Theoretical models and simulation of optoelectronic properties of a-Si-H PIN photosensors

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Abstract— **this research aims to study and discuss the theoretical models and simulation of optoelectronic properties of a-Si-H PIN photosensors based on Shockley–Read-Hall assumptions. The variation of carrier life time, recombination and generation rates as a function of the intrinsic layer (I-layer) thickness will be simulated using MATLAB program. The effects of intrinsic layer thickness on electrons and holes concentration, collection efficiency and short circuit current density have been studied and analyzed. It has been found that as the thickness increased, the parameters: recombination rate, generation rate, internal electric field, electrons and holes concentration, carriers' life times, and short circuit current density, were subjected to some variations.**

Keywords-Silicon photosensors; PIN photodiode; amorphous Si; optoelectronic properties.

I. INTRODUCTION

Amorphous silicon (a-Si) has been favored for its good characteristics compared to crystalline silicon and polysilicon, such as higher absorption coefficient, better response in low light environment and lower cost material for photosensors. The disorder inherent in the material creates many charge defect states that impede carrier transport. The presence of charged defects in the optically active material, which is the intrinsic layer (I-layer) in the a-Si:H PIN photodiode reduces the built in electric field [1, 2] and consequently increases the local optical absorption coefficient [3], also reduces the free carriers mean lifetime, and decreases the response time, while on the other hand improves the responsivity and sensitivity. High responsivity and sensitivity of photosensors with low dark current are required increasingly for short distance optical communications, optical storage systems, active pixel sensors and imaging sensors [4, 5].

The usual way of operating an amorphous silicon PIN diode to detect photons is to apply a reverse bias on the diode and to measure the signal which is induced by the motion of the photo-generated charge carriers; i.e., the radiation-induced information is acquired by comparing the leakage current before irradiation and signal current after irradiation. Thus, the leakage current limits the sensitivity of the PIN diode and the transient behavior of the leakage current is modeled by using two different components of the thermal generation and the injection currents [6]. The main idea is the time-dependent variation of the electric field at interface, which originates from the variation of the ionized dangling bond density due to emission of trapped charge; this determines the behavior of the transient leakage current. The bias-dependent transient and steady-state behavior of dark current in hydrogenated amorphous silicon (*a*-Si:H) PIN photodiode have been developed by considering the depletion of electrons from the I-layer and carrier injection through P–I interface. For photodiodes that have very good junction properties, the high initial dark current decreases with time monotonously and reaches a plateau. However, in case of poor junctions, the injection current can be the dominating mechanism for transient leakage current at relatively high biases, the dark current decays initially and then rises to a steady-state value [7]. The mid-gap states energy levels and their spatial distribution in I-layer and at P-I interface can be obtained [8, 9] from the transient dark current and steady-state thermal generation current. Emission of carriers from the P-I and N-I interface and thermal generation in I-layer, which is a voltage dependent at low biases, mainly contributes to the dark current. The optical and electronic properties of a-Si:H PIN determine transient current relevance for device application.

The recombination via dangling bonds as the main recombination centers and transport through localized states contributes to the transient current as described [1, 2]. The influence of deeply-trapped charge on the transient photocurrent has been studied by various authors using the transient photocurrent method and the constant photocurrent method [6, 7]. It is found that the dangling bond states energy levels distributed in range from shallow to deep levels and activated at low bias voltages and visible pulses illumination, are responsible for the characteristic photodiode response shape [8]. The advantages of PIN photodiode and MOS structure have been combined together to produce lateral PIN photosensors with maximum photocurrent and low dark current and achieved high sensitivity and responsivity with low voltage bias [9]. LPIN photodiode fabricated in CMOS processes [10] achieved bandwidth compatible with 10 Gb/sec and even higher data rate [11].

This research aims to study and analyze the a-Si-H PIN photosensor based on Shockley-Read–Hall assumptions. The variation of carrier life time, recombination and generation rates as a function of I-layer thickness will be simulated using MATLAB program. The effect of I-layer thickness on electron and holes concentration, collection efficiency and short circuit current density will be discussed.

