

Implementation of an Improved Leak Detection Technique in a Pipeline System Using Flow Induced Vibration-Based Wireless Sensor Network

¹Dilibe C. G., ²Ayinla S. L., ³Azubogu A.C.O., ⁴Onyeyili T. I.

¹Electronics Development Institute, Awka, Anambra State, Nigeria

²Department of Computer Engineering, University of Ilorin, Ilorin, Kwara State, Nigeria

^{3,4}Department of Electronic and Computer Engineering, Nnamdi Azikiwe University Awka, Anambra State, Nigeria.

Chijioke4christ39@gmail.com

Olanan2x@yahoo.com

austinazu@yahoo.com

onyeyilitoch@gmail.com

ABSTRACT: This paper describes an experimental study of non-invasive leak detection technique using Micro Electro Mechanical System-based WSN in a multi-hop environment. An outdoor test bed of dimension 21m by 18m made up of fifteen (15) PVC pressure pipes of 2 inches diameter was set up; six (6) Valves (V1toV6) installed at each joint of the network. The six (6) pieces of custom-built acceleration-based sensor nodes were attached few meters away from the Valves to sense, process and transmit data to the sink node which forwards the collated packet to the base station. In the monitored pipeline network, leak or rupture was found to correspond to an increased pipeline surface acceleration (measured in g-force). The difference in acceleration data collated from each network joint shows that the acceleration of water flow in a pipeline network tends to be higher in a sloppy area. Non water-flow and water-flow conditions for closed, half and full-open valves condition were considered and graphical plots of acceleration data with time indicating the presence of rupture along the pipeline were presented.

Keywords: WSN, Pipeline Operations, Leak Detection, Testbed.

1.0 Introduction

Modern Society primarily depends on transportation of fluid (water, oil, etc.) through the pipeline. With the widespread demand for the supply of pipeline products, technique for pipeline leak detection is becoming increasingly important [1]. Sometimes, pipeline could be subjected to theft sabotage and corrosion; which usually results in wastage and environmental hazard. The use of human patrol system in pipeline monitoring poses a great difficulty in detecting leakages in pipelines. This is because; the patrol team can only take observations of what is happening when they are present [2]. There are many mechanisms in detecting and locating points of leak in pipeline system. Some mechanisms make use of acoustic emission which generates noise signals which can be picked up by acoustic sensors installed outside the pipeline [3]. The Oil pipeline Supervisory Control and Data Acquisition (SCADA) system for pipeline

monitoring focuses on centralized data collection and control. This makes the pipeline monitoring system expensive and tedious [2].

This paper describes an innovative pipeline leak detection method that involves the use of acceleration-based WSN that ensures that change in pressure of a fluid in a pipeline due to leakage produces change in acceleration of water flow. Wireless Sensor Network (WSN) offers an economical and effective solution in detecting and locating leak points in pipelines.

2.0 Review of Related Works

Many researchers have studied the use of Wireless Sensor Network (WSN) to detect leaks in pipeline system. Different leak detection techniques have been applied in water pipeline.

Authors in [4] used Micro Electro Mechanical System (MEMS) sensor network to develop a non-invasive monitoring of pipeline system to

detect leakages. They incorporated MEMS accelerometers for measuring flow-induced vibration on the surface of a pipe to determine the change in water pressure caused by rupture. Their work presented an experimental investigation of the relationship between flow-induced vibration and pressure fluctuations. From the same work, it was found that there is a non linear but proportional relationship between the flow rate (or pressure) and flow-induced vibration of the pipe surface. Therefore, the major area of improvement is to increase the number of sensor nodes to enable the study of sensor directivity.

