UNIT I

Semiconductor Diodes and Their Applications

Introduction to Electronics Engineering (IEE)

Topic 1: Introduction to Electronics

1.1 What is Electronics?

Electronics is the branch of science and engineering that deals with the study of the flow of electrons through vacuum, gas, or semiconductors. It involves the design and application of circuits using these electron flows to perform specific functions.

An electronic circuit is a closed path formed by the interconnection of electronic components through which electric current flows to perform a specific function.

Types of Electronics

- Analog Electronics
- Digital Electronics
- Power Electronics
- Microelectronics
- Optoelectronics
- Communication Electronics

Topic 2: Atomic Structure and Semiconductor Fundamentals

2.1 Atomic Structure

An atom is the smallest particle of an element that retains the chemical properties of that element.

- Atomic structure refers to the structure of an atom comprising of a nucleus (centre) in which protons (positively charged) and neutrons (neutral) are present.
- The negatively charged particles called electrons revolve around the centre of the nucleus.
- Each permitted orbit has a fixed amount of energy. The larger the orbit (radius), the greater is the energy of electrons.
- If an electron gains additional energy (heat, light, etc.), it moves to a higher orbit. The atom is then in a state of excitation.

Key Formulae:

Atomic Weight: Number of Protons + Number of Neutrons

Atomic Number: Number of Protons = Number of Electrons in the atom

2.2 Semiconductor

In terms of their electrical properties, materials can be classified into three groups: conductors, semiconductors, and insulators.

- **Semiconductor:** A material whose electrical conductivity lies between that of a conductor and an insulator, and whose conductivity can be controlled by adding impurities (doping) or applying external fields.
- The behaviour of electrons in solids is governed by their arrangement in energy bands.

Energy Bands

Conduction Band: The energy band where electrons are free to move and contribute to electrical conductivity.

Valence Band: The energy band where electrons are bound to atoms and do not contribute to conductivity.

Fermi Level: The highest energy level that an electron can occupy at absolute zero temperature. It lies between the valence band and conduction band.

Most Common Semiconductors

- Semiconductor materials fall into two classes: single-crystal and compound.
- The three semiconductors most frequently used in electronic devices are: Germanium (Ge), Silicon (Si), and Gallium Arsenide (GaAs).
- In a pure silicon or germanium crystal, the four valence electrons of one atom form a bonding arrangement with four adjoining atoms — this is called covalent bonding.

2.3 Comparison of Materials: Conductors, Semiconductors, and Insulators

Parameter	Conductor	Semiconductor	Insulator
Forbidden Energy Gap	Not Exist	Small (1 eV)	Large (>5 eV)
Resistivity	Low	Moderate	High
Flow of Current	Due to movement of free electrons	Due to movement of electrons and holes	Almost negligible but only due to free electrons
Charge Carriers in Conduction Band	Completely filled	Partially filled	Completely vacant
Charge Carriers in Valence Band	Almost vacant	Partially filled	Completely filled
Example	Copper, Aluminium, Graphite	Silicon, Germanium, Arsenic	Paper, Rubber, Glass, Plastic
Applications	Conducting wires, Transformers, Electrical cords	Diodes, Transistors, Optocouplers	Sports equipment, Home appliances

2.4 Types of Semiconductors

A. Intrinsic Semiconductors

- Pure-form semiconductor materials without any significant impurities. Examples: Silicon (Si) and Germanium (Ge).
- In an intrinsic semiconductor, the number of electrons in the conduction band equals the number of holes (empty states in the valence band).
- Conductivity is low at room temperature and increases with temperature.

B. Extrinsic Semiconductors (Doped)

Extrinsic semiconductors are created by adding specific impurities (called dopants) to an intrinsic semiconductor to enhance its electrical conductivity.

N-Type Semiconductor

- Created by adding pentavalent impurity elements (5 valence electrons) such as Antimony (Sb), Arsenic (As), and Phosphorus (P).
- The impurity atoms donate a free electron, so they are called donor atoms.
- Majority carriers: Electrons | Minority carriers: Holes

P-Type Semiconductor

- Created by adding trivalent impurity elements (3 valence electrons) such as Boron (B), Gallium (Ga), and Indium (In).
- The impurity atoms accept an electron, creating a hole; they are called acceptor atoms.
- Majority carriers: Holes | Minority carriers: Electrons

The controlled addition of dopants allows precise control over the electrical properties of semiconductors, making them essential in devices like diodes, transistors, and integrated circuits.