II. STRUCTURE AND PHYSICAL MODEL

The basic structure of a thin-film PIN photodetector is shown in Fig. 1. The photodetector built of a P^--type silicon film (which is known the intrinsic- layer) into which a P^+ region and N^+ region are usually formed by ion implantation. An ITO deposited on the top P^+ layer which is used as transparent gate electrode. The silicon-film thickness should be sufficiently thick to allow a large fraction of the incident light to be absorbed. The silicon-film thickness, P^-, is 500 nm with low carrier concentration of 10^{14} cm^{-3}. Thickness of the contacts N^+ and P^+ regions is 10 nm each, with doping concentration of 10^{18} cm^{-3}.

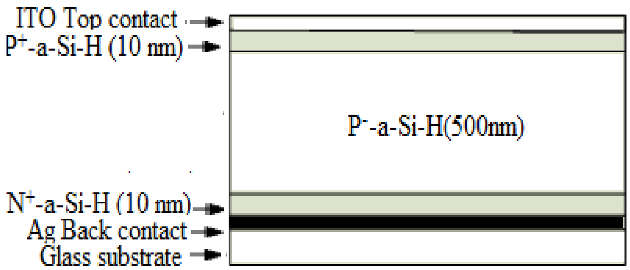


Figure 1 Schematic diagram of thin-film PIN photodetector

III. MATHEMATICAL MODEL BASED ON SHOCKLEY – READ – HALL (SRH) ASSUMPTIONS

The structure model is considered a single junction cell with structure of glass/ITO/PIN/metal contact, and with the following assumptions:-

1- Instead of assuming a constant generation rate of charge carriers through I-layer as [12], it is consider that the generation rate depends on the position within I-layer.

2- For designing a PIN type single junction device, I- layer is considered to be the only active layer.

3- To calculate the carrier concentration, it must be assumed that the capture time at the dangling bond densities is variable.

4- All results are achieved at AM1.5 illumination, the wavelength λ is selected to 400 nm and implicitly assumed the reflection coefficient R=0. When incident light falls on the device surface (P^+), light absorption in the channel produces electron–hole pairs. Pairs produced within the diffusion length will eventually be separated by the electric field, leading to current flow in the external circuit. In PN reverse-biased junction, there is drift current under the internal reverse-biased electric field, directly contributing to the external current. Diffusion and drift coexist in carrier-transport processes throughout the channel. The number of absorbed photons that produce electron hole pairs can be calculated [13]:

$$n_{pi} = \int f(\lambda)\alpha_{pi}(\lambda)\frac{\lambda}{hc}d\lambda \quad (1)$$

Where n_{pi} number of absorbed photons at the intrinsic layer, $f(\lambda)$ illumination intensity at AM1.5, $\alpha_{pi}(\lambda)$ the absorption coefficient , h plank constant and c is the light velocity . SRH assumptions suggest that recombination may occur by four mechanisms through the energy gap: recombination with single level trap, recombination at the end of the gap, recombination at the surfaces and recombination at the dangling bonds. Following the above assumptions; free carrier concentration, the electric field across the intrinsic layer, recombination rate, carrier life time, can be calculated using the parameters given in table 1 and solving the steady state continuity and transport equations [12]

TABLE1: PIN photosensor parameters used in the analysis

Parameters	Value
M^- ($e+D^\circ \rightarrow D^-$) ($cm^{-1}v^{-1}$)	2.5×10^{8}
M^+ ($h+D^\circ \rightarrow D^+$)($cm^{-1}v^{-1}$)	4×10^{7}
α_{pi} (cm^{-1})	$6x10^{4}$
μ_n (cm^2/v.sec)	20
μ_p (cm^2/v.sec)	4
V_{bi} (Volts)	1.2
J_o (A/cm^2)	10^{-12}
η (ideality factor)	1.4