Authors in [5] demonstrated the concept of leak detection in pipeline system using WSN. When there was rupture along the pipeline, the fluid pressure would change which equally led to change of acceleration of pipe surface along the pipe length. The work is limited to be applied on a small scale pipe network since it contained a sensor and ball valve. The major limitation to this literature is that a single sensor will be unable to analyze sensor directivity. In order to enhance the leak detection, sensor directivity should be studied and implemented with multiple sensors. This is only possible when many sensors are deployed on the test bed. Authors in [6] used Pressure Point Analysis (PPA) in detecting leak points in pipeline system. The PPA method detects leaks by monitoring pipeline pressure at a single point along the line and comparing it with a running statistical trend constructed from previous pressure measurements. However, it is difficult for this method to be used in wide leak points. Therefore, the application range of PPA is too narrow. Moreover, pressure point analysis is cost effective and easy to maintain. Another major limitation is that it detects only small leaks and due to its narrow range of application, it is difficult to be used in localizing leaks in pipelines. Authors in [7] used MEMS accelerometers for measuring vibration on the surface caused by rupture and damage location. Their work showed a novel damage detection method based on MPAG (maximum pipe

acceleration gradient) instead of MWHG (maximum water head gradient). The limitation to above literature is that there is no local processing algorithm for rupture detection data and enhanced communication protocol between sensor nodes. Thus, inaccuracy in sensing a leak point may be inevitable. Authors in [8] used the detection principle of the pattern recognition method that is based on transient feature extraction and structural pattern recognition for the negative pressure wave caused by a pipeline leak. This type of detection method can effectively reduce the false alarm rate and the missing detection rate, and improve the accuracy of leak detection. The major limitation of pattern recognition is that it is expensive. Authors in [9] proposed WSN called PipeNet, with fixed nodes. It integrates sensors which are able to generate acoustic vibration and collect acoustic/vibration data at high sampling rates. It equally provides algorithms to detect leakages in the pipe network. The uniformity of the liquid characteristics is not guaranteed during detection of leaks. Authors in [10] developed a sensor network platform that uses acoustic sensing devices such as lead Zircarnate Titanate (PZT) to generate acoustic signals. The acoustic sensors are customized to the structure of the pipeline thereby making the method inappropriate for other types of pipeline technologies.

2.0 Wireless Sensor Network

A wireless sensor network is a collection of sensor nodes interconnected by wireless communication channels. A wireless sensor node is a small wireless device that encompasses a microcontroller, a radio transceiver, an antenna, a power source, and one or more sensors. A lightweight operating system enables a node to function and provides features such as sensor polling, data aggregation and manipulation, wireless communication, and remote access. Wireless networks are broadly divided into infrastructure and infrastructure less network, where infrastructure network consists of wireless node with a network backbone and infrastructure less network consist of

distributed, independent, dynamic topology, low-power, task-oriented wireless sensor nodes. Cellular wireless network falls under the category of infrastructure network whereas ad-hoc and wireless sensor network (WSN) are part of infrastructure less network. In an ad-hoc wireless network, the wireless devices integrate and communicate with each other by making an on-spot dynamic wireless link.

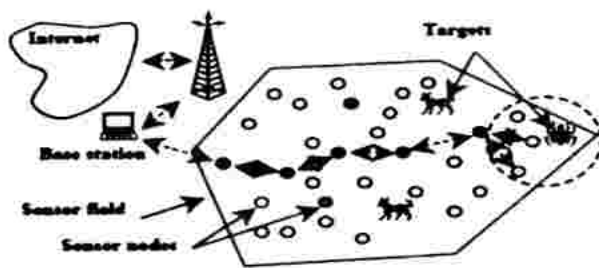


Figure 1: WSN Architecture

3.0 Methodology

This project describes the use of acceleration-based wireless sensor nodes to monitor pipe surface acceleration between network joints non-invasively and detect the leak point on the pipeline. Acceleration-based sensor nodes are placed at uniformly spaced intervals on a water pipeline to monitor water flow. When there is leakage, there will be sudden disturbance in the water flow which induces corresponding sudden change in acceleration of the pipe surface vibration. This change in the pipe acceleration is measured. Rupture is simulated by opening and closing of valves and switching the pumping machine on/off.

