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Influence of Temperature Changes on the Performance Characteristics of Some Selected Semiconductor PN-Junction Diodes

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Abstract: Temperature changes can significantly impact the performance characteristics of semiconductor diodes. The key effects of an increase in temperature on the intrinsic properties of the semiconductor diodes include an increase in charge carrier concentration, a decrease in charge carrier mobility, and a decrease in bandgap. This research was carried out to study and generate data on the effect of temperature changes on the performance characteristics of some selected semiconductor pn-junction diodes. The pn-junction diodes studied include IN5400, IN5401, IN5402, and IN5404 diodes. These diodes were in turn placed in a test circuit, and a heater was used to increase their ambient temperature from 25 ^{0}C to 200 ^{0}C. The voltage was measured and the current, static resistance, and dissipated power were determined for each of the diodes as the temperature varied. The results show that for the forward-biased diodes, the diode voltage generally decreased with an increase in temperature while the current increased with an increase in temperature. The forward static resistance and dissipated power generally decreased with an increase in temperature. The effect of ambient temperature on the reverse-biased diode voltage and current was negligible till the temperature of about 150 ^{0}C. We recommend that designers and manufacturers of electronic devices should study the data on the effect of temperature on any electronic component before such a component is used irrespective of the power capacity of the component. This is because this research has shown that even low-power electronic components can be affected by ambient heat generated from other components.

Keywords: effect of temperature, semiconductor, diodes, forward-biased, reverse-biased

1. Introduction

Temperature changes significantly influence the performance characteristics of semiconductor devices like diodes, transistors, and operational amplifiers. The key effects of an increase in temperature on the intrinsic properties of the semiconductor diodes include an increase in charge carrier concentration, a decrease in charge carrier mobility, and a decrease in bandgap [1, 2]. These effects can lead to a decrease in forward voltage and an increase in reverse leakage current [3]. In addition, an increase in temperature can also lead to a decrease in the diode's breakdown voltage, impacting its ability to handle high voltages [4].

Furthermore, the increase in temperature can also cause a shift in the diode's thermal resistance, affecting its ability to dissipate heat efficiently [5, 6]. This can result in thermal runaway, where the diode fails prematurely due to excessive heat buildup [7, 8, 9, 10]. Overall, temperature plays a crucial role in the performance and reliability of semiconductor devices, highlighting the importance of proper thermal management in electronic design [11, 12, 13].

Understanding these temperature-dependent behaviors is crucial for designing reliable circuits, as it impacts efficiency, stability, and overall performance in various applications.

It is important for engineers to consider thermal management strategies in their designs to ensure that devices operate within their specified temperature ranges. Additionally, temperature variations can also impact the accuracy and precision of sensor measurements involving diodes, making it essential to calibrate and

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compensate for temperature effects in sensor circuits [14]. This is especially critical in industries such as automotive, aerospace, and medical devices where precise measurements are crucial for the safety and functionality of the systems. Temperature compensation techniques, such as using temperature sensors to monitor and adjust for changes in operating conditions, can help mitigate the effects of temperature on sensor accuracy [15]. By incorporating these strategies into their designs, engineers can improve the overall performance and reliability of semiconductor devices in a wide range of applications.

The changes in the temperature of electronic components can be caused by heat generated internally by the devices in question or the ambient heat from other neighboring devices. In most cases, only the power devices that generate much heat internally are considered for heat dissipation provisions. This has led to the premature failure of some electronic devices as some low-power semiconductor components fail due to the ambient heat. In some cases, these failures occur even when the ambient temperature is within the safe operating temperature of such devices as specified by the manufacturers. It is therefore pertinent for researchers to investigate the effect of ambient temperature changes on the performance characteristics of low-power semiconductor devices. This will help in the generation of data that can aid electronic system designers in identifying and making heat dissipation provisions for such low-power semiconductor devices prone to ambient heat damage.

1.1 PN-Junction Diode

The pn-junction diode has two terminals, the anode and the cathode. Current flows through the device if the anode is positively biased and the cathode is negatively biased. Some of the typical applications of diodes include: voltage rectification, isolation of signals from a supply, voltage reference, controlling the size of a signal, mixing of signals, detection of signals, and lighting. Some of the most commonly used pn-junction diodes include: the IN5400 diode, IN5401 diode, IN5402 diode, and IN5404 diode. The picture and symbol of a pn-junction diode are shown in Figure 1.

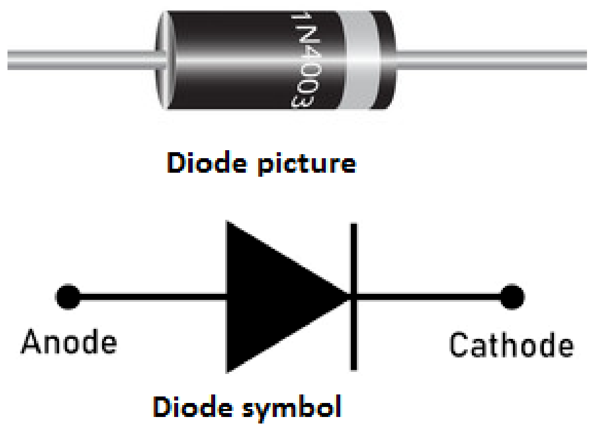

Figure 1. PN-Junction diode's picture and symbol

These diodes are widely used in various electronic circuits and systems due to their reliable performance and versatility. The IN5400 series diodes, for example, are commonly used for voltage rectification in power supplies and electronic devices. The IN5401 diode, on the other hand, is often utilized for signal isolation and voltage reference applications. The IN5402 diode is known for its ability to control the size of a signal, while the IN5404 diode is commonly used for signal mixing and detection purposes. Overall, pn-junction diodes play a crucial role in modern electronics and are essential components in ensuring the proper functioning of electronic systems.

These diodes are designed to handle a wide range of current and voltage levels, making them suitable for various applications in different electronic circuits. Additionally, their small size and low cost make them ideal for mass production and integration into complex electronic systems. In addition to their use in power supplies and signal processing, pn-junction diodes are also commonly found in radio frequency (RF) circuits, voltage regulators, and voltage clamping circuits [16]. The maximum ratings and electrical characteristics of these diodes as provided by the manufacturer are given in Table 1.

Table 1. Maximum Ratings and Electrical Characteristics of IN5400, IN5401, IN5402, and IN5404 Diodes (Source [17])

Parameter	IN5400	IN5401	IN5402	IN5404
Maximum Recurrent Peak Reverse Voltage (V)	50	100	200	400
Maximum RMS Voltage (V)	35	70	140	280
Maximum DC Blocking Voltage to T =150 ^{0}C	50	100	200	400
Maximum Average Forward Rectified Current at T =75 ^{0}C (A)	3	3	3	3
Maximum Forward Voltage at 3.0A Peak (V)	1.2	1.2	1.2	1.2
Maximum Reverse Current at T =25 ^{0}C (μA)	10	10	10	10
Maximum Reverse Current at T = 25 ^{0}C (μA)	500	500	500	500
Maximum Full Load Reverse Current at T =105 ^{0}C	500	500	500	500
Typical Junction Capacitance (pF)	50	50	50	50
Storage Temperature Range T_A (^{0}C)	-65 to +175	-65 to +175	-65 to +175	-65 to +175
Operating Temperature Range T_J (^{0}C)	-65 to +170	-65 to +170	-65 to +170	-65 to +170

The current-voltage (I-V) characteristics of pn-junction diodes provide significant insights into their operational performance under varying conditions. The Shockley diode equation describes the relationship between the current flowing through the diode and the applied voltage, which can be expressed as [18]:

$$I_D = I_S\left(e^{\frac{qV_D}{nk_BT}} - 1\right) \quad (1)$$

Where I_D is the net current flowing through the diode; I_S is the dark saturation current; V_D is the applied voltage across the terminals of the diode; q is the absolute value of the electron charge; n is the ideality factor (a number between 1 and 2); k_B is the Boltzmann's constant ($= 1.3806 \times 10^{-23} JK^{-1}\ or\ 8.6173 \times 10^{-5}\ eVK^{-1}$); and T is the absolute temperature in Kelvin. The dark saturation current is a very important parameter that differentiates one diode from another. It is the diode's leakage current in the absence of light. It is directly proportional to the recombination in a diode. It also increases with an increase in temperature and decreases with an increase in material quality.

