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Electrical Characterization of a P-N Junction Diode Using Keithley 2400 Source Measure Unit

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Abstract

In this article, the forward and reverse biases characteristics of a p-n junction diode using a Keithley 2400 source measure unit were measured and the important parameters of diode such as, forward Voltage Test (V_F) for forward-bias were found to be 0.625, 0.65, and 0.7V for different sweep delay 1sec,0.01sec and 0.1sec respectively and for the reverse-bias, the Breakdown Voltage Test (V_R), and Leakage Current Test (I_R),and Ideality factor (k) were found to be -11V, -3.03nA,and 0.9857 and,respectively. The graphs of I-V Characteristics were drawn for different sweep delay time of 0.01s, 0.1s and 1s for both forward-bias and reverse-bias.

Keywords: Diode, forward bias , reverse-bias, Keithley 2400**,**Breakdown Voltage Test (V_R), Leakage Current Test (I_R) ,Ideality factor (k).

1.0 Introduction

The electrical characterization of p-n junction diodes is critical to ensure compliance with manufacturers' specifications and to identify and weed out defective devices before they are brought to the international market. The p-n junction devices are constructed by creating an n+ well in the p-type substrate by thermal diffusion [1].
Most types of diodes undergo at least three basic DC parametric tests during this final inspection process: the Forward Voltage Test (V_F), Breakdown Voltage Test (V_R), and Leakage Current Test (I_R). While the reliability of these tests is essential to ensuring product quality, it's equally important that they be conducted quickly to maintain high production output.
This functional test (V_F) involves sourcing a specified forward bias current within the normal operating range of the diode, then measuring the resulting voltage drop after a specified period of time (e.g., 1ms).
In the (V_R) test, a specified reverse current bias is sourced and the resulting voltage drop across the diode is measured after a specified period of time (e.g., 1ms). The avalanche breakdown voltage is related to the doping concentration [2].The leakage test verifies the low level of current that leaks across the diode under reverse voltage conditions. For this test, a specified reverse voltage is sourced for a specified period of time (e.g., 10ms), and then the resulting leakage current is measured. The Keithley's Series 2400 Source Meter instruments [3] are widely used for diode production testing because they enable test engineers to configure a test system using a single instrument that can source and measure both current and voltage.
Generally, the p-n junction diodes will have larger turn-on voltages, lower leakage currents, larger breakdown voltages, and slower switching speeds as compared to Schottky diodes [4]. Moreover, another important requirement for p-n diodes is to have a highly conductive p-type layer with a high holes concentration [5-8].
The I–V characteristics of the p-n junctions may therefore be thought of as surface measurements. For this reason, all characterization will follow the analysis of the abrupt junction diode [9].
In this study, the electrical I-V characteristics of p-n junction diodes were determinedusing a Keithley 2400 source measure unit.

1.1 Theory

A semiconductor in the un-bias state equilibrium considerations demands that the Fermi levels, E_f (energy bands) is constant throughout the bulk of the material. This causes distortion of the energy bands at the junction and results in an electric field across the junction. The field is known as a build-in field. At equilibrium, there is a small depletion layer containing fixed ionized atoms and substantially no mobile charge carriers.
Under reverse-bias conditions the depletion layer increases with the electric field across the junction, which thus acts as a

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barrier to current flow. Thermally generated charge carriers diffusion into the depletion layer are swept across the junction by the electric field and thus produce a small reverse saturation current I_R.
Under the forward-bias conditions the built-in field virtually disappears and charge carriers are attracted across the junction into the opposite polarity type (where they become minority carriers and cause a current to flow in an external circuit. The current-voltage relationship of an ideal p-n homojunction under forward-bias condition obeys an exponential relationship:

$$I = I_0\left(e^{qv/KT} - 1\right) \tag{1}$$

Where q is the electric charge, v is the diode voltage applied, K is the Boltzmann constant and T is the thermodynamic temperature.
This is the Shockley equation (or ideal diode equation) and assumes that the current is due to the diffusion of charge carriers across the junction that the injected minority carrier density is small compared to the majority carrier density, and there is no generation or recombination of charge carriers in the depletion region.
In the practical point, this condition are always not fulfilled, particularly in silicon where the intrinsic carrier concentration is low, and it is found that the Shockley equation may be modified so that the term $qv/_{KT}$ is replaced by $qv/_{nKT}$, where n has a value between one and two known as the ideality factor.

