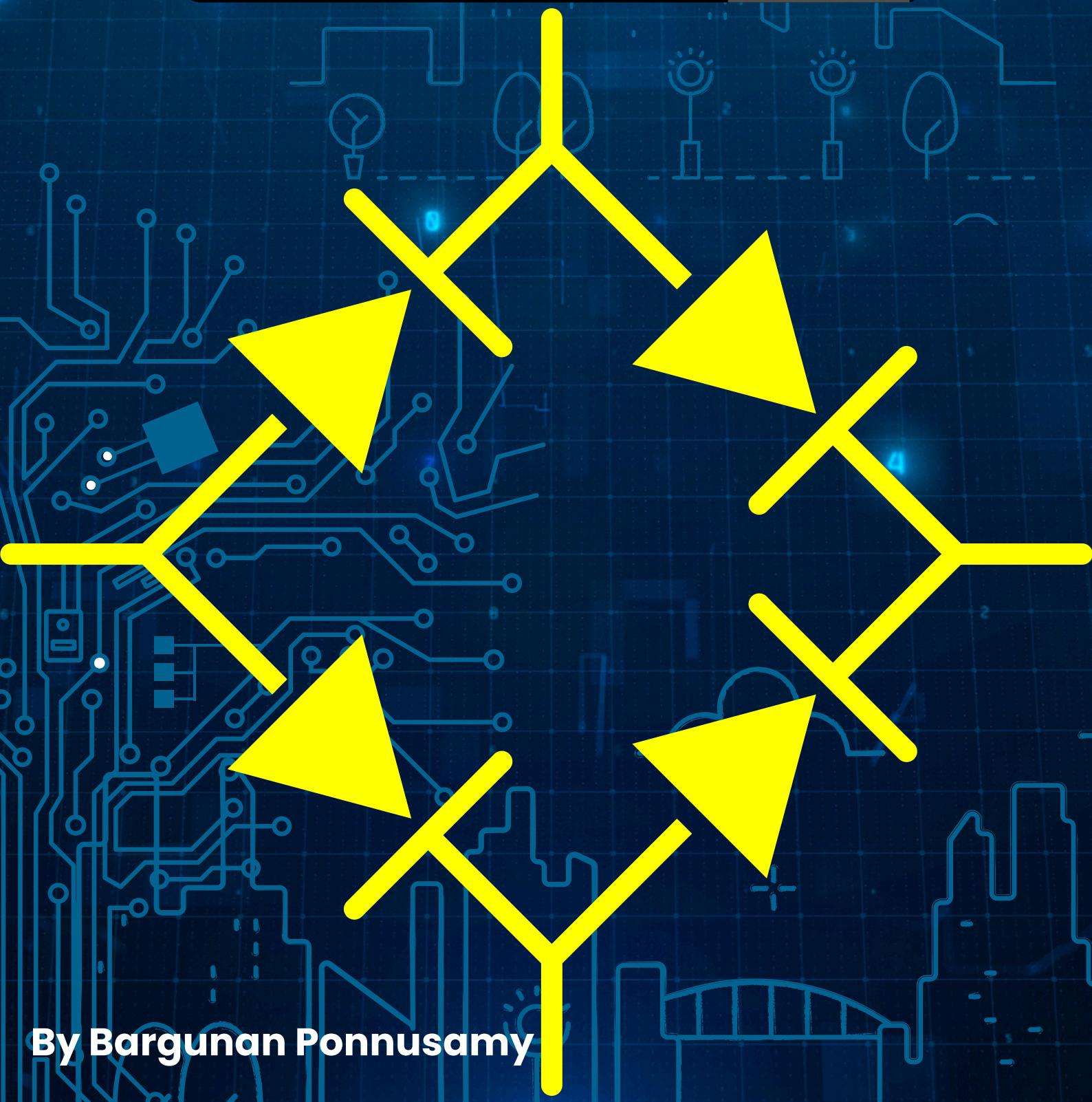


DIODE



By Bargunan Ponnusamy

INTRODUCTION TO DIODES

Basic Principle

- A diode is a fundamental semiconductor device that permits current flow primarily in one direction.
- It operates as a one-way valve for electrical current, conducting efficiently when forward-biased and blocking effectively when reverse-biased.
- At its core, a diode is formed by a PN junction—the interface created when a P-type semiconductor (positively charged, having holes as majority carriers) meets an N-type semiconductor (negatively charged, having electrons as majority carriers).
-
- When voltage is applied in the forward direction (positive on the P-side and negative on the N-side), the diode conducts electricity. Conversely, when reverse voltage is applied, it blocks current flow, allowing only a minimal leakage current.

Importance and Usage in Electronics

Diodes are essential to nearly all electronic systems due to their versatile applications. Their capability to control current direction enables vital electronic functions.

- **Rectification:** Converting Alternating Current (AC) into Direct Current (DC), crucial for virtually all electronic devices.
- **Voltage Regulation:** Ensuring stable voltage references and protections through specialized diodes (e.g., Zener diodes).
- **Protection:** Preventing damage due to voltage spikes or incorrect polarity connections (ESD and reverse-polarity protection).
- **Signal Conditioning:** Limiting voltage and protecting sensitive electronic components (clamping and clipping circuits).
- **Switching and High-Speed Applications:** Allowing rapid current switching in digital circuits, RF communications, and power electronics.
- **Optical Applications:** Emitting and detecting light in LED displays, laser diodes, and photodiodes for sensors and communications.

CONSTRUCTION & WORKING PRINCIPLE

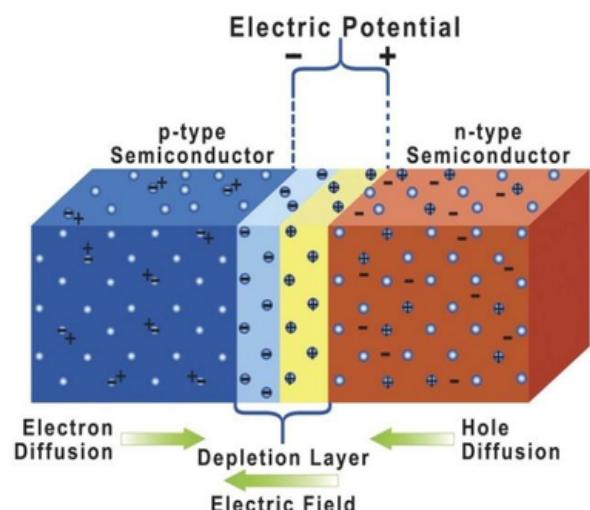
Semiconductors are materials whose electrical conductivity lies between conductors (like metals) and insulators (like glass or rubber).

PN Junction Formation:

A diode's fundamental structure is a PN junction, formed when a P-type semiconductor is joined with an N-type semiconductor.

Upon forming the junction:

- Electrons from N-region and holes from P-region diffuse across, recombining near the interface.
- This diffusion forms a depletion region free of mobile charge carriers.
- The depletion region creates an insulating barrier with a built-in potential, preventing further carrier diffusion at equilibrium.



Forward Bias:

- Positive voltage at the P-type region, negative voltage at the N-type region.
- Reduces depletion width, enabling easy carrier flow across the junction.
- Diode conducts current once forward voltage surpasses threshold (~0.7V silicon, ~0.3V germanium).

Reverse Bias:

- Negative voltage at the P-type region, positive voltage at the N-type region.
- Expands depletion width, significantly limiting current flow.
- Only small leakage current (minority carriers) occurs.
- Exceeding rated reverse voltage leads to diode breakdown and potential damage, except in specially designed diodes (e.g., Zener diodes).

CONSTRUCTION & WORKING PRINCIPLE

Ideal Diode:

- **Forward bias:** Conducts immediately; zero voltage drop.
- **Reverse bias:** Blocks current entirely; infinite resistance.

