Simulation of I-V Characteristics of Si Diode at Difference Operating Temperature:Effect of Ionized Impurity Scattering

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Abstract— The usage quality of Si Diode was influenced by the operating temperature. The increment of temperature caused the increased number of ionized impurities. Coulomb interaction between the impurities and the local charge carrier caused the scattering on the impurity. Furthermore, this scattering causes changes in the velocity and mobility of charge carriers. This gives an effect on the distribution of charge carriers, causing changes in the diffusion current density. In this paper, we perform the I-V characteristic of Si diode, simulated in two dimensional structure. Several temperatures (200K-473K) and also the charge carrier mobility were observed as the input parameter of the equation modelled. The simulation results show that the value of current density diffusion of Si Diodes was maximum at temperature of 200K and decreasing at a higher temperature of 473K..

Keywords— Si Diode, Ionized Impurity Scattering, I-V Characteristics.

INTRODUCTION

Diode is an electronic component that frequently used as a rectifier device in electronic circuit. One of the example is silicon (Si) diode, which used silicon as intrinsic material, added by such element of group III as impurity to make p-type semiconductor and elemen in group V to make n-type semiconductor [1]. At room temperature, the impurity that is added in silicon will receive heat energy. When the heat energy is larger than electron's bond energy, the impurity would be ionized then creates coulomb interactions between impurity and local charge carriers. These interactions cause the scattering on the impurity. Furthermore, this scattering causes changes in the velocity and mobility of charge carriers because mobility is the function of rate charge energy [2].

$$\mu = \frac{v}{\varepsilon} \tag{1}$$

Where:

μ= charge carriers mobility ($m^2/V.s$)
v= velocity (m/s)
ε= electric field (V/m)

When the temperature increases, there are more energy received by impurity and more impurity ionized. If the total of ionized impurity increases, the probability of scattering also increased then makes the value of charge carriers mobility decrease [3].

$$\mu \propto \frac{T^{\frac{3}{2}}}{N} \tag{2}$$

Where:
T= temperature (K)
N=$N_D^+ + N_A^-$ (total ionized impurity)

The fluctuation of charge carrier mobility causes the change of charge carriers concentration distribution in the silicon diode. This can affect the value of silicon diode diffusion current, because the diffusion current generated diode is the contribution of the imbalance charge carrier concentration [4]. The characteristics of diffusion currents generated on silicon diode can be observed from the I-V characteristics curve, which define relation between the density of diffusion current and the voltage applied on silicon diode [5].

The study about I-V characteristic curve silicon diode had been done by Priyanka (2013) with simulated iteration voltage data on the TED (Thermionic emissions diffusion) equation [6], so the generated current is the total of silicon diode current. Furthermore, the current degradation can not be observed at any point. In order to obtain the current value at any point. We performed simulation of silicon diode I-V characteristics on difference temperature, so that we can determine the effect of ionized impurity scattering on the resulting current diode with finite element method. Finite element method divides the domain into small triangular shaped subdomains, and the general solution is the sum of each subdomain solution [7].

METHODS

The simulation begins with making diode geometry in the form of two-dimensional, where this geometry is divided into two domains. The first domain represents p-type semiconductor, and the second domain represents n-type semiconductor. Because the simulation was performed using finite element method, this domain is divided into small triangular shaped subdomains as shown in figure 1. Based on figure 1, it is known that there are nine boundary conditions, where number 5 is the boundary between anode and metal, number 2 is the boundary between catode and metal, and number 4 and 9 boundaries are junction domain between n-type and p-type of semiconductor.