The diode equation can also be written as:

$$I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right) \quad (2)$$

Where $V_T (= \frac{k_BT}{q})$ is called the thermal voltage and it has a value of $25.85\ mV$ at room temperature (300 K). When the diode is reverse biased and $V_D \ll nV_T$, $e^{\frac{V_D}{nV_T}} \ll 1$. Therefore, the diode equation reduces to

$$I_D \approx -I_S \quad (3)$$

This means that a reverse-biased diode has a tiny negative current (reverse saturation current) flowing through it.

Additionally, the diode resistance is also temperature dependent, affecting the efficiency and voltage drop across the diode when in operation. There are two types of diode resistance, namely: DC or static resistance and AC or dynamic resistance. DC or static resistance is the resistance of the diode when operating in a DC circuit. It is calculated from the equation:

$$R_D = \frac{V_D}{I_D} \quad (4)$$

Generally, the lower the current through a diode, the higher the DC resistance becomes. On the other hand, the AC or dynamic resistance is the resistance of the diode when operating in an AC circuit. It is calculated from the equation:

$$r_D = \frac{dV_D}{dI_D} \approx \frac{\eta V_T}{I_D} \quad (5)$$

Where η is the diode's ideality factor and $V_T\ (= \frac{k_BT}{q})$ is the thermal voltage. Also, the lower the current through a diode, the higher the dynamic resistance becomes. Decreased diode resistance at higher temperatures leads to a decreased power dissipation. The power dissipated by a diode in a DC circuit can be calculated from the equation:

$$P_D = I_DV_D = I_D^2R_D \quad (6)$$

Moreover, the temperature stability of semiconductor dielectrics and insulation can significantly influence the diode's behavior under extreme thermal conditions. Events such as electrostatic discharge (ESD) may arise from insufficient insulation strength at elevated temperatures, leading to unwanted failure modes. It is critical for designers to ensure adequate dielectric materials are used in conjunction with semiconductor devices to provide robust thermal performance.

1.2 Review of previous related works

Emre *et al*. [19] investigated the effect of high temperature on the characteristics of zinc oxide (ZnO) Schottky barrier diode. The study found that the ideality factor almost remains constant in the temperature range from 240 – 400 K, which shows the stability of the Schottky contact in this temperature range.

Kang *et al*. [20] researched temperature dependence and the effect of series resistance on the electrical characteristics of polycrystalline diamond metal-semiconductor diode. They discovered that between 25 – 300 ^{0}C, the current-voltage (I-V) characteristics of the device show rectifying behavior, with forward bias transmission limited by series resistance over the temperature range investigated. The I–V characteristics data confirmed that the transmission mechanism of the diode is controlled by extrapolating the forward saturation current data, and the ideality factor was observed to decrease from 2.4 to 1.1 while the apparent barrier increased linearly from 0.68 to 1.02 eV in the same temperature range.

Ejderha*et al*. [21] researched the effect of temperature on current, capacitance, and conductance – voltage characteristics of Ti/n-GaAs diode. They discovered that the temperature coefficient of barrier height changes from metal to metal in relation to the nature of the contact metal or metal electromagnetivity. This result was achieved through the construction and fabrication of Ti/n–GaAs Schottky barrier diode by DC magnetron sputtering. Voltage–capacitance was investigated in the temperature range of 80 to 320 K. The ideality factor and barrier height values werecalculated from the forward current-voltage characteristics. The variation of the diode parameters with the sample temperature was attributed to the presence of the lateral inhomogeneities of the barrier height.

Kenji *et al*. [22] researched on high-temperature characteristics and stability of Cu/diamond Schottky diodes. They discovered that the Cu/diamond Schottky diode exhibited clear rectification up to 700 ^{0}C indicating that high-temperature operation is possible using these diodes. This is thought to be due to their large Schottky barrier height of approximately 1.6 eV. The high-temperature stability of the Cu/diamond Schottky diodes was also better than that of diodes using Ag or Ni, probably because of less interfacial reaction or interdiffusion between the Cu and diamond. This result was achieved by examining and comparing the electrical stability of Cu/diamond Schottky diodes and other Schottky diodes using Ag and Ni electrodes.

Kungen, *et al*. [23] investigated the thermal stability of boron nitride/silicon p-n heterojunction diodes. They discovered a highly rectifying p-type CBN/thick silicon junction diode which indicates irreversible rectification properties mainly characterized by a marked decrease in reverse current by an order of size in an initial temperature ramp/down cycle. This irreversible behavior was confirmed by conducting the circle twice or more. The temperature-dependent properties confirm an overall increase in effective barrier heights for carrier injection and transmission by biasing at high temperatures, which therefore increases the thermal steadiness of the diode performance. This result was achieved by the fabrication of heterojunction p-type cubic boron nitride (CBN) and n-type silicon with sp^2-bonded BN (SP^{2BN}) interlayers under low energy ion impact by plasma-enhanced chemical vapour deposition, and their rectifications properties were studied at temperature up to 573 K.

A lot of scholars have worked on both high and low-temperature effect on a number of semiconductor diodes. From the reviews and research done so far on this subject matter, the authorities and scholars on this research topic came up with the conclusion that high temperatures affect the performance characteristics of semiconductor diodes. Some of the scholars like Emre *et al*., [19] subjected the diodes to high temperatures, like from 200 to 500 °C, but inour own research, our interest is to know the performance characteristics of theselected semiconductor diodes, when they are subjected to temperatures from 25 °C to 200 ^{0}C.

2. Materials and Methods

The materials, electronic components, and equipment used for this research includean electrical heater, digital multimeters, breadboard, Vero board, thermometer, batteries, jumper wires, resistors, and diodes (IN5400, IN5401, IN5402, and IN5404).

The experimental procedure commenced with the soldering of the jumper wires to the pins of an 8-pin IC carrier which would be used to connect and hold each diode in place. With this and all other needed equipment ready, it was time for the setting up of the experimental circuits. The experimental setup is shown in Figure 2. The digital multimeters were used to measure the series resistor voltage and the diode voltage while the thermometer was used to read the ambient temperature of the diode as it was heated. The digital multimeters and the thermometer were arranged in a way that their screens could be videoed with a camera simultaneously.

