CHAPTER #2#

POWER SEMICONDUCTOR DIODES

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Introduction

Function of power semiconductor diodes in power electronic circuits:

- Switches in rectifiers.
- Freewheeling in switching regulators.
- Charge reversal of capacitor & energy transfer between components.
- Voltage isolation.
- Energy feedback from load to power source.
- Trapped energy recovery.
✓ Power diode is a two-layer, two-terminal, p-n semiconductor device.
✓ It has one p-n junction formed by alloying, diffusing or epitaxial growth.
✓ The two terminals of diode are called anode and cathode.
DIODE V-I CHARACTERISTICS

✓ When anode is positive with respect to cathode, diode is said to be forward biased. With increase of the source voltage $V_s$ from zero value, $I_D=0$. From $V_s=0$ to cut-in voltage, the forward-diode current is very small. Cut-in voltage is also known as turn-on voltage. Beyond cut-in voltage, the diode current rises rapidly and the diode is said to conduct.

✓ For silicon diode, the cut-in voltage is around 0.7 V. When diode conducts, there is a forward voltage drop of the order of 0.8 to 1 V.

✓ When cathode is positive with respect to anode, the diode is said to be reverse biased. In reverse biased condition of the diode, a small reverse current, called leakage current, of the order of the microamperes or mill amperes (for large diodes) flows. The leakage current increases slowly with the reverse voltage until breakdown or avalanche voltage is reached. At this breakdown voltage, diode is turned on in the reversed direction.
The practical characteristics shown in figure can be expressed by the Shockley diode equation, which is given by

\[ I_D = I_S \left( e^{\frac{V_D}{nV_T}} - 1 \right) \]

- **Diode current**
- **Diode voltage**
- **Thermal voltage**
- **Leakage current**, the range \(10^{-6}\) to \(10^{-15}\) A
- **Emission coefficient or ideality factor** which varies between 1 and 2
- **Boltzmann's constant** given as \(1.3806 \times 10^{-3}\) J/K
- **Absolute temperature in Kelvin** \(K = 273 + ^\circ C\)
- **Electron charge** given as \(1.6022 \times 10^{-19}\) coulomb (C)
At a specified temperature, the leakage current, $I_s$ is a constant for a specified diode.

In addition at a specified temperature, $V_T$ can be calculated and is also a constant.

The diode characteristics can be divided to three regions:

1. **Forward-biased region**, where $V_D > 0$
2. **Reversed-biased region**, where $V_D < 0$
3. **Breakdown region**, where $V_D < -V_{ZK}$

**Forward-biased Region**

In this region, $V_D > 0$. $I_D$ is small if $V_D$ is less than the turn-on voltage ($V_{TD}$). This voltage is small in range (0.5V to 0.7V). The diode conducts fully if $V_D$ is higher than $V_{TD}$.

Hence the diode equation can be approximated to within 2.1% error to

$$I_D \approx I_s \left( e^{V_D/nV_T} \right)$$
**Reverse-biased Region**

- $V_D < 0$ volts and if $|V_D| >> V_T$, $I_D$ can be written as:

$$I_D = I_S \left( e^{V_D/nV_T} - 1 \right) \approx -I_S$$

**Breakdown Region**

- When the reverse voltage exceeds the breakdown voltage $V_{BR}$, the diode is said to be in the breakdown region.
- In this region, the IR increases rapidly for small increases in $V_R$ beyond $V_{BR}$.
- Diode operation in the breakdown region is not destructive, provided that the power dissipation is within a safe level as specified by the manufacturer.

**EX2-1 page No. 23**
A p-n junction diode has a reverse saturation current rating of 50 nA at 32°C. What should be the value of the forward current (I_f) for a forward voltage drop of 0.5V. Assume V_T = kT/q at 32°C = 26 mv.

**Answer**

\[ I_F = I_s \left( e^{V/V_T} - 1 \right), \quad I_s = 5 \times 10^{-8} \text{A}, \quad V_T = 26 \times 10^{-3} \text{V} \quad V = 0.5 \text{V} \]

\[ \therefore I_F = 11.24 \text{ Amps.} \]

(3) For the diode of Ex. above, calculate the dynamic ac resistance \( R_{ac} = \frac{dI_f}{dV_f} \) at 32°C and a forward voltage drop of 0.5V.

