Evolution in Electrical and Electronic Engineering Vol. 2 No. 2 (2021) 140-147

EEEE

Homepage: http://publisher.uthm.edu.my/periodicals/index.php/eeee
e-ISSN : 2756-8458

Investigation of PIN Diode Characteristics for Wireless Communication Application

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DOI: https://doi.org/10.30880/eeee.2021.02.02.017
Received 03 July 2021; Accepted 14 August 2021; Available online 30 October 2021

Abstract: PIN diode is one of the key devices in wireless communication circuits that enable the RF wireless communication services to the users due to the difference in the characteristics of the PIN diode. The electrical properties, switching speed and power handling of PIN diodes for wireless communication applications are being investigated in this paper. Generally, a set of pre-determined controlled factors, which are specified by particular formulas, will impact the output properties of the PIN diode. The results suggest that the width of the PIN diode does play a crucial part as per functionality of the PIN diode, in which wider width of the PIN diode will result in lower resistance. It is concluded that there are several characteristics of PIN diode that should be considered to suit the application of wireless communication.

Keywords: PIN Diode, Wireless Communication, Diode Characteristics

1. Introduction

PIN diode is one of the key devices in wireless communication circuit that is used extensively in RF, UHF and microwave circuits due to the difference of the characteristics of PIN diodes at the forward and reverse bias condition [1], [2]. The I-region performance of the PIN diode is largely determined by chip geometry and the type of the semiconductor material used in the final diode. Previous studies in [3]–[6] varies from the geometrical structure of PIN diode, the I-V performances, width modulation and frequency dependant. Hence, this paper focuses on the electrical characteristic and operation of PIN diode for wireless communication application by running a series of graphical simulation using MATLAB.

1.1 PIN Diode Structure

A PIN diode is a silicon (Si) semiconductor device, which name attributes by its structure that is formed of a high resistivity intrinsic I-region sandwiched between a P-type and N-type layer [7]–[9] as shown in Figure 1. The intrinsic layer of the PIN diode is the one that provides the most important changes in properties compared to a normal PN junction diode. It is also called an undoped semiconductor or I-layer semiconductor without any significant dopant species present. The intrinsic

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region comprises of the undoped or virtually undoped semiconductor and in most PIN diodes, the width is very thin and varies between 5 and 100 µm [8]. The conductivity of intrinsic semiconductors is due to their own internal charge carriers and number of electrons in the conduction band is equal to the number of holes in the valence band. On the other hand, the resistivity of the I-layer varies according to the quantity of electrons and positive holes, and these factors change the high frequency series resistance [10].

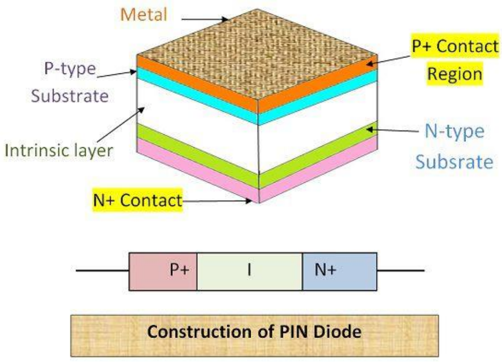

Figure 1 : PIN Diode Structure [11]

A PIN diode behaves as a current-controlled resistor at radio and microwave frequencies. It allows current flow in one direction when forward biased, but not in the other when it is reverse biased. Holes and electrons are pumped from the P and N regions into the I field when a PIN diode is biased. Such charges do not immediately recombine. Rather, a finite amount of charge remains stored and causes a reduction in the resistivity of the region [7]. The sum of retained charge, Q, depends on the time of recombination, τ and the forward bias current, I_F, as shown in Eq. 1. The resistance of the I-region under forward bias, Rs, is inversely proportional to Q as expressed in Eq. 2.

$$Q = I_F\tau \quad \text{Eq. 1}$$

$$R_s = \frac{W^2}{(\mu_n + \mu_p)Q} \quad \text{Eq. 2}$$

2. Materials and Methods

In this study, MATLAB is used as a tool to simulate the graphical curve to describe the operation and electrical characteristics of PIN diode. Figure 2 illustrates the flowchart of the project that is used as a guideline to develop the findings of the project.

