EE236 Electronic Devices Lab

WADHWANI ELECTRONICS LABORATORY

Temperature and material dependence of PN diode, IV characteristics

14/08/2023

Contents

1 Theory **2**

1.1 Diode Current Equation 2

1.2 PN diode material parameters 3

1.3 PN diode temperature dependence 4

2 Simulation Exercises **5**

2.1 Material Dependence 5

2.2 Non Idealities of a PN Diode 5

2.3 Temperature Dependence 5

1 Theory

1.1 Diode Current Equation

The current equation of a PN junction diode is given by the following expression, where I_{SAT} is the saturation current, V_d is the applied voltage and η is the ideality factor

$$I = I_{SAT}[e^{(\frac{qV_d}{\eta kT})} - 1]$$

For $V_d > 100$ mV,

$$I = I_{SAT}[e^{(\frac{qV_d}{\eta kT})}]$$
$$log(I) = log(I_{SAT}) + \frac{qV_d}{\eta kT}$$

We can also write I_{SAT} current as

$$I_{SAT} = qAn_i^2(\frac{1}{N_D}\sqrt{\frac{D_p}{\tau_p}} + \frac{1}{N_A}\sqrt{\frac{D_n}{\tau_n}})$$

Where n_i is the intrinsic carrier concentration and D is the diffusion constant, a material parameter. One can express the intrinsic carrier concentration n_i as follows

$$n_i = A_{const}T^{3/2}e^{\frac{-E_g}{2kT}}$$

1.1.1 Non-Idealities in diode current equation

The current equation of an ideal diode has $\eta = 1$, given by I_D

$$I_D = I_{SAT}[e^{(\frac{qV_d}{kT})} - 1]$$

But experimentally, based on the operating point, the value of η can be different, due to

- Recombination-generation (RG) currents: additional current components due to recombination of carriers (in case of forward bias), and generation of carriers (in case of reverse bias) in the depletion region. The effect of RG currents is more apparent for low forward and reverse bias (due to recombination current, we observe an ideality factor between 1 and 2 for low forward bias).

In case of forward bias,

$$I_D = I_{SAT}[e^{(\frac{qV_d}{kT})} - 1]$$
$$I_{RG} \propto e^{(\frac{qV_d}{2kT})}$$
$$I = I_D + I_{RG}$$

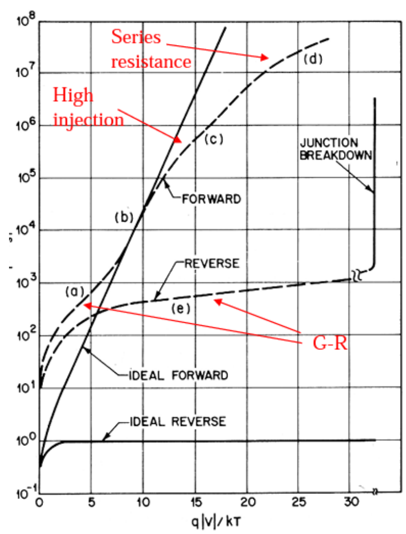
In case of reverse bias,

$$I_D = I_{SAT}$$
$$I_{RG} = \frac{AqWni}{2\tau}$$
$$I = I_D + I_{RG}$$

- High-level injection: As the voltage approaches the built in potential, the minority carrier concentration near the depletion region begins to approach the majority carrier concentration, current in this regime follows $\eta = 2$

$$I \propto e^{(\frac{qV_d}{2kT})}$$

I-V characteristics of a Si diode



From Sze, 1981

1.2 PN diode material parameters

In the above equation of the saturation current various parameters such as the diffusion constant, the band gap of the semiconductor and the intrinsic carrier concentration, are dependent upon the type of material used. The differences in these material parameters result in differences in the IV characteristics of diodes made with different materials (e.g., cut-in voltage, AC response, breakdown voltage, etc.) Apart from silicon another commonly used pn diode is the germanium pn diode, which delivers a much higher current, and a lower cut-in voltage under similar operating conditions.

