Non-Linear Devices

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May 25, 2017

Diode characteristics:Temperature

Another key patarameter to consider is as always **temperature**. It associated to the diode voltage v_D.

$$v_D = V_T ln\left(\frac{i_D}{I_S} + 1\right) = \frac{kT}{q} ln\left(\frac{i_D}{I_S} + 1\right) \approx \frac{kT}{q} ln\left(\frac{i_D}{I_S}\right)$$

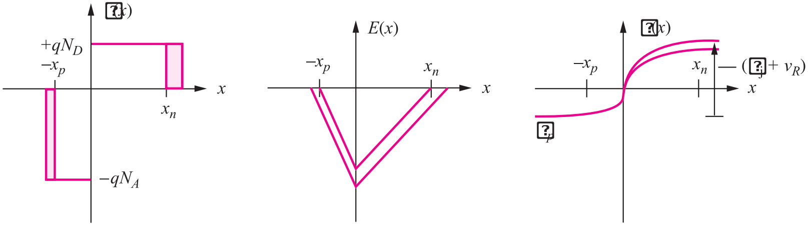
Obtaining the gradient for the above equation, why? because we're looking for small variations in it... and because we can..

$$\frac{dV_D}{dT} = \frac{v_D - V_{GO} - 3V_T}{T}$$

it is considered that $i_D >> I_S$ and $I_S \, \alpha \, n_I^2$, and v_D is the diode voltage, V_{GO} is the Si band gap energy at 0 K (V_{GO}) and V_T is the thermal potencial.

Diodes under reverse bias

By biasing the diode in inverse several effect occurs such as increasing the internal electric field that requires further internal charge at the depletion region.

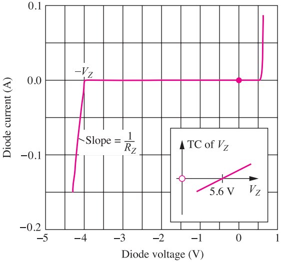


(a) Space charge density (b) Electric field (c) Electrostatic potential

$$w_d = (x_n + x_p) = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(\phi_j + v_R)}$$

Reverse Breakdown

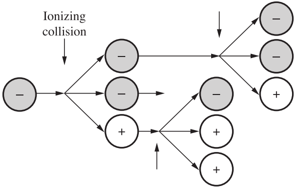
- By increasing the reverse voltage, the electric field within the device also increases
- Eventually, the diode enters into the breakdown region



- Breakdown voltage V_Z for the diode is between $2 \leq V_Z \leq 2000$ V. The value is determined by the doping level.
- The heavier the doping the smaller the breakdown voltage of the diode

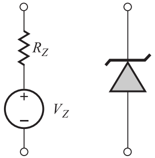
Breakdown types: Avalanche and Zener

- For Si diodes with breakdown voltages ¿ 5.6 V occurs due to avalanche breakdown mechanism
- As the SCR increases due to inverse bias, free carriers within it are accelerated by $\vec{E}$ and collide with fixed atoms
- Due to the large width of the SCR and $\vec{E}$, some carriers can gain enough energy to break covalent bonds due to impact, ergo it creates e$^-$, h$^+$ pairs.
- The new carriers can create additional electron–hole pairs through this impact-ionization process.



Breakdown types: Avalanche and Zener

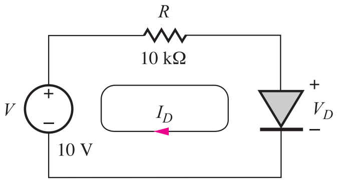
- Zener breakdown only occurs in heavy doped diodes
- High doping creates a quite narrow SCR, as a result an inverse bias produces that the carriers tunnel between the conduction and valence bands
- It results in a fast increasing in the reverse current diode



(a) (b)

Diode Circuits

- A new (ish) type of circuits that requires same of tools and a few new to analyze them
- Circuits now contain a voltage source, resistor, and diode
- Equivalences for R and V might represent the Thévening equivalent of a far more complex 2-port network
- For this kind of circuits, we require to find the quiescent operating point (Q-point) or bias point for the diode



Quiescent point

- Q-point is defined by the I_D & V_D that represents the operation point or the i-v diode characteristics
- The analysis starts by writing the loop eq. $V = I_D R + V_D$, follow figure shows the key values for I_D & V_D

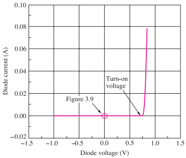


Figure 3.8 Graph of the *i-v* characteristics of a *pn* junction diode.

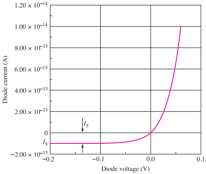
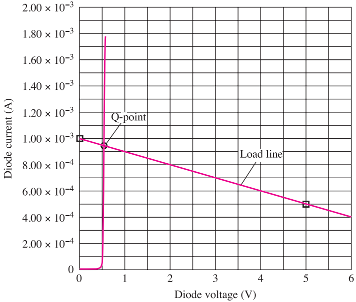


Figure 3.9 Diode behavior near the origin with $I_S = 10^{-15}$ A and $n = 1$.