2.1 Electrical characteristics

There are three electrical characteristics of PIN diode presented; which are I-V, C-V and R-I curve. At DC and very low frequencies, PIN diode is similar to the general PN junction diode. Therefore, the basic equation of PN junction diode as shown in Eq. 3 and Eq. 4 is used in the source code to plot the I-V curve of the PIN diode to see the correlation of current and voltage of the PIN diode.

$$I = I_0(e^{\frac{qV}{nkT}} - 1) \quad \text{Eq. 3}$$

$$V = n\frac{kT}{q}ln(\frac{I}{I_0} + 1) \quad \text{Eq. 4}$$

A common equation of capacitance that is inversely proportional to voltage is used to simulate capacitance-voltage curve as shown in Eq. 5. The PIN diode are simulated under a forward bias condition, therefore the equation of resistance of the I region under forward bias, R_s as expressed in Eq.

6 is used to simulate resistance-current curve. There are four width variation of PIN diodes used to simulate the electrical and operation of PIN diode in this study, which are 5×10^{-6}m, 55×10^{-6}m, 100×10^{-6}m and 150×10^{-6}m.

$$C = \frac{Q}{V} \qquad \text{Eq. 5}$$

$$R_s = \frac{W^2}{(\mu_n + \mu_p)I_f\tau} \qquad \text{Eq. 6}$$

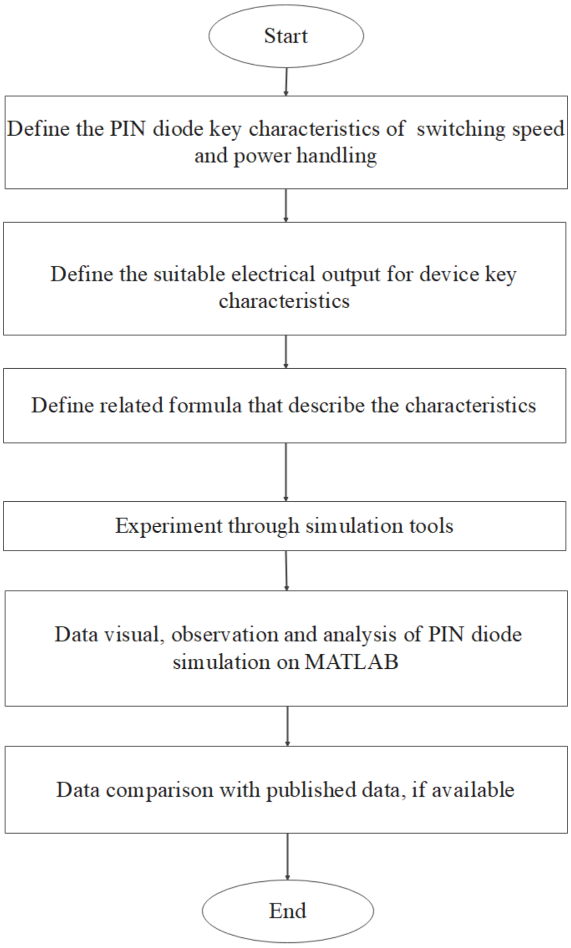

Figure 2: Flowchart of project

2.2 Switching Speed

Generally, switching speed is the time it takes to fill or remove charge from the I-region layer. Fast switching speed is crucial in application where high frequency transmitting and receiving rates need to be used. Therefore, a graph of frequency as a function of minimum lifetime of PIN diode are investigated using the equation shown in Eq. 7. In addition, a long transit time requires very thick I-region layer which in this project, width of four variation of PIN diode in μm is used to illustrate the transit time as a function of width of PIN diode using the equation shown in Eq. 8.