Property	Silicon	Germanium
Bandgap (eV)	1.12	0.66
Intrinsic carrier concentration (cm^{-3})	10^{10}	10^{13}
Electron mobility (cm^2/Vs)	1500	3900
Hole mobility (cm^2/Vs)	450	1900
Electron diffusion constant (cm^2/s)	39	101
Hole diffusion constant (cm^2/s)	12	49

1.3 PN diode temperature dependence

From the following equations for the current characteristics one can also observe dependence of IV characteristics of the diode on temperature,

$$I_{SAT} = qAn_i^2(\frac{1}{N_D}\sqrt{\frac{D_p}{\tau_p}} + \frac{1}{N_A}\sqrt{\frac{D_n}{\tau_n}})$$
$$n_i = A_C T^{3/2} e^{\frac{-E_g}{2kT}}$$
$$I_{SAT} = qAA_C^2 T^3(\frac{1}{N_D}\sqrt{\frac{D_p}{\tau_p}} + \frac{1}{N_A}\sqrt{\frac{D_n}{\tau_n}})e^{\frac{-E_g}{kT}}$$
$$I_{00} = qAA_C^2 T^3(\frac{1}{N_D}\sqrt{\frac{D_p}{\tau_p}} + \frac{1}{N_A}\sqrt{\frac{D_n}{\tau_n}})$$
$$I_{SAT} = I_{00} e^{\frac{-E_g}{kT}}$$

Apart from this, the bandgap of a material is also dependent on the temperature. As the temperature rises the bandgap reduces, in the following way for Si and Ge respectively

$$Eg_{Si} = 1.165 - 2.84 \cdot 10^{-4} \frac{ev}{K} \frac{1}{T}$$
$$Eg_{Ge} = 0.732 - 3.9 \cdot 10^{-4} \frac{ev}{K} \frac{1}{T}$$

2 Simulation Exercises

2.1 Material Dependence

1. Simulate the IV characteristics of silicon (Vapplied varies from -5 V to 5 V) & germanium diodes (Vapplied varies from -5 V to 5 V), using default parameters at 300 K, and plot them as a csv file (use old version of PN junction lab https://nanohub.org/tools/abacus). Number of points in the simulation must be 100.
2. For the forward IV characteristics, plot them in the same plot on both, linear and log scales.
3. Note down the value of the voltage (cut-in voltage) in both the diodes when the current density reaches a value of 10 A/cm^2.
4. Explain the differences in the current densities and the cut-in voltages based on the material parameters of the two diodes

2.2 Non Idealities of a PN Diode

1. Simulate the IV characteristics of the silicon diode at 300K, (Vapplied varies from 0 to 1.2 V). Take 20 to 25 points.

2. Use the following parameters

$$\begin{aligned} N_a &= 1e18/cm^3 \\ N_d &= 1e14/cm^3 \\ \tau_{electrons} &= 1e-7s \\ \tau_{holes} &= 1e-7s \end{aligned}$$

3. Extract values of the ideality factor for all the three regimes by taking the slopes in the following voltage ranges of the log IV plot

- Recombination (0 - 0.2V)
- Ideal (0.3V - 0.5V)
- High Injection (0.6V - 0.8V)

4. In the forward IV characteristics of both the Ge and Si pn diodes, we observe that at higher voltages, the currents begin to saturate, what is the reason for this?

2.3 Temperature Dependence

1. Simulate the IV characteristics of the silicon diode from 250 K to 400 K, in steps of 25 K

2. Use the following parameters

$$\begin{aligned} N_a &= 1e16/cm^3 \\ N_d &= 1e15/cm^3 \\ \tau_{electrons} &= 5e-8s \\ \tau_{holes} &= 1e-7s \end{aligned}$$

3. Note the values of the applied voltage when the current reaches 1 A/cm^2 for different temperatures and comment on the increasing/decreasing trend of this voltage vs temperature.

4. Plot the log plot for the forward IV characteristics and extract the value of the saturation current from the intercept $ln(I_{SAT})$. Plot a graph of the $ln(\frac{I_{SAT}}{T^3})$ vs 1/kT and extract the bandgap of Si from the slope of this line.