**Answer:**

\[ i_F = I_s \left( e^{V_F/V_T} - 1 \right) \therefore \frac{dI_f}{dV_f} = \frac{I_s}{V_T} e^{V_F/V_T} \]

Now \( I_s = 5 \times 10^{-8} \text{A}, \quad V_F = 0.5 \text{V}, \quad V_T = 26 \times 10^{-3} \text{V} \) at 32°C

\[ \therefore \frac{dV_F}{dI_f} = r_{ac} = \frac{V_T}{I_s} e^{-V_F/V_T} = 2.313 \text{ m\Omega} \]
Reverse Recovery Characteristics

- When a diode is switched quickly from forward to reverse bias, it continues to conduct due to the minority carriers which remains in the p-n junction.

- The minority carriers require finite time, i.e., \( (tr_r) \) reverse recovery time to recombine with opposite charge and neutralise.

- Effects of reverse recovery are increase in switching losses, increase in voltage rating, over-voltage (spikes) in inductive loads.
\( t_{rr} \) = reverse recovery time, measured as the time between the initial zero crossing of the diode current to the time when this current reaches 25% of the peak reverse current.

\( I_{RR} \) = maximum reverse current

\( t_a \) = time between zero crossing and the maximum reverse current and it is due to the charge stored in the depletion region of the junction

\( t_b \) = time between maximum reverse current \( I_{RR} \) and 25% of the of the maximum reverse current \( I_{RR} \) and is due to charge stored in the bulk semiconductor material

The reverse recovery time is measured from the initial zero crossing from forward conduction to reverse blocking condition of the diode current to 25% of the maximum reverse current \( I_{RR} \). Its magnitude depends on:

1. junction temperature
2. rate of fall of forward current
3. forward current prior to commutation.
From the graph it can be seen that,

\[ t_{rr} = t_a + t_b \]

\[ I_{RR} = t_a \frac{di}{dt} \]

**Reverse Recovery Charge**

- This is the amount of charge carriers that flow across the diode in the reverse direction due to changeover from forward conduction to reverse blocking condition. Its value is determined from the area enclosed by the path of the reverse recovery current.

\[ Q_{RR} = \frac{1}{2} I_{RR} t_a + \frac{1}{2} I_{RR} t_b = \frac{1}{2} I_{RR} t_{rr} \]

\[ I_{RR} = \frac{2Q_{RR}}{t_{rr}} \]

\[ t_{rr} \approx t_a \]

\[ t_{rr} \approx \sqrt{\frac{2Q_{RR}}{\text{di/dt}}} \]

\[ t_a t_{rr} = \frac{2Q_{RR}}{\text{di/dt}} \]

\[ I_{RR} = \frac{2Q_{RR}}{t_{rr}} \approx \sqrt{2Q_{RR} \frac{\text{di}}{\text{dt}}} \]
Ideally diodes should not have a reverse recovery time, and it is possible to construct such a diode. However, the manufacturing cost of such a diode would be quite high for such a feature which in most cases has minor consequences.
**Power Diodes Types**

- **Line frequency** (general purpose):
  - On state voltage: very low (below 1V)
  - Large trr (about 25us) (very slow response)
  - Very high current ratings (up to 5kA)
  - Very high voltage ratings (5kV)
  - Used in line-frequency (50/60Hz) applications such as rectifiers.

- **Fast recovery**
  - Very low trr (<1us).
  - Power levels at several hundred volts and several hundred amps
  - Normally used in high frequency circuits.

- **Schottky**
  - Very low forward voltage drop (typical 0.3V)
  - Limited blocking voltage (50-100V)
  - Used in low voltage, high current application such as switched mode power supplies.
Effects of Forward and Reverse Recovery Time

Consider the chopper circuit shown below without a di/dt limiting inductor. This cct would be used to display the effects of forward and reverse recovery time.

- SW is turned on at time \( t = 0 \) and remains for a steady load current to flow. 
  \[ I_0 = \frac{V_s}{R} \]
  - the freewheeling diode \( D_m \) is reverse-biased.

- SW is opened at time \( t = t_1 \). Inductor \( L \) will now discharge
  - its stored energy through diode \( D_m \).

- SW is turned on again at time \( t = t_2 \). Now at time \( t_2 \), diode \( D_1 \) would conduct and diode \( D_m \) goes from forward biased to reverse biased.

\[ I_{RR} \approx \sqrt{\frac{2Q_{RR}}{\text{di/dt}}} \]
This problem can be overcome by connecting a current limiting inductor in series with diode $D_1$.

**Series-Connected Diodes**

- Use 2 diodes in series to withstand higher reverse breakdown voltage.
- Both diodes conduct the same reverse saturation current, $I_s$.
- When diodes are connected in series, the blocking voltages will differ slightly.