3.1 Leakage Detection Technique

A leak is identified when less fluid leaves the pipe than is expected from the measurements of input flow and estimates of the pipe contents. There are various techniques for detecting leak in a pipeline network. Change in induced vibration of pipe surface due to rupture was adopted in this work as the leakage detection technique. More specifically, Micro Electro Mechanical System (MEMS) sensors were installed at all the joints in the pipe network. As a result, at least two ends of every link of the

network were monitored. The accelerometer sensors used in this work ensured that change in water pressure in a pipeline induced by leakage produced change in acceleration of the water flow. Therefore, leakage was identified directly from the value of acceleration at each point. When a leak occurred in the monitored network, the transient change in the water pressure propagated through the network and induced corresponding change in the acceleration of pipe surface vibration.

3.2 Experimental Test Bed Description

To demonstrate the concept of Leak detection and localization in pipeline system, a mini water pipeline Test bed was setup behind the block A wing of Prof. Gordian Ezekwe Faculty of Engineering building, Nnamdi Azikiwe University, Awka Anambra State. The rectangular test bed has a dimension of 21 meter by 18 meter with 15 pieces of 18 feet PVC pressure pipes of 2 inches diameter equipped with 6 valves.

Both ends were terminated at water pump location; the thickness of the pipeline is 6mm. The pipeline was filled with high pressure water being supplied by the water pumping machine. The acceleration sensor nodes were attached at the uniformly spaced interval from the valves and the valves were used to emulate ruptures. In the experiments, rupture was emulated by the opening and closing of the valves. The valves were adjusted manually to three different stages: closing, half-opening and complete opening, where closing means high pressure and no water flow from the outlet of the valve; half-opening means medium pressure with water flowing; and complete opening means low pressure with water flowing. The acceleration sensor nodes were attached on the pipes, and pipe accelerations were Measured during the process of opening and closing of the valves. The measurements were carried out for three days and the average data was obtained. The readings of the sensor nodes were displayed at the base station. Fig.1 shows the engineering Test bed drawing drawn to scale.



Figure 2: Experimental Test bed

3.3 Principles of Pipeline Operation

Normal pipeline operations involved the operation of controlling the valves at each point. Leak detection systems were therefore operated over a wide range of process conditions, some of which appeared to have the characteristics of leak patterns. The basic challenge is to distinguish between the normal operational processes that would indicate leak occurrences and some other non-typical processes which would equally indicate leak occurrences. The leak occurrences were emulated using valves opening and closing. Some other non-typical processes include: leakage caused by vandalism and earthquake. In normal operational process, when the pumping machine was switched ON, Water was allowed to circulate through the pipeline with a maximum pressure. The maximum pressure was obtained by manually covering the other end of the pipe which terminates at the Water Reservoir. Immediately the pressure of the water got to optimum level; at about 240seconds, measurement was taken assuming a non-leak condition. Then, each valve was half-opened and full-opened for 240seconds respectively and vibration data were collated via the sink node and sent to the base station. This is called a leak condition. Rupture was found along the pipe when comparing the leak-free data with that of leak data.

4.0 Result Analysis

The nodes were deployed on the developed Testbed for experiments after confirming that they are working according to design specifications. Firstly, data was recorded by the

base station when no fluid was flowing through the pipeline network so as to differentiate its result from what was obtained when fluid was flowing into the network, and then the valves labeled V1 through V6 were adjusted manually but sequentially to three states: closing, half opening, and complete opening, where closing means high pressure and no water flow through the valves; half opening means medium pressure with water flowing in the pipeline network; and complete opening means low pressure with water flowing through the valves. Initially, the valves were closed to allow the pressure to build up gradually, and after 240seconds, the valve at V1 was half opened and allowed to stay in that position for 240seconds to simulate partial or half rupture before closing, and subsequently the valve at V6 was completely opened also for about 240seconds to simulate full rupture at V6.

From the theory supporting the design of the system for monitoring of rupture in a linear network using information from pipe accelerations, it was seen that change in acceleration along the pipe was occasioned by a sharp change in pipe vibration at the corresponding locations along the network. The recorded data were processed in the form of distribution charts and graphs subsequently analyzed. The graphs of fig. 3 to 6 show the representation of the pipeline system on non-water flow condition, water flow condition; half rupture and full rupture situations.