2.0 Experimental Procedure

To measure the forward and reverse biases characteristics of a p-n junction diode using a Keithley 2400 source measure unit to calculate the important parameters of the diode: the Forward Voltage Test (V_F), Breakdown Voltage Test (V_R), and Leakage Current Test (I_R), Fill factor (FF), Ideality factor (n).

2.1 Forward I-V Measurement

The diode was connected in the forward biased direction to the Keithley 2400 measurement configuration as shown in the above diagram of figure 1.1 above. With the aid of a computer soft ware (Labtracer software), the experiment was programmed to source the voltage from 0 - 0.7 V with a step- size of 0.05 V. With a 1 second sweep delayed and no filtering, the source measure unit was instructed from the Labtracer to measure the current while sourcing the voltage. The experiment was then repeated with the following data: voltage of 0 – 1V, a sweep delay of 10 ms, and no filtering. The current was measured again while sourcing the voltage. The experiment was performed again but this time sourcing the current from 0 – 100 mA in 101 steps while measuring the voltage with a compliance of 1 V, and a sweep delay of 100ms.

2.2 Reverse I –V Measurement

The diode was connected in the reversed bias mode to the Kiethley 2400 source measure unit as shown in the diagram above using the 4-wire measurement configuration.

2.2.1 The Ideality Factor(k)

As with any product manufactured, the end product is never as good as the ideal design. It is for this reason that methods are employed to measuring the quality of each device used to ascertain how good and how close to the ideal product each end product is. In real life, diodes do not behave in a completely ideal manner, so a parameter need to be added to compensate for this non-ideal behavior known as the ideal factor or slope parameter (η).

$$\eta = \frac{q\Delta V log(e)}{K_B T} \tag{2}$$

Where; $\Delta V =$ Change in voltage across the junction per decade of current and e is the constant given by 2.71828. Temperature, T was assumed at room temperature = 300K ,The electronic charge, q = $1.602176\ x10^{-19}$ C
The Boltzman's constant $K_B = 1.38065x10^{-23}$ J/K.The ideal diode factor is found to be between 1.1 and 1.2 from literature [5]. As the ideality factor increases, the non-linearity of the diode decreases changing the gradient of its I-V plot; the effect of this is to reduce all aspects of the standard performance whether it is being used forharmonic generation or radio frequency mixes.The ideal diode equation and the electricalcharacteristics can be generally evaluated by using an equation based on a well-known standard thermionic-emission (TE) relation for electron transport from a metal-semiconductor contact (for qV > 3 kT) [10-11]. It can be given as

$$I = I_O\left[exp\left(\frac{qV}{K_B T}\right) - 1\right], \tag{3}$$

and when V$> 50 - 100mV$, we can ignore the first term and taking natural log of both sides of equation (3) gives

$$\ln I = \ln I_O + \left(\frac{qV}{K_B T}\right). \tag{4}$$

The I is the current through the diode, V is the voltage across the diode, Io is the saturation current, and k is the ideality factor. A graph of In (I) against voltage is used to deduce the ideality factor of the diode.

$$k = \frac{q}{K_B T}\left(\frac{dV}{dInI}\right) \quad (5)$$

The slope of the graph is related to the ideality factor by the following relation:

$$slope = \frac{dV}{dInI} = \frac{q}{kK_B T} \quad (6)$$

where k is the ideality factor, T is the absolute temperature ($\approx 300k$), and the Boltzman's constant K_B is given by K_B = 1.3806503 x10^{-23}k/J .