2.5 Intrinsic vs. Extrinsic Semiconductors — Comparison Table

Property	Intrinsic Semiconductor	Extrinsic Semiconductor (n-type & p-type)
Purity	Pure (no impurities)	Doped with impurities
Conductivity	Low at room temperature	Higher due to the presence of free charge carriers
Charge Carriers	Equal number of electrons and holes	Majority and minority carriers (electrons or holes)
Effect of Temperature	Conductivity increases with temperature	Conductivity depends on doping and temperature
Types	Not applicable	n-type (electron majority) and p-type (hole majority)
Energy Band Structure	No additional energy levels	Donor or acceptor energy levels present

2.6 Majority and Minority Carriers

When a semiconductor is doped, one type of charge carrier becomes dominant:

Material Type	Carrier Information
N-Type	Majority Carrier: Electrons | Minority Carrier: Holes
P-Type	Majority Carrier: Holes | Minority Carrier: Electrons

Topic 3: PN Junction Diode

3.1 Introduction

- The PN junction is the fundamental building block of semiconductor devices such as diodes, transistors, and integrated circuits.
- The PN junction diode is created by simply joining an n-type and a p-type semiconductor material together.

Operating Conditions of a Diode

1. No Bias — No external voltage applied ($V_D = 0$)
2. Forward Bias — Positive terminal to p-region, negative to n-region
3. Reverse Bias — Positive terminal to n-region, negative to p-region

Bias: The application of an external voltage across the two terminals of the device to extract a response.

3.2 PN Junction: No Bias Condition

- Electrons from the n-region diffuse into the p-region; holes from the p-region diffuse into the n-region. Movement continues until equilibrium is established.
- Electrons and holes recombine near the junction, creating a depletion region — a region with no free charge carriers. Only immobile ions remain (negative ions on p-side, positive ions on n-side).
- An electric field develops across the depletion region, opposing further diffusion.
- In the absence of applied bias, the net flow of charge in any direction is zero.

Characteristics of the Depletion Region

Width: Depends on doping concentration. Heavily doped regions have narrower depletion regions.

Charge Distribution: p-region contains negatively charged acceptor ions; n-region contains positively charged donor ions.

Electric Field: Points from positively charged n-region to negatively charged p-region.

Barrier Potential (Built-in Potential)

The electric field creates a potential barrier (V_b) that prevents further diffusion of charge carriers:

- Silicon: $V_b = 0.7$ V
- Germanium: $V_b = 0.3$ V

3.3 Reverse Bias

When the positive terminal is connected to the n-region and the negative terminal to the p-region:

- Potential barrier is increased
- Depletion region widens
- Charge carriers cannot cross the junction
- Very little current flows (due to minority charge carriers only)
- If the reverse voltage exceeds a critical value, breakdown can occur through Zener or Avalanche breakdown

Reverse Saturation Current (I_S)

Also called leakage current. It is caused by thermally generated minority carriers swept across the junction by the built-in electric field.

- Very small in magnitude
- Almost constant with reverse voltage
- Strongly increases with temperature

3.4 Forward Bias

When the positive terminal is connected to the p-region and the negative terminal to the n-region:

- Potential barrier is reduced
- Charge carriers can cross the junction
- Electrons move toward the p-region; holes move toward the n-region
- Results in significant forward current flow
- In silicon diodes, forward voltage must be approximately 0.7 V for significant conduction

3.5 Shockley's Diode Equation

The general current-voltage relationship for a semiconductor diode is given by Shockley's equation:

$$I_D = I_s \left(e^{(VD / n*VT)} - 1\right)$$

Symbol	Definition
I_D	Diode current
I_s	Reverse saturation current
V_D	Applied forward-bias voltage across the diode
n	Idealist factor: n = 1 for Germanium; n = 2 for Silicon
V_T	Thermal Voltage = k * T_K / q
k	Boltzmann's constant = 1.38×10^{-23} J/K
T_K	Absolute temperature in kelvins = 273 + Temperature (°C)

Symbol	Definition
q	Magnitude of electronic charge = 1.6×10^{-19} C

3.6 Current-Voltage (I-V) Characteristics

Forward Bias Region

- When voltage exceeds the threshold (0.7 V for silicon, 0.3 V for germanium), current increases exponentially.
- Diode conducts current easily once threshold is crossed.