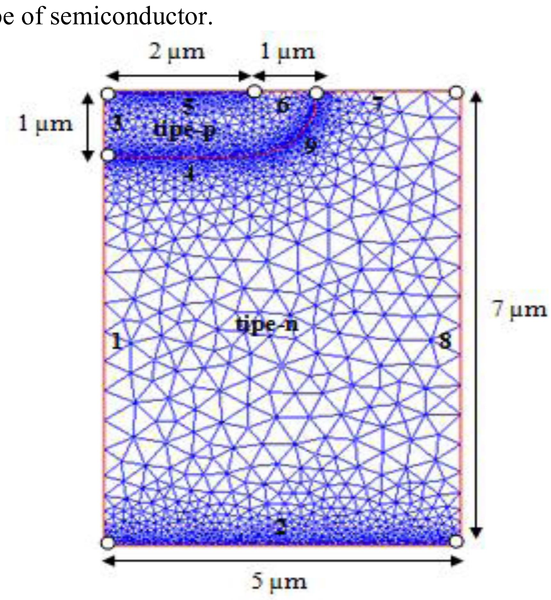


Fig.1. Geometry of Silicon diode

The second step is inserting parameter data of silicon diode. The silicon diode parameters used are vacuum permittivity, material permittivity, electron's charge, Boltzmann constant, electrons diffusion coefficient, holes diffusion coefficient, life time of electrons, life time of holes, temperature, charge carriers mobility, voltage current, and scaling factor. The voltage current is observed from 0V until 0.5V with increment of 0.02V. The temperature used in this simulation are 200K, 223K, 273K, 323K, 373K, 423K, and 473K where the charge carriers mobility changed depend on temperature.

The next step is setting the boundary condition. There are two boundary condition (Neumann boundary condition and Dirichlet boundary condition). Dirichlet boundary condition used to give boundary between contact and metal that represented in figure 1 with number 2 and 5. Dirichlet boundary condition used the following equation [8].

$$\Psi = V + \frac{kT}{q} ln\left(\frac{\frac{N}{2}+\sqrt{\left(\frac{N}{2}\right)^2+n_i^2}}{n_i}\right) \quad (3)$$

$$n = \frac{N}{2} + \sqrt{\left(\frac{N}{2}\right)^2 + n_i^2} \quad (4)$$

$$p = -\frac{N}{2} + \sqrt{\left(\frac{N}{2}\right)^2 + n_i^2} \quad (5)$$

where N in equation 3, 4, 5 are dopant concentration function that written in equation 6 [8]:

$$N = ND_n + ND_{nmax} e^{-\left(\frac{y+y1}{ch}\right)^2} - NA_{pmax} e^{-\left(\frac{y}{ch}\right)^2} \left((x<ac)+(x\geq ac)e^{-\left(\frac{x-ac}{ch}\right)^2}\right) \quad (6)$$

where *ch*:

$$ch = \frac{ju}{\sqrt{log(NA_{pmax}/ND_n)}} \quad (7)$$

where:

ND_n = donor concentration at n-type (1 x $10^{15}/cm^2$)
ND_{nmax} = the highest donor concentration at n-type (1x$10^{17}/cm^2$)
ND_{pmax} = the highest acceptor concentration at p-type (1x$10^{17}/cm^2$)
ac = lenght of boundary 5 on diode geometry (2 µm)
ju = lenght of boundary 6 on diode geometry (1 µm)
y1 = lenght of diode geometry (7 µm)

Whereas Neumann boundary condition used to give boundary between contact and non metal, that represented with boundary 1, 3, 4, 6, 7, 8, and 9 in figure 1. This boundary condition used the following equation [8]:

$$\hat{n}.\vec{E} = 0 \quad (8)$$
$$\hat{n}.\vec{J}_n = 0 \quad (9)$$
$$\hat{n}.\vec{J}_p = 0 \quad (10)$$

After completing boundary condition setting, we deal with Poisson and Continuity equations. Poisson equation explains the divergence of electric field with concentration component of charge carrier and impurity concentration. When temperature has been varied, impurity atom concentration will consider ionized entirely. Therefore, the equation can be written as follow [8]:

$$\nabla^2\psi = \frac{q}{\varepsilon}(n-p-N) \quad (11)$$

In this simulation, the equation is modified as the following equation:

$$\lambda^2\Delta\psi = n_i\left(e^{\psi}u - e^{-\psi}v\right) - N \quad (12)$$

Continuity equation explains recombination (R) and generation (G) processes. From this process, the value of density current charge carriers can be calculated. In this simulation uses ideal diode so that there is no generation process in this condition. Therefore the equation can be written as follows [8]:

$$\nabla J_n + qR_{SRH} \quad (13)$$
$$\nabla J_P = -qR_{SRH} \quad (14)$$

And the equation are modified as following equation:

$$\nabla J_n = \frac{n_i(uv-1)}{\tau_p(ue^{\psi}+1)+\tau_n(ve^{-\psi}+1)} \quad (15)$$

$$\nabla J_p = -\frac{n_i(uv-1)}{\tau_p(ue^{\psi}+1)+\tau_n(ve^{-\psi}+1)} \quad (16)$$

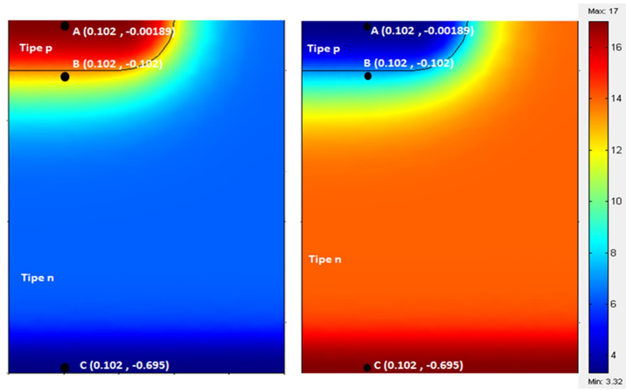
Where:

ψ = electrostatic potential (V)
ε = material permittivity (F/cm)
n = electronss concentration (cm^{-2})
p = holes concentration (cm^{-2})
N = total donor and acceptor concentration (cm^{-2})
u = variable for electronss
v = variable for holes
n_i = intrinsic concentration (cm^{-2})
R_{SRH} = Shockly Ready Hall recombination
J_n = current dencity of electronss (A/cm^2)
J_p = current dencity of holes (A/cm^2)

After we get the density current, the last step is make I-V characteristic curve, and then analyzed.

RESULTS AND DISCUSSION

The final result obtained from this simulation are I-V characteristics curve at some operating temperature, but first we must know the concentration distribution of the charge carriers. The concentration distribution profile of electrons and holes in simulation at 200K shown in figure 2, where figure 2.a is the concentration distribution profile for holes and 2.b is the concentration distribution profile for electrons.



(a) (b)

Fig.2. Concentration distribution profile of charge carriersat 200K: (a) Concentration distribution of electrons, (b) Concentration distribution of holes

There are 3 point of observation, i.e., point A (0.102: -0.00189) in area near anode, point B (0.102:-0.102) in area pn junction, and point C (0.102:-0.695) in area near cathode. The difference of color between figure 2.a and 2.b indicate that the concentration distribution of electrons and holes in the silicon diode is different. If we seen the legend, we can assume that holes concentration in the silicon diode is maximum at point A, then decreases as it approaches the cathode area. Otherwise, electrons concentration in the silicon diode is maximum at point C, then decreases as it approaches the anode area. These assumptions are supported by concentration data of electrons and holes that shown in Table 1.

Table 1. Charge carrier concentration at 200K

Coordinat	Electronss concentration (μm^{-1})	Holes concentration (μm^{-1})
A (0.1 , -0.00139)	3.33063 x 10^4	1.69922 x 10^{18}
B (0.1 , -0.102)	6.97260 x 10^8	1.33501 x 10^{14}
C (0.1 , -0.694)	1.69938 x 10^{18}	3.32932 x 10^4

Simulation results of the charge carriers distribution for other temperature have the same pattern with charge carriers distribution at 200K. However, if we observe one by one, it will show the change of concentration with increasing temperature. The result as shown in Table 2 and table 3, where Table 2 shows holes concentration and table 3 shows electrons concentration.