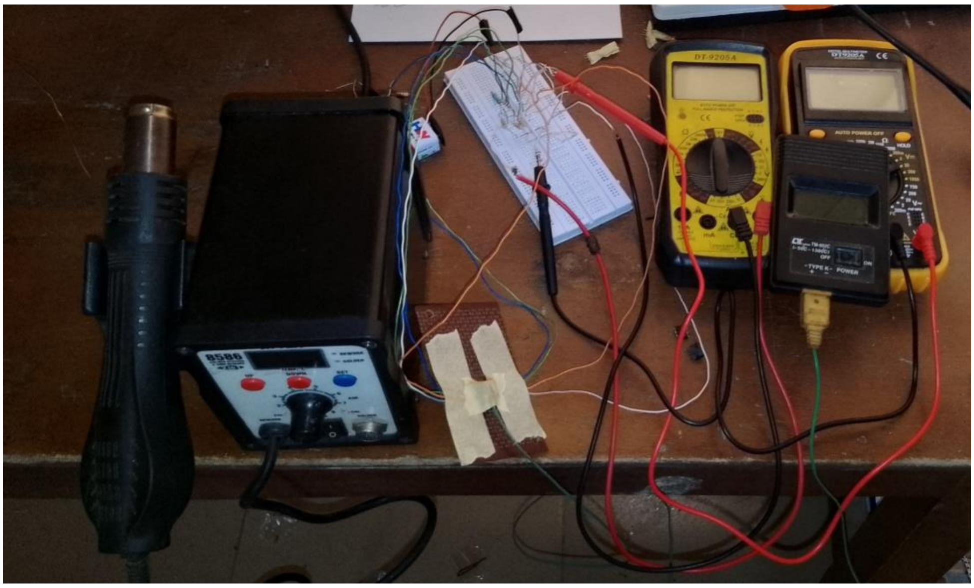

Figure 2. The experimental setup

The forward-biased diode experiment circuit was configured following the circuit diagram in Figure 3. With the help of a masking tape, the thermometer's sensor wire was taped to the first diode's body (IN5400) and the diode was plugged into the appropriate carrier ports. The circuit was then powered ON and with the heater (which blows hot air) focused on the diode; a camera was used to video the screens of the meters as the measured ambient temperature of the diode increased from 25^{0}C to 200^{0}C. From the recorded video, the readings of voltage across the diode and series resistor were recorded at intervals of 25^{0}C. The reading screenshot for the forward-biased IN5400 diode at 150^{0}C ambient temperature is shown in Figure 4. The experiment was repeated with each of the remaining three diodes (IN5401, IN5402, and IN5404) in place. The current through the diode was calculated using equation (7) while the diode static resistance and dissipated power were calculated using equations 4 and 6, respectively. The results were tabulated.

The experiment for each of the diodes was repeated with the diode reverse-biased as shown in Figure 5. The reading screenshot for the reverse-biased IN5400 diode at 200 ^{0}C ambient temperature is shown in Figure 6. The current through the diode was also calculated using equation (7) on the reverse-biased diode circuit. The results were also tabulated.

$$\boldsymbol{I_D = \frac{V_R}{R}} \quad \textbf{(7)}$$

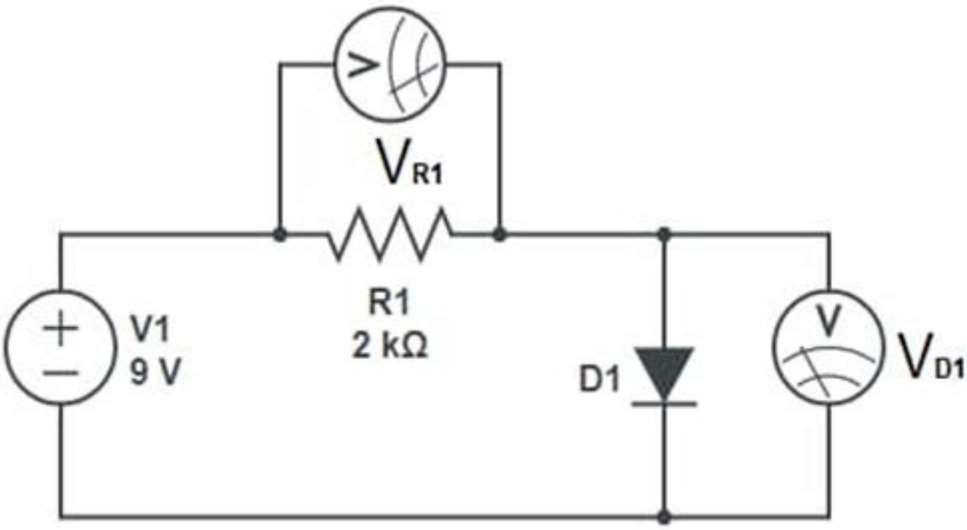

Figure 3. The forward-biased diode experiment circuit diagram

Figure 4. One of the reading screenshots for the forward-biased IN5400 diode

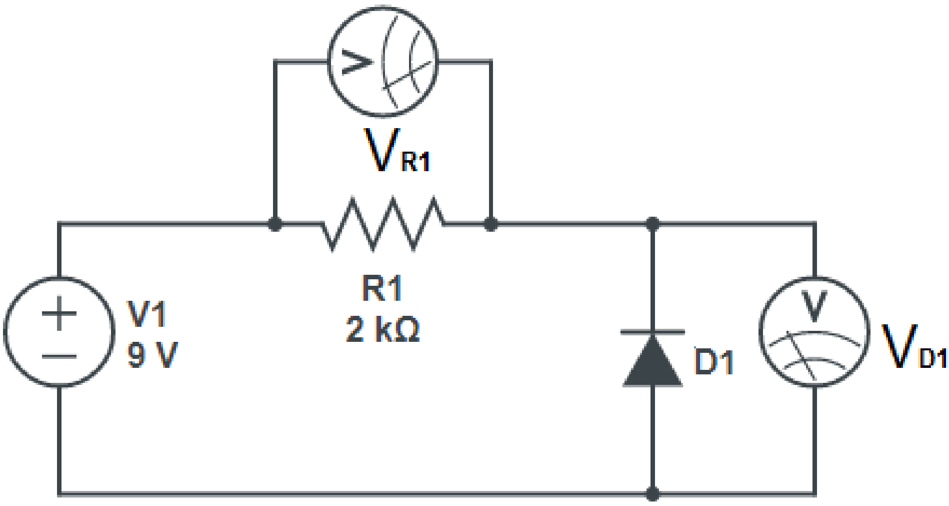

Figure 5.The reverse-biased diode experiment circuit diagram

Figure 6. One of the reading screenshots for the reverse-biased IN5400 diode

3. Results and Discussion

Results of the diode forward-biased and reverse-biased tests are presented in Tables 2, 3, and 4.As shown in these result tables, diode voltage and series resistor voltage were direct readings obtained from the experiments while the diode current, static resistance, and dissipated power were computed using equations 7, 4, and 6, respectively.

Table 2. Test Results of the Forward-Biased Diode IN5400 and IN5401

S/N	Temp (^{0}C)	Diode 1 (IN5400) V_{D1} (V)	I_{D1} (mA)	V_{R1} (V)	R_{D1} (Ω)	P_{D1} (mW)	Diode 2 (IN5401) V_{D2} (V)	I_{D2} (mA)	V_{R2} (V)	R_{D2} (Ω)	P_{D2} (mW)
1	25	0.34	4.43	8.86	76.75	1.51	0.35	4.40	8.79	79.64	1.54
2	50	0.34	4.43	8.86	76.75	1.51	0.35	4.40	8.79	79.64	1.54
3	75	0.32	4.45	8.89	71.99	1.42	0.35	4.40	8.80	79.55	1.54
4	100	0.26	4.47	8.94	58.17	1.16	0.33	4.41	8.82	74.83	1.46
5	125	0.24	4.48	8.96	53.57	1.08	0.29	4.43	8.86	65.46	1.28
6	150	0.16	4.52	9.04	35.40	0.72	0.26	4.45	8.89	58.49	1.16
7	175	0.11	4.54	9.08	24.23	0.50	0.19	4.48	8.95	42.46	0.85
8	200	0.07	4.56	9.12	15.35	0.32	0.13	4.51	9.01	28.86	0.59