Reverse Bias Region

- Only a very small reverse saturation current (I_s) flows.
- If the reverse voltage exceeds the breakdown voltage, the diode conducts large currents — this may permanently damage regular diodes.

Knee Voltage: The minimum forward voltage after which the forward current starts increasing exponentially. For Si: ~0.7 V; for Ge: ~0.3 V.

3.7 Diode Resistance

Static Resistance (DC Resistance) — R_D

Defined at a specific operating point on the I-V characteristics:

$$R_D = V_D / I_D$$

Dynamic Resistance (AC Resistance) — r_d

Calculated using the slope of the I-V curve at the operating point:

$$r_d = \Delta V_d / \Delta I_d = n*V_T / I_D$$

At room temperature (27°C), V_T ≈ 26 mV, and for n = 1:

$$r_d = 26\ \text{mV} / I_D$$

3.8 Temperature Effects on Diodes

- As temperature increases, it adds energy to the diode.
- It reduces the required forward bias voltage for conduction.
- It increases the amount of reverse saturation current.
- Germanium diodes are more sensitive to temperature variations than silicon or gallium arsenide diodes.

Temperature Dependence of Reverse Saturation Current

Reverse saturation current approximately doubles for every 10°C rise in temperature:

$$I_s \approx I_{s0} \times 2^{((T - T\_0) / 10)}$$

Effect on Forward Bias Characteristics

- In the forward bias region, the silicon diode characteristic shifts to the left (lower voltage) at a rate of approximately 2.5 mV per °C increase in temperature.
- Forward bias voltage decreases with increasing temperature.

3.9 Breakdown Mechanisms

1. Avalanche Breakdown

- Occurs in lightly doped diodes where the depletion region is wide.
- A very large electric field at the junction ruptures covalent bonding, generating a large number of charge carriers — this results in avalanche multiplication.
- Temperature characteristic: Positive — requires more voltage at higher temperature.

2. Zener Breakdown

- Occurs in heavily doped diodes where the depletion region is narrow.
- Even a small reverse voltage at the junction ruptures covalent bonding and generates a large number of charge carriers — this is the Zener mechanism.
- Temperature characteristic: Negative — requires less voltage at higher temperature.

Property	Zener Breakdown	Avalanche Breakdown
Doping Level	Heavily doped	Lightly doped
Depletion Width	Narrow	Wide
Voltage Required	Low (< 5 V typically)	High
Temperature Coefficient	Negative	Positive

3.10 Diode Capacitance

Depending upon the biasing condition, two types of capacitive effects exist in diodes:

A. Junction Capacitance (Depletion Capacitance) — C_j

- Most significant capacitance; varies with reverse bias voltage applied.
- Associated with the depletion region of the diode.
- As reverse bias voltage increases, depletion region widens, so junction capacitance decreases.

The junction capacitance is given by:

$$C_j = (\varepsilon \times A) / W$$

ε	Permittivity of the dielectric
A	Area of the junction
W	Width of the depletion region

B. Diffusion Capacitance — C_d

- Appears in a forward-biased PN junction due to storage of charge in the diffusion region.
- As forward bias increases, the depletion region narrows and the concentration of injected charge carriers increases.
- This rate of change of injected charge with applied voltage is defined as diffusion capacitance.
- Increases with forward current; significant only when the diode is forward-biased.
- Typically, less than junction capacitance in most applications.

The diffusion capacitance is given by:

$$C_d = (\tau \times I\_D) / V_T$$

τ	Carrier lifetime
I_D	Diode current
V_T	Thermal voltage

3.11 Equivalent Model of Diode

The forward voltage V_F applied across the actual diode must overcome two quantities:

4. Potential barrier V_0
5. Internal voltage drop $I_f \times r_f$

$$V_F = V_0 + I_f \times r_f$$

Diode Models Summary

S.No.	Type	Characteristic / Description
1	**Approximate Model**	Includes ideal diode + barrier potential V_0 + internal dynamic resistance r_f. Forward voltage: $V_F = V_0 + I_f \times r_f$
2	**Simplified Model**	Includes ideal diode + barrier potential V_0 only (r_f is neglected). Suitable for most analysis.
3	**Ideal Model**	Diode treated as a perfect switch: zero forward voltage drop, infinite reverse resistance. Used for quick estimates.