$$f = \frac{1}{2\pi\tau_o} \qquad \text{Eq. 7}$$

$$I_t = \frac{W}{V_s} \quad \text{Eq. 8}$$

2.3 Power Handling

Power handling capacity of PIN diodes switches used in this project is being controlled by parameters of breakdown voltage and the charge storage capability of the device. Similarly, width of PIN plays an important parameter to determine the functionality of PIN diode in power handling. Therefore, the relation of PIN diode voltage breakdown in respect to the width of PIN diode and transit time are being described by using the equation shown in Eq. 9 and Eq. 10.

$$W = \frac{V_B}{E_m} \quad \text{Eq. 9}$$

$$I_t = \frac{\frac{V_B}{E_m}}{Vs} \quad \text{Eq. 10}$$

3. Results and Discussion

The results and data discussed help in defining the key characteristics of PIN diodes that will suit the wireless communication application. As shown in Figure 3, the voltage values are set to be in range of 0.3 V - 0.7 V which produces output current starting 0.001 mA until 100 mA. This satisfies that current is directly proportional with voltage thereby the increment of current increases the voltage.

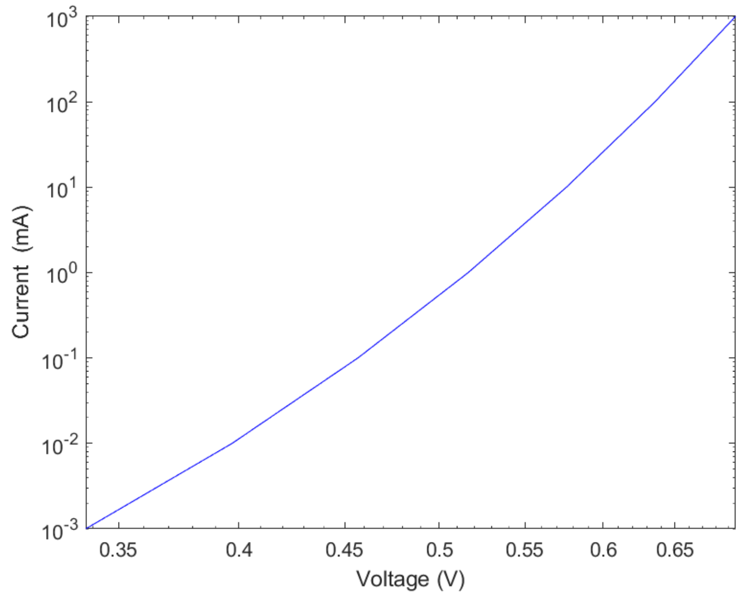

Figure 3: PIN Diode I-V Curve

Besides, PIN diodes have a lower capacitance as the depletion region will be wider than a conventional diode. Wider depletion region means higher value of voltage. Therefore, this satisfies the simulation result of the C-V curve as shown in Figure 4 and the equation stated in Eq. 5. This PIN diode characteristic can have significant advantages in several RF applications - for example when a PIN diode is used as an RF switch. The simulation is also repeated using much higher scale varies from 0 V – 30 V in comparison to published data in order to check the reliability of the gained results. As a result, the pattern of capacitance decrement over voltage increment is verified.

