
Electronics Devices & Circuits

Chapter 1 : DIODE

Complete Engineering Notes

Theory • Diagrams • Tables • Solved Examples • 15 MCQs with Answer Key • 10 Broad Questions

Topics Covered

- **1.1** Elementary idea of ordinary diode, forward biased and reverse biased condition, V-I characteristics of ordinary diode
- **1.2** Breakdown: Zener and avalanche – construction and operation of Zener diode in reverse biased condition
- **1.3** Characteristics, equivalent circuits and specifications – simple voltage regulator circuit

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Chapter 1 : Diode

Chapter Overview

The diode is the simplest and most fundamental semiconductor device, and it is the starting point of the whole subject of electronic devices and circuits. Rectifiers, clippers, clampers, voltage regulators, detectors and logic gates are all built around it. In this chapter we study how an ordinary PN junction diode works under forward and reverse bias, how its V-I characteristic is obtained, what happens when a junction breaks down in reverse bias, and how the Zener diode uses this breakdown region to hold a voltage constant.

After studying this chapter you will be able to:

- Explain the formation of a PN junction, depletion region and barrier potential.
- Describe forward and reverse biased conditions and draw the V-I characteristics of an ordinary diode.
- Distinguish between Zener and avalanche breakdown.
- Explain the construction and reverse-bias operation of a Zener diode.
- Draw and use the equivalent circuits of ordinary and Zener diodes and read their specifications.
- Analyse and design a simple Zener voltage regulator.

1.1 Elementary Idea of Ordinary Diode, Forward and Reverse Bias, V-I Characteristics

1.1.1 Semiconductor Background

A **semiconductor** is a material whose electrical conductivity lies between that of a conductor and an insulator. Silicon (Si) and germanium (Ge) are the two commonly used elements; each has four valence electrons and forms a crystal lattice of covalent bonds. A pure crystal is called an **intrinsic semiconductor**. Its conductivity is low because only a few bonds break at room temperature, creating equal numbers of free electrons and holes.

Conductivity is increased enormously by adding a very small amount of impurity, a process called **doping**. The doped crystal is an **extrinsic semiconductor** and is of two types:

Property	N-type semiconductor	P-type semiconductor
Dopant added	Pentavalent (donor) atom: phosphorus, arsenic, antimony	Trivalent (acceptor) atom: boron, aluminium, gallium, indium
Majority carriers	Free electrons	Holes
Minority carriers	Holes	Free electrons
Immobile ions left in lattice	Positive donor ions	Negative acceptor ions
Overall charge of crystal	Electrically neutral	Electrically neutral

1.1.2 The PN Junction Diode

An **ordinary (PN junction) diode** is a two-terminal device obtained by forming a P-type region and an N-type region in one continuous crystal. The P-side terminal is the **anode (A)** and the N-side terminal is the **cathode (K)**. The diode allows current easily in one direction (anode to cathode) and blocks it in the other, so it behaves like a one-way valve for electric current. The circuit symbol is an arrow-head (triangle) pointing from anode to cathode, ending in a bar.

Formation of the depletion region

1. **Diffusion:** because of the large difference in carrier concentration, free electrons from the N-side diffuse into the P-side and holes from the P-side diffuse into the N-side.
2. **Recombination:** near the junction these carriers recombine with each other, so the area close to the junction loses its mobile carriers.
3. **Space-charge layer:** the fixed donor ions (positive) on the N-side and acceptor ions (negative) on the P-side are left uncovered. This layer, free from mobile carriers, is the **depletion region** (also called the space-charge region or transition region).
4. **Built-in field:** the uncovered ions set up an electric field directed from the N-side to the P-side. It opposes further diffusion of majority carriers but helps minority carriers to drift across.
5. **Equilibrium:** diffusion current becomes equal to drift current, so the net current is zero. The potential difference across the depletion region is the **barrier potential** (junction or contact potential) V_0 .

