

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-

hole pairs while minimizing the recombination of electron-hole pairs. Previous reports on the statistics of carrier recombination in relation to Auger recombination have 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 [5]. 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 photo stability of silicon solar cell against ionization. This is advancement in the fabrication of silicon beyond state of art technology.

2.0 Materials and Methods

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. 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 repulsive coulomb interactions provide an additional driving force that in combination with an energy gradient at the hetero-interface, keeps electrons and holes apart. The measured time resolved photoluminescence spectra indicates a transient red shift of the PL maximum indicating partial separation between electrons and holes which produces the exciton-

exciton repulsion. Another step is to manage Auger auto-ionization and electron thermalization in the device. The Nano-crystal can be Auger auto-ionized only if the band offset in the conduction or valence band is smaller than the Nano-crystal band gap energy. But by removing the photo-excited hole from the Nano-crystal to the Nano-crystal surface, the rate of electron thermalization is reduced. Also removing the hole from the Nano-crystal decreases the probability of energy transfer from the electron to the hole which again reduces Auger-like thermalization process. Consequently the magnitude of the auger recombination at high carrier injection density was controlled. Also 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 presented in Figure 1.

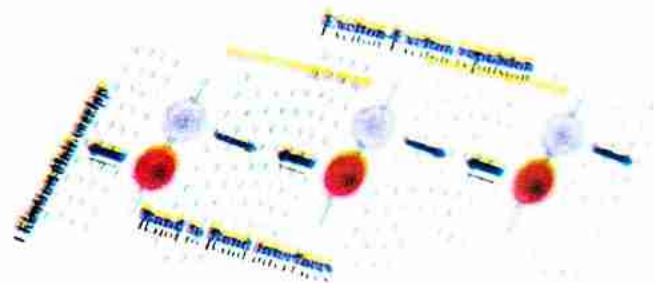


Figure 1: Suppression of Auger recombination in a Silicon Solar Cell achieved through manipulation of the Effective Spatial Extent of Electronic Wave Functions.

2.1 Theory/Calculations

A. 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:

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:

$$\tau_{Auger-l} = \frac{1}{C_p N_D} \quad (4)$$

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

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

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

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]:

$$T_{intr,adv} = \frac{\Delta n}{(np - n_{i,eff}^2)(2.5 \times 10^{-31} g_{eeh} n_o + 8.5 \times 10^{-32} g_{eeh} p_o + 3.0 \times 10^{-29} \Delta n^{0.92} + B_{rad} B_{low})} \quad (8)$$

The enhancement factors described by:

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

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

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, $4.73 \times 10^{15} \text{ cm}^3 \text{ s}^{-1}$ at 300 K
B_{rel}	Relative radiative recombination coefficient for lowly doped and lowly injected silicon
$N_{0,rel}$	$3.3 \times 10^{14} \text{ cm}^{-3}$
$N_{0,rel}$	$7.0 \times 10^{14} \text{ cm}^{-3}$

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 dependence 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 30 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}

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

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

τ_{Auger} is the Auger Recombination Lifetime

τ_{rad} is the Radiative Recombination Lifetime

$\tau_{Surface}$ 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 12cm/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.

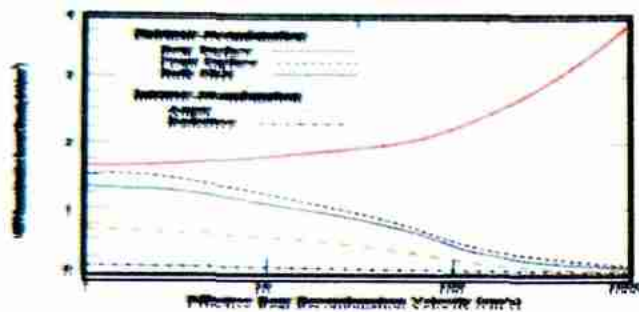


Figure 2. Comparison of the various Recombination Mechanisms

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.