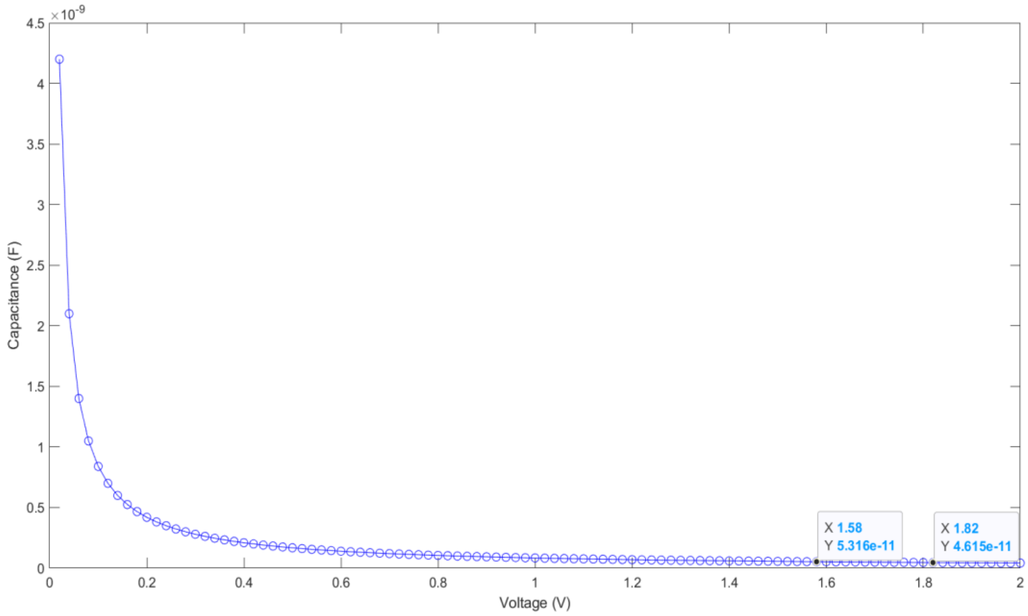

Figure 4: PIN Diode C-V Curve

At forward bias, the PIN diode serves as a variable resistor. Throughout the junction, a high electric field is generated that allows the charge carrier to transport from the P region to the N region through the I region. Hence, resistance is inversely proportional to forward bias current. Figure 5 shows the PIN Diode R-I curve in respect to I-region width variation. The variation of PIN diode's width in meters used in this study are 5×10^{-6}, 55×10^{-6}, 100×10^{-6} and 150×10^{-6}. From the simulation result, it is observed that higher value of the width, W, produces higher value of resistance, R_s, and the current increases as the resistance decreases.

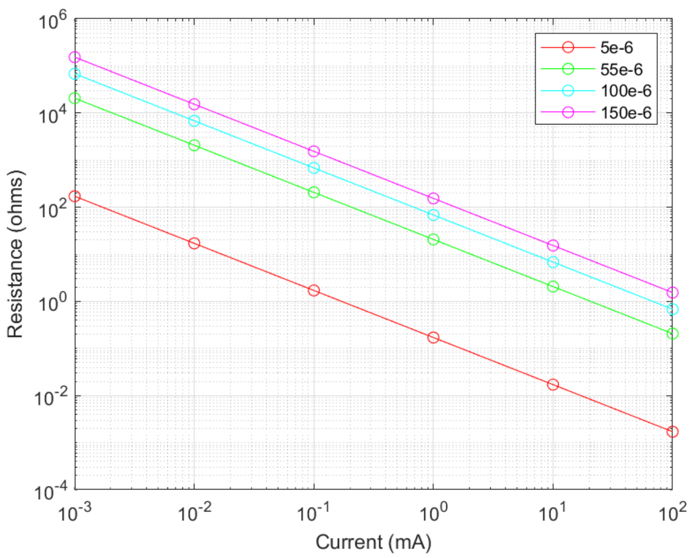

Figure 5: PIN Diode R-I curve in respect to I-region width variation

Figure 6 depicts the variation in PIN diode frequency as a function of the minimum lifetime of PIN diode. From this figure, it can be observed that the minimum lifetime of PIN diode increases with the decrement of PIN diode frequency which the minimum lifetime varies from 0.01 to 10 µs. This satisfies the formula describe in Eq. 7 which is used in simulating the curve of frequency vs. minimum lifetime of PIN diodes.