3.0 Results

3.1 For Forward I-V Measurement

After sourcing the voltage from 0V to 0.7V with a step-size of 0.05V, and the current measured with the compliance limit set to 100mA,1second sweep delay, no filtering, 4-wire remote mode, we obtained the following I-V characteristics (see Fig.1)

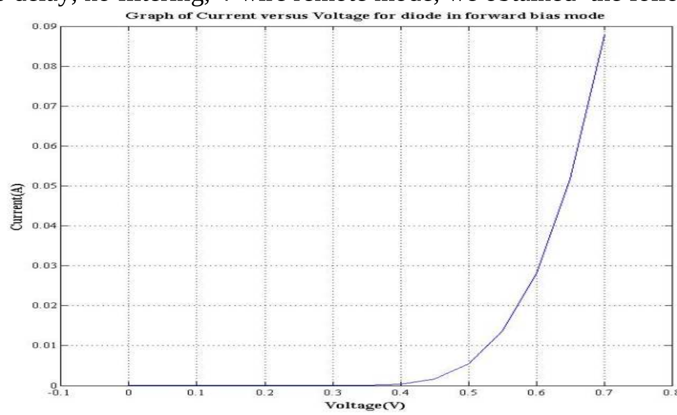

Figure 1: Graph of Current versus voltage for forward bias diode with a sweep delay of 1 second

A straight-line approximation of the forward characteristics allows a resistance value (the forward slope resistance) to be calculated from the slope of the straight line.

Cross section (A)of junction diode = 1 mm^2.

The current density, $J = \frac{I}{A}$ of all the experiments was determined. The corresponding current density graph from the data is plotted in Fig. 2:

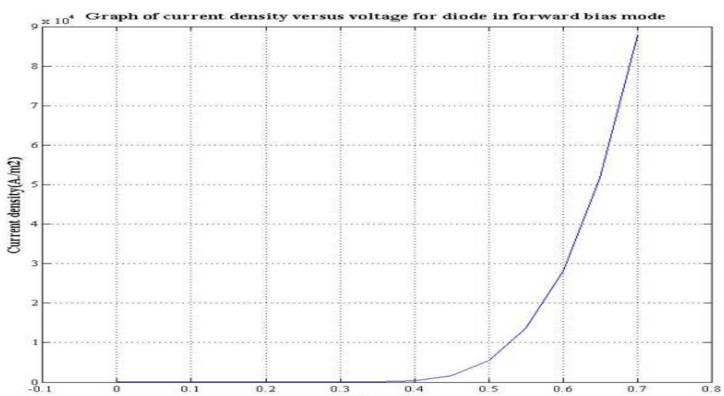

Figure 2: Graph of Current density versus voltage for forward bias diode with a sweep delay of 1 second

The experiment was repeated with the following values: 0 to 1V in 101 steps, 200mA compliance, 10ms sweep delay and no filtering. We saved the data which was used to obtain Fig.3:

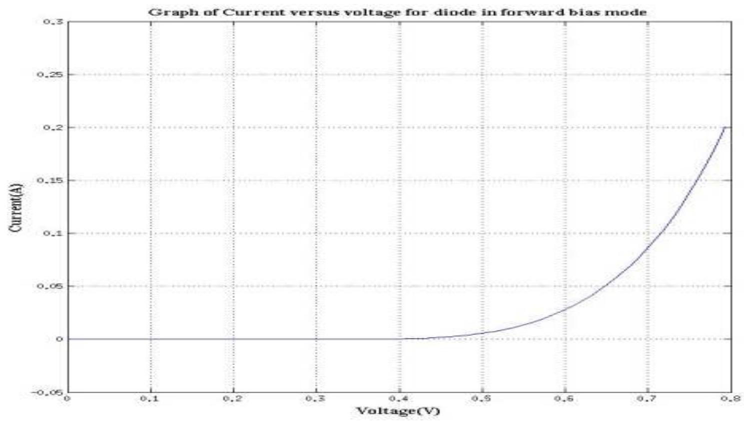

Figure 3: Graph of Current versus voltage for forward bias diode with a sweep delay of 0.01 second