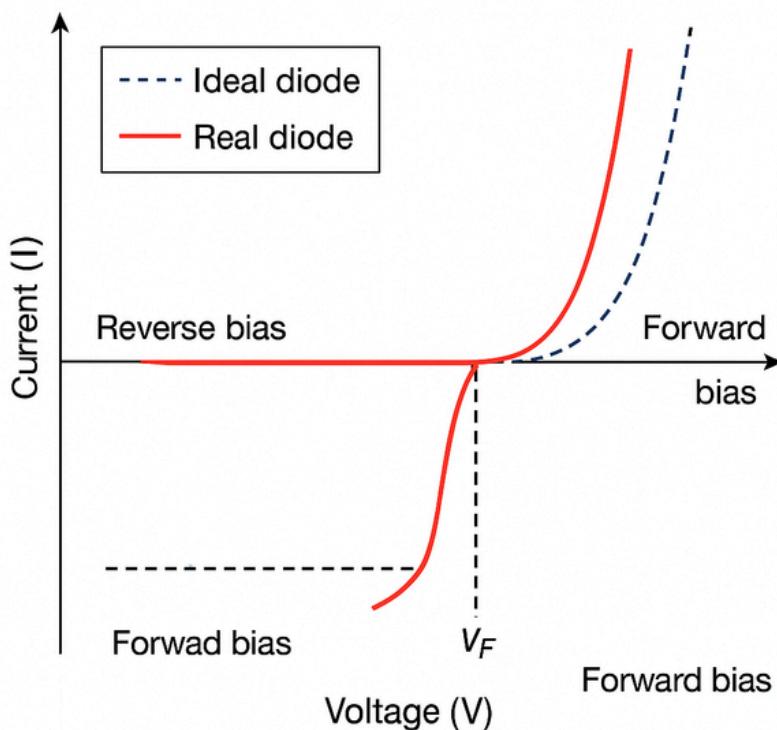
Real-World Diode:

- **Forward bias:** Conducts after threshold voltage (~0.7V silicon); current then rises rapidly.
- **Reverse bias:** Minimal leakage current until rated breakdown voltage is reached, causing sudden conduction.

Parameter	Ideal Diode	Real Diode	Practical Impact
Forward Voltage Drop	0 V	~0.3–1.2 V	Power loss
Reverse Current	0 A	Small (nA to μ A)	Affects precision
Switching Speed	Instant	Finite (ns to μ s)	EMI, losses
Temperature Stability	Perfect	~2mV/ $^{\circ}$ C drift	Accuracy issues

Practical diode characteristics include forward voltage drop, reverse leakage current, finite switching speeds, and temperature sensitivity, impacting circuit design and performance.

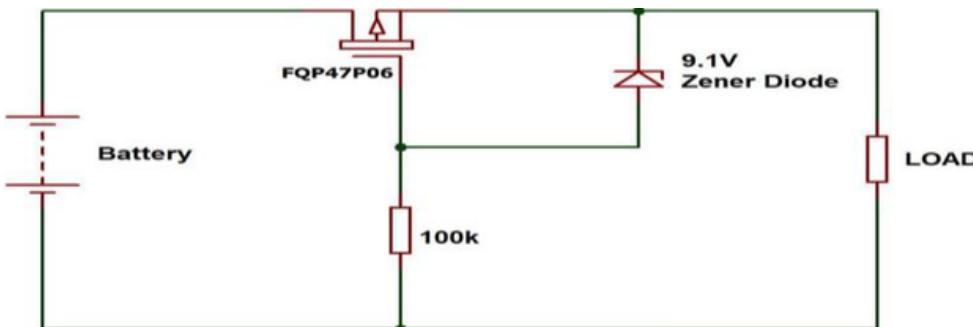
Voltage-Current (VI) Characteristics



DIODES APPLICATIONS

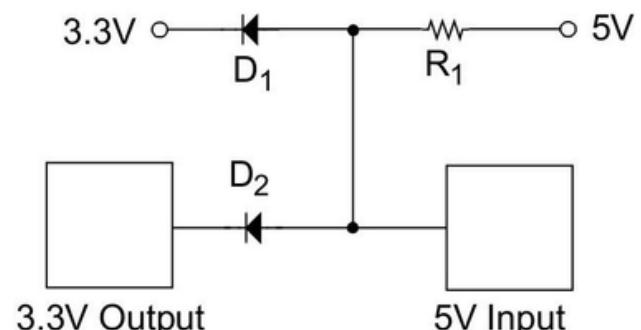
Polarity Protection

- Protects circuits from reversed connections.
- **Implementation:** P-channel MOSFET + Zener combination.
- Benefit: Low forward drop ($\sim 0.3V$) ensures minimal power loss.
- Commonly used in battery-powered devices.



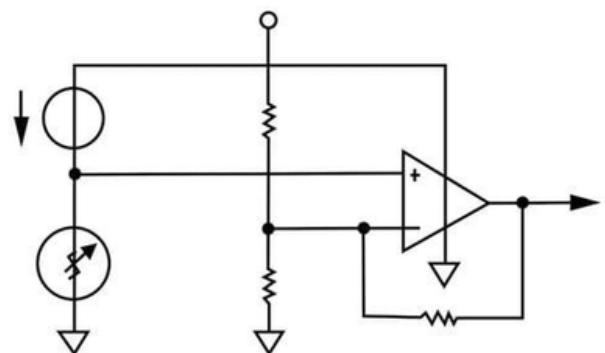
Level Shifting

- Interfaces 5V logic with 3.3V systems.
- **Implementation Methods:**
 - Voltage Divider
 - Diode Clamp
 - Resistors
- **Applications:** MCU communication, mixed-voltage logic systems.



Temperature Sensing

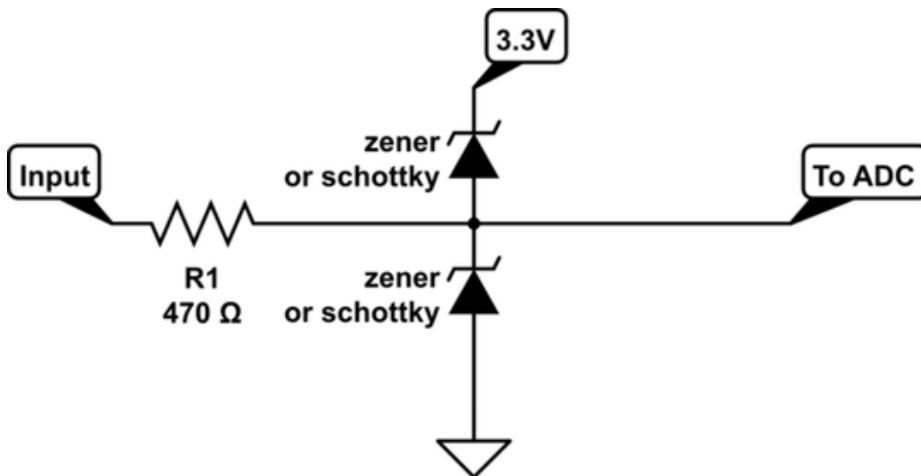
- Diode forward voltage has a temperature coefficient of $-2mV/^\circ C$.
- **Key Characteristics:**
 - Linear response ($-40^\circ C$ to $+125^\circ C$).
 - Better linearity than thermistors.
 - Accuracy: $\pm 2^\circ C$ with calibration.
- **Implementation:** Constant current drives diode, voltage drop measured as temperature reference.