Table 3. Test Results of the Forward-Biased Diode IN5402 and IN5404

S/N	Temp. (^{0}C)	Diode 3 (IN5402) V_{D3} (V)	I_{D3} (mA)	V_{R3} (V)	R_{D3} (Ω)	P_{D3} (mW)	Diode 4 (IN5404) V_{D4} (V)	I_{D4} (mA)	V_{R4} (V)	R_{D4} (Ω)	P_{D4} (mW)
1	25	0.60	4.37	8.73	137.46	2.62	0.46	4.33	8.65	106.36	1.99
2	50	0.60	4.37	8.73	137.46	2.62	0.46	4.33	8.65	106.36	1.99
3	75	0.59	4.37	8.74	135.01	2.58	0.44	4.34	8.67	101.50	1.91
4	100	0.56	4.38	8.76	127.85	2.45	0.41	4.35	8.70	94.25	1.78
5	125	0.54	4.39	8.78	123.01	2.37	0.36	4.37	8.74	82.38	1.57
6	150	0.52	4.40	8.80	118.18	2.29	0.33	4.39	8.77	75.26	1.45
7	175	0.46	4.43	8.86	103.84	2.04	0.27	4.42	8.84	61.09	1.19
8	200	0.37	4.48	8.95	82.68	1.66	0.22	4.44	8.88	49.55	0.98

From the results of Tables 2 and 3, bar charts comparing the forward-biased diode voltage and current against temperature were plotted as presented in Figures 7 and 8. Graphs showing the variation of the forward-biased diode voltage and current against temperature for each of the diodes were plotted as shown in Figures 9 to 12.From these charts and figures, it can be seen that for the forward-biased diode, the diode voltage generally decreased with an increase in temperature while the current increased with an increase in temperature. Also plotted as shown in Figures 13 and 14 were graphs of the diode's static resistance and dissipated power against temperature.

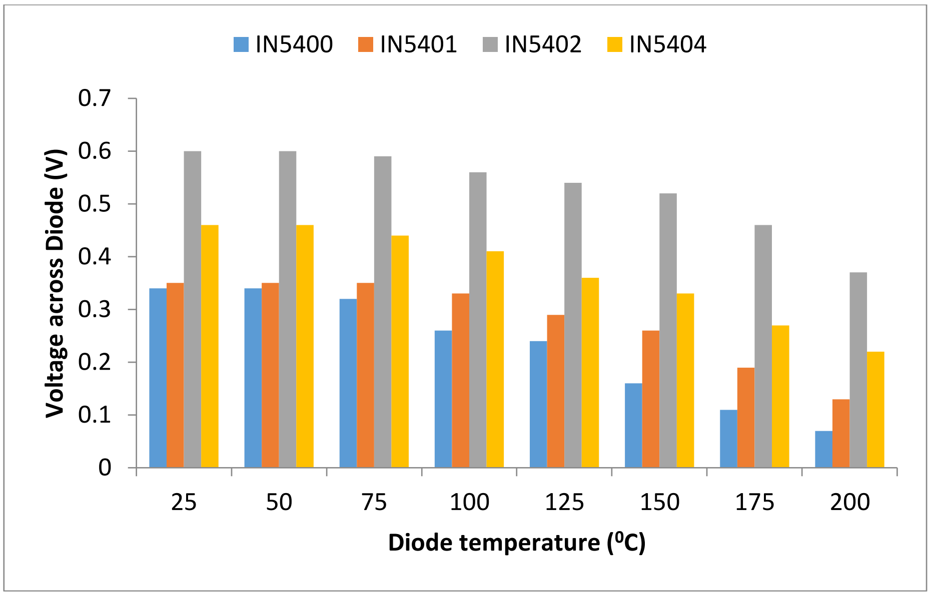

Figure 7. A bar chart comparing the forward-biased diodes' voltage against temperature

The chart of Figure 7 shows the comparative effect of temperature on the forward-biased diode voltage for the four diodes (IN5400, IN5401, IN5402, and IN5404) as the ambient temperature varied from 25 ^{0}C to 200 ^{0}C. On increasing the temperature, the IN5400 diode had a constant voltage of 0.34 V from 25 ^{0}C to 50 ^{0}C, IN5401 had a constant voltage of 0.35V from 25 ^{0}C to 75 ^{0}C, IN5402 had a constant voltage of 0.60 V from 25 ^{0}C to 50 ^{0}C, and IN5404 had a constant voltage of 0.46 V from 25^{0}C to 50^{0}C. The voltages then dropped gradually to values of 0.07 V, 0.13 V, 0.37 V, and 0.22 V, respectively at 200 ^{0}C.

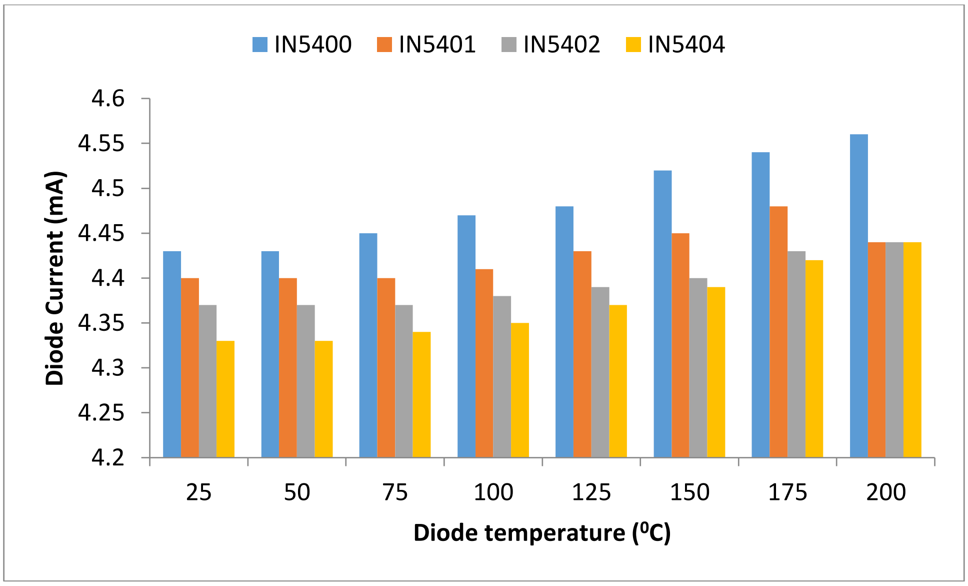

Figure 8. A Bar Chart Comparing the Forward-Biased Diodes' Current against Temperature

A look at Figure 8 shows that for all the diodes, the current increased with an increase in temperature. The increase in current is due to the decrease in the diode voltage occasioned by high temperature-induced changes in some of the diode's intrinsic properties. The high temperature-induced changes as has been established in literature include an increase in charge carrier concentration, a decrease in charge carrier mobility, and a decrease in bandgap [1, 2] which in turn leads to a decrease in the diode resistance and voltage [3].