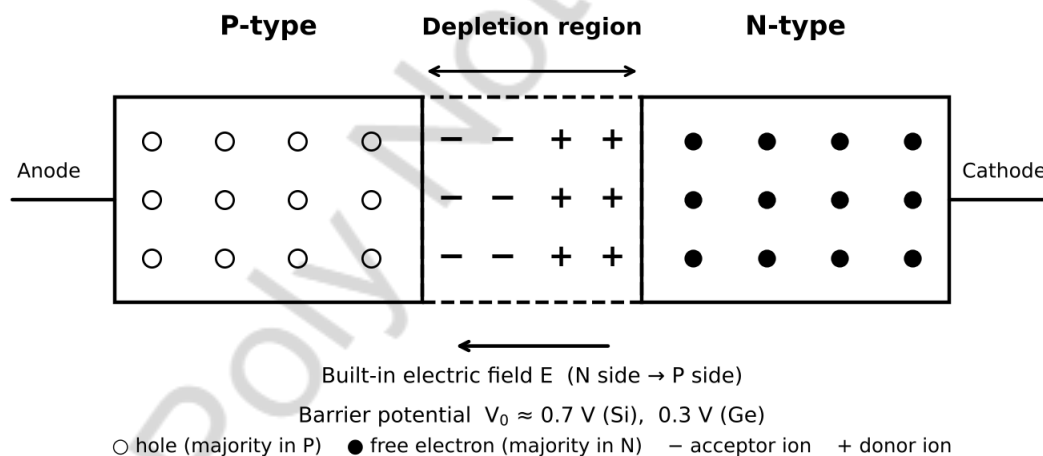


Fig. 1.1: PN junction with depletion region and barrier potential

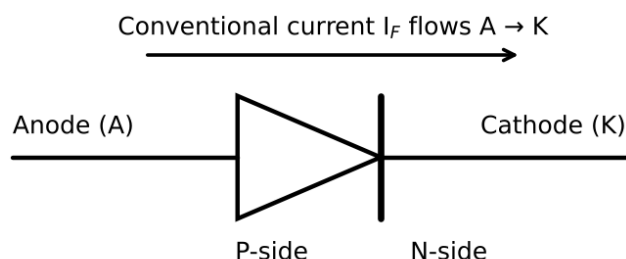


Fig. 1.2: Circuit symbol of an ordinary PN junction diode

Parameter	Silicon (Si) diode	Germanium (Ge) diode
Barrier potential V_0 at room temperature	≈ 0.7 V	≈ 0.3 V
Cut-in (threshold) voltage V_y	0.6 – 0.7 V	0.2 – 0.3 V
Reverse saturation current I_S	Very small (nA range)	Larger (μ A range)
Maximum junction temperature	High (about 150 – 175 °C)	Low (about 75 – 100 °C)
Sensitivity to temperature	Less sensitive	More sensitive
Common use	General purpose, most circuits	Low-voltage detectors, special applications

1.1.3 Forward Biased Condition

When the external battery is connected with its **positive terminal to the P-side (anode)** and **negative terminal to the N-side (cathode)**, the junction is **forward biased**. A series resistor R is always included to limit the current.

- The applied voltage V acts opposite to the barrier potential, so the effective barrier becomes $(V_0 - V)$ and the depletion region **narrows**.
- Battery pushes holes of the P-side and electrons of the N-side towards the junction; majority carriers cross the junction easily.
- Below the cut-in voltage the barrier is still large and the forward current is negligibly small.
- Once V exceeds the cut-in voltage (≈ 0.7 V for Si, 0.3 V for Ge) the barrier is almost removed and current rises very rapidly (exponentially).
- The forward current is a **majority-carrier current** of the order of milliamperes to amperes; the diode behaves like a closed switch with a small voltage drop.
- Without the series resistor, excessive current would overheat and destroy the junction.

1.1.4 Reverse Biased Condition

When the **positive terminal of the battery is connected to the N-side (cathode)** and the **negative terminal to the P-side (anode)**, the junction is **reverse biased**.

- The applied voltage adds to the barrier potential, making the barrier $(V_0 + V_R)$ and the depletion region **widens**.
- Majority carriers are pulled away from the junction, so they cannot cross it; the diode behaves like an open switch.
- A very small current still flows because thermally generated **minority carriers** are swept across the junction by the field. This is the **reverse saturation current (I_S)**, nanoamperes for Si and microamperes for Ge.
- I_S is almost independent of the reverse voltage but depends strongly on temperature; it approximately **doubles for every 10 °C rise**.
- If V_R is increased beyond a limit, the junction breaks down and a large reverse current flows (Section 1.2).

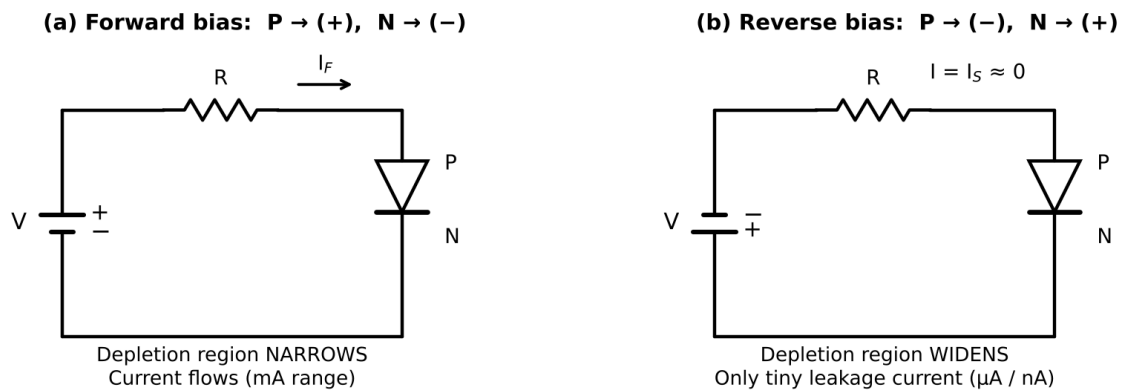


Fig. 1.3: Forward biased and reverse biased PN junction diode

Zero bias: with no external voltage the diffusion and drift currents balance, the net current is zero and the depletion region has its equilibrium width.

Comparison of forward and reverse bias

Feature	Forward bias	Reverse bias
Connection	P to (+), N to (−)	P to (−), N to (+)
Depletion region	Becomes narrow	Becomes wide
Barrier potential	Reduced ($V_0 - V$)	Increased ($V_0 + V_R$)
Current carriers	Majority carriers	Minority carriers
Magnitude of current	mA to A (large)	nA to μA (very small)
Resistance offered	Very low (a few ohms)	Very high (megaohms)
Diode acts as	Closed switch (ON)	Open switch (OFF)

1.1.5 V-I Characteristics of an Ordinary Diode

The V-I characteristic is the graph between the voltage applied across the diode and the current through it. The current at any voltage is given by the **diode (Shockley) equation**:

$$I = I_S [\exp(V / \eta V_T) - 1]$$

- I_S = reverse saturation current; V = voltage across the diode (positive for forward bias, negative for reverse bias).
- $V_T = kT/q = T/11600$ is the thermal voltage; at room temperature (300 K) $V_T \approx 26$ mV.
- η = emission (ideality) factor: $\eta = 1$ for germanium and $\eta \approx 2$ for silicon (at low currents).

For forward voltages much larger than V_T , the equation reduces to $I \approx I_S \exp(V/\eta V_T)$; for large reverse voltage, $I \approx -I_S$.