DIODES APPLICATIONS

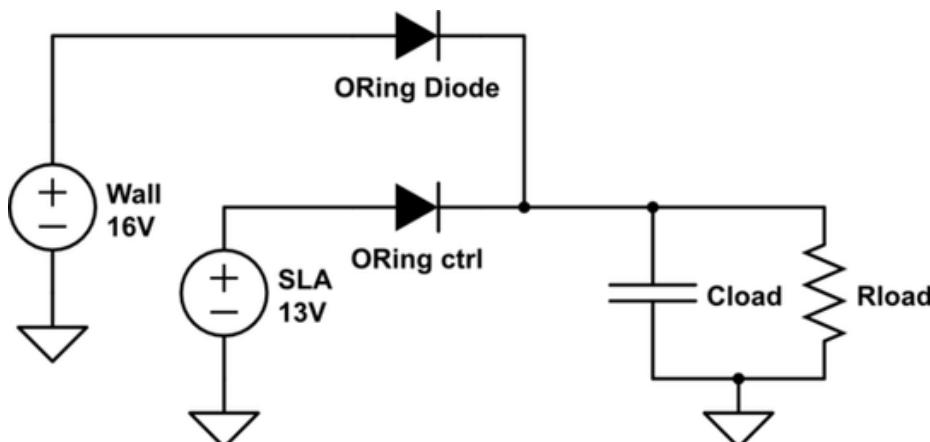
Voltage Clamping

- Limits signal excursions to protect sensitive inputs (e.g., ADCs).
- **Implementation:**
 - Two diodes to VCC and GND + series resistor.
- **Clamp Voltage:**
 - High clamp \approx VCC + 0.7V
 - Low clamp \approx GND - 0.7V



Logic Isolation (OR-ing)

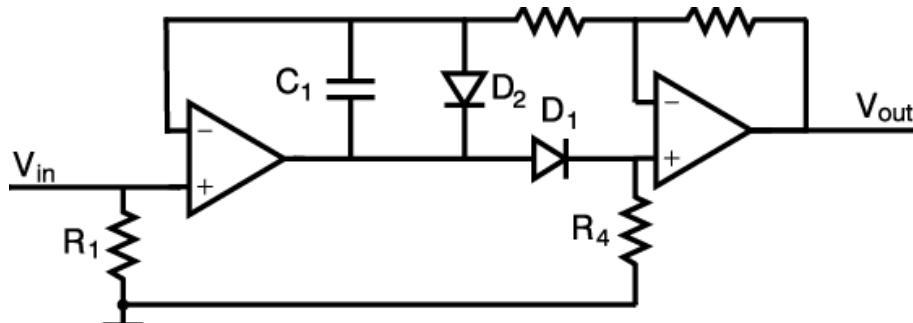
- Combines multiple digital signals without interaction.
- Wired-OR Implementation: Output = HIGH when any input is HIGH.
- Prevents reverse current.
- Widely used in redundant power supply OR-ing circuits.



DIODES APPLICATIONS – IN ANALOG

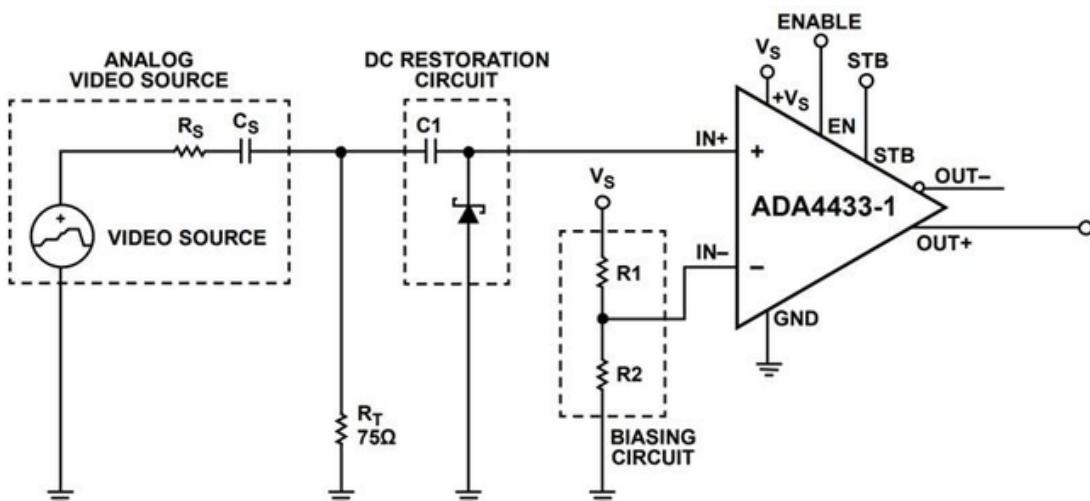
Precision Rectifiers

- Problem: Standard diodes (0.7V drop) cause signal loss at low voltages.
- Active Rectifier Solution: Op-amp compensates forward drop.
- Full-Wave Rectifier: Combines half-wave rectifiers.
- **Design Points:**
 - Matched resistors critical.
 - Op-amp offset impacts accuracy.
 - Bandwidth limited by op-amp.
- **Applications:** Instrumentation, signal recovery.



Analog Clamping

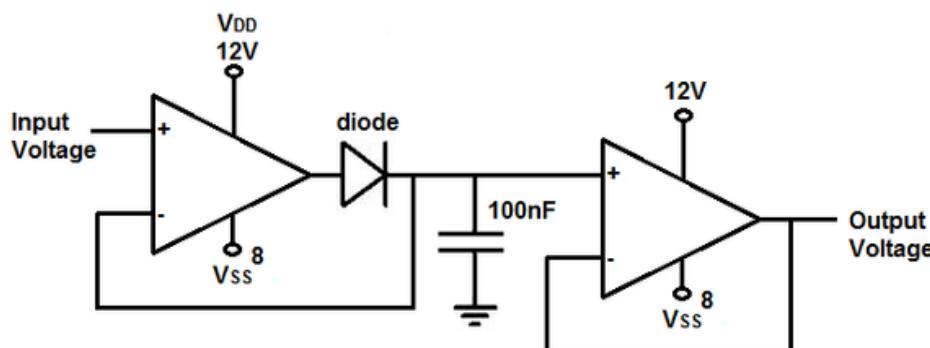
- **DC Restoration Circuits:** Restore DC in AC-coupled signals.
 - **Simple Diode Clamp:** Capacitor blocks DC, diode clamps peaks.
 - **Precision Clamp:** Uses op-amp rectifier for accuracy.
- **Voltage Limiting Circuits:** Prevent analog over-voltage damage.
- **Example:** Video signal DC restoration.



DIODES APPLICATIONS – IN ANALOG

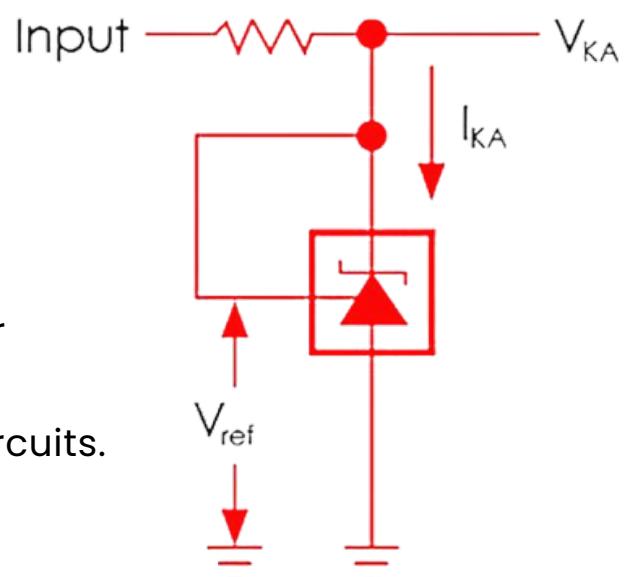
Peak Detection

- Captures signal peaks without loading input.
- **Precision Peak Detector:**
 - No input loading
 - Accurate peak storage
 - Low output impedance
 - Reset capability
- **Applications:** RF detection, envelope detectors, instrumentation.



