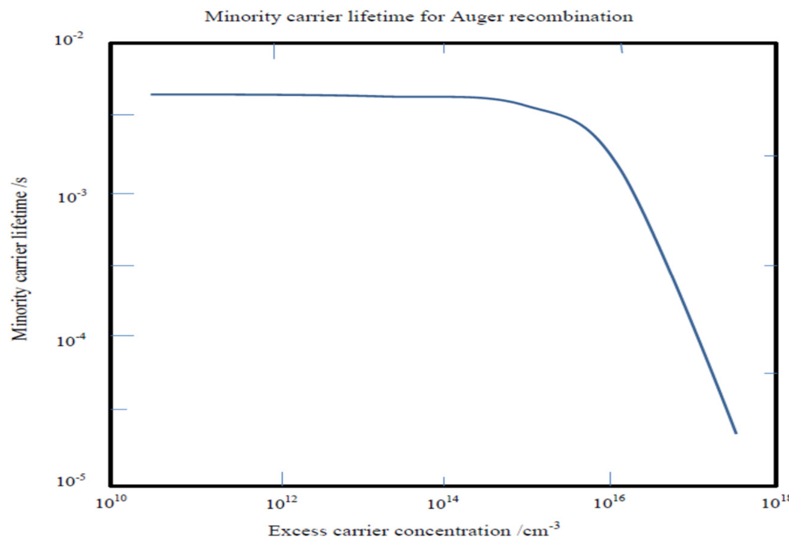

Figure 3: Auger recombination lifetime

The dependence of auger recombination on carrier injection concentration is presented in Figure 3. Theoretically auger carrier lifetime depends on the inverse of the carrier density squared as shown in the Equation 12.

$$\tau_{Auger,high} = \frac{1}{(C_n + C_p)\Delta n^2} \quad (12)$$

$\tau_{Auger,high}$ is the Auger recombination lifetime at high carrier injection concentration.

C_n is the auger coefficient; n and p are the concentration of free electrons and free holes respectively. Δn^2 is change in the carrier concentration squared.

Previous reports also reveal that auger recombination shows a stronger dependence with the injection level than radiation lifetime (Altermatt *et al.*, 2006; Liao *et al.*, 2017). More so, since silicon is an indirect bandgap semiconductor, there are less chances of radiative recombination. Consequently, the impact of radiative recombination on carrier injection concentration is very negligible as shown in Figure 4.

The efficiency of the modified silicon solar cell which suppresses auger recombination was measured. The enhanced attributes of the solar cell are presented in Table 2. The recorded overall efficiency improved from 18.7% to 20.25% at 315 K. This signifies an enhancement in the efficiency of the device by 8.3% of its initial value attributed to the suppression of Auger recombination in the device.

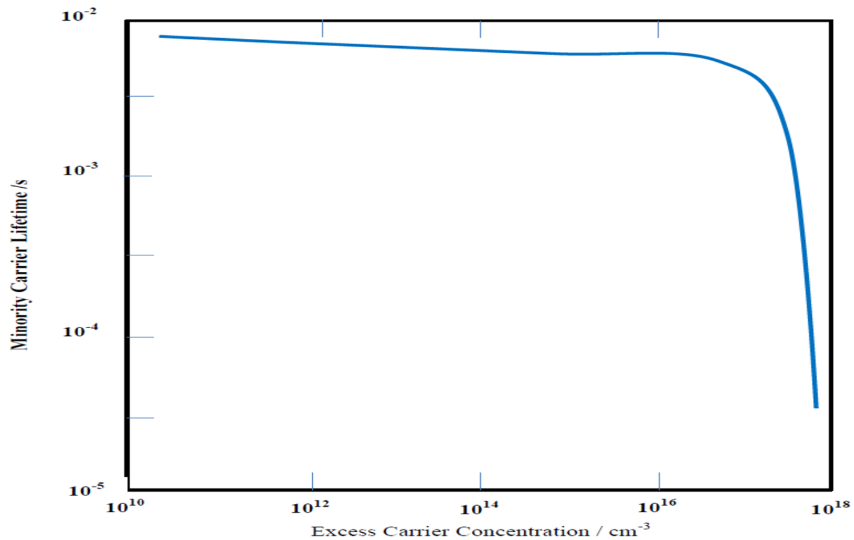

Figure 4: Impact of radiative recombination on minority carrier lifetime

Table 2: Efficiency of the conventional silicon solar cell compared to the one modified to suppress auger recombination

Parameter	Conventional silicon solar cell	Silicon solar cell with suppressed auger recombination
Light intensity (W/m^2)	1000	1000
Photon absorption area (m^2)	0.64	0.64
Short circuit current (A)	7.32	6.96
Open circuit voltage (V)	20.64	21.09
Fill factor	0.792	0.883
Maximum power (W)	119.67	129.6
Maximum voltage (V)	18.212	20.15
Maximum current (A)	6.571	6.432
Efficiency (%)	18.7	20.25

In Figure 5, the bulk recombination lifetime variations with carrier injection concentration is shown to be more uniform at lower carrier concentrations than at higher carrier concentrations.