$$G_n(x) - R_n(x) = -\frac{1}{e}\frac{d}{dx}J_n(x) \quad (2)$$

$$G_p(x) - R_p(x) = \frac{1}{e}\frac{d}{dx}J_p(x) \quad (3)$$

$$J_n(x) = e\mu_n n(x)E_o \quad (4)$$

$$J_p(x) = e\mu_p p(x)E_o \quad (5)$$

Where: G(x): generation rate, R(x): recombination rate, e: electronic charge, $J_n(x)$: electrons current density, $J_p(x)$: holes current density, μ_n: electrons mobility, μ_p: holes mobility and E_o is the internal electric field. Using SRH assumptions, the recombination rates that occur through negative and positive defects can be calculated as:

$$R(x) = [p(x)n(x) - n_i^2]Cv\sigma_n\{\frac{1}{(n(x)+C_p)}\int_{Etpa}^{Etna} G_a(E)dE + \frac{I}{(C_n+p)}\int_{Etpd}^{Etnd} G_d(E)dE\} \quad (6)$$

Where E_{tna}, E_{tpa}, E_{tnd}, E_{tpd} are the acceptor and donor defect levels for electrons and holes respectively, C_n and C_p are the cross section of optical emission for electrons and holes respectively, ν frequency of incident light and C=(σ_c/σ_n) where σ_c and σ_n are the cross section of optical emission for free and neutral charges respectively.

Using the boundary condition $n_x = 0$ and $p_{x=L} = 0$, Eqs. (2) and (3) can be solved analytically to get:-

1- Electrons concentration (n(x))

$$n(x) = \left[C_2 + \frac{1}{\mu_n|E_o|}G(0)\right]\left[1 - e^{-bx}\right] - \frac{e^{-bx}}{\mu_n|E_o|}\int_0^x e^{bx}G(x)dx \quad (7)$$

2- Holes concentrations (p(x))

$$p(x) = \tau_p G(x) - \frac{\tau_p n(x)}{\tau_n} + \tau_p\mu_n|E_o|\frac{dn(x)}{dx} \quad (8)$$

$$C_2 = \frac{G(0)}{\mu_n|E_o|} - \frac{\tau_{no}\exp(-bL)\int_0^L \exp(bx)G(x)dx}{L_p(1-\frac{L_n}{L_p})} \quad (9)$$

$$b = \frac{L_n - L_p}{L_n L_p} \quad (10)$$

Where L_n and L_p are drift lengths given by:-

$$L_n = \mu_n\tau_n|E_o| , L_p = \mu_p\tau_p|E_o| \text{ and } E_o = V_o/L \quad (11)$$

τ_n , τ_p : electron and hole life times respectively , V_o the built in voltage and L is I-layer thickness. τ_n and τ_p can be calculated [14] as a function of the defect density: $N_d=(M/\mu\tau)$. Where: M is constant parameter given in table 1 for negative and positive charge defects.

Figure 2 shows the simulation result of carrier concentrations as a function of I-layer thickness. From figure 2-a ; it is clear that there is no electrons accumulation at P^+-I interface, while they accumulate at the N^+-I interface (more than $10^{16}cm^{-3}$) which yields high charge gradient. This charge gradient will setup diffusion current that is balanced by drift current build up by the field gradient. The holes accumulation (figure 2-b) is not linear. It falls down to zero at 400 nm length due to recombination. The difference between electrons and holes concentrations comes from the dissimilarity of amorphous silicon.

