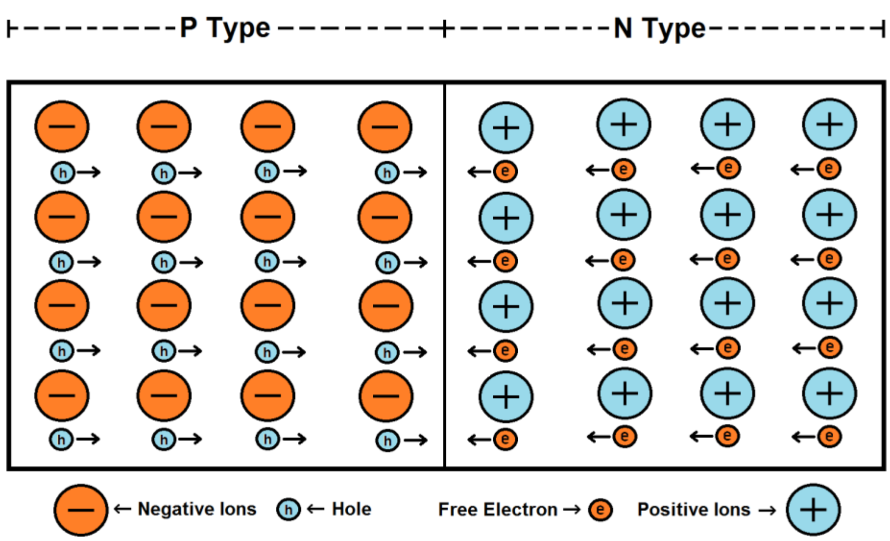
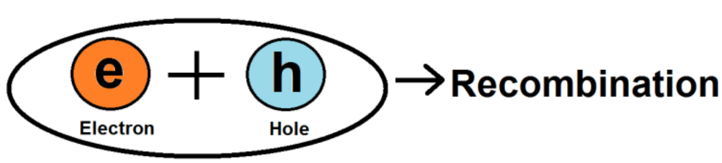
P-N Junction

The P-N Junction is produced by placing a layer of P type semiconductor next to the layer of N type semiconductor. The contact surface is called the P-N junction. The P type semiconductor has mobile holes and the same number of fixed negative accepter ions. Similarly the N type semiconductor has mobile or free electron and the same number of fixed donor positive ions.

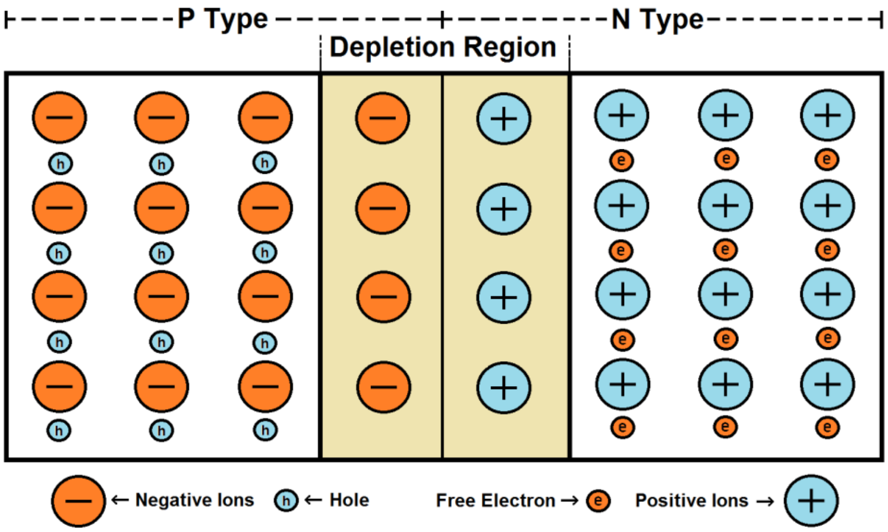
In the formation of P-N junction some of the holes from P type material tend to diffuse across the boundary in to the N type material and some of free electrons diffuse into the P type material as shown in figure. This happens because concentration of holes is higher on P side than that of N type and concentration of electrons is higher on N side than that on P side. This process is known as diffusion. As a result of the displacement of the charges, an electric field appears across the junction. Equilibrium is established when the field becomes large enough to restrain the process of diffusion. The electric charge is confined to the neighborhood of the junction and consists of immobile ions.