4.1 Pipeline Network During No Water Flow

Figure 2 shows the plot of acceleration with time when no water is flowing in the pipeline network. The acceleration data with time and also the mat lab program code for plotting the acceleration with time were recorded. From the figure 2, it is seen that there is almost equal value of acceleration of all the nodes since no water is flowing through the pipe network.

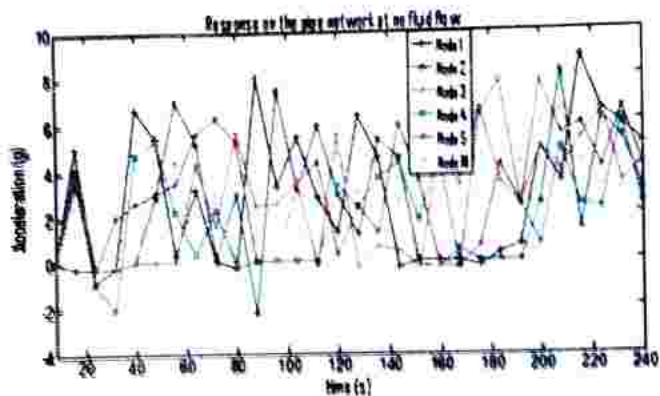


Figure 3: A graph of acceleration with time at no water flow

4.2 Pipeline Network During Water Flow

Figure 3 shows the plot of acceleration with time the water is flowing and valves (V1 through V6) are fully closed. From figure 3, nodes 5 and M have the highest acceleration as result of the topography of the test bed environment.

These were installed on pipe network which were located at sloppy terrain. This means the acceleration of the water flow would be high compared to that of other nodes. Node 5 has the highest acceleration (38.61g) at 170 seconds. The pipe acceleration has very high values when compared to non-flow condition in figure 2

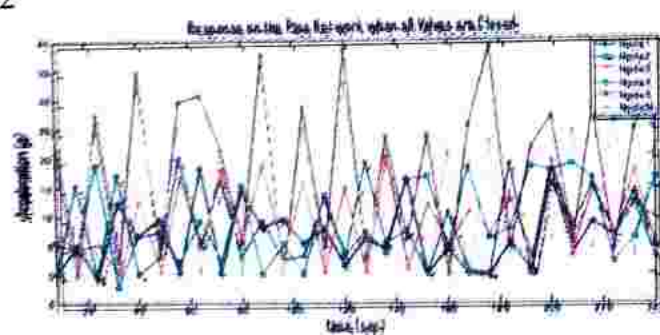


Figure 4: A graph of acceleration with time at flow when all valves are closed

4.3 Half Rupture at Water Flow (V1 is Half Opened)

From figure 4, it is seen that node 1 has the highest acceleration value of 67g at exactly 90 seconds and 200 seconds. This suggests the presence of partial rupture around node 1. This relies on the hypothesis that rupture of

considerable size in the system causes sudden Expulsion of water, resulting in abrupt change in water acceleration through the pipe network. Also, the figure 4 shows that there is a sharp change in the acceleration of the pipe surface at 98 seconds and 200 seconds when valve V1 is half opened.

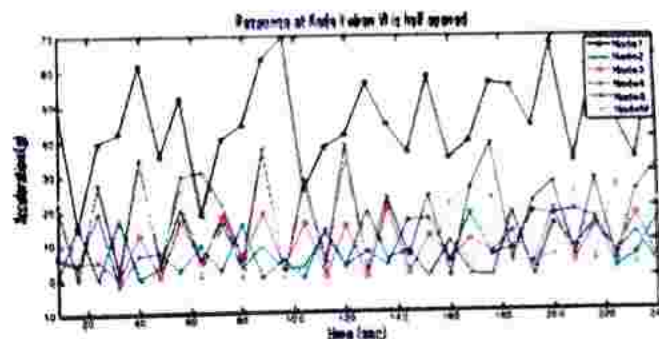


Figure 5: A graph of acceleration with time when V1 was half opened

4.4 Analysis of Full Rupture at Water Flow (V6 is Fully Opened)

From figure 4, when the water flows through the pipeline network, and V6 is fully opened, it will be seen there is sharp change in acceleration of the fluid at exactly 90seconds, 122seconds, 179seconds 200seconds 210seconds and 220seconds with their corresponding acceleration at 122.36g, 139.56g, 89.34g, 118.41g, 120.78g and 125.13 respectively. This suggests that full rupture takes place at V6. The values of acceleration data at this node are highest than other nodes acceleration data. This is as result of the topography of the test bed environment. It shows that the node is located at sloppy terrain which validates the fact that water flow rate is at maximum in a sloppy terrain.