Topic 4: Applications of PN Junction

4.1 Applications Overview

Application	Diodes	Rectifiers	LEDs
Function	Allow current in one direction only	Convert AC to DC	Emit light when forward biased
Application	Signal processing, protection	Power supply circuits	Displays, indicators

4.2 Rectifier Circuits

A rectifier converts an AC signal to a DC signal. A complete power supply system includes:

Transformer: Steps down the high voltage AC from the mains to a lower, usable voltage level (e.g., 230 V AC → 12 V AC).

Rectifier: Converts AC to a unipolar (one-direction) output using diodes.

Filter: Converts the pulsating rectified output to a nearly constant DC using capacitors.

Regulator: Reduces the ripple and stabilizes the DC output voltage.

4.3 Half-Wave Rectifier

Uses a single diode. Only the positive half-cycle of AC passes through; the negative half is blocked.

Key Components and Functions

- **Transformer:** Steps down AC voltage to a usable level.
- **Signal Diode (Rectifier):** Acts as a one-way valve. Allows current only when the anode is positive relative to the cathode (Forward Bias). Clips off the negative half of the AC cycle.
- **Filter Capacitor:** Stores energy during peaks and releases it during troughs, smoothing the pulsating DC into a nearly constant voltage.
- **Load:** The component that consumes DC power. Output voltage is measured across this load.

Half-Wave Rectifier — Performance

Ripple Factor (γ): 1.21 (High ripple — poor quality DC)

Maximum Efficiency (η): 40.6%

Output Frequency: Same as input frequency (f_{in})

PIV Rating: V_m (peak input voltage)

4.4 Full-Wave Rectifier

Utilizes both half-cycles of the AC waveform. Two main configurations exist:

Centre-Tapped Full-Wave Rectifier vs. Bridge Full-Wave Rectifier

Feature	Centre-Tapped Full-Wave	Bridge Full-Wave
Number of Diodes	2	4
Transformer	Requires Centre-Tapped (bulkier & expensive)	Standard (smaller & cheaper)
Peak Inverse Voltage (PIV)	$2V_m$	V_m
Transformer Utilization (TUF)	~0.693 (low)	~0.812 (higher)

Feature	Centre-Tapped Full-Wave	Bridge Full-Wave
Output Frequency	$2 \times f_{in}$	$2 \times f_{in}$
Max Efficiency	81.2%	81.2%
Cost	Higher (specialized transformer)	Lower (standard components)
Suitability	Low voltage, high current	General-purpose DC power supplies

4.5 Rectifier Performance Metrics

1. Ripple Factor (γ)

Measures the amount of AC component (unwanted noise) remaining in the DC output. A lower value is better.

$$\gamma = \sqrt{[(V_{rms} / V_{dc})^2 - 1]}$$

- Half-Wave: $\gamma = 1.21$
- Full-Wave: $\gamma = 0.48$

2. Rectifier Efficiency (η)

The ratio of DC output power to applied AC input power:

$$\eta = (P_{dc} / P_{ac}) \times 100\%$$

- Half-Wave: max 40.6%
- Full-Wave: max 81.2%

3. Peak Inverse Voltage (PIV)

The maximum reverse voltage a diode must withstand without breakdown:

- Half-Wave: V_m
- Full-Wave (Centre-Tap): $2V_m$
- Full-Wave (Bridge): V_m

4.6 Summary: Half-Wave vs. Full-Wave Rectifier

Parameter	Half-Wave Rectifier	Full-Wave Rectifier (Bridge & Centre-Tap)
Ripple Factor (γ)	1.21 (High ripple, poor DC quality)	0.48 (Low ripple, smoother DC)
Max Efficiency (η)	40.6%	81.2%
Output Frequency	f_{in} (same as input, e.g., 50 Hz)	$2 \times f_{in}$ (double, e.g., 100 Hz)
PIV Rating	V_m (peak voltage)	Bridge: V_m | Centre-Tap: $2V_m$
Number of Diodes	1	Bridge: 4 | Centre-Tap: 2

Parameter	Half-Wave Rectifier	Full-Wave Rectifier (Bridge & Centre-Tap)
Transformer Type	Standard	Bridge: Standard | Centre-Tap: Special (bulkier)

Topic 5: Diode Clippers and Clampers

5.1 Diode Clippers (Limiters)

A clipper is a circuit that removes (clips) a portion of the input signal — positive half, negative half, or both — without distorting the remaining part. It is used for protection or waveform shaping.