Voltage References

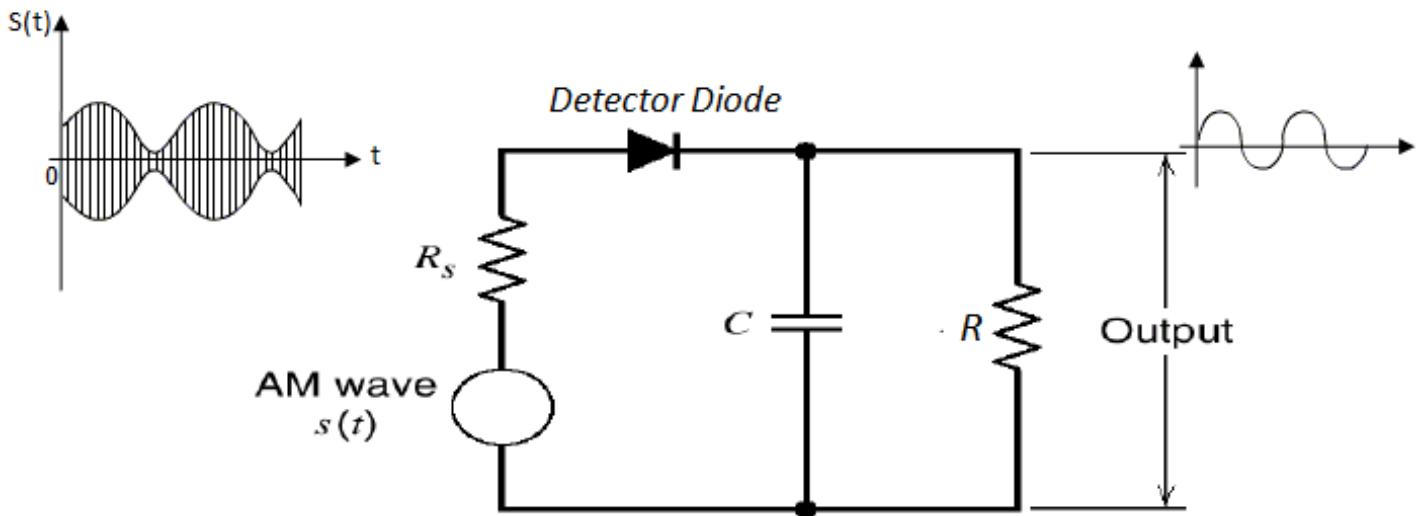
- **Diode-Based Voltage References:** Exploit diode temperature coefficient.
- **Bandgap Reference Principle:**
 - Forward diode drop: $-2\text{mV}/^\circ\text{C}$
 - Resistor drop: $+3.3\text{mV}/^\circ\text{C} \times V$
- **Precision Considerations:**
 - Accuracy: $\pm 0.1\%$
 - Drift: $< 10\text{ppm}/^\circ\text{C}$
 - Long-term stability: $< 100\text{ppm/year}$
 - Noise: $< 10\mu\text{V RMS}$
- Widely used in ADC/DAC reference circuits.



DIODES APPLICATIONS – IN ANALOG

Analog Signal Processing

- **Amplitude Demodulation (AM):** Uses diode non-linearity for demodulation.
- **Balanced Modulator:** Suppresses carrier, outputs sidebands.
- **Applications:**
 - DSB-SC generation
 - Frequency translation
 - Phase-sensitive detection
 - RF mixing circuits



Diodes extend far beyond simple rectification. They:

- Protect circuits (polarity protection, voltage clamping, TVS).
- Enable communication (logic level shifting, isolation).
- Process signals (rectifiers, peak detectors, AM demodulators).
- Provide references (voltage regulators, bandgap references).
- Aid in sensing (temperature detection).

This makes diodes indispensable in modern electronics, from power supplies and analog design to RF systems and digital interfaces.

TYPES OF DIODES & KEY FEATURES

Silicon PN Junction Diode

General-purpose rectification in power supplies.

Key Features:

- Forward voltage drop: ~0.7V (silicon)
- Handles moderate current and voltage
- Slow reverse recovery time (not suitable for high-speed switching)
- Inexpensive and widely available



Schottky Diode

High-speed switching, low voltage applications (e.g., SMPS, logic level protection)

Key Features:

- Low forward voltage drop: 0.15V – 0.45V
- Very fast switching (no minority carrier storage)
- High reverse leakage current
- Low breakdown voltage (<200V)



Zener Diode

Voltage regulation, clamping, reference circuits

Key Features:

- Operates in reverse breakdown region
- Available in standard voltage ratings (e.g., 5.1V, 12V, 24V)
- Knee current and power rating are critical for design
- Common in voltage references and overvoltage protection

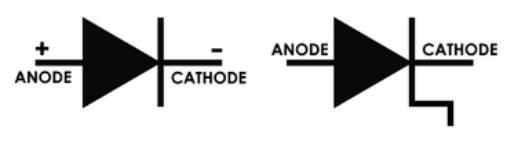


Fast Recovery Diode

Switching power supplies, inverters, SMPS freewheeling paths

Key Features:

- Reverse recovery time: <500ns
- Optimized for reduced switching losses
- Available in moderate voltage/current ratings
- Better performance than standard silicon diodes in high-frequency applications



Fast Recovery Diode Step Recovery Diode

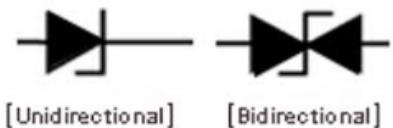
TYPES OF DIODES & KEY FEATURES

TVS Diode

ESD and surge protection for data lines, power inputs

Key Features:

- Very fast clamping (<1ns response)
- Handles peak pulse power (400W to 30kW+)
- Available in low-capacitance versions for signal integrity
- Reusable (non-latching unless damaged)



LED

Indication, lighting, display, and optoelectronic systems

Key Features:

- Emits light when forward-biased
- Forward voltage: 1.6V–3.3V depending on color
- Highly efficient and long life
- Sensitive to overcurrent and reverse voltage



Photodiode

Light detection in sensors, optical receivers

Key Features:

- Generates current proportional to incident light
- Operates in photovoltaic or photoconductive mode
- Fast response time in reverse bias
- Low noise and high sensitivity



Varactor (Varicap) Diode

Voltage-controlled capacitance in RF tuning circuits

Key Features:

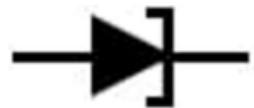
- Acts as a variable capacitor in reverse bias
- Capacitance varies inversely with reverse voltage
- Common in voltage-controlled oscillators (VCOs), PLLs
- Very small package and low power



TYPES OF DIODES & KEY FEATURES

Tunnel Diode

High-frequency oscillators, amplifiers

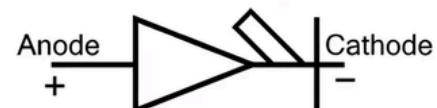


Key Features:

- Negative resistance region due to quantum tunneling
- Operates at microwave frequencies
- Very fast response time
- Limited to niche RF applications

PIN Diode

RF switch, attenuators, photodetectors

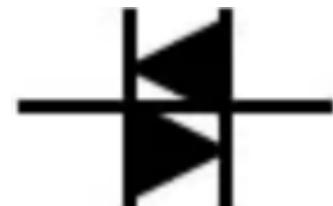


Key Features:

- Intrinsic layer between P and N increases carrier storage
- High isolation and low distortion at RF frequencies
- Resistance varies with forward current
- Ideal for RF and microwave applications

Diac (Diode for Alternating Current)

Triggering triacs in AC circuits (e.g., light dimmers)



Key Features:

- Bidirectional conduction after breakdown threshold
- Symmetrical behavior in both polarities
- Commonly used with triacs in power control circuits

Triac

AC power switching (fan, lamp dimmers, motor control)



Key Features:

- Bidirectional current flow
- Triggered by gate pulse
- Acts like a latch once turned on
- Efficient solid-state switch for AC circuits

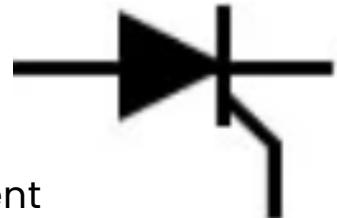
TYPES OF DIODES & KEY FEATURES

Silicon-Controlled Rectifier (SCR)

Controlled rectifiers, power control, crowbar circuits

Key Features:

- Acts like a diode with a gate control
- Conducts when triggered and stays on until current drops
- Used in high-voltage/current applications



SILICON DIODES

Physics & Characteristics

Silicon PN junction diodes are the workhorses of power electronics, engineered to handle significant voltage and current stress. Unlike signal diodes, these devices are specifically optimized for power conversion, rectification, and protection in both AC and DC systems.