(A)



(B)



(C)

Figure: (A, B and C) Formation of depletion region

The negative potential on the P side prevents the migration of any more electrons from the N type material to the P type material. Similarly the positive potential on the N side prevents any further migration of holes across the boundary. Thus the initial diffusion of charge carriers creates a barrier potential at the junction.

The region around the junction is completely ionized. As a result, there are no free electrons on the N side, nor holes on the P side. Since the region around the junction is depleted of mobile charges and it is called the depletion region, the space charge region or the transition region.

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P-N Junction as a Diode

The essential electrical characteristics of a P-N junction is that it constitutes a diode which permits the easy flow of current in one direction but restrains the flow of current in the opposite direction as shown in figure. These characteristics depend on the biasing of the P-N junction.

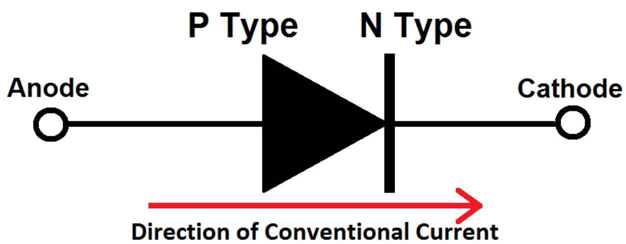

Figure: Symbol of a Diode

(i) Forward Biasing

The junction is said to be forward biased when an external field is applied across the junction in such manner that P region connected to positive terminal and N region connected to negative terminal of the battery as shown in figure.

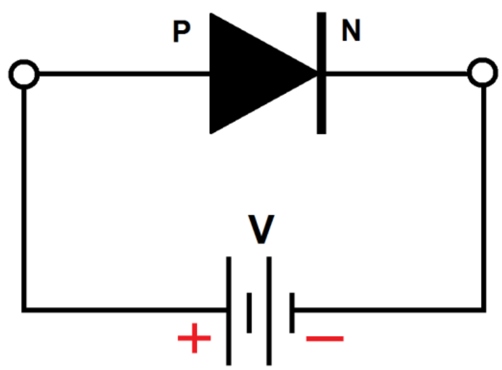

Figure: Forward Bias configuration

In this circuit arrangement, the holes on the P side being positively charged particles are repelled from the positive terminal of the battery. Similarly, the electrons on the N side are repelled from the negative terminal of the battery and driven towards the junction. The result is that the depletion region is reduced in width and the barrier potential is also reduced as shown in figure.

If the applied bias voltage is increased from zero, the barrier potential gets progressively smaller and smaller until it effectively disappears and charge carrier can easily flow across the junction. Electrons from N side are then attracted across to the positive terminal on the P side and holes from the P side flows across to the negative terminal on the N side. Thus a majority carrier current flows. Since barrier potential is very small (0.3 V

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for Ge and 0.7 V for Si), therefore, a small forward voltage is sufficient to eliminate the barrier completely. Once the barrier is eliminated by the forward voltage, junction resistance becomes almost zero and low resistance path is established in the entire circuit. The current in circuit is called the forward current.