Types of Clippers

1. Series Clipper

- The diode is placed in series with the load resistor.
- When the diode is OFF: no current flows, output is zero (clipped).
- When the diode is ON: input signal passes through to the output.

2. Shunt (Parallel) Clipper

- The diode is placed in parallel with the load.
- When the diode is ON: it short-circuits the signal to ground (clips it).
- When the diode is OFF: signal passes through to the load.

5.2 Diode Clampers (DC Restorers)

A clamper is a circuit that shifts the entire waveform up or down by adding a DC component to the signal. Unlike a clipper, it does NOT change the shape of the waveform — it only changes the DC level (baseline).

- **Key Component Required:** A capacitor is essential for clamper operation.

Types of Clampers

1. Positive Clamper

- Shifts the waveform upward.
- The negative peak of the signal is clamped to zero (or a reference voltage).
- The entire waveform sits above the x-axis.

2. Negative Clamper

- Shifts the waveform downward.
- The positive peak is clamped to zero.
- The entire waveform sits below the x-axis.

Feature	Clipper	Clamper
Function	Removes part of waveform	Shifts waveform up or down
Waveform Shape	Changed (distorted)	Unchanged (shape preserved)
Key Component	Diode (+ resistor)	Diode + Capacitor (essential)
Output Level	Clipped at threshold	DC shifted

Topic 6: Solved Numerical Examples

6.1 Thermal Voltage Calculation

Example 1: At a temperature of 27°C, determine the thermal voltage V_T.

Given: T = 27°C, $k = 1.38 \times 10^{-23}$ J/K, $q = 1.6 \times 10^{-19}$ C

Solution:

T_K = 273 + 27 = 300 K

$$V_T = (k \times T_K) / q = (1.38 \times 10^{-23} \times 300) / (1.6 \times 10^{-19}) \approx 25.875 \text{ mV} \approx 26 \text{ mV}$$

6.2 Series Diode Circuit — Forward Biased

Example 2: For a series diode configuration with E = 8 V and R = 2.2 kΩ (Silicon diode), determine V_D, V_R, and I_D.

Solution: The applied voltage is sufficient to turn the silicon diode ON.

$V_D = 0.7$ V (barrier potential of silicon)

$V_R = E - V_D = 8 - 0.7 = 7.3$ V

$I_D = V_R / R = 7.3 \text{ V} / 2200\ \Omega \approx 3.32$ mA

6.3 Series Diode Circuit — Insufficient Voltage

Example 3: For a series Silicon diode with E = 0.5 V and R = 1.2 kΩ, determine V_D, V_R, and I_D.

Solution: The applied voltage (0.5 V) is insufficient to turn the silicon diode ON (requires 0.7 V).

$I_D = 0$ A

$V_R = I_D \times R = 0 \text{ A} \times 1200\ \Omega = 0$ V

$V_D = E = 0.5$ V (all voltage appears across the diode)

6.4 Dual Diode Circuit — Finding Current

Example 4: In a circuit with $E_1 = 24$ V, $E_2 = 4$ V, R = 2 kΩ, D1 (forward biased, Si) and D2 (reverse biased), find current I.

Solution: D1 is ON; D2 is OFF (acts as open circuit).

$$I = (E_1 - E_2 - V_0) / R = (24 - 4 - 0.7) / 2000 = 19.3 / 2000 = 9.65\ mA$$

6.5 Ideal Diode Circuit

Example 5: A circuit has ideal diodes D1 (reverse biased) and D2 (forward biased), with a 10 V supply, R_1 = 2 Ω, R_2 = 3 Ω, R_3 = 2 Ω. Find current through R_1.

Solution: D1 is reverse biased (open circuit); D2 is forward biased (short circuit for ideal diode).