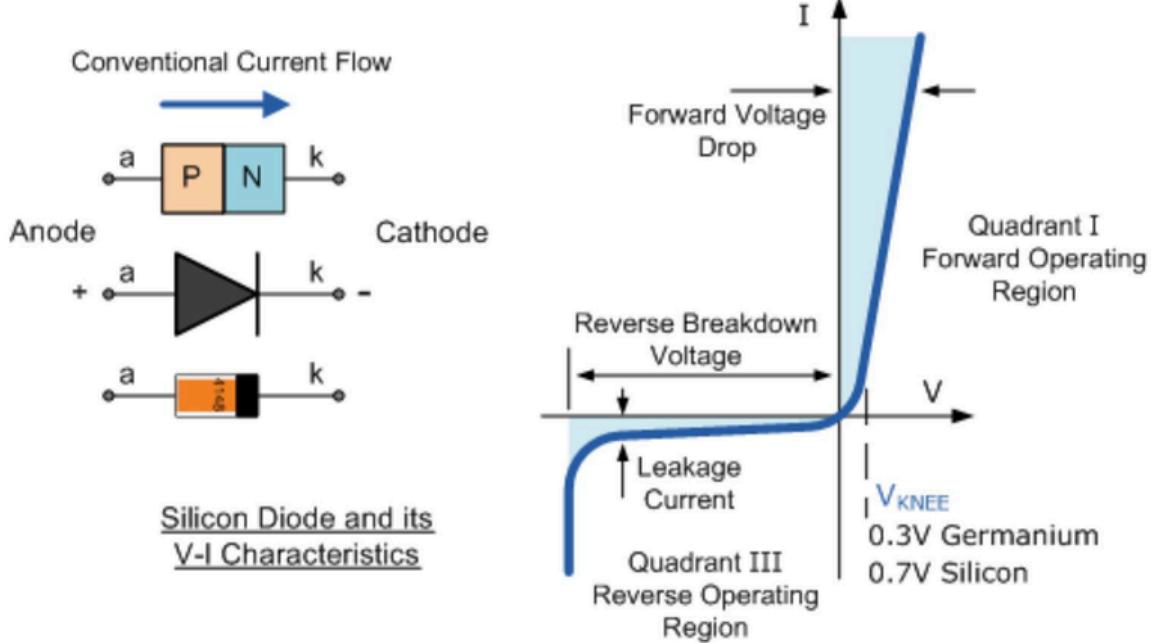
Fundamental Physics:

- Formed by joining P-type and N-type silicon to create a depletion region at the junction.
- In forward bias, the barrier potential is overcome (~0.7V), allowing current to flow.
- In reverse bias, the depletion zone widens, blocking current until breakdown voltage is reached.
- The V–I characteristic includes two major regions:
 - Forward operating region (Quadrant I)
 - Reverse blocking and breakdown region (Quadrant III)

Key Performance Benefits:

Feature	Benefit
High Current Handling	Ranges from 1A up to 1000A continuous (industrial-grade)
High Voltage Tolerance	Withstands reverse voltages up to 1000V+ PIV
Rugged Construction	Endures surge currents and thermal stress without degradation
Cost-Effective	Mass-produced for cost-sensitive power designs
Predictable Behavior	Well-characterized failure modes and linear performance curves
Thermal Stability	Consistent electrical behavior across a wide temperature range

SILICON DIODES



- **Forward Bias Region (Quadrant I):** Current rises sharply once $V_F > \sim 0.7V$ (for silicon)
- **Reverse Bias Region (Quadrant III):** Only leakage current flows until breakdown voltage is reached
- **Knee Voltage (V_{KNEE}):** $\sim 0.7V$ for silicon, $\sim 0.3V$ for germanium

Full-Wave Bridge Rectifier

The full-wave bridge rectifier is a widely used configuration that eliminates the need for a center-tapped transformer while still providing full-wave rectification. It uses four diodes arranged in a bridge, allowing both halves of the AC waveform to contribute to the DC output.

Key Advantages

Feature	Benefit
Better Transformer Utilization	Up to 81.2% – more efficient energy usage
Lower Ripple	Ripple factor reduced to 48.2% compared to 121% in half-wave
No Center-Tap Required	Standard transformer is sufficient, simplifying design
Reduced PIV Stress	Each diode sees V_{PEAK} instead of $2 \times V_{PEAK}$

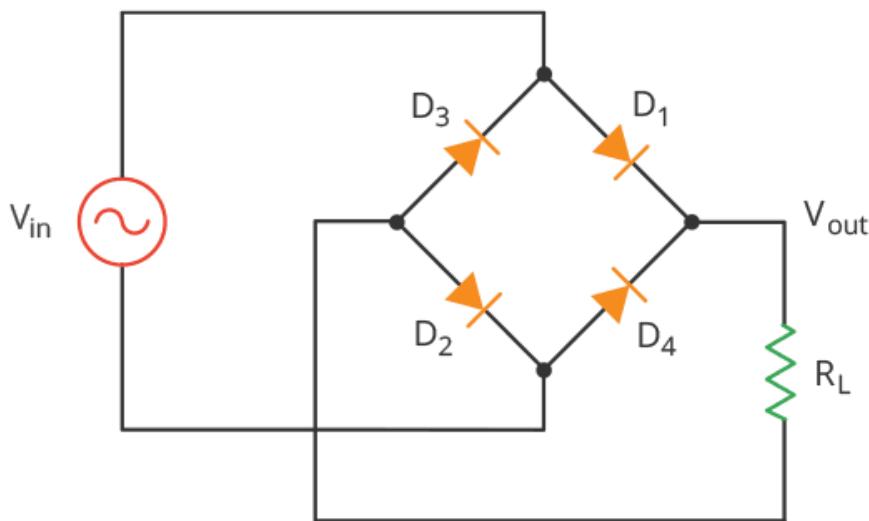
SILICON DIODES

Limitations

Trade-Off	Impact
Higher Forward Voltage	Two diode drops in series → more power loss
More Components	Four diodes vs. two (in center-tap or half-wave designs)
Lower Efficiency	Slightly reduced due to additional diode in conduction path

Performance Comparison

Parameter	Half-Wave	Full-Wave (Center-Tap)
Transformer Utilization	2.870%	5.740%
Ripple Factor	121%	4.820%
Peak Inverse Voltage (PIV)	VPEAK	2×VPEAK
Diode Conduction Current	ILOAD	0.5×ILOAD



- Input: AC voltage (V_{in})
- Diode Path (Positive Half): D_1 and D_2 conduct
- Diode Path (Negative Half): D_3 and D_4 conduct
- Output: Full-wave pulsating DC at V_{out} across load R_L

This design ensures that both halves of the AC waveform contribute to the output, increasing efficiency and reducing transformer core size.

SILICON DIODES

Reverse Recovery in Switching Circuits

Silicon diodes store charge during forward conduction. In switching applications (like SMPS), this stored charge must be removed when the diode suddenly switches to reverse bias – leading to reverse recovery, which directly affects efficiency, EMI, and switching losses.

Reverse Recovery Process (Tr_r Breakdown)

- **Forward Conduction:** Diode conducts and stores minority carriers across the junction.
- **Reverse Bias Applied:** Switch changes polarity – diode is now reverse-biased.
- **Reverse Current Flow:** Stored charge exits → diode briefly conducts in reverse.
- **Sharp Cutoff:** Current abruptly stops → high di/dt , causing EMI.
- **Voltage Overshoot:** Rapid current change across circuit inductance creates high-frequency spikes.

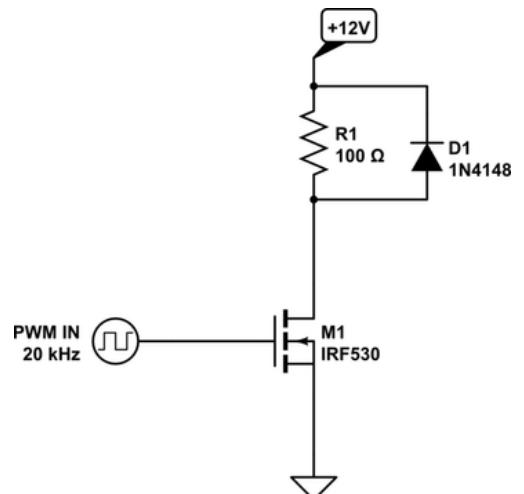
Impact on SMPS Performance (50kHz Buck Converter)

Diode Type	Switching Loss	EMI Level
1N5408 (Standard)	HIGH	SEVERE
UF5408 (Fast)	MEDIUM	MODERATE
SB5100 (Schottky)	MINIMAL	LOW

- **Standard Diodes** (like 1N5408) exhibit long Tr_r, leading to heat, EMI, and ringing.
- **Fast Recovery Diodes** reduce Tr_r via optimized carrier lifetime.
- **Schottky Diodes** have negligible Tr_r due to majority carrier conduction.