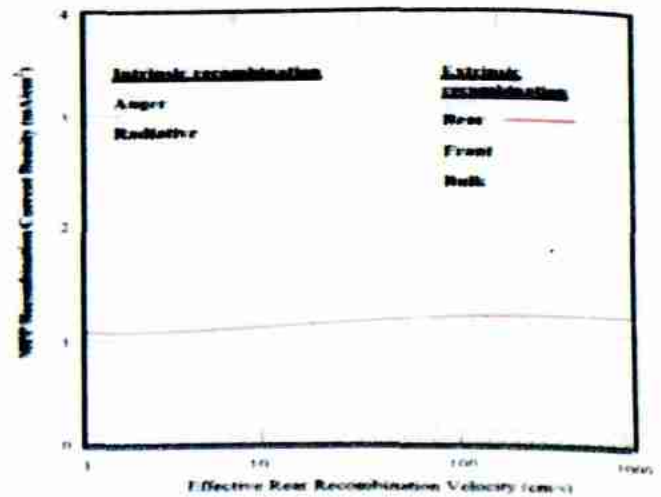


Figure 3. Suppression of Auger Recombination
The control of the abruptness of the interfaces modified the carrier relaxation and recombination.

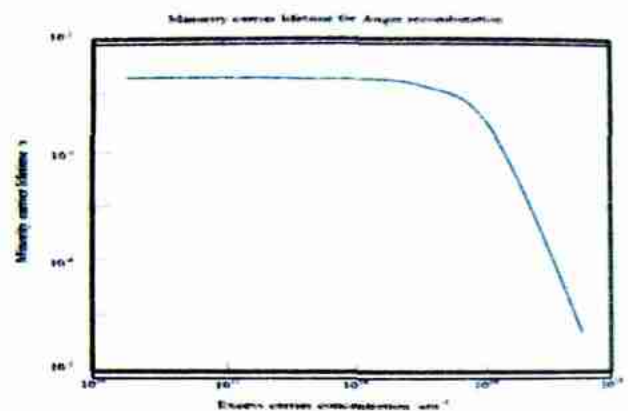


Figure 4. Auger Recombination Lifetime

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.

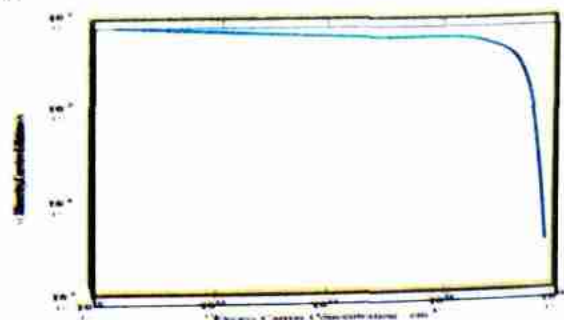


Figure 5. Extended Carrier Lifetime

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.

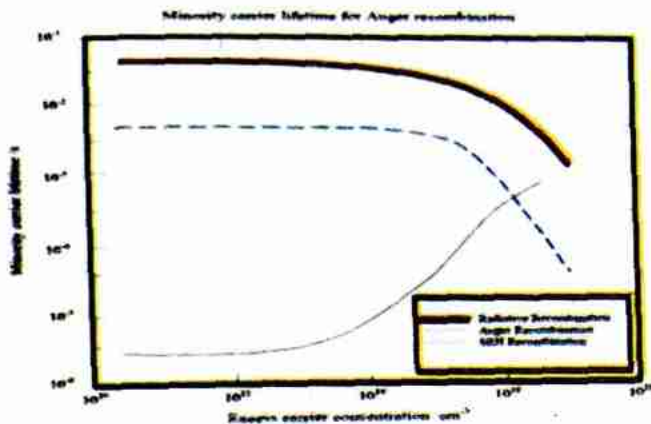


Figure 6: Comparison of Bulk recombination lifetime curves for Auger recombination, Radiative recombination, and Shockley Red Hall recombination.

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.

Acknowledgment

Our gratitude goes to the Nanotechnology Laboratory team of Technische Universität Ilmenau, Germany, for providing the laboratory facilities for this experiment. We are also grateful to the Research and Innovations team of University of Lagos, Nigeria, for their guidance during this research work.