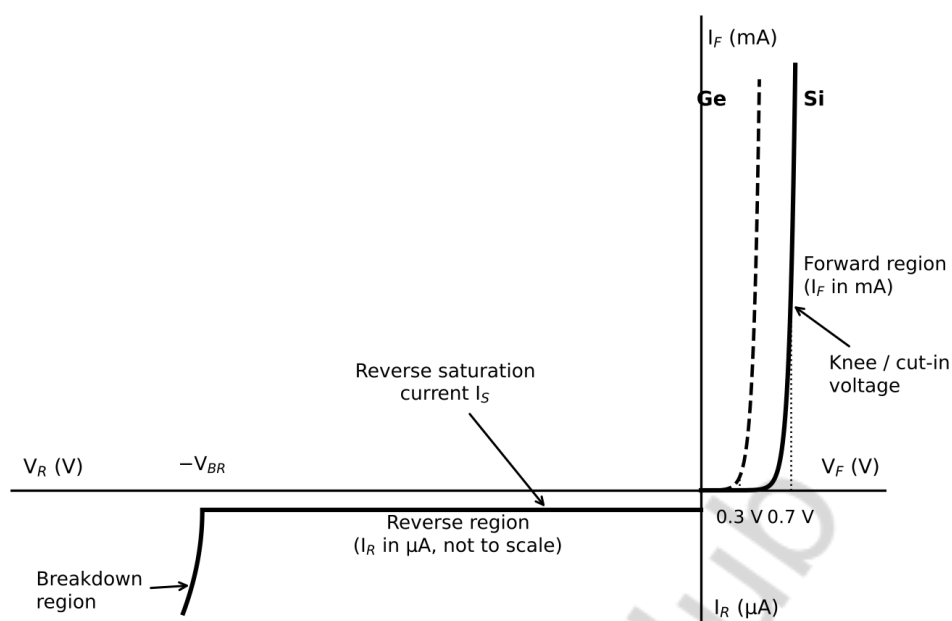


Fig. 1.4: V-I characteristics of a PN junction diode (forward and reverse scales are different)

Regions of the characteristic

Region	Behaviour of the diode
Forward region ($V > 0$)	Current is negligible up to the knee (cut-in) voltage ; beyond it, current increases rapidly while voltage rises only slightly (Si ≈ 0.7 V, Ge ≈ 0.3 V). The curve is exponential.
Reverse region ($V < 0$)	A tiny, almost constant current I_S flows. The diode is effectively OFF.
Breakdown region ($V = V_{BR}$)	At the breakdown voltage the reverse current rises abruptly. An ordinary rectifier diode is damaged if the power dissipation exceeds its limit, so it is never operated here.

Effect of temperature on the characteristic

- The forward voltage drop for a given current **decreases by about 2 mV per °C** (the curve shifts to the left as temperature rises).
- The reverse saturation current **doubles for approximately every 10 °C** rise, so the reverse leakage of Ge diodes becomes troublesome at high temperature.

1.1.6 Diode Resistance

Type	Definition	Expression / remark
Static (DC) resistance R_{DC}	Ratio of dc voltage to dc current at the operating point	$R_{DC} = V / I$. Differs at every point of the curve.
Dynamic (AC) resistance r_d	Reciprocal of the slope of the characteristic at the operating point	$r_d = \Delta V / \Delta I = \eta V_T / I_F \approx 26 \text{ mV} / I_F$ (for $\eta = 1$)
Reverse resistance	Resistance in the reverse biased state	Very large (megaohm range)

Solved Example 1.1

- Problem:** Find the dynamic resistance of a diode ($\eta = 1$, $V_T = 26 \text{ mV}$) carrying a forward current of 5 mA.
- Solution:** $r_d = \eta V_T / I_F = 26 \text{ mV} / 5 \text{ mA} = 5.2 \Omega$

Solved Example 1.2

- **Problem:** A silicon diode is connected in series with a 1 kΩ resistor and a 5 V supply in forward bias. Find the circuit current.
- **Solution:** $I = (V_{\text{supply}} - V_D) / R = (5 - 0.7) / 1000 = 4.3 \text{ V} / 1 \text{ k}\Omega = \mathbf{4.3 \text{ mA}}$
- If the supply is reversed, the diode is OFF: $I \approx 0$ and almost the entire 5 V appears across the diode.

Exam Tips - Section 1.1

- Always draw the V-I curve with **different scales**: volts and mA in the forward region, volts and μA in the reverse region.
- Mark the knee voltage (0.7 V Si / 0.3 V Ge), the reverse saturation current I_S and the breakdown voltage V_{BR} on the graph.
- Remember: forward current = majority carriers; reverse current = minority carriers.

1.2 Breakdown: Zener and Avalanche; Construction and Operation of Zener Diode

1.2.1 Reverse Breakdown

In reverse bias, only the small saturation current flows as long as the applied voltage is low. When the reverse voltage is increased to a critical value called the **breakdown voltage** V_{BR} , the reverse current suddenly increases to a very large value while the voltage across the diode remains almost constant. This phenomenon is called **reverse (junction) breakdown**. Breakdown is not harmful by itself; it becomes destructive only when the product of voltage and current exceeds the power rating of the diode. There are two mechanisms of breakdown: **avalanche breakdown** and **Zener breakdown**.

1.2.2 Avalanche Breakdown

Avalanche breakdown occurs in **lightly doped** junctions that have a **wide depletion region**, and it needs a relatively high reverse voltage (generally above about 6 - 7 V, and up to hundreds of volts).