Table 2. Holes concentration at varied operating temperature

Temperature (K)	point A (μm^{-1})	point B (μm^{-1})	point C (μm^{-1})
200 K	1.69922 x 10^{18}	1.33501 x 10^{14}	3.32932 x 10^4
223 K	1.69921 x 10^{18}	1.33968 x 10^{14}	3.32941 x 10^4
273 K	1.69921 x 10^{18}	1.34869 x 10^{14}	3.32970 x 10^4
323 K	1.69920 x 10^{18}	1.36144 x 10^{14}	3.33063 x 10^4
373 K	1.69920 x 10^{18}	1.36497 x 10^{14}	3.33006 x 10^4
423 K	1.69919 x 10^{18}	1.37129 x 10^{14}	3.33024 x 10^4
473 K	1.69919 x 10^{18}	1.37681 x 10^{14}	3.33041 x 10^4

Table 2 shows that holes concentration at point A tends to decrease with increasing temperature, while holes concentration at point B and C tends to increase with increasing temperature.

Table 3. Electrons concentration at varied operating temperature

Temperature (K)	point A (μm^{-1})	point B (μm^{-1})	point C (μm^{-1})
200 K	3.33063×10^4	6.97260×10^8	1.69934×10^{18}
223 K	3.33065×10^4	6.91284×10^8	1.69933×10^{18}
273 K	3.33068×10^4	6.83581×10^8	1.69930×10^{18}
323 K	3.33072×10^4	6.71781×10^8	1.69930×10^{18}
373 K	3.33075×10^4	6.67305×10^8	1.69927×10^{18}
423 K	3.33079×10^4	6.60981×10^8	1.69925×10^{18}
473 K	3.33083×10^4	6.55460×10^8	1.69923×10^{18}

The tendency of electrons concentration is inversely propotional with holes concentration. At point A electron concentration tends to increase with increasing operating temperature, and at point B and C electron concentration tends to decrease with increasing temperature. These matter cause electrons diffuse from cathode area passing through junction area toward the anode area. As a result, electrons concentration at cathode area and junction area decrease, while electrons concentration at anode area increases because they get extra concentration electrons that diffuse from chatode and junction area. Thus, the opposite occurs on holes concentration. The diffusion process is affected by silicon diode temperature. when diode received heat energy that larger than its bound energy, the impurity is ionized then generated interaction with local charge carriers. This interaction causes ionized impurity scattering. When the temperature increases, there are more impurity ionized and occurs. This scattering. This scattering will hinder electrons diffusion so that at higher temperatures the number of electrons that diffuse decrease, but the diffuision process still flows.

The concentration distribution of electrons and holes that obtained is used to determine I-V characteristics of silicon diode due to ionized impurity scattering at varied operating temperature with difference mobility for each temperature. From the research that has been done by inserting the value of the input voltage from 0 V to 0.5 V, we obtain I-V characteristic curve as given in Figure 3.

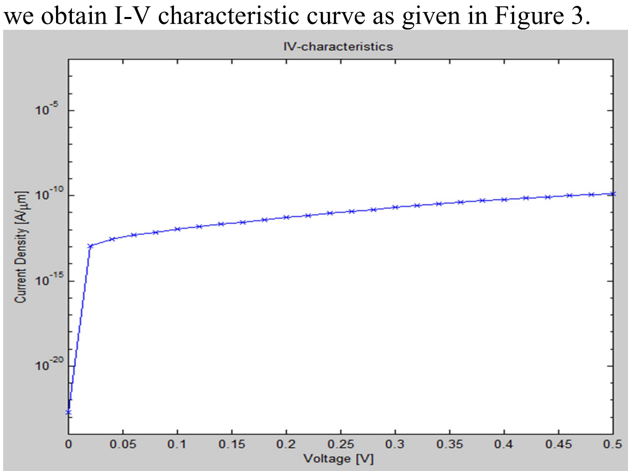


Fig. 3. I-V characteristic curve of Silicon diode at 323K

Figure 3 shows that when the greater voltage is applied at silicon diode, the value of current density will be greater too. The large voltage (nears barrier potential) can ease the charge carriers diffusion. When forward bias voltage applied with the specific voltage, the Coulomb force will occur between electrons and holes in the silicon diode with positive and negative electrodes. This cause limited barrier potential in the silicon diode that make electrons and holes easier to diffuse. Therefore the current silicon diode increases.