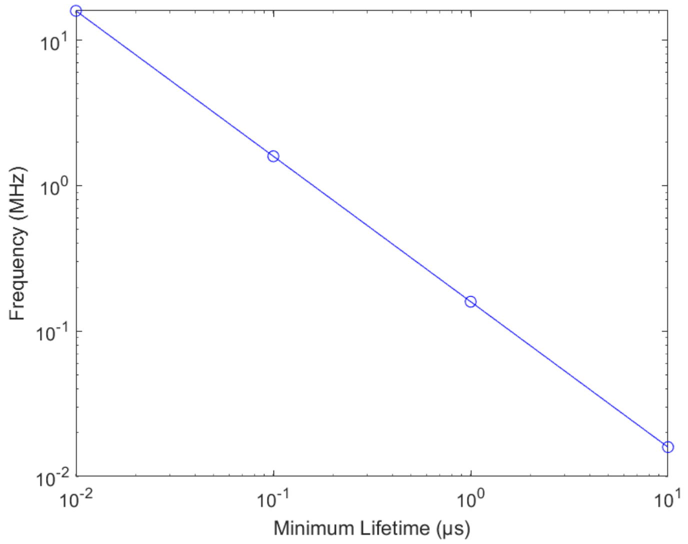

Figure 6: Frequency vs. Minimum Lifetime

The transit time of PIN diode as a function of the I-region width ranges from 5×10^{-6} m to 150×10^{-6} m is shown in Figure 7. From the graph, it can be observed that the transit time increase from 0.0005 to 0.0150 at width of 5×10^{-6} m to150×10^{-6} m. This shows that a wider I-region layer will have longer transit time. This can be explained due to the phenomena of the carrier charge inside the I-region layer to move from anode to cathode as well as the formula described in Eq. 8. In addition, a diode with a long transit time is more likely to keep its stored charge at a low level. The capacity of a thick I-region width of PIN diode to follow the stored charge model for PIN diode resistance is reflected in its transit time.

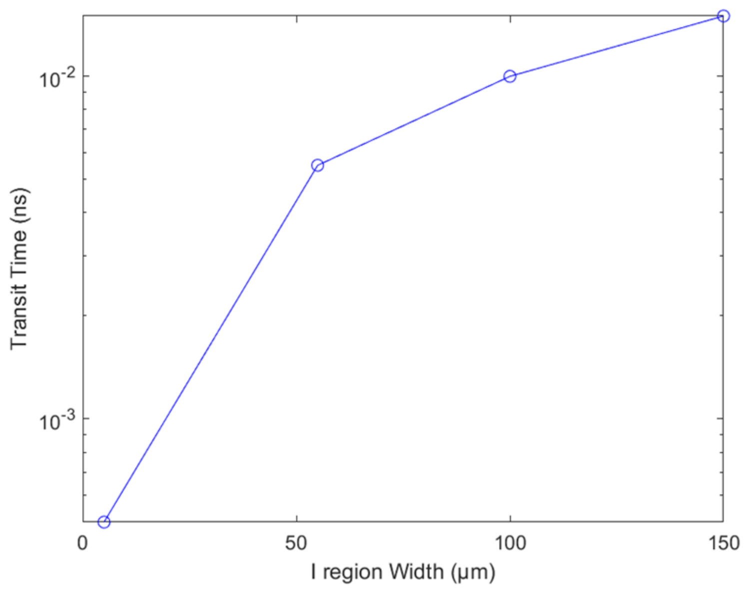

Figure 7: Transit Time vs. I-region Width

Based on the graph of voltage breakdown vs. I-region width illustrated in Figure 8, it can be seen that the voltage breakdown is directly proportional to the I-region width with an increase in voltage breakdown prior to the increase of the I region width. It is known that breakdown voltage of a p-n junction depends on the width of depletion region which in the case for PIN diode, the depletion region occurs at the I-region layer. Larger depletion region has high breakdown voltage whereas narrow depletion region has low breakdown voltages