1. The minority carriers crossing the wide depletion region are accelerated by the strong reverse field and gain high kinetic energy.
2. These fast carriers collide with atoms of the lattice and break covalent bonds, creating new electron-hole pairs. This is **impact ionisation**.
3. The newly generated carriers are also accelerated and produce further pairs, so the number of carriers multiplies like an avalanche (**carrier multiplication**).
4. The reverse current therefore rises very sharply at nearly constant voltage.

Avalanche breakdown has a **positive temperature coefficient**: as temperature rises, lattice vibrations shorten the mean free path of carriers, so a higher voltage is needed to reach breakdown.

1.2.3 Zener Breakdown

Zener breakdown occurs in **heavily doped** junctions that have a very **narrow depletion region**. Because the region is so thin, even a small reverse voltage (below about 5 V) produces an extremely strong electric field across it (of the order of 10^7 V/m). This field is strong enough to pull electrons directly out of the covalent bonds (**field ionisation** or tunnelling), generating a large number of free carriers and hence a large reverse current.

Zener breakdown has a **negative temperature coefficient**: with rise in temperature the valence electrons gain energy, so less field is needed to release them and V_Z decreases slightly.

Zener breakdown versus avalanche breakdown

Feature	Zener breakdown	Avalanche breakdown
Doping of junction	Heavy	Light
Depletion region	Very narrow	Wide
Breakdown voltage	Low (below about 5 V)	High (above about 6 – 7 V)
Mechanism	Direct breaking of covalent bonds by a strong electric field (field ionisation / tunnelling)	Impact ionisation of lattice atoms by fast minority carriers; carrier multiplication
Temperature coefficient	Negative	Positive
Between about 5 V and 7 V	Both mechanisms act together; the temperature coefficient is nearly zero, which is useful for voltage references	Both mechanisms act together

Note: in practice all diodes designed for stable operation in the breakdown region, whether the mechanism is Zener or avalanche, are commercially called **Zener diodes**.

1.2.4 Zener Diode - Construction

A **Zener diode** is a specially designed silicon PN junction diode that is intended to operate **continuously in the reverse breakdown region** without being damaged, so that it can serve as a voltage reference or voltage regulator.

- Made of **silicon**, because of its low leakage current and good temperature stability.
- Both P and N regions are **heavily doped** (P^+ and N^+), giving a very thin, abrupt junction with a narrow depletion region.
- The **doping level fixes the Zener voltage V_Z** : heavier doping gives a thinner depletion layer and a lower V_Z ; lighter doping gives a higher V_Z . Manufacturers therefore make diodes with standard values such as 3.3 V, 5.1 V, 6.8 V, 9.1 V, 12 V and so on.
- Metal contacts are provided on both faces and the chip is sealed in a glass, plastic or metal case; a **band marks the cathode**.
- Power ratings range from a fraction of a watt (e.g. 0.25 W, 0.5 W) to several tens of watts, and the junction is made large enough to dissipate this power safely.

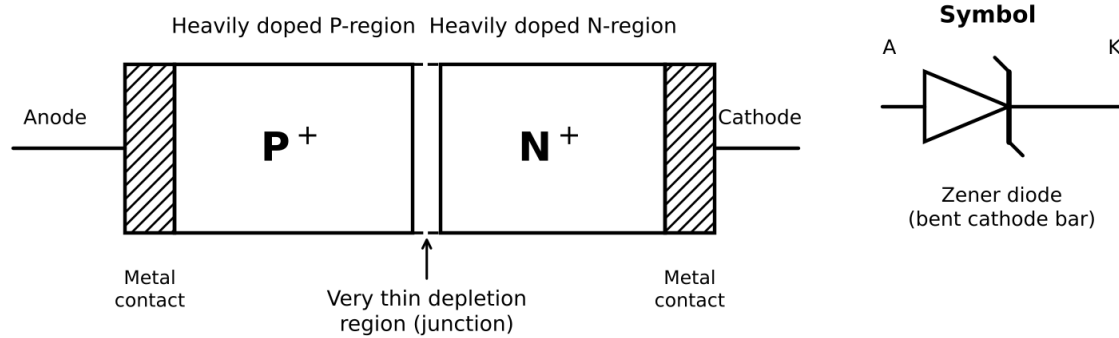


Fig. 1.5: Construction (cross-section) and symbol of a Zener diode

1.2.5 Operation of Zener Diode in Reverse Biased Condition

For voltage regulation the Zener diode is connected in **reverse bias**: the cathode is joined to the positive side of the supply and the anode to the negative side, through a series resistor that limits the current.

1. **Reverse voltage below V_Z** : the diode behaves like an ordinary reverse biased diode and only a very small leakage current flows (open circuit).
2. **At $V = V_Z$** : breakdown starts; the current increases rapidly from the knee current I_{ZK} .
3. **Beyond V_Z** : large changes in current cause only a very small change in the voltage across the diode, so the terminal voltage remains almost constant at V_Z .
4. **Current limiting**: any extra supply voltage is dropped across the series resistor, which keeps the Zener current below the maximum value $I_{ZM} = P_{Z(max)}/V_Z$.
5. **Reversibility**: if power dissipation is within the rated limit, breakdown is non-destructive and the diode recovers completely when the voltage is reduced.

In **forward bias** a Zener diode conducts like an ordinary silicon diode with a drop of about 0.7 V.

Ordinary diode versus Zener diode

Feature	Ordinary PN diode	Zener diode
Doping	Moderate / light	Heavy
Depletion region	Wide	Narrow
Normal operating region	Forward bias (rectification)	Reverse breakdown region
Breakdown	Damaging; to be avoided	Normal, safe operation if power is within rating
Main use	Rectifier, detector, switch	Voltage regulator, voltage reference, clipper
Symbol	Straight cathode bar	Cathode bar with bent ends (Z shape)

Key Points - Section 1.2

- Zener breakdown: heavy doping, thin depletion layer, $V_Z < 5\text{ V}$, negative temperature coefficient.
- Avalanche breakdown: light doping, wide depletion layer, $V_{BR} > 7\text{ V}$, positive temperature coefficient.
- A Zener diode is always operated in **reverse bias** with a series current-limiting resistor.
- In breakdown, voltage across the Zener remains nearly constant even though the current changes widely.