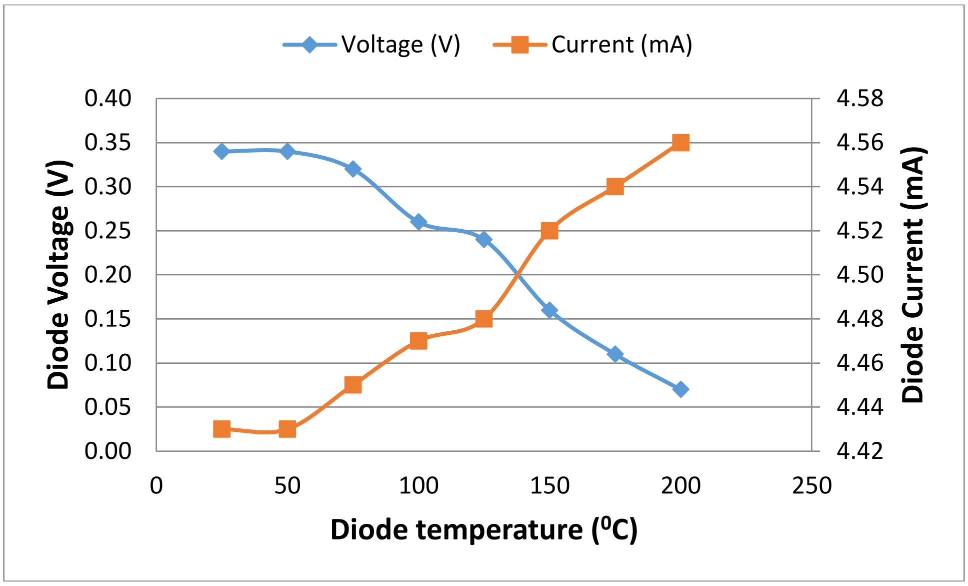

Figure 9. A graph of the forward-biased IN5400 diode voltage and current against temperature

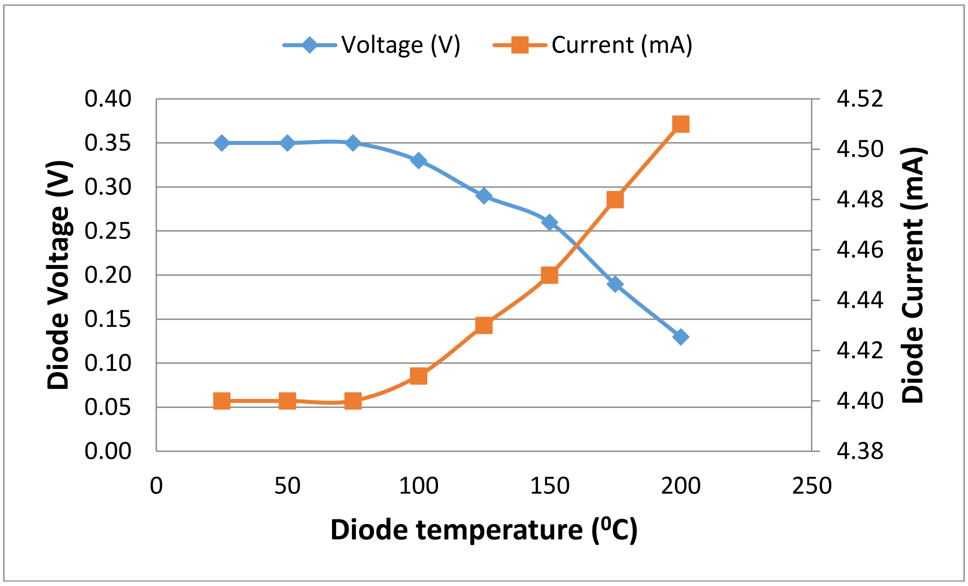

Figure 10. A graph of the forward-biased IN5401 diode voltage and current against temperature

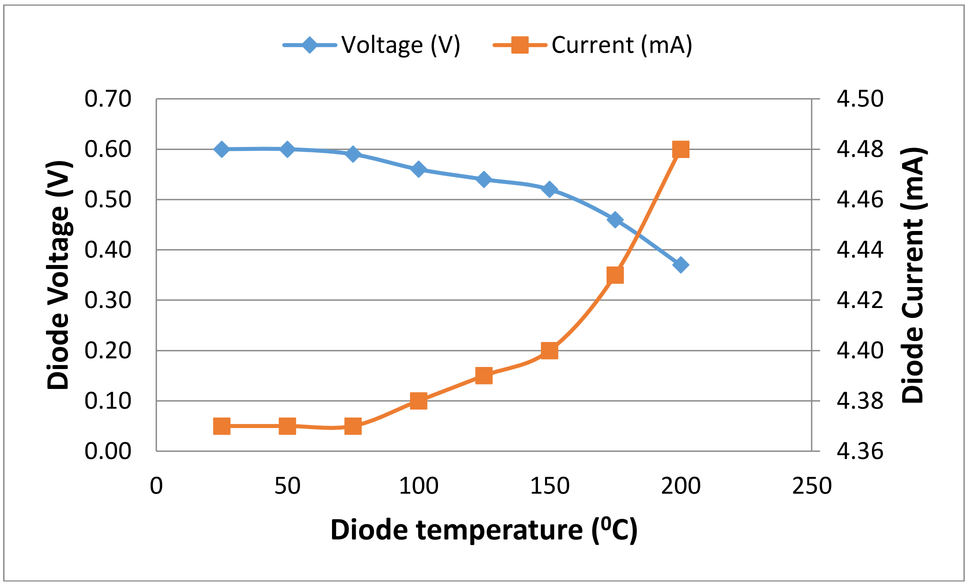

Figure 11. A graph of the forward-biased IN5402 diode voltage and current against temperature

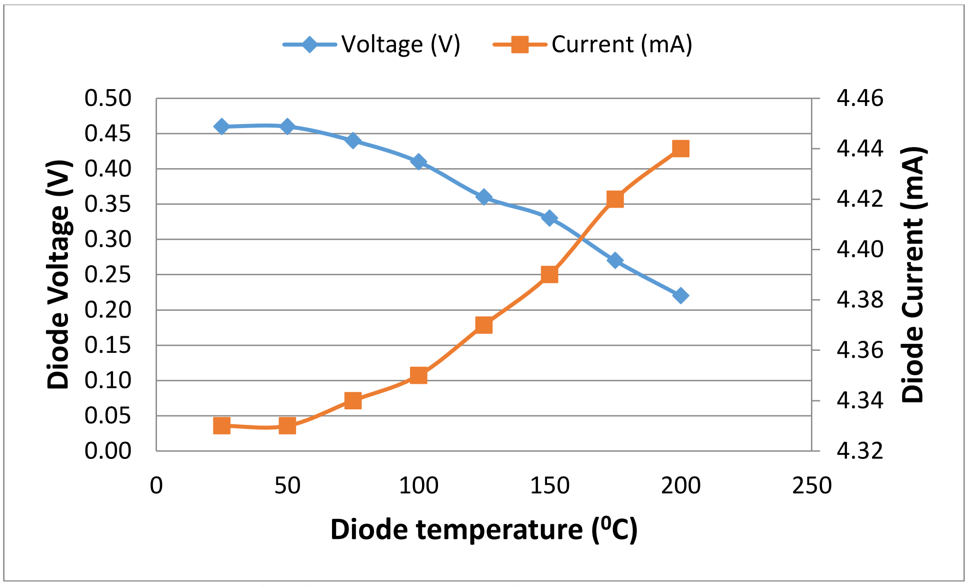

Figure 12. A graph of the forward-biased IN5404 diode voltage and current against temperature