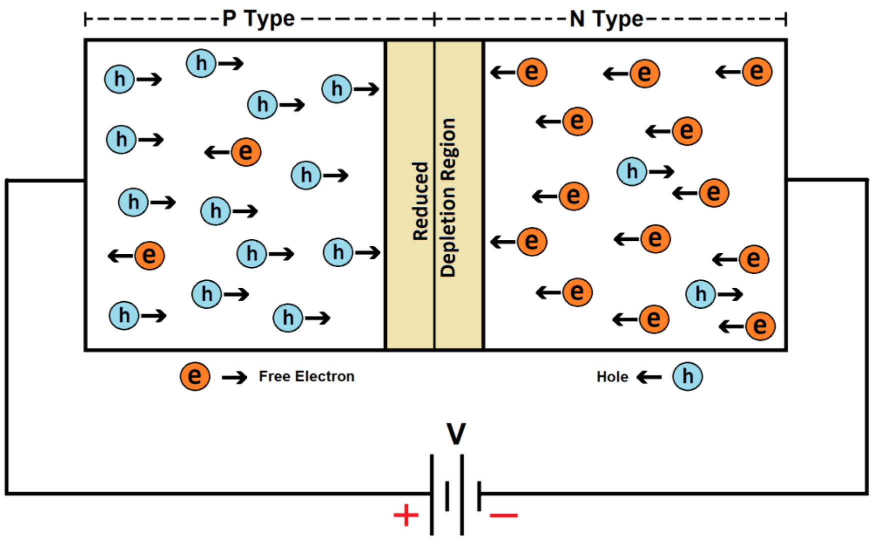

Figure: Forward bias with less than barrier potential

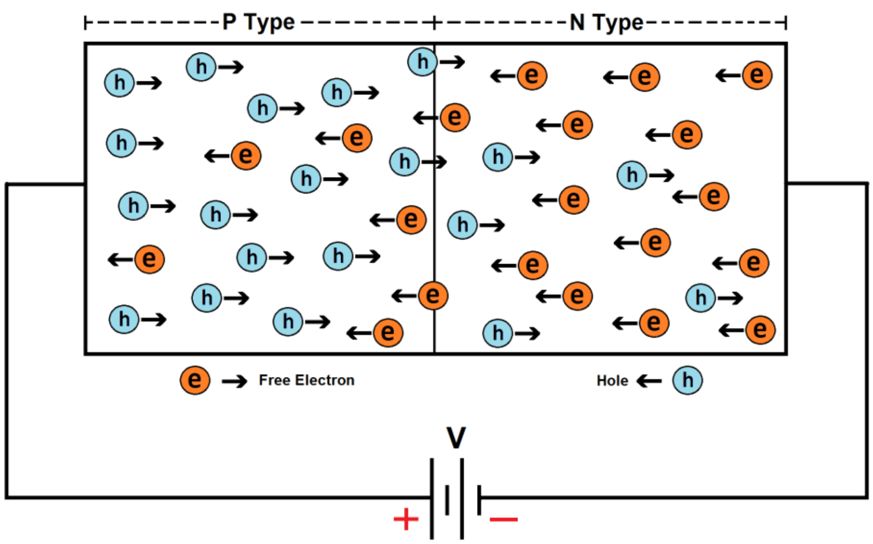

Figure: Forward bias with greater than barrier potential

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(ii) Reverse Biasing

If an external bias voltage is applied with positive terminal to N side and negative to the P side of a P-N junction as shown in the figure, the junction is said to be reverse biased.

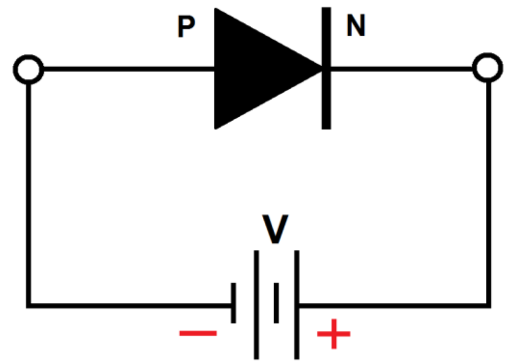

Figure: Reverse Bias configuration

In this arrangement electrons from the N side are attracted to the positive terminal and the holes from the P side are attracted to the negative terminal. Thus as shown in the figure holes of P side of the junction are attracted away from the junction, and the electrons of the N side are attracted away from the junction thus the depletion region is widen and the barrier potential is increased by the magnitude of applied bias with increased barrier potential, there is no possibility of majority carrier current flow across the junction. Thus the P-N junction is in non conductive state. But very small current flows due to minority carrier called reverse saturation current.