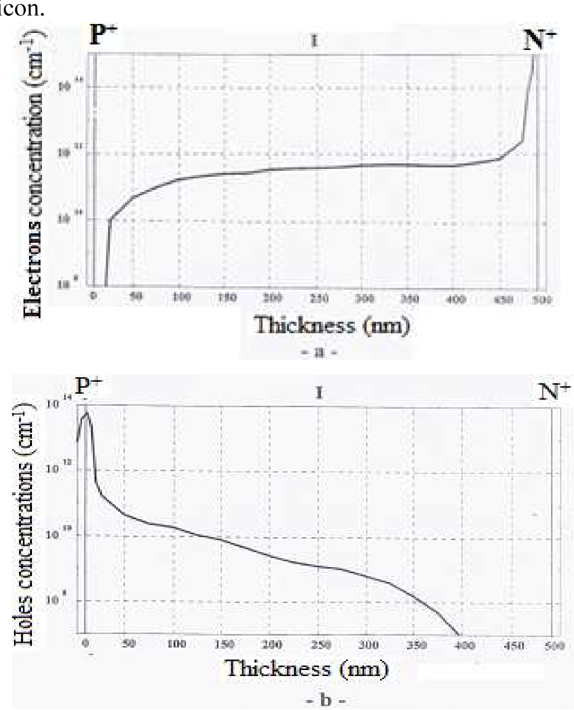


Figure 2: Variation Carriers concentration with thickness: a- Electrons b- Holes

Figure 3 shows the electric field intensity as a function of distance through I-layer. The internal electric field intensity is high at interfaces (>10^5 V/cm) due to high space charge densities at these regions. Increasing the electric field intensity will enhance the drift current at the interfaces. On the other hand increasing the drift current will cause the diffusion current to be increased, the total current will be constant. The minimum electric field falls down less than 10^4 V/cm at 400nm length; this is called the critical electric field (E_c) and can be calculated as: $E_c= (KT/qL_p)$ and defined as the minimum electric field that enhance the drift current.

Most of the defect states can be found at the bottom of the energy gap. For this reason the diffusion current of holes is less than of electrons. The initial recombination process occurs from electrons defect levels to holes defect levels near Fermi level. Figure 4 shows the recombination rates as a function of distance as the same conditions given before. Most of the recombination happens near P^+-I and N^+-I interfaces where the holes and electrons concentrations are maximum. Maximum loss of photogenerated carriers happens there.

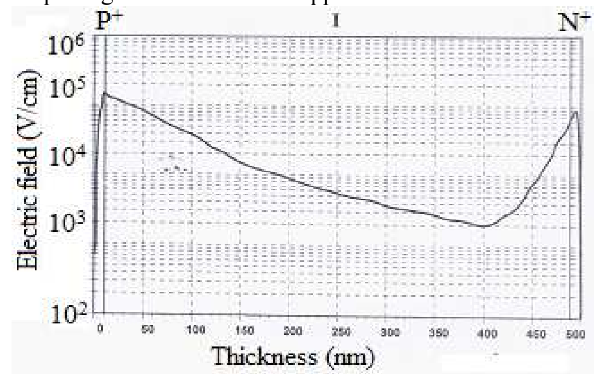


Figure 3: Variation of electric field with thickness.

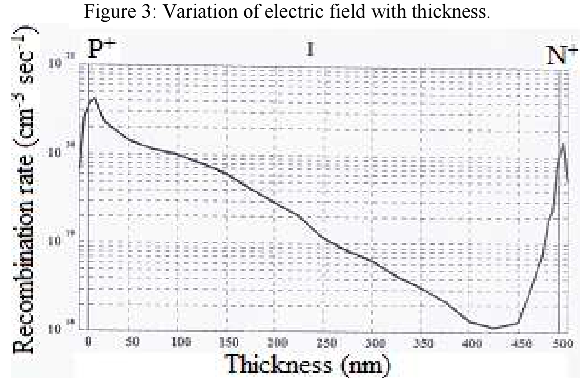


Figure 4: variation of recombination rate with thickness

Knowing the recombination rates and the carriers concentrations, the carriers life times can be calculated as: $\tau_n=n(x)/R(x)$ and $\tau_p=p(x)/R(x)$. It has been considered before [15] that the carrier life time is constant, but It has been proved in this research that the carriers' life times are variable and are a function of device thickness as shown in figure 5. It is noticed that at the doped layers (P^+ and N^+) the majority carriers have long life times while the minority carriers have a very short life times. Due to the dissimilarity of amorphous silicon the variation of carriers life times are different. The life times of holes carriers is almost constant, while life times of electrons carriers varies almost linearly with distance.