I-V characteristics curve for other temperature with logharithmic curve is shown in figure 4, with each temperature has a value of its own charge carrier mobility. According to figure 4, it can be seen that the maximum value of diffusion current density silicon diode is generated at 200K, and minimum diffusion current density is generated at 473K. Therefore, it can be assumed that diffusion current density of silicon diode decreases along with increasing temperature. The decreasing current density of silicon diode maybe caused by reduced charge carrier mobility of electrons and holes in the silicon diodes that related by ionized impurity scattering. Previous discussions have stated that the increase temperature of silicon diode cause many ionized impurity scattering. This complicates the diffusion of electrons and holes. In other words, ionized impurity scattering cause mobility of the charge carriers decreases.

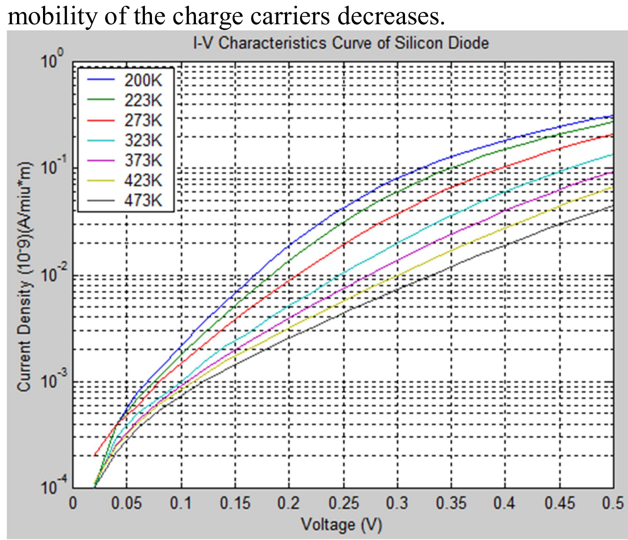


Fig.4. I-V characteristic curve of silicon diode at varied operating temperature

The decreasing of charge carriers mobility can affect electrons and holes concentration that diffuses, so that charge carrier distribution will be changed. As the result, the diffusion current density of silicon diode becomes smaller, because the diffusion current density is strongly influenced by the imbalance of electrons and holes concentration in the silicon diode. Thus the I-V characteristics curve will decrease with increasing operating temperature.

CONCLUSION

Based on the foregoing discussion above, it can be concluded that the ionized impurity scattering affects the trend of I-V characteristic curve silicon diode. Where the diffusion currents generated by silicon diode decrease along with increasing operating temperature.

REFERENCES

[1] A. P. Malvino, “Aproksimasi Rangkaian Semikonduktor”. Jakarta: Erlangga Publisher, 1994.

[2] P. L. Gareso, “Fisika semikonduktor”. Makassar: Hasanuddin university, 2012.

[3] A. Subekti, “Semikonduktor (Transportasi Listrik, Generasi dan Rekombinasi)”. Jember: Faculty of Mathematics and Natural Sciences Jember University, 2002.

[4] A. Sconza, G. Torzo, and G. Viola, “ Experiment on The Physics of The PN Junction”. American Journal of Physics. vol. 62. No. 66.

[5] R. Boylestard and L. Nashelsky, “ Electronic Devices and Circuit Theory”. New Jersey: Prentice Hall, 2009.

[6] K. Priyanka, C. Subhash, and O. Jozef, “Current-Voltage Characteristic of Schottky Diode Simulated Using Semiconductor Device Equation”. International Journal of Electronics. vol. 100. No. 5: 686-698, 2013.

[7] I. Usman, “Penumbuhan Lapisan Tipis Silikon Amorf Terhidrogenasi dengan Teknik HWC-VHF-PECVD dan Aplikasinya pada Sel Surya”. Dissertation. Bandung: ITB, 2006.

[8] E. Danielsson, “FEMLAB Model Library for Semiconductor Device Model”. Stockholm: The Royal Institute of Institute, 2000.