$R_{eff} = R_1 + R_3 = 2 + 2 = 4\ \Omega$

$$I \text{ through } R_1 = V / R_{eff} = 10 / 4 = 2.5\ A$$

6.6 Shockley Equation — Germanium Diode

Example 6: A germanium diode has a reverse saturation current I_0 = 0.19 μA. Find the current when forward biased with 0.3 V at 27°C. (n = 1 for Ge)

Given: I_o = 0.19 μA, V_D = 0.3 V, T = 27°C, n = 1

Step 1: Calculate thermal voltage:

$$V_T = T_K / 11600 = (273 + 27) / 11600 = 300 / 11600 = 25.862\ mV$$

Step 2: Apply Shockley's equation:

$$I_D = 0.19 \times 10^{-6} \times (e^{(0.3\ /\ (1 \times 25.862 \times 10^{-3}))} - 1) \approx 20.72\ mA$$

6.7 Forward Bias Voltage Calculation — Silicon Diode

Example 7: The forward current in a Silicon diode is 15 mA at 27°C. If reverse saturation current is 0.24 nA, find the forward bias voltage. (n = 2 for Si)

Given: I_D = 15 mA, I_o = 0.24 nA, T = 27°C, n = 2

$$V_T = 300 / 11600 = 25.862\ mV$$

$$V_D = n \times V_T \times \ln(I_D/I_o + 1) = 2 \times 25.862 \times 10^{-3} \times \ln(15m/0.24n + 1) \approx 0.928\ V$$

6.8 Static and Dynamic Resistance — Germanium Diode

Example 8: Calculate the static and dynamic resistance of a PN Junction diode when V_D = 0.25 V for a Germanium diode. I_o = 1 μA, T = 300 K, n = 1.

Given: I_o = 1 μA, V_D = 0.25 V, T = 300 K, n = 1

$$V_T = 300 / 11600 = 25.862\ mV$$

$$I_D = 1\mu A \times (e^{(0.25/(1 \times 25.862m))} - 1) = 15.782\ mA$$

(a) Static Resistance:

$$R_D = V_D / I_D = 0.25 / 15.782m = 15.84\ \Omega$$

(b) Dynamic Resistance:

$$r_d = n \times V_T / I_D = 1 \times 25.862m / 15.782m = 1.638\ \Omega$$

Topic 7: Quick Reference — Key Formulae and Definitions

7.1 Key Formulae Summary

Quantity	Formula	Notes
Diode Current (Shockley)	$I_D = I_s(e^{(VD/nVT)} - 1)$	n=1 (Ge), n=2 (Si)
Thermal Voltage	$V_T = kT_K/q$	≤26 mV at 27°C
DC (Static) Resistance	$R_D = V_D / I_D$	At a specific operating point
AC (Dynamic) Resistance	r_d = 26mV / I_D (for n=1)	Slope of I-V curve
Junction Capacitance	$C_j = \varepsilon A / W$	Reverse biased
Diffusion Capacitance	$C_d = \tau I_D / V_T$	Forward biased
Ripple Factor	$\gamma = \sqrt{[(V_{rms}/V_{dc})^2 - 1]}$	HW: 1.21, FW: 0.48
Rectifier Efficiency	$\eta = P_{dc}/P_{ac} \times 100\%$	HW: 40.6%, FW: 81.2%
Reverse Current vs. Temperature	$I_s \approx I_{s0} \times 2^{((T-T\_0)/10)}$	Doubles every 10°C

7.2 Key Definitions at a Glance

Semiconductor: A material with electrical conductivity between conductors and insulators; conductivity can be controlled by doping or external fields.

Doping: The deliberate addition of impurities to a pure semiconductor to alter its electrical properties.

Depletion Region: A region at the PN junction devoid of free charge carriers, containing only immobile ions.

Barrier Potential (V_b): The built-in potential that opposes the flow of majority carriers across the junction; 0.7 V for Si, 0.3 V for Ge.

Forward Bias: Positive voltage applied to p-region; reduces barrier potential and allows current flow.

Reverse Bias: Positive voltage applied to n-region; increases barrier potential and blocks current flow.

Knee Voltage: The minimum forward voltage beyond which the forward current rises exponentially.

Rectifier: A circuit that converts AC to DC using diodes.

Clipper: A circuit that removes part of the input waveform without distorting the remainder.

Clamper: A circuit that shifts the DC level of a waveform without changing its shape.

Ripple Factor: A measure of AC content in the DC output of a rectifier; lower is better.

PIV (Peak Inverse Voltage): Maximum reverse voltage a diode must withstand without breaking down.