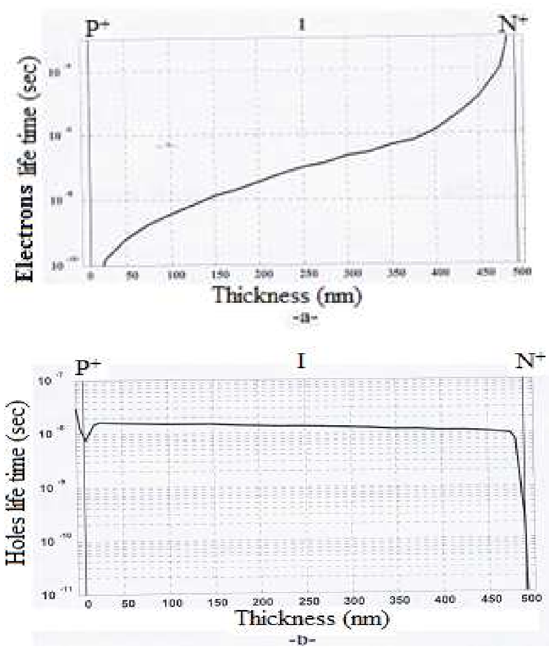
Figure 6 shows the variation of simulated photogenerated short circuit current density with distance. The photogenerated current density increases as the distance increases and saturated at maximum value (18 mA / cm^2) starting at 500 nm. The light is applied from the P^+ side when the minority carriers are the electrons that move to the other side where there are no holes carriers that cause the photogenerated current to be constant and maximum.

The collection efficiency (χ) of a PIN photodiode is defined as the ratio of the number of charge carriers contributed from the photovoltaic current to the total number of photogenerated charge carriers. The collection efficiency plays an important role in the PIN photodiode performance and it is calculated as followed [15].

$$\chi = \frac{\int_0^L \{G(x) - R(x)\}\,dx}{\int_0^L G(x)\,dx} \qquad (12)$$

Where, L: is the distance inside the I- layer and

$$R(x) = \frac{n(x)}{\tau_n} + \frac{p(x)}{\tau_p} \qquad (13)$$



life times with thickness: a- Electrons,
b- Holes
Figure 5: Variations of carriers

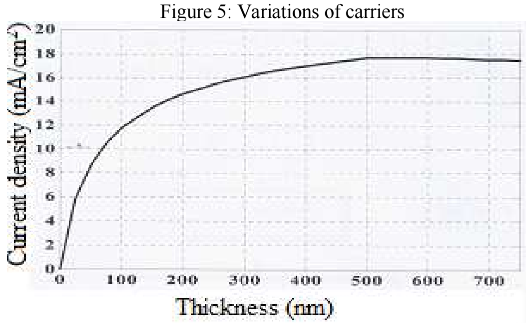


Figure 6: Variation of current density with thickness

The collection efficiency has been calculated as a function of I-layer thickness for different values of defect density (N_d) using equation (12), as shown in figure 7. It is clear that as the I-layer thickness increased the collection efficiency decreased. It can be noticed that the decrease in the efficiency is steeper with higher values of N_d. This can be explained that the reduction in the collection efficiency becomes more countable when the defect density is increased particularly when the layer thickness is less than 150 nm.

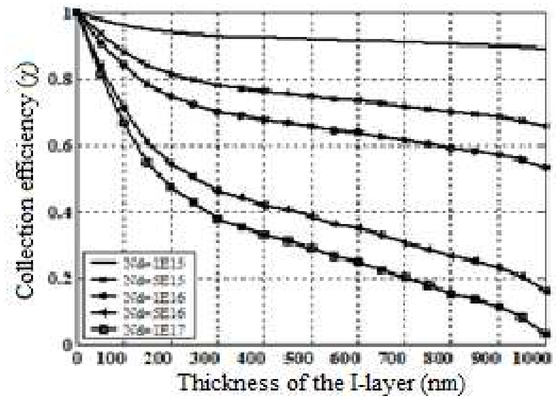


Figure 7: Collection efficiency (χ) as a function of I-layer thickness for five different defect densities.

IV. CONCLUSIONS

The disorder inherent in amorphous silicon creates many charge defect states that impede carrier transport. It is found that the dangling bond states energy levels distributed in a range from shallow to deep levels are responsible for characteristic photodiode response shape. Shockley-Read-Hall assumptions were employed to derive a mathematical model for a-Si-H PIN photodiode sensors. The mathematical model was formulated analytically using MATLAB computer program and found that:

1- The concentration of photogenerated electrons and its life times increased as I-layer thickness increased. The concentration of photogenerated holes gradually decreased to minimum at thickness 400 nm while the life times remained almost constant over a wide range of I-layer thickness.