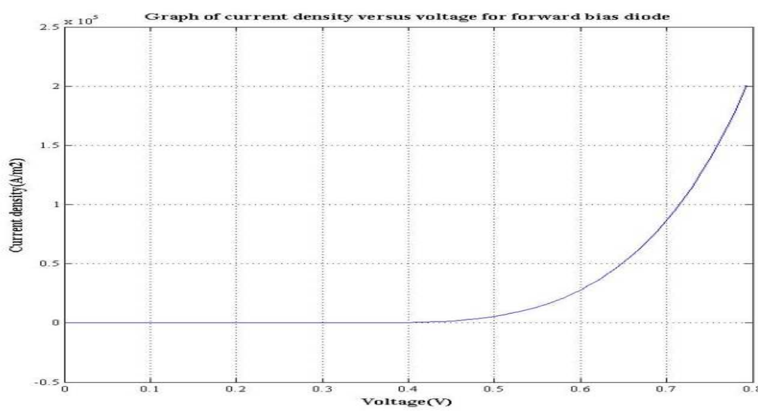

Figure 4: Graph of Current density versus voltage for forward bias diode using a sweep delay of 0.01 second

In the last case of forward I-V measurement, the current was sourced from 0 to 100mA in 101 steps and the voltage measured. The following additional settings were used: 1V compliance, 100ms sweep delay. This yields the following I-V characteristic (see Fig.5):

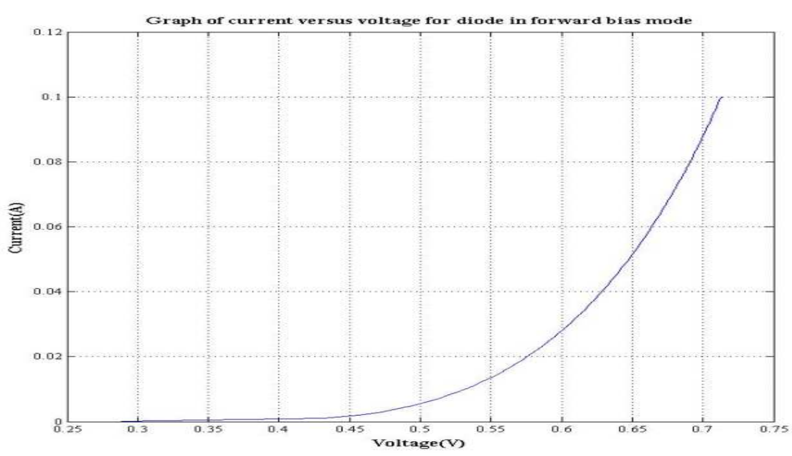

Figure 5: Graph of Current versus voltage for forward bias diode using a sweep delay of 0.1 second

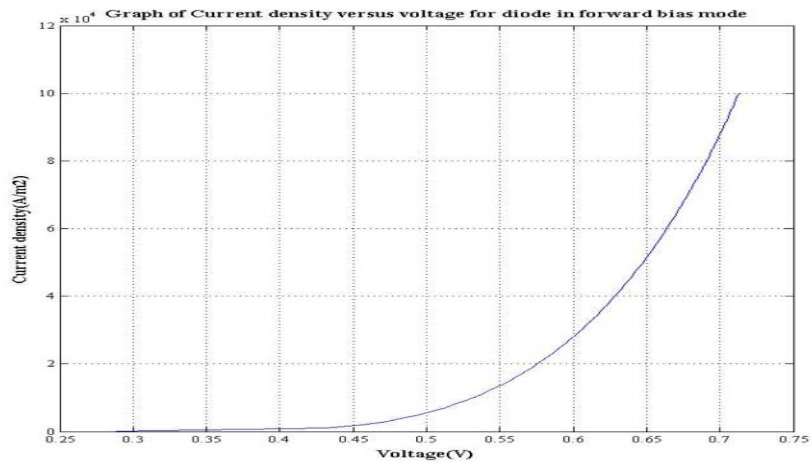

Figure 6: Graph of Current density versus voltage for forward bias diode using a sweep delay of 0.1 second