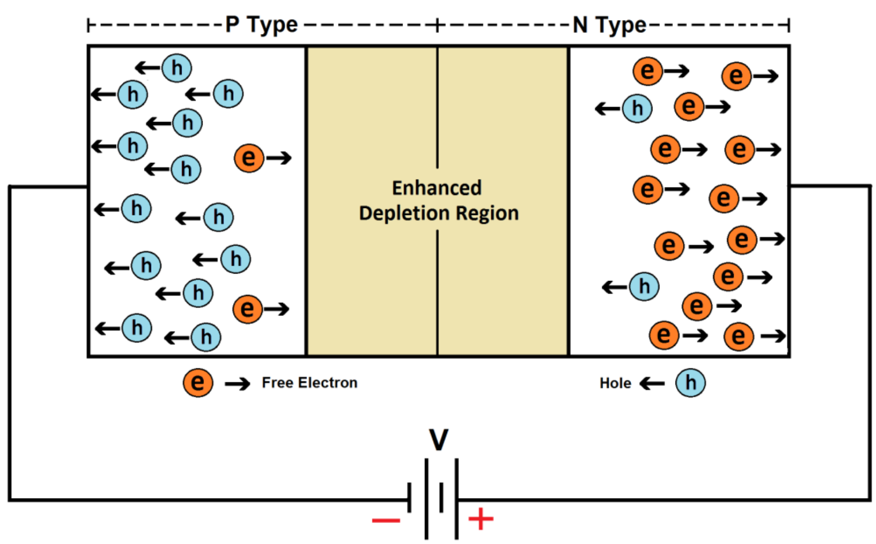

Figure: Reverse bias with less than breakdown voltage

V-I Characteristics of P-N Junction Diode

The graph plotted between the potential differences across the P-N junction and the circuit current is known as volt ampere characteristics of a P-N junction diode as shown in figure.

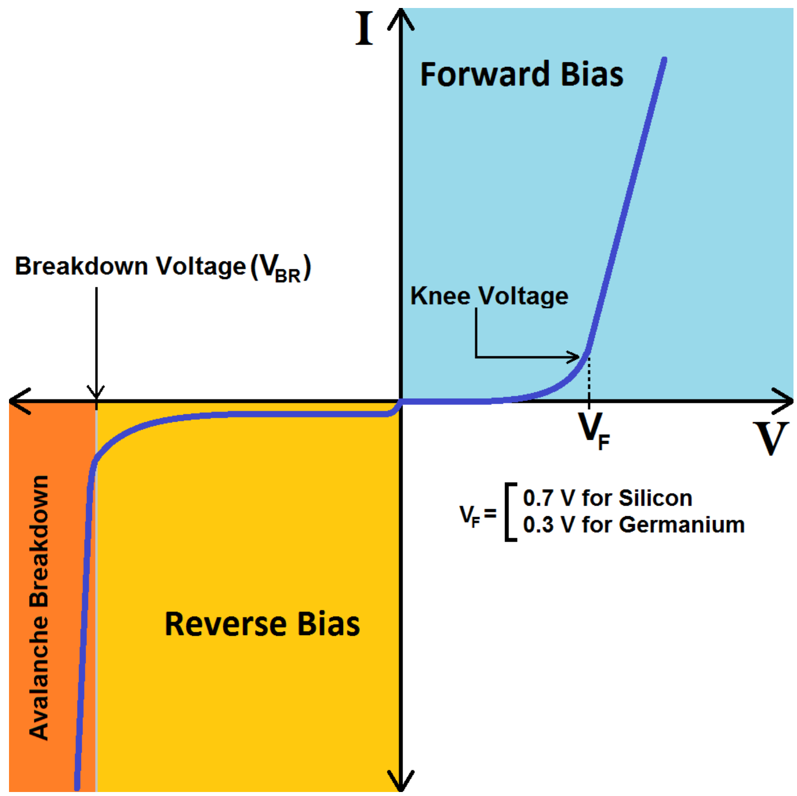

Figure: V-I Characteristics of P-N Junction Diode

(i) Forward Characteristics

When the forward bias is applied to the P-N junction very little current, called the forward current, flows until the forward voltage exceeds the junction barrier potential (0.3 V for Ge and 0.7 V for Si). The characteristics follow an exponential law. As the forward voltage is increased to the knee voltage the barrier potential is progressively reduced to zero, allowing more and more majority charge carrier to flow across the junction. Beyond the knee voltage, the potential barrier is completely eliminated, forward current increases almost linearly with the increase in forward voltage.

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(ii) Reverse Characteristics

When the reverse bias is applied, the potential barrier at the junction is increased, therefore the junction resistance becomes very high and there is no possibility of majority carrier flowing across a reverse bias junction. But still minority carriers generated on each side can cross the junction. Electrons on the P side are attracted across the junction to the positive terminal on the N side and the holes on the N side may travel across the junction to the negative terminal on the P side. This results in a very small current. This current is called reverse saturation current and it is due to minority carriers. However if the reverse bias is increased, a point is reached when the junction breaks down and the reverse current increases abruptly as shown in the figure. The critical value of the voltage at which break down occurs is called the breakdown voltage.