2- The recombination rates decreased as the thickness increased and exhibited minimum value for thickness around 425 nm.

3- The simulated photogenerated short circuit current density increased as the thickness increased and it is saturated beyond 500 nm.

4- The collection efficiency decreased as the I-layer thickness increased particularly when the layer thickness is less than 150 nm. The decrease is a function of the defect density and is steeper at higher values of the defect density.

REFERENCES

[1] W. Fuhs "Recombination and transport through localized states in hydrogenated amorphous and microcrystalline silicon" J. Non-Cryst. Solids, Vol. 354, 2008, pp. 2067-2078.

[2] S.R. Dhariwal, M. Smirty "On the sensitivity of open-circuit voltage and fill factor on dangling bond density and Fermi level position in amorphous silicon p-i-n solar cell" Sol. Energy Mater. Sol. Cells, Vol. 90, 2006, pp. 1254-1272.

[3] E. A. Schiff, H. T. Grahn, R. I. Devlen, J. Tauc, S. Guha "Picosecond photocarrier transport in hydrogenated

amorphous-silicon PIN diodes" IEEE Trans. Electron Devices, Vol. ED-36, 1989, pp. 2781- 2784.
[4] G.F. Della Betta, S. Ronchin, A. Zoboli, N. Zorzi "High-performance PIN photodiodes on TMAH thinned silicon wafers" Microelectronics J. Vol. 39, 2008, pp. 1485–1490.
[5] S.M. Csutak, J.D. Schaub, W.E. Wu, J.C. Campbell "High-speed monolithically integrated silicon receiver fabricated in 130 nm CMOS technology" IEEE Photonics Technol. Lett. 14, 2002, pp. 193–196.
[6] H. J. Kim and G. Cho "Analysis of the transient leakage current of an a-Si:H PIN diode" Journal of the Korean Physical Society, Vol. 40, No. 5, 2002, pp. 908-912.
[7] S. A. Mahmood and M. Z. Kabir "Modeling of transient and steady-state dark current in amorphous silicon PIN photodiodes" Current Applied Physics, Vol. 9(6), 2009, pp. 1393–1396.
[8] R.V.R. Murthy, V. Dutta "Underlying reverse current mechanisms in a-Si: H p+-i-n+ solar cell and compact SPICE modeling" J. Non-Cryst. Solids, Vol. 354, 2008, pp. 3780-3784.
[9] W. F. Mohammed, M. M. Ali, M. N. Al-Tikriti, K. Kaleel "The effects of MOS layers on sensing properties of MOS photosensor" International Journal on Smart Sensing and Intelligent Systems, Vol. 6, No.3, 2013, pp.1102.
[10] V. Gradišnik "Characterization of a-Si:H P-I-N photodiode response" J. of Microelectronics, Electronic Components and Materials, Vol. 42, No. 1, 2012, pp. 23 – 28.
[11] Guoli Li, Yun Zeng, Wei Hu and Yu Xia "Analysis and simulation for current–voltage models of thin-film gated SOI lateral PIN photodetectors" Optik, Vol. 125 (1), 2014, pp. 540 – 544.
[12] M. Hack & M. Shur "Physics of amorphous silicon alloy PIN solar cell" J. Appl. Phys, Vol. 58(2), 1985.
[13] S. Cuha & A. Banerjee, "Amorphous silicon alloy photovoltaic research – present and future" Program Photovoltaic Res. Appl., Vol. 8, 2000, pp. 141-150.
[14] W. F. Mohammad, M. Hammodi and M. N. Al-Tikriti "Simulation of photogenerated current of PN silicon photodetector enhanced by impurity photovoltaic effect" Renewable and Sustainable Energy Reviews, Vol. 26, 2013, pp. 408–413.
[15] P. Stulik and J. Singh "Calculation of collection efficiency for amorphous silicon solar cells" J. of non-Crystalline Solids, Vol. 242, 1998, pp. 115-121.