The graphs show that the effect of simulated rupture in terms of acceleration depends on the distance of the rupture and the sensor locations. The closer the nodes to the point of rupture the higher the acceleration changes. The magnitude of acceleration change decreases as one moves away from the rupture point with distance. The peak values obtained are considered as the main parameter in identifying the rupture in the pipeline network.

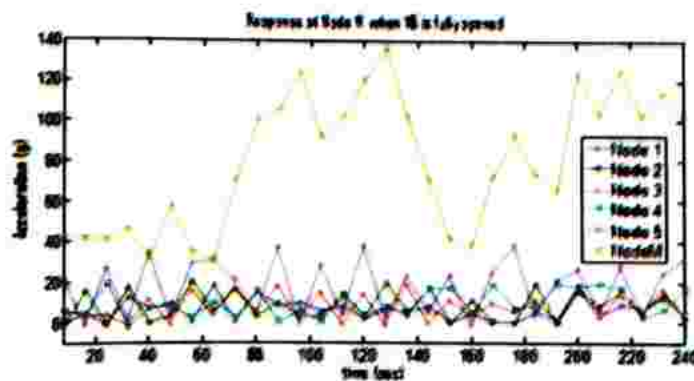


Figure 6: A plot of acceleration with time when V6 was fully opened

5.0 Conclusion

In this research work, a water-pipe rupture detection method based on time-correlated acceleration data collected using MEMS-sensor network from different joints in the water distribution system was developed. It uses MEMS accelerometers for the measurement of acceleration on the pipe surface to determine induced vibration caused by rupture. Experimental observation shows that there is sharp change in acceleration of water flow which is always accompanied by a sharp change in induced vibration of the pipe at the corresponding locations along the pipe length. The ruptured segment of the system shows a distinctly different transient response compared to the responses associated with other common ambient forces.

The difference in acceleration data collected from each network joint shows that acceleration of water flow in a network tends to be higher in a sloppy area. The results show that it is possible to detect rupture in a water pipeline by time-correlated acceleration data analysis.

5.1 Recommendation for Further Studies

The further work will encompass the expansion of the experimental test bed to create more sensor nodes and valves and allow the system to stay for longer period. Further studies are needed to effectively analyze situations where there are multiple ruptures occurring at the same time in the water distribution system. Rupture events should better be analyzed in frequency domain instead of time domain as to show discrepancy between signal from earthquake and ambient noise from that of pipe rupture event.

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Effective Control of Auger Recombination in Silicon Solar Cell

¹Uzoma Ifeanyi Oduah, ²Wu Yang

¹Department of Applied Physics, Faculty of Science, University of Lagos, Lagos, Nigeria.

²Optik Design, Technische Universität Ilmenau, Germany.

uoduah@unilag.edu.ng; uzoma_i_oduah@yahoo.com

Yang.wu@tu-ilmenau.de; yangwu@hotmail.de

Abstract Silicon Solar cells efficiency 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 Nano-crystals and the value of the potential well surrounding it, to control the Auger recombination by modifying the Nano-crystal surface and size. Numerical modelling and simulation are 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 315K. This signifies an enhancement in the efficiency of the device by 8.3% of its initial value.

Keywords Auger recombination, Auger ionization, Auger parameterization, Solar cell, Exciton

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. Previous study reveals that there is a direct relationship between the auger recombination and the efficiency of silicon solar cell [1, 2]. 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. 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. 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. Among other factors, recombination is associated with the lifetime of the material, and thus of the solar cell. Previous study reveals that auger recombination is a reverse ionization

process which involves three carriers [3]. 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 [4]. Also, these recombination losses affects 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 is classified according to the region of the cell in which it occurs.