1.3 Characteristics, Equivalent Circuits, Specifications; Simple Voltage Regulator

1.3.1 V-I Characteristics of Zener Diode

The forward characteristic of a Zener diode is the same as that of an ordinary silicon diode. The important difference lies in the reverse region, where the characteristic shows a sharp, almost vertical rise of current at the Zener voltage.

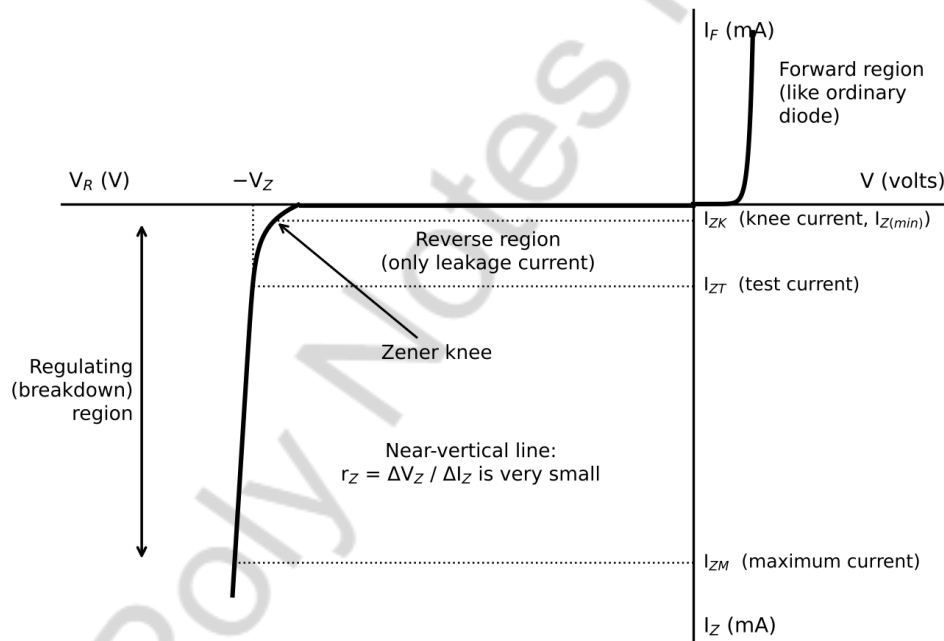


Fig. 1.6: V-I characteristics of a Zener diode

Parameter	Meaning
Zener voltage V_Z	Voltage across the diode in breakdown, specified at the test current I_{ZT}
Test current I_{ZT}	Current at which V_Z and r_Z are measured
Knee current I_{ZK} ($I_{Z(min)}$)	Minimum current needed to keep the diode in breakdown and regulating
Maximum current I_{ZM}	Largest current the diode can carry without exceeding its power rating: $I_{ZM} = P_{Z(max)} / V_Z$
Dynamic (Zener) impedance r_Z	$r_Z = \Delta V_Z / \Delta I_Z$; typically a few ohms to tens of ohms. The smaller it is, the better the regulation.

Parameter	Meaning
Temperature coefficient	Change in V_Z per $^{\circ}\text{C}$ (negative below about 5 V, positive above about 6 V, near zero around 5 – 6 V)

The useful (regulating) range of operation is between I_{ZK} and I_{ZM} .

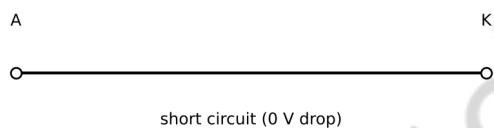
1.3.2 Equivalent Circuits

An equivalent circuit replaces the non-linear diode by simple linear elements (switches, batteries and resistors) so that circuits can be analysed easily. The choice of model depends on the accuracy required.

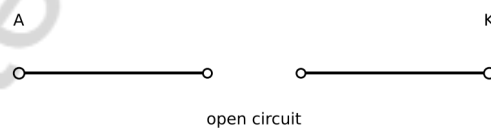
(A) Equivalent circuits of an ordinary diode

Model	Forward biased (ON)	Reverse biased (OFF)	Use
Ideal diode	Short circuit (switch closed, zero drop)	Open circuit	Quick approximate analysis
Constant voltage drop (simplified)	Battery of $V_y = 0.7 \text{ V}$ (Si) / 0.3 V (Ge)	Open circuit	Most common model for Si circuits
Piecewise linear	Battery V_y in series with dynamic resistance r_d	Open circuit (or very large resistance)	More accurate calculations

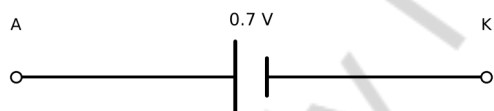
(a) Ideal diode – forward biased (ON)



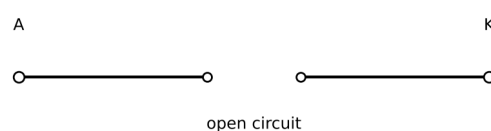
(a) Ideal diode – reverse biased (OFF)



(b) Constant-voltage-drop model – forward biased (ON)



(b) Constant-voltage-drop model – reverse biased (OFF)



(c) Piecewise-linear model – forward biased (ON)



(c) Piecewise-linear model – reverse biased (OFF)