References

- Landsberg P.T. "Trap-Auger recombination in silicon of low carrier densities". *Journal of Applied Physics*. 1987. Vol. 50. pp. 745-747.
- [2] Dziwior J., and Schimd W. "Auger coefficient for highly doped and highly excited silicon" *Applied Physics Letters*. 1997. Vol. 31 no.5, pp.346- 348.
- [3] Err M.J., and Cuevas A. "General parameterization of Auger recombination in crystalline silicon" *Journal of Applied Physics*. 2002. Vol. 91. pp. 2473-2480.
- [4] Altermatt P.P., Schmidt J., and Heiser G. "Assessment and parameterization of coulomb-enhanced auger recombination coefficients in lowly injected crystalline silicon" *Journal of Applied Physics*. 1997. Vol. 82. pp. 4938-4944.
- [5] Shockley W., and Read W. "Statistics of the recombinations of holes and electrons". *Physical Review*. 1952. Vol. 87. pp. 835- 842
- [6] Hangleter A. and Hacker R. "Enhancement of band-to-band Auger recombination by electron-hole concentration" *Physical Review Letters*. 1990. Vol. 65 pp.215- 218.

- [7] Laks D.B., Neumark G.F., and Pantelides S.T. "Accurate interband-Auger recombination rates in silicon" *Physical Review B*. 1990. Vol. 42. pp.5176-5178.
- [8] Haug A. "Carrier density dependence of Auger recombination". *Solid-State Electronics*. 1978. Vol. 21, pp. 1281-1284.
- [9] Benick J., Richter A., Hermle M., and Glunz S.W. "Thermal stability of the Al_2O_3 passivation on p-type silicon surfaces for solar cell application" *Phys. Stat. Sol. RRL*. 2009. Vol. 3. Pp. 233-235.
- [10] Schmidt J., Veith B., and Brendel R. "Effective surface passivation of crystalline silicon using ultrathin Al_2O_3 films and $\text{Al}_2\text{O}_3/\text{SiN}_3$ stacks" *Phys. Stat. Sol. RRL*. 2009. Vol. 3 pp. 287-289.
- [11] Luder T., Hahn G., and Terheiden B. "Passivation of Si Wafers by ALD- Al_2O_3 films with different surface conditioning". *Energy Procedia*. 2011. Vol.8, pp. 660-665.
- [12] Rein S. "Lifetime spectroscopy: A method of defect characterization in silicon for photovoltaic applications" Springer, Berlin, Germany. 2004. pp. 87-91.
- [13] Richter A., Werner F., Cuevas A., Schmidt J., and Glunz S.W., "Improved parameterization of Auger recombination in silicon," *SciVerse Science Direct*, Vol. 27. pp. 88-94 (2012).
- [14] Wang S. and Macdonald D. "Temperature dependence of Auger recombination in highly injected crystalline silicon" *AIP Journal of Applied Physics*. 2012. Vol. 112 No. 11 pp.3708-3710.
- [15] 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. "Non-blinking semiconductor nanocrystals" *Nature letters*. 2009. Vol. 459. pp. 686-689.
- [16] Trupke T. and Bardos R.A., "Self-consistent determination of the generation rate from photoconductance measurements". *Applied physics letters*. 2004. Vol. 85. pp. 3611-3614.
- [17] Hacker R. and Hangleiter A. "Intrinsic upper limits of the carrier lifetime in silicon". *Journal of Applied Physics*. 1994. Vol. 75. pp. 7570-7572.
- [18] Kerr M.J., and Cuevas A., "Very low bulk and surface recombination in oxidized silicon wafers". *Semicond. Sci. Technol*. 2002. Vol. 17, pp. 35-38.
- [19] Altermatt P.P., Geelhaar F., Trupke T., Dai X., Neisser A., and Daub E. "Injection dependence of spontaneous radiative recombination in crystalline silicon: experimental verification and theoretical analysis" *Applied Physics Letters*. 2006. Vol. 88, pp. 261901-261904.
- [20] Grivickas V., Noreika D., Tellefsen J.A. "Surface and Auger recombination in silicon wafers of high carrier density" *Lithuanian Physics Journal*. 1989. Vol. 29, No. 5 pp. 48-53.