U.I. Oduah / Nigerian Research Journal of Engineering and Environmental Sciences
4(1) 2019 pp. 468-478

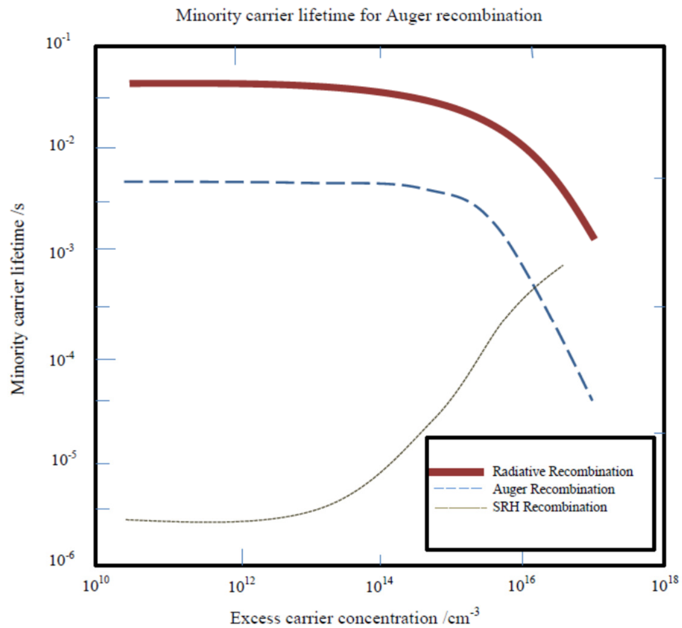

Figure 5: Comparison of bulk recombination lifetime curves for auger recombination, radiative recombination, and Shockley red hall recombination

4. CONCLUSION

In this research, it was demonstrated that Auger recombination in a silicon solar cell can be controlled by modifying the nanocrystals shape and size. Auger recombination which dominates the intrinsic recombination at high carrier injection levels, greatly reduce the effective carrier lifetime which leads to poor performance efficiency of solar cells. By controlling the intrinsic recombination in the silicon solar cell through an innovative technology that suppresses Auger recombination, the effective efficiency of this silicon solar cell was enhanced by 8.3%. This was achieved by engineering the interfacial potential of the silicon wafer using nanocrystals of CdZnSe/ZnSe as presented in the fabrication process. This is very relevant in the development of silicon solar cells at tropical regions where intense sun leads to high carrier injections. The elevated Auger recombination causes a drop in the overall efficiency of the device. Silicon solar cells with enhanced efficiency can be used in the powering of electronic medical devices, household electronic gadgets, and various electronic devices.

5. ACKNOWLEDGMENT

All thanks to the Nanotechnology Research Group of University of Lagos, for providing the facilities for this research project.

6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

Altermatt, P.P., Geelhaar, F., Trupke, T., Dai, X., Neisser, A. and Daub, E. (2006). Injection dependence of spontaneous radiative recombination in crystalline silicon: experimental verification and theoretical analysis. *Applied Physics Letters,* 88, pp. 261901- 261904.

Benick, J., Richter, A., Hermle, M. and Glunz, S.W. (2009). Thermal stability of the Al_2O_3 passivation on p-type silicon surfaces for solar cell application. *Physica Status Solidi Rapid Research Letters,* 3, pp. 233-235.

Cuevas, A. (2014). The recombination parameter Jo. *Journal of Electron Spectroscopy and Related Phenomena*, 195, pp. 66-70.

Fa-jun, M, Haohui, L., Baochen, L., Jia, C., Zheren, D., Ganesh, S.S., Armin, G.A., Bram, H. and Ian, M.P. (2014), Impact of auger recombination parameterization on predicting silicon wafer solar cell performance. *Journal of Computational Electronics,* 13(3), pp. 647 – 656.

Fiacre, E., Chang S. and Daniel M. (2018), Determining the charge states and capture mechanisms of defects in silicon through accurate recombination analysis: A review solar energy materials and solar cells. *Solar Energy Materials and Cells,* 187, pp. 263 – 272.

Haug, H. and Greulich, J. (2016). PC1Dmod 6.2 –improved simulation of c-Si devices with updates on device physics and user interface. *Energy Procedia,* 92, pp. 60- 68.

Hongliang, G., Qiang S. and Yiyong W. (2019). Simulation of solar cells by delocalized recombination model and its applications. *Solar Energy,* 181, pp. 83 – 87.

Kerr, M.J. and Cuevas, A. (2002). Very low bulk and surface recombination in oxidized silicon wafers. *Semiconductor Science Technology,* 17, pp. 35-38.