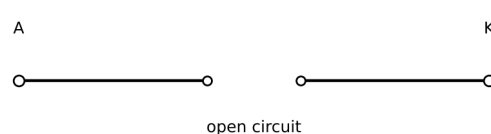
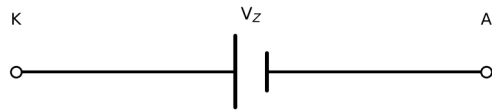


Fig. 1.7: Equivalent circuits of an ordinary diode (A = anode, K = cathode)

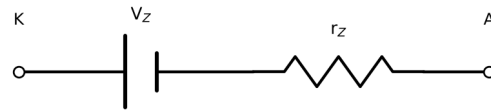
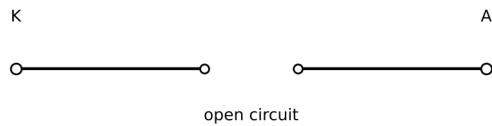
(B) Equivalent circuits of a Zener diode

- **Ideal Zener in breakdown:** a constant voltage source V_Z (positive towards the cathode).
- **Practical Zener in breakdown:** a voltage source V_Z in series with the dynamic impedance r_Z , so $V_Z' = V_{Z0} + I_Z r_Z$.
- **Reverse bias below V_Z ($I < I_{ZK}$):** an open circuit.
- **Forward biased:** same as an ordinary silicon diode, i.e. 0.7 V in series with r_d .

(a) Breakdown region – ideal



(b) Breakdown region – practical

(c) Reverse bias, $V < V_Z$ ($I < I_{ZK}$)

(d) Forward biased

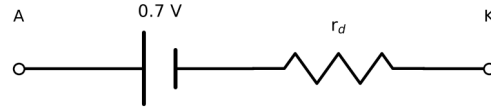


Fig. 1.8: Equivalent circuits of a Zener diode

1.3.3 Specifications

Specifications (data-sheet ratings) tell the designer the limits within which a diode can be used safely. The main specifications of an ordinary diode are:

Specification	Meaning
Peak inverse voltage (PIV) / V_{RRM}	Maximum reverse voltage the diode can withstand without breakdown
Maximum average forward current $I_{F(AV)}$	Largest average forward current for continuous operation
Peak surge current I_{FSM}	Maximum short-duration (non-repetitive) forward current
Forward voltage drop V_F	Voltage across the diode at a stated forward current
Reverse leakage current I_R	Reverse current at a stated reverse voltage and temperature
Maximum power dissipation P_D	Largest power the diode can dissipate safely
Reverse recovery time t_{rr}	Time needed to switch from ON to OFF state; important at high frequency
Junction capacitance C_j	Capacitance of the depletion layer (pF)
Operating temperature range	Allowed junction temperature limits

Example: the rectifier diode 1N4007 has $V_{RRM} = 1000\text{ V}$ and $I_{F(AV)} = 1\text{ A}$.

Specifications of a Zener diode

Specification	Meaning
Nominal Zener voltage V_Z and tolerance	Breakdown voltage at I_{ZT} , with a tolerance of typically $\pm 5\%$ or $\pm 10\%$
Test current I_{ZT}	Current at which V_Z and r_Z are specified
Maximum power dissipation $P_{Z(max)}$	e.g. 400 mW, 500 mW, 1 W, 5 W
Maximum Zener current I_{ZM}	$I_{ZM} = P_{Z(max)} / V_Z$
Knee current I_{ZK}	Minimum current for regulation
Dynamic impedance r_Z	Specified at I_{ZT} , in ohms
Temperature coefficient	mV/°C or %/°C
Power derating factor	Reduction of allowable power per °C rise above a reference temperature, in mW/°C
Leakage current and forward voltage	Reverse current below breakdown; forward drop at stated current

Example: the Zener diode 1N4733A has $V_Z = 5.1$ V, $P_{Z(max)} = 1$ W and $I_{ZT} = 49$ mA. (Always confirm values from the manufacturer's data sheet.)

Solved Example 1.3 - Power derating

- **Problem:** A 500 mW Zener diode has a derating factor of 4 mW/°C above 50 °C. Find the permissible dissipation at 100 °C.
- **Solution:** $P_Z(100\text{ °C}) = 500 - 4 \times (100 - 50) = 500 - 200 = \mathbf{300\text{ mW}}$

1.3.4 Zener Diode as a Simple Voltage Regulator

The output of an unregulated power supply changes when the ac mains voltage varies (**line variation**) or when the load current changes (**load variation**). A voltage regulator keeps the output voltage constant. Because the voltage across a Zener diode in breakdown is almost constant, a Zener diode connected **in parallel with the load** and fed through a series resistor R_S forms the simplest shunt voltage regulator.