SILICON DIODES

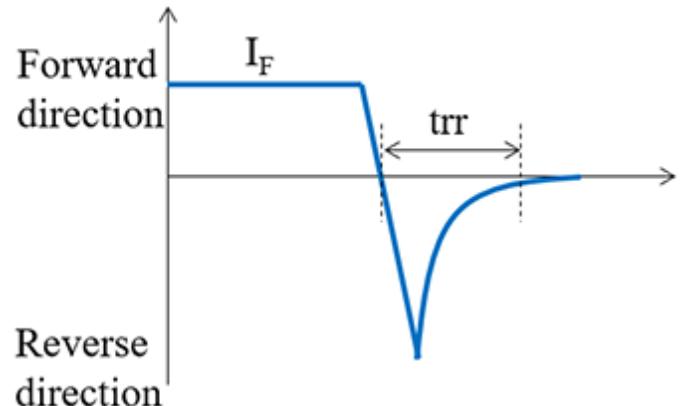
- A 1N4148 used in a switching test setup with a MOSFET (IRF530) driven by PWM.
- This demonstrates real-world reverse recovery behavior and overshoot.



Fast Recovery Rectifiers

Engineered silicon diodes with shortened carrier lifetime to minimize Trr.

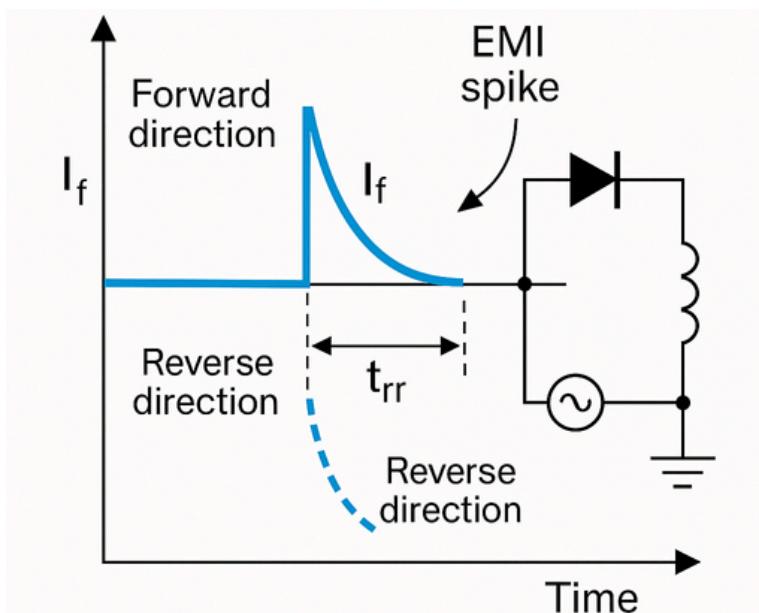
Part	Rated	Voltage Rating
UF4007	1A	1000V
UF5408	3A	1000V
MUR1560	15A	600V
RHRP1512	15A	1200V



The waveform graph shows:

- **Positive current (If)** during forward conduction
- **Reverse recovery spike** due to stored charges
- **Trr (reverse recovery time)** is the duration until current fully ceases

EMI spike diagram



SILICON DIODES

Selection Criteria

Selection of the proper diode type is crucial for circuit efficiency, reliability, and cost-effectiveness. Criteria vary based on whether you're designing a power supply, signal processing chain, or operating in a harsh environment.

A. Power Rectifier Diode Selection

Used in power conversion circuits (e.g., AC-DC rectification, SMPS, battery charging).

Parameter	Design Guideline
Average Forward Current	Rated $\geq 1.5 \times$ expected current
Peak Repetitive Current	Rated $\geq 5 \times$ nominal current for inrush or fault tolerance
PIV (Peak Inverse Voltage)	Rated $\geq 2 \times$ peak reverse voltage in the circuit
Forward Voltage Drop (VF)	Choose lower VF for higher efficiency, especially in low-voltage systems
Thermal Resistance	Ensure adequate heat dissipation to avoid junction overheating
Package	Select based on current handling, PCB space, and heat sink compatibility

B. Signal Rectifier Diode Selection

Used for logic-level signals, detectors, and sensing circuits.

Parameter	Design Consideration
Forward Voltage	Must be low and predictable for accurate threshold behavior
Reverse Leakage	Critical in high-impedance or precision analog circuits
Capacitance (C_J)	Impacts frequency response, especially in RF or fast digital applications
Package Size	Miniaturization required for portable and embedded systems
Cost	Choose trade-off between performance and budget

SILICON DIODES

C. Environmental Criteria (for rugged and high-reliability designs)

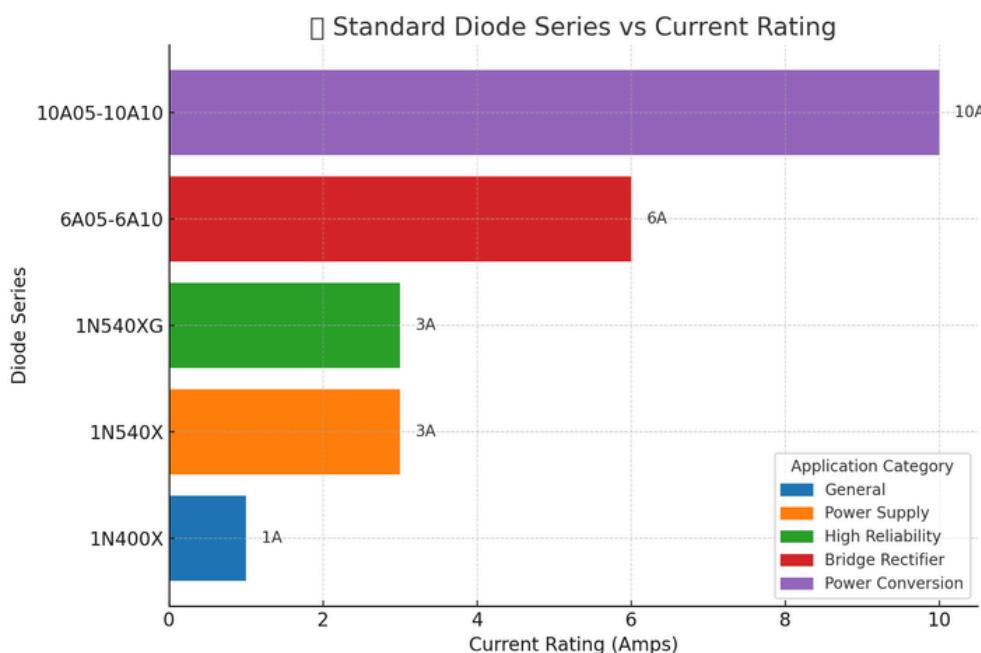
Factor	Guidance
Temperature Range	Choose diodes rated for industrial temp range: -55°C to +175°C
Humidity	Use glass-passivated diodes in moisture-prone environments
Vibration	Through-hole packages offer better mechanical retention than SMD in high-vibration setups
Radiation	Space and aerospace circuits require radiation-hardened diode screening

Standard Silicon Rectifier Series Comparison

Series	Current	PIV Range	Package	Typical Application
1N400X	1A	50V-1000V	DO-41	General Purpose
1N540X	3A	50V-1000V	DO-201	Power Supplies
1N540XG	3A	50V-1000V	DO-15	High Reliability
6A05-6A10	6A	50V-1000V	PR600	Bridge Rectifier Blocks
10A05-10A10	10A	50V-1000V	TO-220	Power Conversion Modules

Design Tip

When in doubt, **check thermal headroom and derating margins first**, then evaluate switching losses if used in SMPS or high-speed applications.