Liao, T, Yang, Z, Peng, W., Chen, X. and Chen, J. (2017). Parametric characteristics and optimum criteria of a near-field solar thermophotovoltaic system at the maximum efficiency. *Energy Conversion Management.* 152, pp. 214-220.

Luder, T., Hahn, G. and Terheiden, B. (2011). Passivation of Si Wafers by ALD-Al2O3 films with different surface conditioning. *Energy Procedia,* 8, pp. 660 - 665.

Ngo, H.T., Gil, B., Damilano, B., Lekhal, K. and Mierry, P.D. (2017). Internal quantum efficiency and Auger recombination in green, yellow, and red InGaN-based light emitters grown along the polar direction. *Superlattices and Microstructures,* 103, pp. 245-251.

Plebaniak, Z. and Wibig, T. (2016). Elastic scattering in geometrical model. *Physics Letters B.* 761. pp. 469- 474.

Rein, S. (2004). Lifetime spectroscopy: *A method of defect characterization in silicon for photovoltaic applications.* Springer, Berlin, Germany. pp. 87-91.

Rens, L., Hiroshi, S., Nathan, R.N. and Minoru, F. (2018), Critical size for carrier delocalization in doped silicon nanocrystals: A study by ultrafast spectroscopy. *American Chemical Society Photonics,* 10, pp. 4037 – 4045.

Richter, A., Werner, F., Cuevas, A., Schmidt, J. and Glunz, S.W. (2012). Improved parameterization of Auger recombination in silicon. *SciVerse Science Direct*, 27, pp. 88-94.

Satyal, S., Joglekar, P.V., Shastry, K., Kalaskar, S., Dong, Q., Hulbert, S.L., Bartynski, R.A. and Weiss, A.H. (2014). Measurement of the background in Auger-photoemission coincidence spectra (APECS) associated with inelastic or multi-electron valence band photoemission processes. *Journal of Electron Spectroscopy and Related Phenomena,* 195, pp. 66-70.

Schmidt, J., Veith, B. and Brendel, R. (2009). Effective surface passivation of crystalline silicon using ultrathin Al_2O_3 films and Al_2O_3/SiN_3 stacks. *Physica Status Solidi Rapid Research Letters,* 3, pp. 287-289.

Seiji, A. (2012). Efficient recombination. *Nature Photonics,* 6, pp. 800 – 808.

Takuya, M, Hitsoshi, S., Adrien, B., Hung-jung, H. and Koji, M. (2018), Progress and limitations of thin-film silicon solar cells. *Solar Energy,* 170, pp. 486 – 498.

Timothy, G. M., Lakshay, J., Mark, A. and Patanjali, K. (2019). Direct observation of vibronic coupling between excitonic states of CdSe nanocrystals and their passivating ligands. *Journal of Physical Chemistry,* 123, pp. 5084 – 5091.

Trupke, T. and Bardos, R.A. (2004). Self-consistent determination of the generation rate from photoconductance measurements. *Applied physics letters*, 85, pp. 3611-3614.

Tuan, M.T., Rens, L. and Tom, G. (2013). Experimental investigations and modeling of Auger recombination in silicon nanocrystals. *Journal of Physical Chemistry,* 117, pp. 5963 – 5968.

Vinnichenko, M., Makhov, I., Balagula, R., Firsov, D., Vorobjev, L., Shterengas, L. and Belenky, G. (2017). The effect of Auger recombination on the non-equilibrium carrier recombination rate in the InGaAsSb/AlGaAsSb quantum wells. *Superlattices and Microstructures,* 109, pp. 743-749.

Vinnichenko, M., Makhov, I., Selivanov, A., Sorokina, A., Vorobjev, L., Firsov, D., Shterengas, L. and Belenky, G. (2016). Effect of Auger recombination on non-equilibrium charge carrier concentration in InGaAsSb/AlGaAsSb quantum wells. *St. Petersburg Polytechnical University Journal: Physics and Mathematics,* 2, pp. 287-293.

Xiaoyong, W., Xiaofan, R., Keith, K., Megan, A.H., Rajeswaran, M., Maccagnano-Zacher, S., Silcox, J., Cragg, E.G., Efros, A.L. and Krauss, T.D. (2009). Non-blinking semiconductor nanocrystals. *Nature letters,* 459, pp. 686-689.

Zebrev, G.I., and Zemtsov, K.S. (2016). Multiple cell upset cross-section modeling; A possible interpretation for the role of the ion energy-loss straggling and Auger recombination. *Nuclear Instruments and Methods in Physics Research Section: Accelerators, Spectrometers, Detectors, and Associated Equipment,* 827, pp. 1- 7.

Zhu, L., Song, Y., Wang, S., Qi, Z., Liangqing, Z, Chen, X., Zha, F., Guo, S. and Shao, J. (2016). Auger recombination at low temperatures in InGaAs/InAlAs quantum well probed by photoluminescence. *Journal of Luminescence,* 169 Part A, pp. 132- 136.