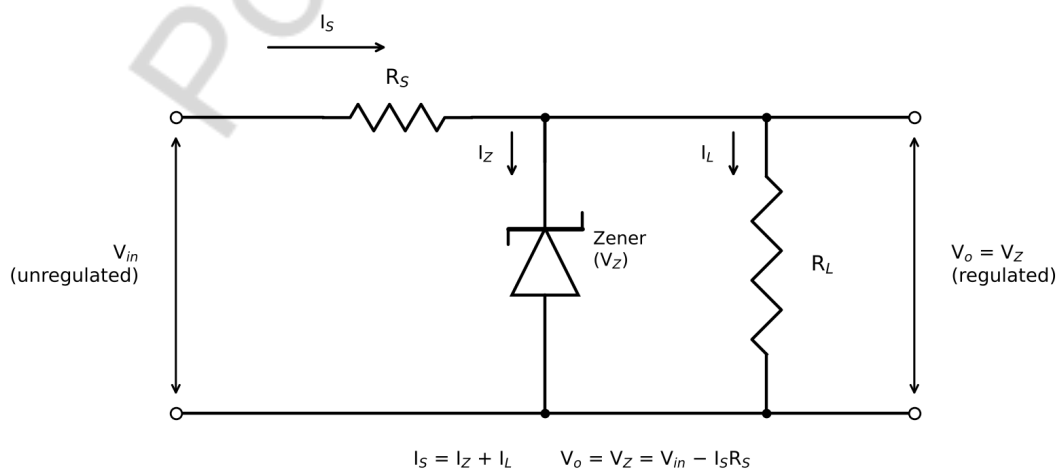


Fig. 1.9: Zener diode shunt voltage regulator

Working

1. The Zener is reverse biased and V_{in} is chosen larger than V_Z , so the Zener operates in breakdown and the output $V_o = V_Z$.
2. **Input (line) variation:** if V_{in} increases, the total current I_S increases. The extra current flows through the Zener (I_Z increases) and the extra voltage drops across R_S ; V_o stays at V_Z . If V_{in} falls, I_Z decreases in the same manner.
3. **Load variation:** if the load current I_L increases (R_L decreases), the Zener current I_Z decreases by the same amount, so I_S and the drop across R_S stay constant and V_o remains V_Z . The reverse happens when the load current decreases.
4. Regulation is maintained as long as I_Z stays between I_{ZK} and I_{ZM} .

Design equations

Quantity	Expression
Series current	$I_S = (V_{in} - V_Z) / R_S$
Load current	$I_L = V_Z / R_L$
Zener current	$I_Z = I_S - I_L$
Power in Zener	$P_Z = V_Z \times I_Z$ (must be less than $P_{Z(max)}$)
Maximum value of R_S	$R_{S(max)} = (V_{in(min)} - V_Z) / (I_{ZK} + I_{L(max)})$
Minimum value of R_S	$R_{S(min)} = (V_{in(max)} - V_Z) / (I_{ZM} + I_{L(min)})$
Line regulation (approx.)	$\Delta V_o / \Delta V_{in} \approx r_Z / (R_S + r_Z)$
Load regulation	$\% = (V_{NL} - V_{FL}) / V_{FL} \times 100$; $\Delta V_o \approx -\Delta I_L (r_Z \parallel R_S) \approx -\Delta I_L r_Z$ (if $r_Z \ll R_S$)

The worst case for the Zener occurs at **maximum input voltage with the load removed** (all the current flows through the Zener), and the worst case for regulation occurs at **minimum input voltage with maximum load current** (the Zener current is smallest).

Solved Example 1.4

- **Problem:** In a Zener regulator $V_{in} = 12$ V, $V_Z = 5.1$ V, $R_S = 220 \Omega$ and $R_L = 1$ k Ω . Find I_S , I_L , I_Z and the power dissipated in the Zener.
- **Solution:** $I_S = (12 - 5.1) / 220 = 6.9 / 220 = \mathbf{31.36 \text{ mA}}$
- $I_L = V_Z / R_L = 5.1 / 1000 = \mathbf{5.1 \text{ mA}}$
- $I_Z = I_S - I_L = 31.36 - 5.1 = \mathbf{26.26 \text{ mA}}$
- $P_Z = V_Z I_Z = 5.1 \times 26.26 \text{ mA} \approx \mathbf{134 \text{ mW}}$

Solved Example 1.5 - Design of R_S

- **Problem:** Design a Zener regulator for $V_Z = 10$ V; input varies from 15 V to 20 V; load current varies from 0 to 20 mA; $I_{ZK} = 5$ mA and $I_{ZM} = 60$ mA.
- **Solution:** $R_{S(max)} = (15 - 10) / (5 \text{ mA} + 20 \text{ mA}) = 5 / 25 \text{ mA} = \mathbf{200 \Omega}$
- $R_{S(min)} = (20 - 10) / (60 \text{ mA} + 0) = 10 / 60 \text{ mA} = \mathbf{166.7 \Omega}$
- So R_S must lie between 166.7 Ω and 200 Ω . Choose the standard value **180 Ω** .
- **Check:** at 20 V and no load, $I_Z = 10 / 180 = 55.6 \text{ mA} (< 60 \text{ mA})$. At 15 V and 20 mA load, $I_S = 5 / 180 = 27.8 \text{ mA}$, so $I_Z = 7.8 \text{ mA} (> 5 \text{ mA})$. Both limits are satisfied.

Solved Example 1.6 - Line regulation

- **Problem:** For $R_S = 220\ \Omega$ and $r_Z = 10\ \Omega$, find the change in output when the input changes by 2 V.
- **Solution:** $\Delta V_o = \Delta V_{in} \times r_Z / (R_S + r_Z) = 2 \times 10 / 230 \approx \mathbf{87\ mV}$. A 2 V input change produces only about 87 mV change at the output.

Advantages and limitations of the Zener regulator

Advantages	Limitations
Very simple circuit with few components	Output voltage is fixed at V_Z ; it cannot be varied
Low cost and compact	Poor efficiency, since power is wasted in R_S and in the Zener
Gives good regulation for small loads	Suitable only for small load currents (up to a few tens of mA)
Also protects the load against over-voltage	V_Z drifts slightly with temperature, and r_Z limits regulation

Chapter Summary

- A PN junction diode conducts when forward biased (above 0.7 V for Si, 0.3 V for Ge) and blocks when reverse biased except for a small saturation current.
- The diode equation is $I = I_S[\exp(V/\eta V_T) - 1]$ with $V_T \approx 26\ \text{mV}$ at 300 K.
- Reverse breakdown occurs by the Zener mechanism (heavy doping, below about 5 V) or avalanche mechanism (light doping, above about 7 V).
- A Zener diode is built to work in the breakdown region and holds its terminal voltage almost constant at V_Z .
- A Zener regulator uses a series resistor R_S and a parallel Zener; R_S must be chosen so that $I_{ZK} \leq I_Z \leq I_{ZM}$ under all conditions.