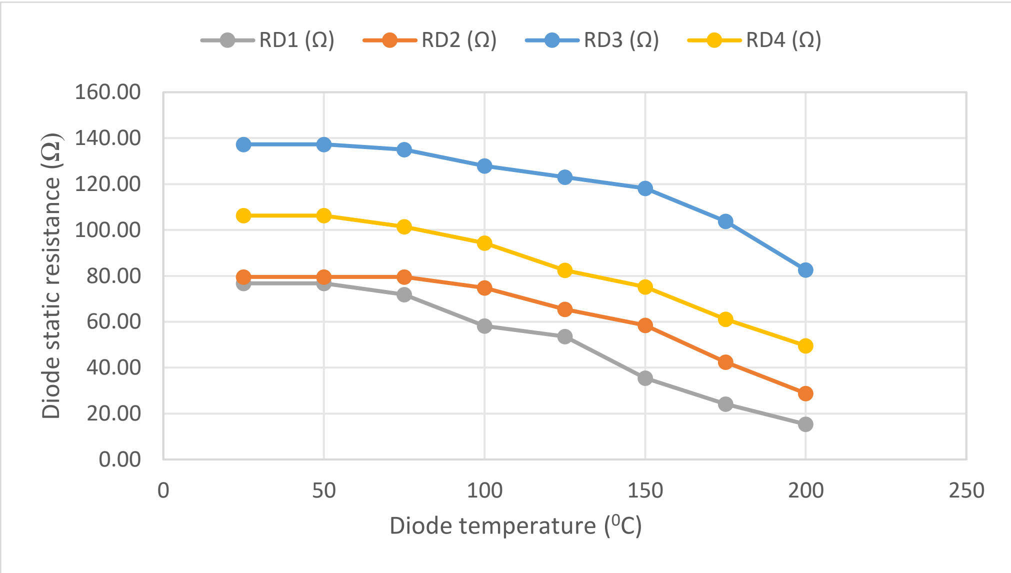

Figure 13. Graph of the forward diode static resistance against temperature for the four diodes

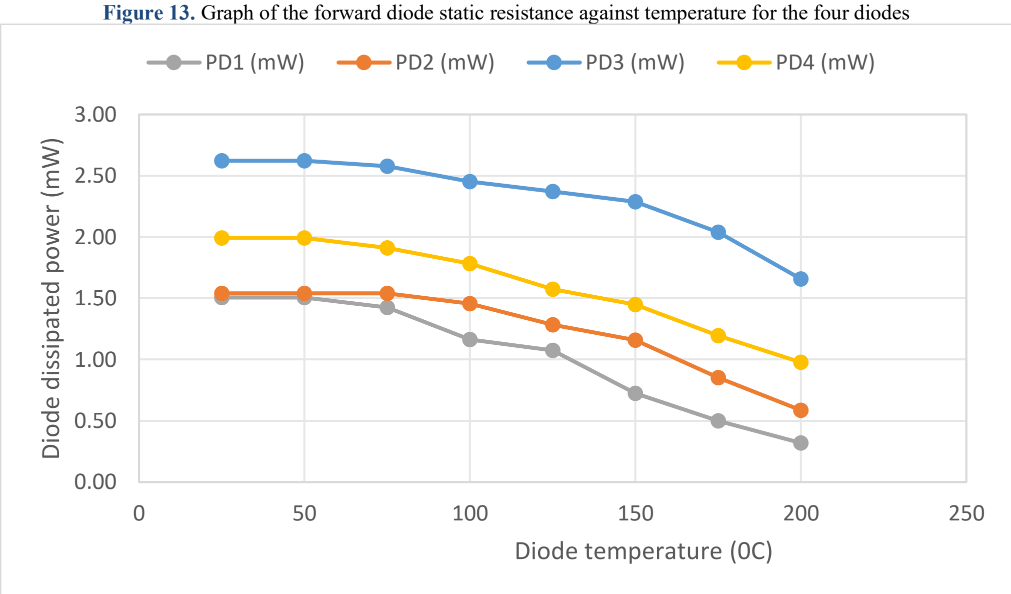

Figure 14. Graph of the forward diode dissipated power against temperature for the four diodes

From Figures 9 to 12, it can be seen clearly that the diode voltage was stable till about temperatures of 50 ^{0}C for IN5400/5404 and 75 ^{0}C for IN5401/5402. The diode voltage, for all the diodes, then decreased with an increase in temperature. The current increased with an increase in temperature while the static resistance and dissipated power decreased with an increase in temperature. These results agreed with thepn junction diode theory as can be seen in the literature [1, 2, 3, 18].The point of intersection of the forward diode voltage and current against temperature were observed to have the following characteristics:

$T = 138$ °C, $V_D = 0.20\,V,\ I_D = 4.50\,mA,\ R_D = 44.44\,\Omega,\ and\ P_D = 0.90\,mW$ for IN5400; $T = 160$ °C, $V_D = 0.23\,V,\ I_D = 4.46\,mA,\ R_D = 51.57\,\Omega,\ and\ P_D = 1.03\,mW$ for IN5401; $T = 185$ °C, $V_D = 0.43\,V,\ I_D = 4.44\,mA,\ R_D = 96.85\,\Omega,\ and\ P_D = 1.91\,mW$ for IN5402; $T = 163$ °C, $V_D = 0.03\,V,\ I_D = 4.40\,mA,\ R_D = 68.18\,\Omega,\ and\ P_D = 1.32\,mW$ for IN5404.

Table 4. Test Results of the Reverse-Biased Diode

S/N	Temp. (^{0}C)	Diode 1 (IN5400) V_{D1} (V)	I_{D1} (mA)	V_{R1} (V)	Diode 2 (IN5401) V_{D2} (V)	I_{D2} (mA)	V_{R2} (V)	Diode 3 (IN5402) V_{D3} (V)	I_{D3} (mA)	V_{R3} (V)	Diode 4 (IN5404) V_{D4} (V)	I_{D4} (mA)	V_{R4} (V)
1	25	9.32	0.03	0.06	9.34	0.00	0.00	9.47	0.00	0.00	9.30	0.00	0.00
2	50	9.32	0.03	0.06	9.34	0.00	0.00	9.47	0.00	0.00	9.30	0.00	0.00
3	75	9.32	0.03	0.06	9.34	0.00	0.00	9.47	0.00	0.00	9.30	0.00	0.00
4	100	9.32	0.03	0.06	9.34	0.00	0.00	9.47	0.00	0.00	9.30	0.00	0.00
5	125	9.29	0.05	0.09	9.34	0.00	0.00	9.47	0.00	0.00	9.30	0.00	0.00
6	150	9.21	0.09	0.17	9.33	0.01	0.02	9.46	0.01	0.01	9.30	0.00	0.00
7	175	9.03	0.18	0.35	9.24	0.05	0.10	9.45	0.02	0.03	9.29	0.01	0.01
8	200	8.46	0.44	0.88	8.58	0.39	0.78	9.38	0.05	0.10	9.25	0.03	0.05

From the results of Table 4, bar charts of the reverse-biased diode voltage and current were plotted as presented in Figures 13 and 14. Graphs showing the variation of the reverse-biased diode voltage and current against temperature for each of the diodes were plotted as shown in Figures 15 to 18.