Here we evaluate the recombination at 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, we consider processes that will promote the generation of electron-

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:

$$U_{ehh} = C_p n p^2 \quad (2)$$

Where C_p is the auger coefficient.

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

$$U_{Auger} = C_n n^2 p + C_p n p^2 \quad (3)$$

Auger recombination life time in n-type silicon under low injection ($\tau_{Auger, l}$) and injection and high injection ($\tau_{Auger, h}$) is given by:

$$\tau_{Auger, l} = \frac{1}{C_p n b} \quad (4)$$

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

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

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

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 shows that lifetime can change when wafers are processed at high temperature or subjected to certain treatments. In this research, the Zochralski method was applied with some modifications. 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 [6 8].

A. The 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) or All Back Contact (ABC) also referred to as Interdigitated Back Contact (IBC) solar cells 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 [9 12].

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 is compared and used as bases to evaluate the performance efficiency of the solar cell. The applied parameterization model for the complete intrinsic recombination is shown in equation 8 and 9 below [13]:

$$T_{int,adc} = \frac{\Delta n}{(np - n_{eff}^2)(2.5 \times 10^{-21} g_{eeh} n_0 + 8.5 \times 10^{-22} g_{eeh} p_0 + 3.0 \times 10^{-29} \Delta n^{0.92} + B_{eeh} B_{low})} \quad (8)$$

The enhancement factors described by

$$g_{eeh}(n_0) = 1 + 13 \left[1 - \tanh \left(\left(\frac{n_0}{N_{eeh}} \right)^{0.66} \right) \right]$$

$$g_{eeh}(p_0) = 1 + 7.5 \left[1 - \tanh \left(\left(\frac{p_0}{N_{eeh}} \right)^{0.63} \right) \right]$$

All the variables are described in Table 1

Table 1: Description of parameters for equation 8

PARAMETER	DESCRIPTION
N	Electron density (cm^{-3})
P	Hole density (cm^{-3})
n_0	Equilibrium electron density (cm^{-3})
p_0	Equilibrium hole density (cm^{-3})
Δn	Excess carrier density (cm^{-3})
n_i	Lowly doped and lowly injected silicon, $9.7 \times 10^9 \text{ cm}^{-3}$ at 300 K
n_{eff}	Effective intrinsic carrier concentration (cm^{-3})
B_{low}	Radiative recombination coefficient for lowly doped and lowly injected silicon, $4.73 \times 10^{11} \text{ cm}^3 \text{ s}^{-1}$ at 300 K
B_{rel}	Relative radiative recombination coefficient for lowly doped and lowly injected silicon
N_{amb}	$3.3 \times 10^{11} \text{ cm}^{-3}$
N_{amb}	$7.0 \times 10^{11} \text{ cm}^{-3}$

A. The Impact of Temperature on Auger Recombination

At tropical locations where intense sun leads to elevated temperatures, the impact of Auger recombination is high. Temperature dependance of auger recombination has previously been studied by [14]. This is very important as carrier injection level is very dependent on temperature. Samples of Boron-doped wafer of 300 μm p-type with thickness of 0.0421 cm. Grown by Czochralski method were studied. Boron doping concentration of $5 \times 10^{15} \text{ cm}^{-3}$ was applied to achieve carrier lifetime measurements of excess carrier densities up to $5 \times 10^{16} \text{ cm}^{-3}$ with a high injection. Using plasma enhanced chemical vapour deposition technique, Silicon nitride films were applied on the surface for passivation. The carrier lifetime measurements were obtained with the aid of a modified temperature and injection dependent quasi-steady state photoconductance carrier lifetime apparatus. The study demonstrated that the ambipolar auger coefficient decrease between 243K and 303K, and then remain approximately constant at higher temperatures. In this research, the auger lifetime in crystalline silicon has been measured under high injection conditions using an injection and temperature dependent photoconductance apparatus, across a temperature range from 240K to 475K. The corresponding ambipolar Auger coefficient was also found to have a value of $1.62 \times 10^{30} \text{ cm}^3/\text{s}$ at 300K at an injection level of $5 \times 10^{15} \text{ cm}^{-3}$ in line with previous reports. The Auger coefficient was found to decrease between the ranges of 240K to 300K, and remain approximately constant up to about 475K.