- In order to get the proper solution, we're exploring a set of techniques such as: Graphical analysis, Mathematical models, Simplified analysis that considers an ideal diode, Simplified analysis that uses the constant drop model

Load line analysis

i-v characteristics, some times only are available in graphic form. Ergo, those are not too accurate... by considering the follow info, V = 10 V, R = 10kΩ, I_D= 1mA, V_D= 0.7 V. We've got
Second point is (vulgarly said) defined by the user as V_D=5 V. As a result, I_D= 0.5 mA
Withose points, a line is traced and where those points cross the I_D line, we've that Q-point = 0.95 mA @ 0.6V



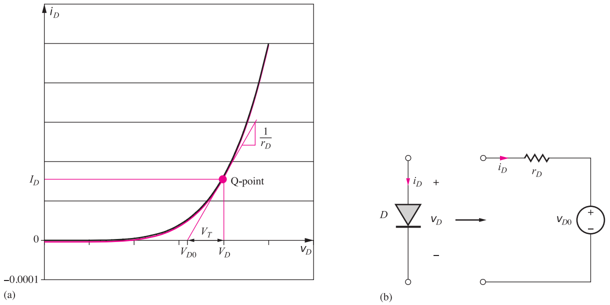
Mathematical model for the Diode

By using one of the equations previously defined for the Diode, we consider the follow key characteristics. $I_S = 10^{-13}$, n=1 and $V_T = 25$ mV

$$I_D = I_S\left[\exp\left(\frac{V_D}{V_T}\right) - 1\right] = 10^{-13}[\exp(40V_D) - 1]$$

$$10 = 10^4 \cdot 10^{-13}[\exp(40V_D) - 1] + V_D$$

There is not an exact solution but a numerical approximation to find the diode Q-point



Mathematical model for the Diode: Process

$$g_D = \frac{\partial i_D}{\partial V_D} = \frac{I_S}{V_T}\left(\frac{V_D}{V_T}\right) = \frac{I_D + I_S}{V_T} \approx \frac{I_D}{V_T}$$

$$r_D = \frac{1}{g_D} = \frac{V_T}{I_D}$$

where g_D is the diode conductance and r_D is the diode resistance

$$V_{DO} = V_D - I_D R_D = V_D - V_T$$

V_{DO} & r_D are the lineal elements for the diode model. By using numerical analysis we can infer the Q-point of the diode in the circuit: Initialize the system, define I_D, calculate $V_D = V_T ln(1 + I_D/IS)$, get the values for V_{DO} & r_D, calculate $I_D = (V - V_{DO})/(R + r_D)$, repeat until it converges...

Mathematical model for the Diode: Process

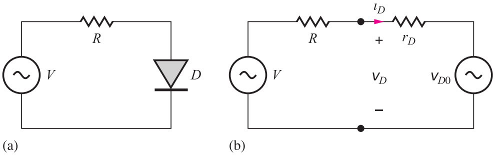


TABLE 3.2
Example of Iterative Analysis

I_D (A)	V_D (V)	R_D( )	V_{D0} (V)
1.0000E-03	0.5756	25.80	0.5498
9.4258E-04	0.5742	27.37	0.5484
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Zener diode: Voltage regulation

- A key application for a Zener diode is as a voltage regulator
- Function for the Zener diode is to keep the voltage contant across the lead resistor R_L
- While Zener diode operates at reverse breakdown, a voltage $\approx V_Z$ will be shown at R_L
- To force that the Zener will always operate at breakdown region, $I_Z > 0$

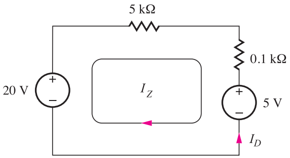


Figure 3.38 Circuit with piecewise linear model for Zener diode. Note that the diode model is valid only in the breakdown region of the characteristic.

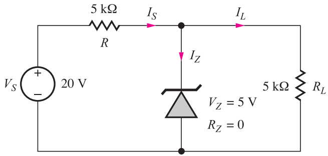
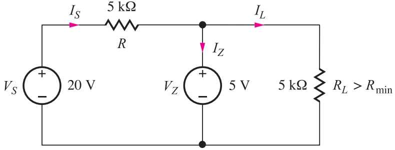


Figure 3.39 Zener diode voltage regulator circuit.

Zener diode: Voltage regulation

- Above circuit has been re-drawn by consider R_Z=0



- Solving it by nodal analysis, we've $I_Z = I_S - I_L$, I_L and I_S are defined as: $I_S = \frac{V_S - V_Z}{R} = \frac{20-5}{5k\Omega} = 3$ mA
  $I_L = \frac{V_Z}{R_L} = \frac{5V}{5k\Omega} = 1$ mA
  Ergo, I_Z=2 mA and $I_Z > 0$
- If $I_Z < 0$, the diode cannot control the voltage across R_L and it has dropped from regulation
- fro the Zener diode works, current must be **positive**

$$I_Z = IS - I_L = \frac{V_S}{R} - V_Z \left(\frac{1}{R} + \frac{1}{R_L} \right) > 0$$

- To ensure that $I_Z > 0$, we need to ensure it by finding the minimum R_L $R_L > \frac{R}{\left(\frac{V_S}{V_Z} - 1\right)} = R_{min}$