**Diode Characteristics**

- Due to differences between devices, each diode has a different voltage across it.
- Would like to “Equalize” the voltages.
Series-Connected Diodes with Voltage Sharing Resistors

✓ In the forward-biased condition, both diodes conduct the same amount of current and the forward voltage drop for each diode would be almost equal.

✓ In the reversed-biased condition, each diode has to carry the same leakage current.

✓ The blocking voltage would differ significantly.

✓ This problem is solved by forcing equal voltage sharing by connecting a resistor across each diode.
\[ I_s = I_{s1} + I_{R1} = I_{s2} + I_{R2} \]
\[ I_{R1} = \frac{V_{D1}}{R_1} \]
\[ I_{R2} = \frac{V_{D2}}{R_2} = \frac{V_{D1}}{R_2} \]
\[ I_{s1} + \frac{V_{D1}}{R_1} = I_{s2} + \frac{V_{D1}}{R_2} \]
\[ \text{Let } R = R_1 = R_2 \]
\[ I_{s1} + \frac{V_{D1}}{R} = I_{s2} + \frac{V_{D2}}{R} \]
\[ V_{D1} + V_{D2} = V_s \]

**Example 2.3**

\[ I_{s1} = 30\text{mA}, I_{s2} = 35\text{mA}, \text{ and } V_D = 5kV \]
(a) \[ R_1 = R_2 = R = 100k\Omega, \text{ find } V_{D1} \text{ and } V_{D2} \]
(b) \[ \text{Find } R_1 \text{ and } R_2 \text{ for } V_{D1} = V_{D2} = V_D/2 \]
Example 2.3 (a)

\(I_{s1} = 30\text{mA}\)

\(I_{s2} = 35\text{mA}\)

\(R_1 = R_2 = R = 100\text{k}\Omega\)

\[-V_D = -V_{D1} - V_{D2}\]

\(V_{D2} = V_D - V_{D1}\)

\[I_{s1} + \frac{V_{D1}}{R} = I_{s2} + \frac{V_{D2}}{R}\]

\(V_{D1} = \frac{V_D}{2} + \frac{R}{2} (I_{s2} - I_{s1})\)

\(V_{D1} = \frac{5\text{kV}}{2} + \frac{100\text{k}\Omega}{2} (35 \times 10^{-3} - 30 \times 10^{-3}) = 2750\text{Volts}\)

\(V_{D2} = V_D - V_{D1} = 5\text{kV} - 2750 = 2250\text{Volts}\)
Example 2.3 (b)

\[ I_{s1} = 30\,\text{mA} \]
\[ I_{s2} = 35\,\text{mA} \]

\[ V_{D1} = V_{D2} = \frac{V_D}{2} = 2.5\,\text{kV} \]

\[ I_{s1} + \frac{V_{D1}}{R_1} = I_{s2} + \frac{V_{D2}}{R_2} \]

\[ R_2 = \frac{V_{D2}R_1}{V_{D1} - R_1(I_{s2} - I_{s1})} \]

\[ R_1 = 100\,\text{k}\Omega \]

\[ R_2 = \frac{V_{D2}R_1}{V_{D1} - R_1(I_{s2} - I_{s1})} = \frac{2.5\,\text{kV}\times100\,\text{k}\Omega}{2.5\,\text{kV} - 100\,\text{k}\Omega \times (35 \times 10^{-3} - 30 \times 10^{-3})} \]

\[ R_2 = 125\,\text{k}\Omega \]
Parallel-Connected Diodes

- In high power applications, diodes are connected in parallel to increase the current carrying capability in order to meet circuit requirements.
- In parallel operation of diodes, current sharing depends on the magnitude of their forward voltage drops.
- Uniform current sharing can be achieved either by the use of equal inductances or by connecting current sharing resistors, (not recommended), because the power losses incurred by the resistive components.
- Selecting diodes with equal forward voltage drops would minimize the unequal sharing of current.
- For steady-state current sharing, the circuit of fig (a) with series resistors are used. Dynamic current sharing is achieved with the use of coupled inductors as indicated by fig(b).
- If the $ID_1$ rises, then the $VL_1$ ($V_L = L \frac{di}{dt}$) increases, causing a voltage of opposite polarity to be induced across $L_2$. This causes a low impedance path for current flow through diode $D_2$, and more current is shifted through this diode.
- The disadvantage of using current sharing devices under dynamic conditions is that the inductors would generate voltage spikes and would be expensive and huge.
(a) Steady-state

(b) Dynamic sharing
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