A. The Impact of Size and Shape of The Microscopic Confinement Potential to Auger Recombination

The oscillatory theoretical dependence of the rate of Auger ionization on the Shape and size of the Nano-crystals forms the basis for this study. In accordance with the report of George E. Cragg and Alexander L. Efros, the size and shape of the microscopic confinement potential affects the non-radiative auger decay rate of confined carriers [15]. The impact of size and shape of microscopic confinement potential is a major factor in the control of Auger recombination. 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 Nano-crystal sizes the non-radiative auger processes are strongly suppressed.

A. 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}

$$\frac{1}{\tau_{\text{eff}}} = \left[\frac{1}{\tau_{\text{SRH}}} + \frac{1}{\tau_{\text{Auger}}} + \frac{1}{\tau_{\text{rad}}} \right] + \frac{1}{\tau_{\text{Surface}}} \quad (9)$$

τ_{SRH} is the Shockley-Read-Hall Recombination Lifetime

τ_{Auger} is the Auger Recombination Lifetime

τ_{rad} is the Radiative Recombination Lifetime

τ_{Surface} is the Surface Recombination Lifetime

The resulting effective lifetime is dominated by SRH recombination at low injection and Auger recombination at high injection level [16-18].

3.0 Results and Discussion

In figure 2, it can be deduced that with decreasing $S_{\text{eff, rear}}$ the contribution of the Auger recombination increases significantly, reaching about 35% of the total $J_{\text{rec, mpp}}$ at $S_{\text{eff, rear}}$ equals 12 cm/s. However, by reducing $S_{\text{eff, rear}}$ from 1000 cm/s to 10 cm/s, the minority carrier density in the bulk and in the emitter region is increased by more than one order of magnitude.

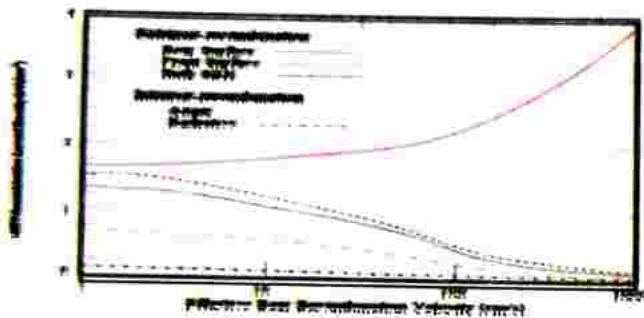


Figure 2. Comparison of the various Recombination Mechanisms

Figure 2 shows various recombination mechanism considering the recombination current density $J_{\text{rec, mpp}}$ at the Maximum Power Point, as a function of the effective rear surface recombination velocity $S_{\text{eff, rear}}$.

This confirms the influence of Auger recombination on the mpp recombination current density.

The result achieved using silicon wafer with Nanocrystals of CdZnSe/ZnSe is as shown in figure 3. The device Auger recombination was heavily suppressed compared to figure 2.

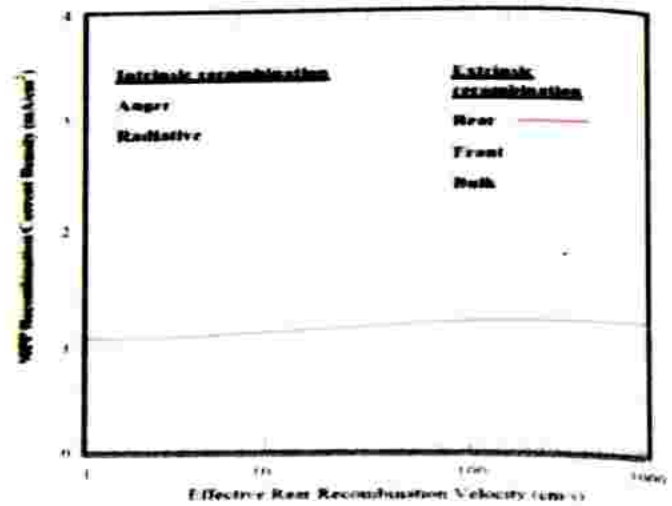


Figure 3. Suppression of Auger Recombination
The control of the abruptness of the interfaces modified the carrier relaxation and recombination.