SILICON DIODES

Common Parameters

Electrical & Thermal Ratings Every Engineer Should Know

This section outlines the most important parameters for evaluating diode behavior under real-world operating conditions.

1. Forward Voltage Drop (VF) vs Current

As forward current increases, so does power loss due to VF.

VF also varies with temperature — dropping slightly at higher junction temperatures.

Current	VF @ 25°C	VF @ 100°C	Power Loss (VF × I)
1A	0.7V	0.6V	0.6W – 0.7W
3A	0.9V	0.8V	2.4W – 2.7W
10A	1.1V	1.0V	10W – 11W

Design Tip: In high-current designs, diode power loss becomes a key contributor to heat. Choose low-VF diodes (e.g., Schottky) to improve efficiency.

2. Package Thermal Characteristics

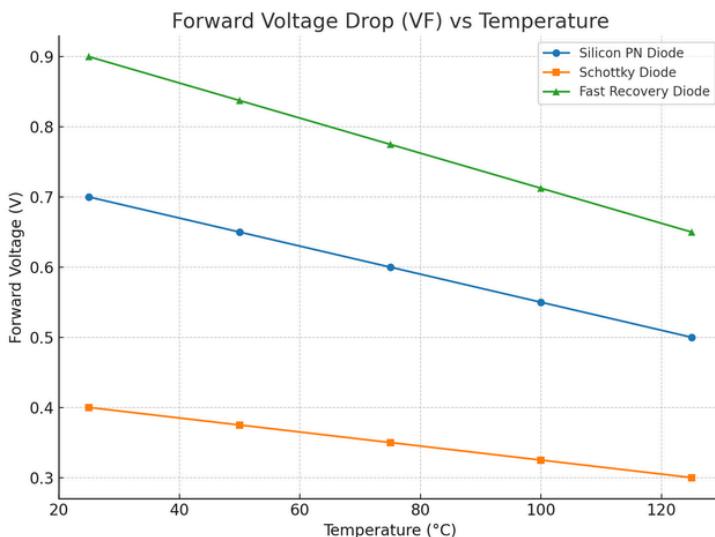
Package selection impacts heat dissipation, especially in continuous conduction applications.

Use this table to guide heat sinking and PCB layout:

Package	θ _{JA} (°C/W)	θ _{JC} (°C/W)	Typical Power Rating
DO-41	100	30	~1W
DO-15	25	8	~5W
DO-201	45	12	~3W
TO-220	5	3	~25W (with heatsink)
TO-3P	40	15	~40W (with heatsink)

Design Tip: Always derate power handling by 20–30% to account for airflow and ambient rise.

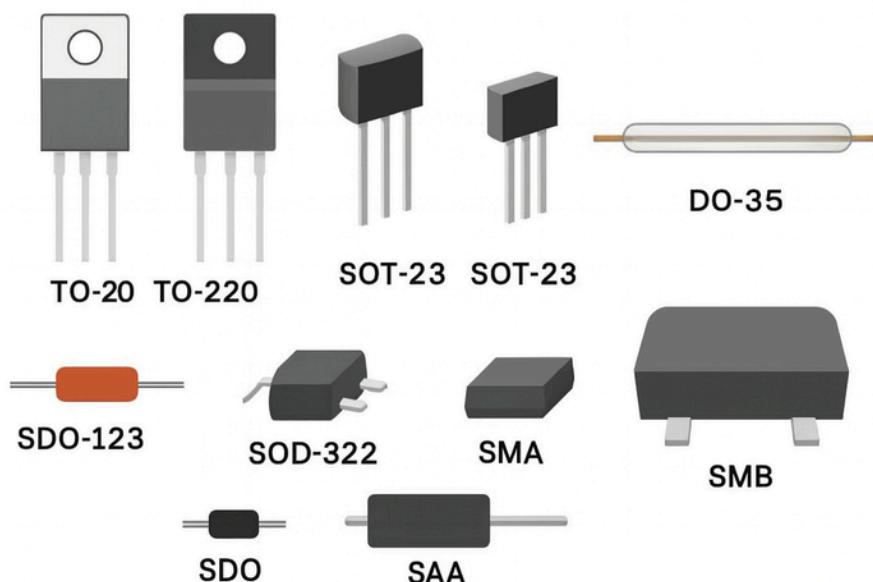
SILICON DIODES



3. Additional Key Parameters to Know

This section outlines the most important parameters for evaluating diode behavior under real-world operating conditions.

Parameter	Importance
Reverse Leakage Current (IR)	Affects performance in low-current and high-impedance circuits
Reverse Recovery Time (Tr _r)	Impacts efficiency and EMI in high-speed switching circuits (e.g., SMPS)
Capacitance (C _j)	Relevant in RF or high-speed signal circuits
Surge Current (IFSM)	Critical for startup and inrush protection
Storage Temperature (T _{STG})	Defines safe limits for transport and non-operating conditions



SCHOTTKY DIODES

Introduction

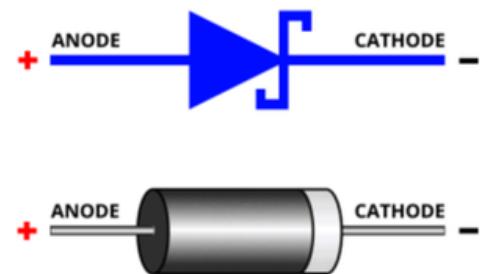
Schottky diodes are fast-switching, low forward-voltage-drop devices that use a metal–semiconductor junction (typically metal and N-type silicon). Unlike PN-junction diodes, they conduct via majority carriers, eliminating charge storage and enabling minimal reverse recovery time –ideal for power and RF applications.

Why Schottky Diodes?

- Low forward voltage drop (typically 0.15V to 0.45V)
- Zero or negligible reverse recovery time ($T_{rr} \sim 0$ ns)
- High-speed switching capability
- Improved efficiency in power converters and digital logic systems

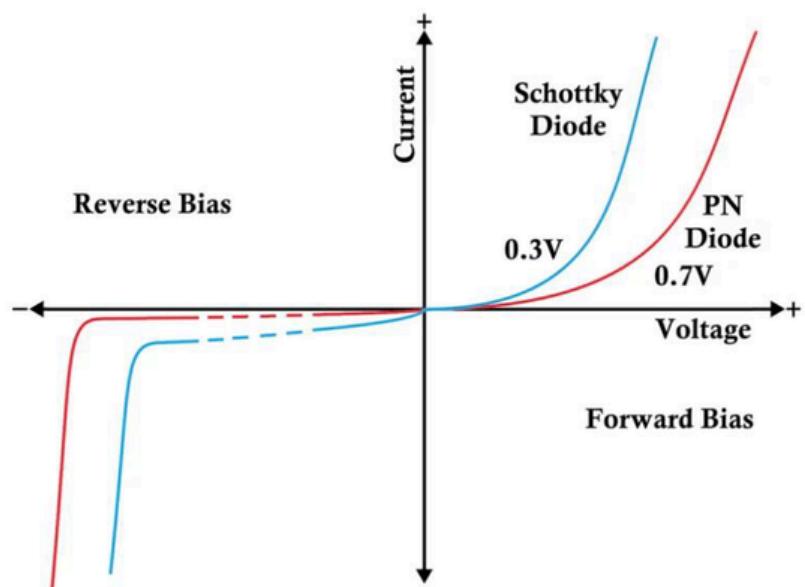
Where They're Used?

- Switched-mode power supplies (SMPS)
- High-frequency DC-DC converters
- OR-ing power supply circuits
- ESD protection and clamping
- Logic level shifting and RF detection



Key Effects:

- No minority carrier injection
- Minimal capacitance and storage time
- Linear and predictable I-V characteristics



Trade off:

- Higher Leakage: 10x to 1000x more than silicon
- Lower Breakdown: <200V maximum
- Cost: 2x to 5x more expensive
- Temperature Sensitive Leakage: Doubles every 10°C

SCHOTTKY DIODES

Key Parameters and Design Considerations

Parameter	Typical Value/Range	Design Impact
Forward Voltage (Vf)	0.15V – 0.45V	Lower conduction losses
Reverse Leakage Current	nA to mA (temperature-sensitive)	Affects standby/power-off leakage
Max Reverse Voltage (VR)	20V – 200V (typical)	Limits use in high-voltage systems
Reverse Recovery Time	~0 ns	Ideal for fast switching
Junction Capacitance	2 pF – 100 pF	Influences behavior in RF applications
Thermal Resistance (Rth)	Depends on package	Critical for continuous power design

Thermal Note: Leakage increases exponentially with temperature. Ensure heat-sinking or derating for high ambient conditions.