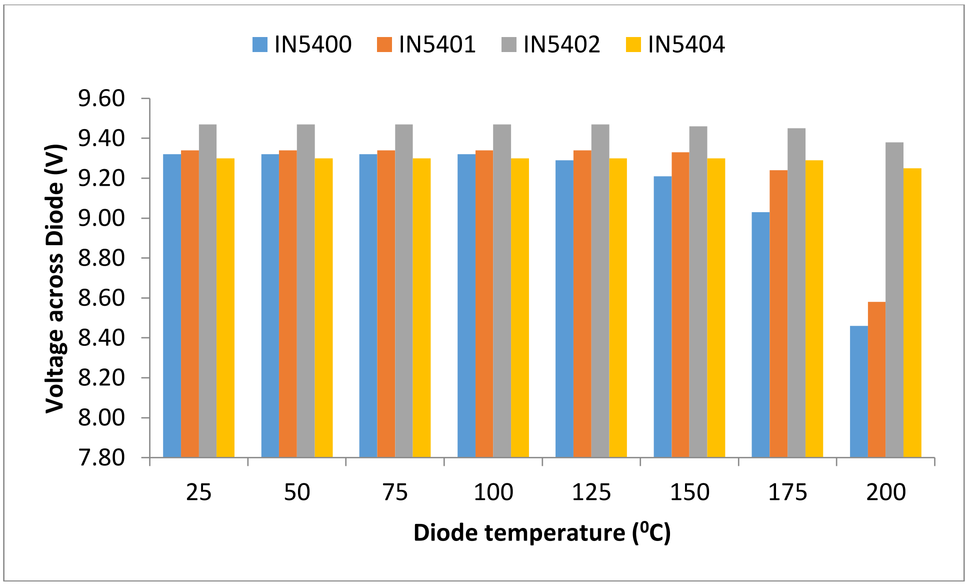

Figure 15. A Bar Chart of the Reverse-Biased Diode Voltage against Temperature

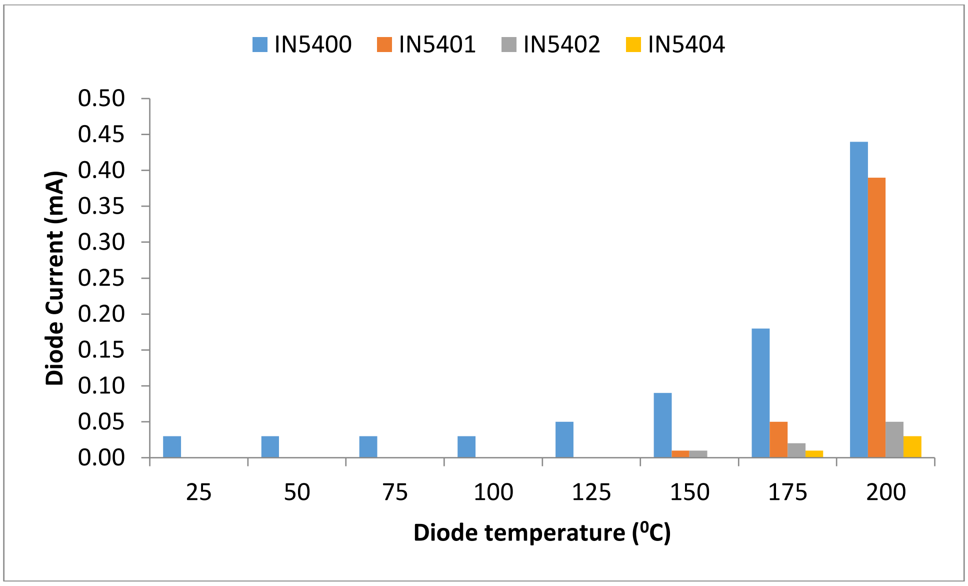

Figure 14. A Bar Chart of the Reverse-Biased Diode Current against Temperature

From Figures 13 and 14, it can be seen that the effect of ambient temperature on the reverse-biased diode voltage and current is negligible till the temperature of about 150 ^{0}C. The voltage was constant with no leakage current till about 150 ^{0}C temperature for all the diodes except IN5400 which had leakage current even at room temperature.

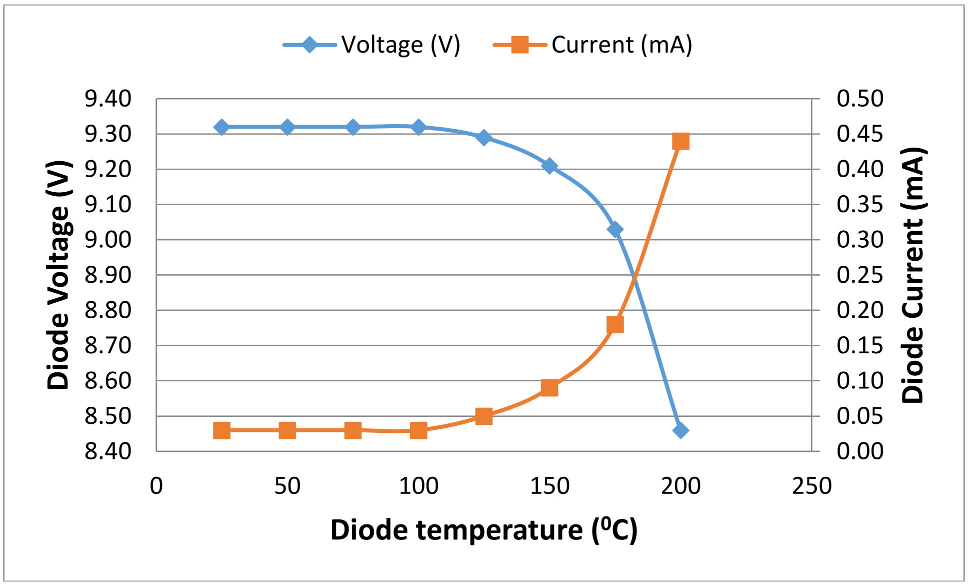

Figure 15. A graph of the reverse-biased IN5401 diode voltage and current against temperature

From Figure 15, it can be seen that the reverse-biased diode voltage of IN5400 was stable at 9.32 V with a leakage current of 0.03 mA till a temperature of 100 ^{0}C. After this temperature, the voltage decreased with an increase in temperature, and the current increased with an increase in temperature till their final values of 8.46 V and 0.44 mA, respectively at 200 ^{0}C temperature.

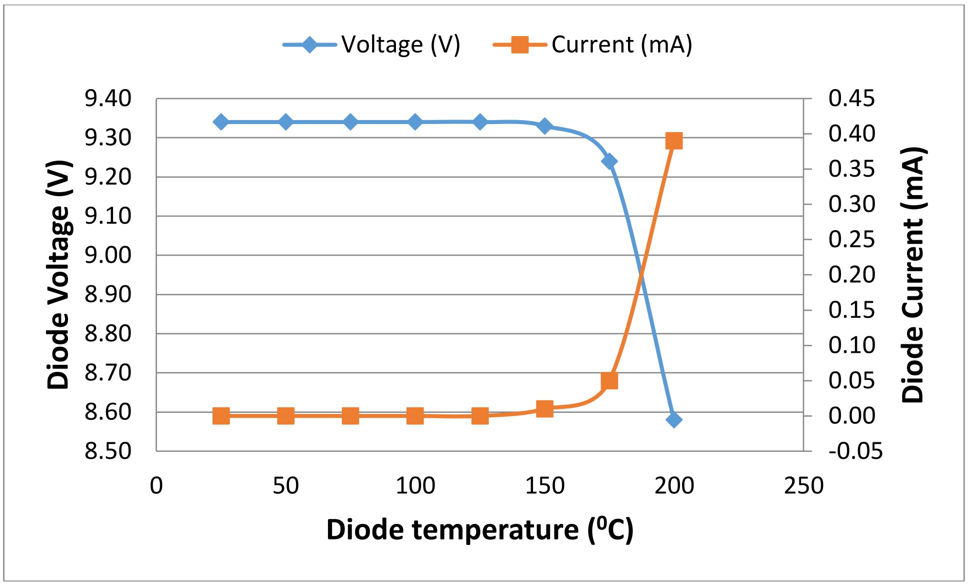

Figure 16. A graph of the reverse-biased IN5401 diode voltage and current against temperature

From Figure 16, it can be seen that the reverse-biased diode voltage of IN5401 was stable at 9.34 V with no leakage current till the temperature of about 150 ^{0}C. From the 150 ^{0}C temperature, the voltage decreased with an increase in temperature, and the current increased with an increase in temperature till their final values of 8.58 V and 0.39 mA, respectively at 200 ^{0}C temperature.