Avalanche Breakdown: A charge carrier in the depletion region acquires energy from the applied potential. This carrier collides with a crystal ion and provides sufficient energy to disrupt the covalent bond and creating new electron hole pair. These new carrier will also acquire sufficient energy form the applied electric field and on collision with another crystal ion they will produce another electron hole pair. Thus each new carrier will produce additional carrier through the collusion. This process is called as avalanche multiplication. It result in large reverse bias current and the diode is said to be in region of avalanche breakdown.

Diode Current Equation

Diode current equation *or the* ***Shockley diode equation****, named after transistor co-inventor William Shockley of Bell Telephone Laboratories, gives the V-I (voltage - current) characteristic of an idealized diode in either forward or reverse bias.*

The current in a P-N diode is bipolar in character (because it is made up of both positive and negative charge carriers) and the total current is constant throughout the device, but the proportion of current due to holes and that due to electrons varies with the distance, as illustrated in figure. Let assume that depletion layer thickness is negligible (i.e., barrier width is zero).

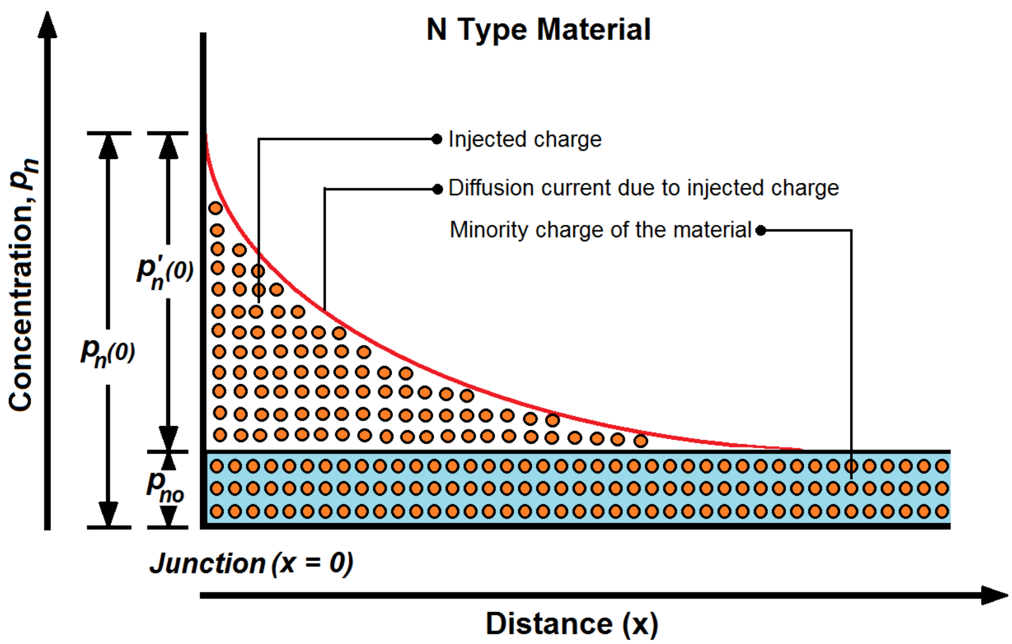

Figure: Variation of excess hole concentration and diffusion current

When a P-N diode is forward biased, holes are injected from P-region into the N- region. The concentration P_n of the holes in the N-region is increased above its thermal equilibrium value P_{no}. The hole concentration in N-region is given as

$$p_n(x) = p_{no} + p_n'(0)e^{-x/L_h} \tag{1}$$

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where P_{no} is the hole concentration in thermal-equilibrium condition, L_h is the diffusion length for holes in N-type material and x is the distance from the junction where concentration is considered.

The injected, or excess, concentration of holes at x = (0), $P_n^{'}(0)$ is given as

$$p_n^{'}(0) = p_n(0) - p_{no} \tag{2}$$

These several hole concentration components are shown in figure, which shows that the concentration $P_n(x)$ falls exponentially with distance x into the N-type material.