Multiple Choice Questions (15 MCQs)

Choose the correct option. The answer key is given after the questions.

- Q1.** The barrier potential of a silicon PN junction at room temperature is approximately:
- (a) 0.1 V
 - (b) 0.3 V
 - (c) 0.7 V
 - (d) 1.2 V
- Q2.** In a forward biased PN junction diode, the width of the depletion region:
- (a) increases
 - (b) remains unchanged
 - (c) decreases
 - (d) becomes infinite
- Q3.** The reverse saturation current of a diode is mainly due to:
- (a) majority carriers
 - (b) donor ions
 - (c) acceptor ions
 - (d) minority carriers
- Q4.** The reverse saturation current of a diode approximately doubles for every:
- (a) 1 °C rise in temperature
 - (b) 10 °C rise in temperature
 - (c) 50 °C rise in temperature
 - (d) 100 °C rise in temperature
- Q5.** The cut-in voltage of a germanium diode is approximately:
- (a) 0.3 V
 - (b) 0.7 V
 - (c) 1.0 V
 - (d) 5.0 V
- Q6.** The thermal voltage V_T at room temperature (300 K) is approximately:
- (a) 2.6 mV
 - (b) 26 mV
 - (c) 260 mV
 - (d) 2.6 V
- Q7.** A diode carries a forward current of 13 mA. Its dynamic resistance ($\eta = 1$, $V_T = 26$ mV) is:
- (a) 0.5 Ω
 - (b) 20 Ω
 - (c) 338 Ω
 - (d) 2 Ω
- Q8.** Zener breakdown mainly occurs in a junction that is:
- (a) lightly doped with a wide depletion region
 - (b) heavily doped with a narrow depletion region
 - (c) forward biased
 - (d) unbiased

Q9. Avalanche breakdown is caused by:

- (a) increase in doping
- (b) tunnelling of electrons through the barrier
- (c) excessive forward current
- (d) impact ionisation and carrier multiplication

Q10. The temperature coefficient of Zener breakdown (V_Z below 5 V) is:

- (a) negative
- (b) positive
- (c) zero at all temperatures
- (d) infinite

Q11. A Zener diode is normally operated in the:

- (a) forward biased region
- (b) saturation region
- (c) reverse breakdown region
- (d) unbiased condition

Q12. In a Zener voltage regulator, the series resistor R_S is used to:

- (a) limit the Zener current and drop the excess voltage
- (b) increase the output voltage
- (c) reduce the PIV of the diode
- (d) forward bias the Zener diode

Q13. A Zener regulator has $V_{in} = 15$ V, $V_Z = 9$ V and $R_S = 300 \Omega$. With the load open, the Zener current is:

- (a) 20 mA
- (b) 30 mA
- (c) 50 mA
- (d) 5 mA

Q14. In the breakdown region, the practical equivalent circuit of a Zener diode is:

- (a) an open circuit
- (b) a short circuit
- (c) a battery V_Z in series with a small resistance r_Z
- (d) a large resistor only

Q15. The peak inverse voltage (PIV) rating of a diode is:

- (a) the maximum forward current it can carry
- (b) the maximum reverse voltage it can withstand without breakdown
- (c) the knee voltage in forward bias
- (d) the minimum voltage required for conduction

Answer Key - MCQs

Q	Ans	Q	Ans	Q	Ans	Q	Ans	Q	Ans
1	(c)	4	(b)	7	(d)	10	(a)	13	(a)
2	(c)	5	(a)	8	(b)	11	(c)	14	(c)
3	(d)	6	(b)	9	(d)	12	(a)	15	(b)

Broad Questions (10 Questions)

- Q1.** Explain the formation of the depletion region and barrier potential in an unbiased PN junction. State the typical values of barrier potential for silicon and germanium.
- Q2.** Describe the forward biased and reverse biased conditions of a PN junction diode with neat circuit diagrams. Explain the effect of each condition on the depletion region and the current.
- Q3.** Draw and explain the V-I characteristics of an ordinary PN junction diode. Define knee (cut-in) voltage, reverse saturation current and breakdown voltage on the graph.
- Q4.** Write the diode equation and explain each term. Define static and dynamic resistance, and calculate the dynamic resistance of a diode carrying 10 mA at room temperature ($\eta = 1$).
- Q5.** What is reverse breakdown? Distinguish between Zener breakdown and avalanche breakdown in a table covering doping, depletion region, voltage range, mechanism and temperature coefficient.
- Q6.** Explain the construction of a Zener diode with a neat sketch. How does the doping level decide the Zener voltage?
- Q7.** Explain the operation of a Zener diode in reverse bias. Draw and explain its V-I characteristic and mark V_Z , I_{ZK} and I_{ZM} .
- Q8.** Draw and explain the equivalent circuits of (a) an ordinary diode and (b) a Zener diode in breakdown, below the knee and in forward bias.
- Q9.** List and explain the important specifications of (a) a rectifier diode and (b) a Zener diode.
- Q10.** With a circuit diagram, explain how a Zener diode works as a voltage regulator for variations in input voltage and load current. A regulator has $V_{in} = 20\text{ V}$, $V_Z = 10\text{ V}$, $R_S = 500\ \Omega$ and $R_L = 1\text{ k}\Omega$; find I_S , I_L , I_Z and the power dissipated in the Zener diode.

Best of luck!

- Revise the diagrams (Fig. 1.1 to Fig. 1.9) and the solved examples before the examination.
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