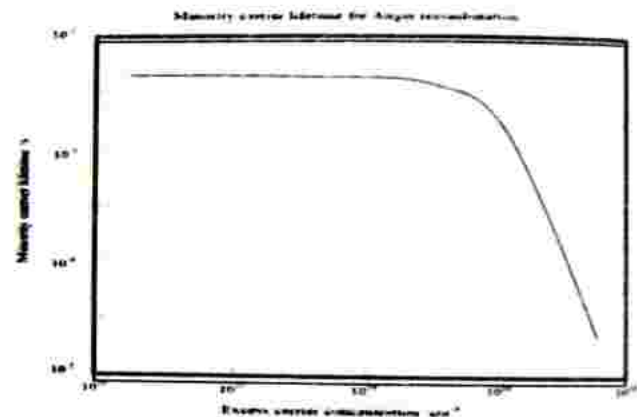


Figure 4. Auger Recombination Lifetime

The auger carrier lifetime depends on the inverse of the carrier density squared. It can be seen on Figure 4 that Auger recombination shows a stronger dependence with the injection level than radiation lifetime [19, 20].

More so, the silicon wafer with Nanocrystals of CdZnSe/ZnSe demonstrates strong extension of generated carrier lifetime as shown in figure 5.

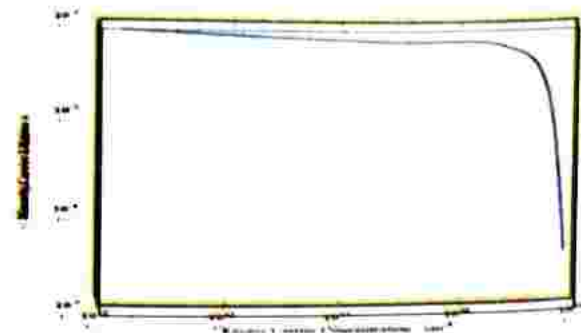


Figure 5. Extended Carrier Lifetime

The efficiency of the developed Silicon Solar cell device was measured. The recorded overall efficiency result improved from 18.7% to 20.25% at 315K.

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.

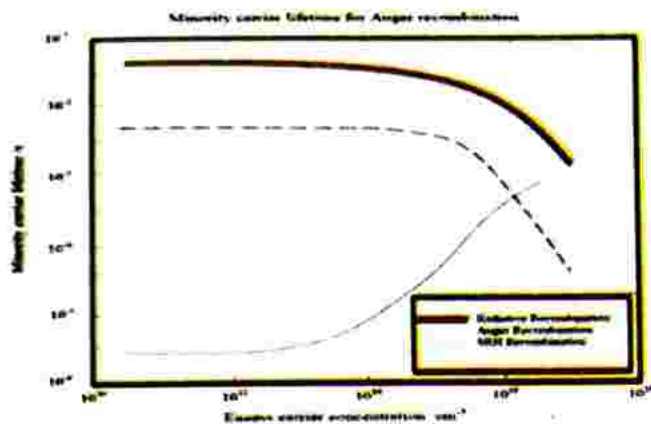


Figure 6: Comparison of Bulk recombination lifetime curves for Auger recombination, Radiative recombination, and Shockley Red Hall recombination.

In figure 6, the Bulk recombination lifetime variations with carrier injection density is shown to be more uniform at lower carrier densities than at higher carrier densities.

4.0 Conclusion

In this research, it was demonstrated that Auger recombination in a silicon solar cell can be controlled by modifying the Nano-crystals 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. So 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 Nano-crystals of CdZnSe/ZnSe. 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.

The patenting of this novel technology is in progress.

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