3.2 For Reverse I –V Measurement

The source measure unit was programmed to source voltage from (0 –250V)in 101 steps, compliance of 200 V, sweep delay of 100 ms, and filtering (average with 5). The current was then recorded. The I-V plot in this case is given in Fig.7:

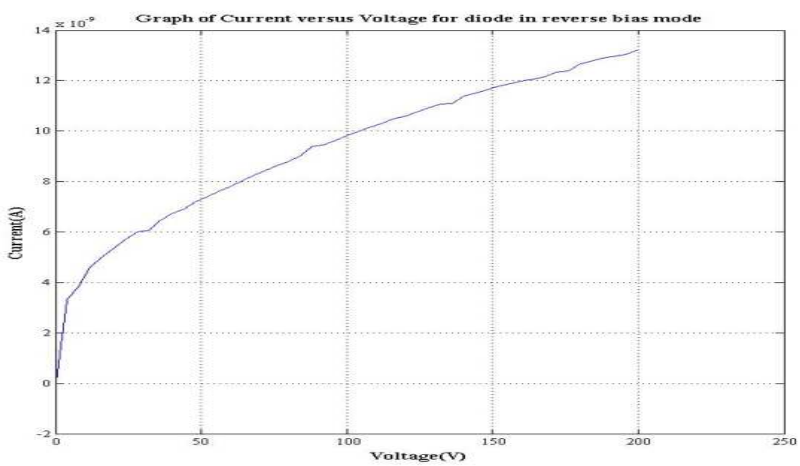

Figure 7: Graph of Current versus voltage for reverse bias diode using a sweep delay of 0.1 second

The current density versus voltage plot is given in Fig.8:

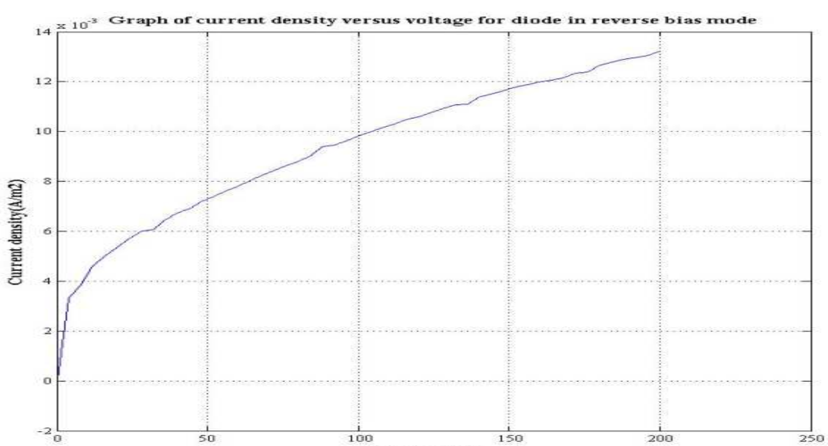

Figure 8: Graph of Current density versus voltage for reverse bias diode using a sweep delayof 0.1 second

The following plot shows lnI versus Voltage, V from whose slope the ideality factor is determined in Fig.9:

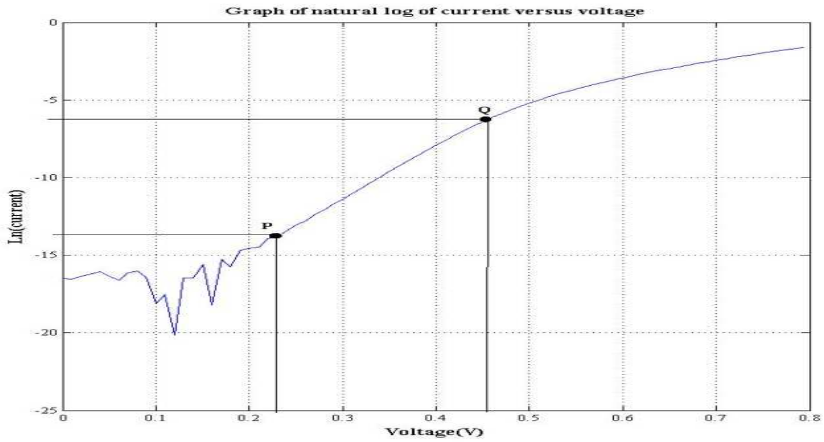

Figure 9: Graph of natural log of current versus voltage for forward bias diode using a sweep delay of 0.1 second

The slope of the linear portion of the graph of figure 1.10 is calculated using the two points P(0.23,-14.5) and Q(0.44,-6.5).

$$slope = \frac{dlnI}{dV} = \frac{-6.5-(-14.5)}{0.44-0.23} = 38.095/V \qquad (7)$$

The slope(s) is calculated to be 38.095 per volts.

The ideality factor can be determine from slope of equation (7)

$$k = \frac{q}{K_B T}\left(\frac{dV}{dlnI}\right) = \frac{q}{K_B T}\frac{1}{slope} = \frac{1.602176 \times 10^{-19}}{1.38065 \times 10^{-23} \times 300} \times \frac{1}{38.095} = 0.9857 \qquad (8)$$

The ideality factor, k=0.9857.

4.0 Discussion

When the voltage on the p-type region of the p-n junction diode is greater (more positive) than the voltage applied to the n-type region, then the diode has a positive voltage across it. This situation is commonly called forward bias.

When the voltage on the p-type region of the p-n junction diode is less (more negative) than the voltage applied to the n-type region, then the diode has a negative voltage across it. This situation was determined commonly to be the reverse bias.

When the forward bias exceeds a threshold known as the turn-on voltage, the diode conducts large amounts of current. This threshold is somewhat subjective, and is usually defined in terms of the application to which the diode is being put.

The current density versus the applied voltage (Fig.2) yields a similar graph like the I-V graph (Fig.1). An initial reading of the current density remains at zero until approximately 0.4V where a further increase in voltage causes a rapid increase in current density. However, higher values of current densities are obtained as compared to the values of the current in the first graph. There are higher values of current per unit area of $1mm^2$.

For Fig. 3, An initial increase in voltage seems not to cause any effect on the current, not until almost getting to a voltage of 0.41 V where the current has been observe to vary exponentially with voltage. The forward voltage test for the experiment can be estimated from the graph is 0.65V. When the voltage was switched on in the forward-bias condition, the built-in field virtually disappears and charge carriers were attracted across the junction into the opposite polarity type where they become minority carriers and cause a current to flow in an external circuit. The corresponding current density versus voltage plot is shown in Fig.4.

An initial increase in voltage seems not to cause any effect on the current, until almost getting to a voltage of 0.30 V where the current starts increasing exponentially with voltage. The forward voltage test for the experiment can be estimated from the graph is 0.7V. The current density-voltage graph corresponding to this situation is shown in Fig.6.

Since the diode has a very small cross section, the current density values for the different settings used are larger compared to the corresponding current values. It is noticed from the above results that the voltage beyond which the current starts increasing from zero amperes varies from one setting to the other. The voltage is smallest when the sweep delay is small and we are sourcing the current and measuring the voltage (Fig.5). It is largest when we have a higher sweep delay time and we are sourcing the voltage and measuring current(Fig.1).

The ideality factor is a unit less value typically between 1 and 2, which accounts for non-idealities such as device geometry, series resistance, etc. The ideality factor was found to be 0.9857 or approximately 1. The deviation of the ideality factor from the ideal value indicates that either there are unusual recombination mechanisms taking place that the recombination changing in magnitude. The derivation of the simple diode equation uses certain assumption about the cell. In practice, there are second order effects so that the diode does not follow the simple diode equation and the ideality factor provides a way of describing them.

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