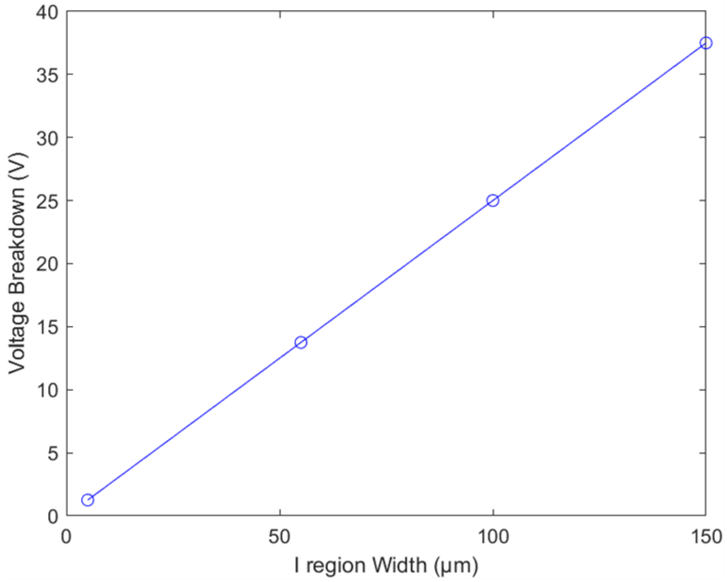

Figure 8 : Breakdown Voltage vs. I-region Width

Figure 9 shows the variation of transit time ranges in between 0.0001 to 1 ns as a function to PIN diode breakdown voltage ranges from 1 to 1000 V. It can be observed that the increment of breakdown voltage results in the increment of transit time as well. This can be explained as the increase of breakdown voltage is related to the I-region layer width where the phenomenon of carrier charge movement happens inside the PIN diode. The time it takes for the charge carrier to pass through the device depends on the width. Hence an increase of breakdown voltage prior to the transit time.

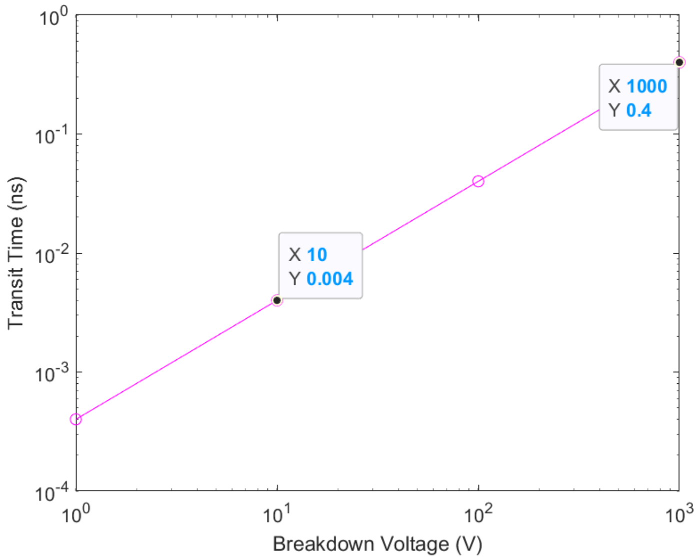

Figure 9: Transit Time vs. Breakdown Voltages

4. Conclusion

Based on the electrical characteristics result findings, the depletion region drops at forward bias that allow current to flow which resistance are inversely proportional to current. Besides, resistance can also be controlled based on the width of PIN diode I-region whereas thicker I-region layer result in high resistance value. Thicker I-region PIN diodes, on the other hand, will have a greater bulk or voltage breakdown with superior distortion properties, which is ideal for next-generation wireless communication, while thinner I-region layers will have faster switching speed. To briefly paraphrase, in PIN diode operations, the thickness of the I-region is just as essential as carrier lifetime, frequency, or any other characteristic parameters. This is due to the fact that the width of a PIN diode is related to the depletion area, which affects the device's transit time, voltage breakdown, and resistance. The controlled thickness of PIN diode I-region will result to a long carrier lifetime and high resistivity.

Acknowledgement

The authors would like to thank the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia for its support.

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