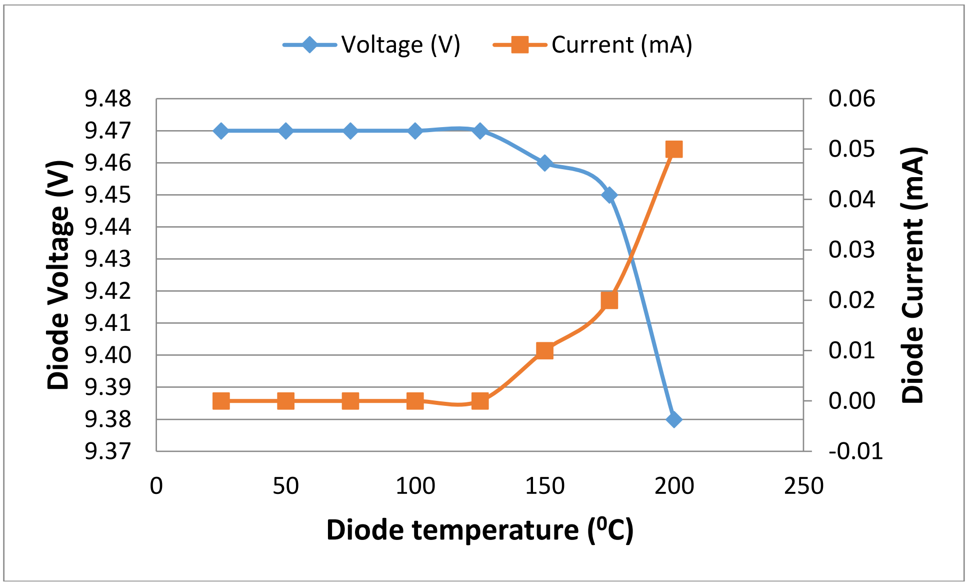

Figure 17.A graph of the reverse-biased IN5402 diode voltage and current against temperature

From Figure 17, it can be seen that the reverse-biased diode voltage of IN5402 was stable at 9.47 V with no leakage current till the temperature of 125 ^{0}C. The voltage then decreased with an increase in temperature, and the current increased with an increase in temperature till their final values of 9.38 V and 0.05 mA, respectively at 200 ^{0}C temperature.

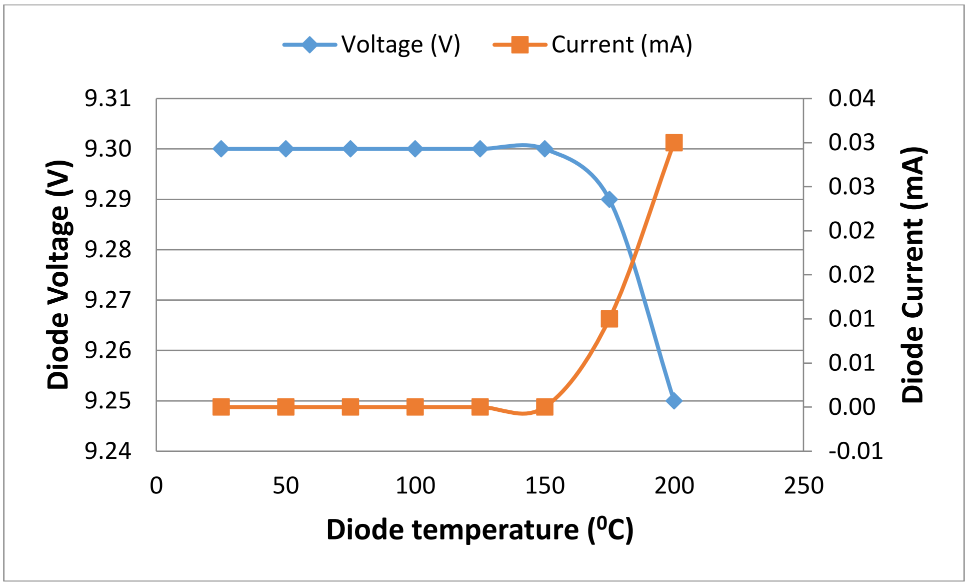

Figure 18. A graph of the reverse-biased IN5404 diode voltage and current against temperature

From Figure 18, it can be seen that the reverse-biased diode voltage for IN5404 was stable at 9.30 V with no leakage current till the temperature of 150 ^{0}C. The voltage then decreased with an increase in temperature, and the current increased with an increase in temperature till their final values of 9.25 V and 0.03 mA, respectively at 200 ^{0}C temperature.

The decrease in the reverse-biased diode voltage and increase in the current with an increase in temperature agreed with the established diode reverse-biased characteristics as can be seen in the literature [3].

4. Conclusion

For the four investigated diodes, IN5400, IN5401, IN5402, and IN5404, the forward voltage generally decreased with an increase in temperature while the current increased with an increase in temperature. The effect of ambient temperature on the reverse-biased diode voltage and current is negligible till the temperature of about 150 ^{0}C. Beyond the 150 ^{0}C temperature, the reverse-biased diode voltage decreases with an increase in temperature while the reverse saturation current increases with an increase in temperature.

Specifically, IN5400 and IN5404 diodes showed stable forward voltages of 0.34 V and 0.46 V, respectively till a temperature of about 50 ^{0}C before decreasing with an increase in temperature till their final voltages of 0.07 V and 0.22 V, respectively at 200 ^{0}C. In the same vein, IN5401 and IN5402 diodes had stable voltages of 0.35 V and 0.60 V, respectively till about 75 ^{0}C temperature after which the voltages decreased with an increase in temperature till their final values of 0.13 V and 0.37 V, respectively at 200 ^{0}C. On the other hand, the currents of IN5400 and IN5404 were stable at 4.43 mA and 4.33 mA, respectively till about 50 ^{0}C before increasing with an increase in temperature till their final values of 4.56 mA and 4.44 mA, respectively at 200 ^{0}C. IN5401 and IN5402 had stable currents of 4.40 mA and 4.37 mA, respectively till about 75 ^{0}C before the currents increased with an increase in temperature till their final values of 4.51 mA and 4.48 mA, respectively at 200 ^{0}C.

The diodes' forward voltage and current characteristic curves against temperature intersected at temperatures of 138^{0}C for IN5400; 160^{0}C for IN5401; 185^{0}C for IN5402; and 163^{0}C for IN5404. Theses points of intersection have the following characteristics: $V_D = 0.20\,V,\ I_D = 4.50\,mA,\ R_D = 44.44\,\Omega,\ and\ P_D = 0.90\,mW$ for IN5400; $V_D = 0.23\,V,\ I_D = 4.46\,mA,\ R_D = 51.57\,\Omega,\ and\ P_D = 1.03\,mW$ for IN5401; $V_D = 0.43\,V,\ I_D = 4.44\,mA,\ R_D = 96.85\,\Omega,\ and\ P_D = 1.91\,mW$ for IN5402; $V_D = 0.03\,V,\ I_D = 4.40\,mA,\ R_D = 68.18\,\Omega,\ and\ P_D = 1.32\,mW$ for IN5404.

The diode static resistance and dissipated power decreased with an increase in temperature from 76.75 Ω and 1.51 mW at 25^{0}C to 15.35 Ω and 0.32 mW at 200^{0}C for IN5400; 79.55 Ω and 1.54 mW at 25^{0}C to 28.82 Ω and 0.59 mW at 200^{0}C for IN5401; 137.30 Ω and 2.62 mW at 25^{0}C to 82.59 Ω and 1.66 mW at 200^{0}C for IN5402; and 106.24 Ω and 1.99 mW at 25^{0}C to 49.55 Ω and 0.98 mW at 200^{0}C for IN5404.

We recommend that designers and manufacturers of electronic devices should study the data on the effect of temperature on any electronic component before such a component is used, irrespective of the power capacity of the component. This is because this research has shown that even low-power electronic components can be affected by ambient heat generated from other circuit components.

Manufacturers of electronic components should carry out or sponsor more research to generate comprehensive temperature effect data of all the existing electronic components as there is limited temperature effect information on the datasheet of these components.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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