The diffusion hole current in the N-region is given as

$$I_{hn} = -\alpha e D_h \frac{dp_n(x)}{dx} \tag{3}$$

Taking the derivative of equation (1) and substituting the value of $\frac{dp_n(x)}{dx}$ in above equation we have

$$I_{hn}(x) = \frac{\alpha e D_h}{L_h} p_n^{'}(0) e^{-x/L_h} \tag{4}$$

At junction i.e., $x = 0$

$$I_{hn}(0) = \frac{\alpha e D_h}{L_h} p_n^{'}(0) \tag{5}$$

$$I_{hn}(0) = \frac{\alpha e D_h}{L_h} [p_n(0) - p_{no}] \tag{6}$$

where α is area of material in m^2, D_h is diffusion constant for holes in m^2/s, e is the magnitude of charge on holes, L_h is the diffusion length of holes in meter, and $p_n^{'}(0)$ is the excess of hole concentration at junction .

Using Boltzmann relationship of kinetic gas theory, we have

$$p_n(0) = p_{no} e^{\frac{V}{V_T}} \tag{7}$$

where V is the voltage applied across the P-N diode and V_T is the volt equivalent of temperature and is defined as

$$V_T = \frac{k'T}{e} = \frac{T}{11{,}600} \tag{8}$$

where k' is the Boltzmann constant. At room temperature, (T=300 °K), V_T *= 26 mV*

from equation (6) and (7)

$$I_{hn}(0) = \frac{\alpha e D_h}{L_h}\left[p_{no}\, e^{\frac{V}{V_T}} - p_{no}\right]$$

$$I_{hn}(0) = \frac{\alpha e D_h}{L_h} p_{no}\left[e^{\frac{V}{V_T}} - 1\right] \tag{9}$$

Similarly

$$I_{ep}(0) = \frac{\alpha e D_e}{L_e} n_{po}\left[e^{\frac{V}{V_T}} - 1\right] \tag{10}$$

In forward bias electrons crossing the junction at x = 0 from right to left constitute a current in the same direction as the holes crossing the junction from left to right. Thus the total current I at x = 0 is given as

$$I_{total} = I_{hn}(0) + I_{ep}(0) \tag{11}$$

where $I_{hn}(0)$ *is the current caused by holes entering the N-region and* $I_{ep}(0)$ *is the current caused by electrons entering the P-region*

$$I = \frac{\alpha e D_h}{L_h} p_{no}\left[e^{\frac{V}{V_T}} - 1\right] + \frac{\alpha e D_e}{L_e} n_{po}\left[e^{\frac{V}{V_T}} - 1\right]$$

$$I = \left[\frac{\alpha e D_h}{L_h} p_{no} + \frac{\alpha e D_e}{L_e} n_{po}\right]\left(e^{\frac{V}{V_T}} - 1\right)$$

$$I = \left[\frac{\alpha e D_h}{L_h} p_{no} + \frac{\alpha e D_e}{L_e} n_{po}\right]\left(e^{\frac{V}{V_T}} - 1\right)$$

$$I = I_0\left(e^{\frac{V}{V_T}} - 1\right) \tag{12}$$

where $I_0 = \left[\frac{\alpha e D_h}{L_h} p_{no} + \frac{\alpha e D_e}{L_e} n_{po}\right]$ *is reverse saturation current.*

The **diode current equation** or **shockley diode equation** relating the voltage V and current I is given by (13). The ideality factor η typically varies from 1 to 2 (though can in some cases be higher), depending on the fabrication process and semiconductor material and is set equal to 1 for the case of an "ideal" diode. The ideality factor was added to account for imperfect junctions as observed in real examples. The factor mainly accounts for carrier recombination as the charge carriers cross the depletion region.

$$I = I_0\left(e^{\frac{V}{\eta V_T}} - 1\right) \tag{13}$$

where

I	:	Diode current
I_O	:	Diode reverse saturation current
V	:	External voltage applied to the diode
η	:	A constant, 1 for Germanium and 2 for Silicon
V_T	:	volt equivalent of temperature (Thermal voltage) V_T = kT/q =T/11600,
k	:	Boltzmann's constant ($1.38066 X 10^{-23}$ J/K)
q	:	Charge of the electron ($1.60219 X 10^{-19}$ C)
T	:	Temperature of the diode (K) = (°C + 273°)