Applications and Benefits

Typical Uses:

- Output rectifiers in buck/boost converters
- Flyback freewheeling paths
- Power rail OR-ing for redundancy
- Reverse polarity protection
- Clamping in USB, HDMI, and ESD-sensitive lines

Benefits Over Silicon Diodes:

- Reduced power dissipation due to lower Vf
- Higher switching efficiency in high-frequency designs
- No EMI-causing recovery spikes
- Compact form factor available in SMD (SMA, SOD-123, etc.)

SCHOTTKY DIODES

Package Options and Thermal Design

Package	Max Current	Thermal Resistance	Applications
DO-41	~1A	High	General purpose
SMA/SMAF	~1–3A	Medium	PCB power sections
TO-220	~10–15A	Low (with heatsink)	Power converters
DPAK	~3–6A	Low-Med	Automotive, telecom

Recommendation: Always consider a copper pour or thermal vias under SMD packages to reduce thermal rise.

Common Part Numbers

Part Number	VR (V)	IF (A)	Package	Notes
1N5819	40	1	DO-41	Popular for low-V circuits
SS14	40	1	SMA	Compact, general-purpose
SS34	40	3	SMB	Widely used in DC-DC converters
MBR2045CT	45	20	TO-220	High-current dual diode
SR360	60	3	TO-220	Freewheeling in power drives

Limitations and Failure Modes

- Leakage Current Rise:** Schottky diodes are more sensitive to thermal runaway.
- Voltage Limitations:** Typically not used beyond 200V reverse due to breakdown.
- Failure Case:** Short due to over-voltage, or thermal stress leading to leakage rise.

SCHOTTKY DIODES

Design Mitigations:

- Derate current by 20–30% for reliability
- Ensure reverse voltage headroom >2x expected reverse peak
- Monitor junction temp ($T_j < 125^\circ\text{C}$ preferred)

Testing and Verification

- **Forward Voltage Test (DMM):** Expect 0.2–0.4V drop
- **Reverse Leakage Test:** Use high-impedance meter or source measure unit
- **Curve Tracer:** Shows sharp forward conduction and early breakdown
- **T_{rr} Verification:** Via oscilloscope in pulse circuit (should be ~0 ns)

Schottky in Switch-Mode Power

Traditional silicon diodes are unsuitable for modern high-frequency switch-mode power supplies due to excessive reverse recovery time and associated losses.

✗ Reverse Recovery Problem in Silicon Diodes:

When switching polarity, silicon diodes exhibit stored charge effects, causing:

1. Stored charge must be cleared before blocking reverse voltage
2. Brief reverse conduction, leading to power loss
3. Sharp current transitions, generating EMI
4. Increased power loss with higher frequencies

These limitations result in inefficiency and noise in fast-switching converters.

SCHOTTKY DIODES

Schottky Diode in Buck Converters

Schottky Diode Advantage in Buck Converters

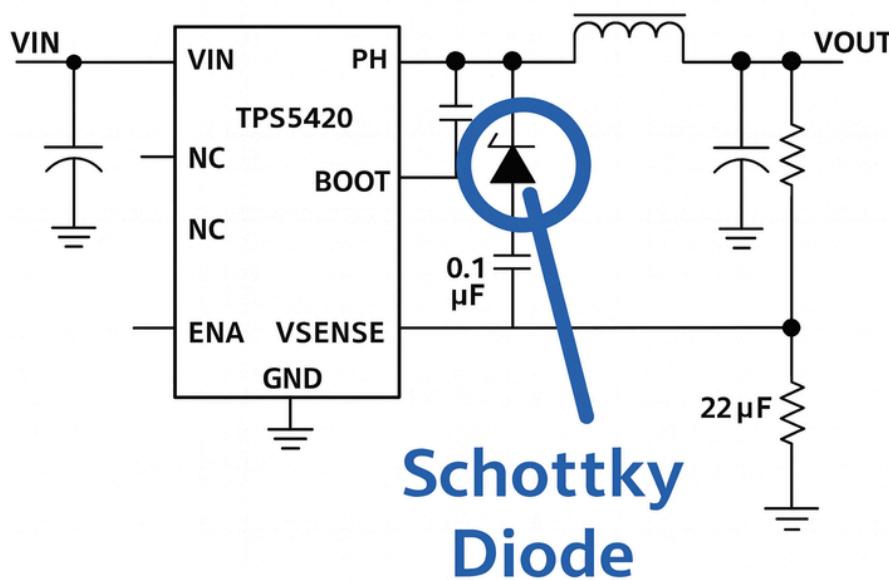
In a buck converter, the freewheeling diode conducts when the main switch (MOSFET) turns off. Schottky diodes are preferred due to their:

- Zero reverse recovery time
- Low forward voltage drop
- Minimal EMI generation

Performance Comparison:

Diode Type	VF @ 5A	Recovery	Loss @ 100kHz
1N5408 (SI)	1.0V	30ns	High + EMI
MBRF2045CT	0.65V	0ns	~35% Less Loss
SB5100	0.55V	0ns	~45% Less Loss

Insight: Even a 0.3V drop reduction at 5A = 1.5W saved → significant for thermals and efficiency!



In buck regulators like TPS5420, a Schottky diode is placed across the inductor to provide a low-loss current path when the high-side switch turns off.

SCHOTTKY DIODES

Logic Fast Switching - Level Shifter

Schottky Diodes in Level Shifting Applications:

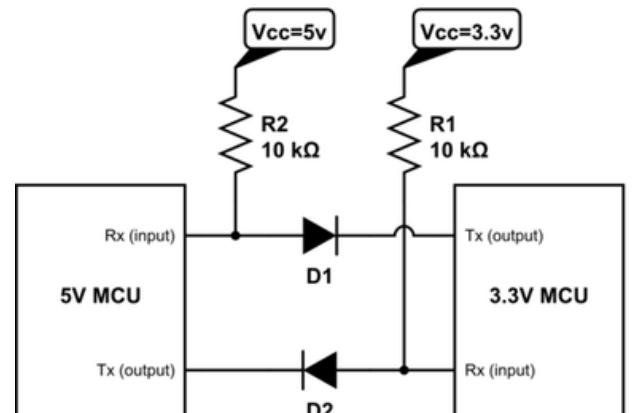
Schottky diodes are highly effective in mixed-voltage digital systems where level translation is required – particularly between 5V and 3.3V logic families. Their fast switching, low forward voltage, and minimal charge storage make them ideal for fast, low-power, bidirectional level shifting.

5V \leftrightarrow 3.3V Bidirectional Level Shifter:

Using Schottky diodes (D1 and D2) along with pull-up resistors, this simple yet effective level shifter allows communication between two different logic families:

Advantages:

- Fast propagation delay (in nanoseconds)
- Low power consumption
- Bidirectional signal flow
- No active components required (e.g., MOSFETs or buffers)
- Works well for UART, SPI, and GPIO lines



Application Use Case:

5V microcontroller (e.g., ATmega328P) interfacing with 3.3V sensor or SoC (e.g., ESP32, STM32)

Working Principle:

- When the 5V MCU drives a HIGH signal (5V), Schottky diode D1 clamps the voltage to ~3.6V on the 3.3V side ($V_f \sim 0.3V-0.4V$), protecting the 3.3V device.
- When the 3.3V side transmits, the diode D2 allows signal transfer back toward the 5V domain.
- Pull-up resistors ensure default logic HIGH when idle.

SCHOTTKY DIODES

Power OR-ing Circuits

Multiple Power Sources with Schottky Diodes:

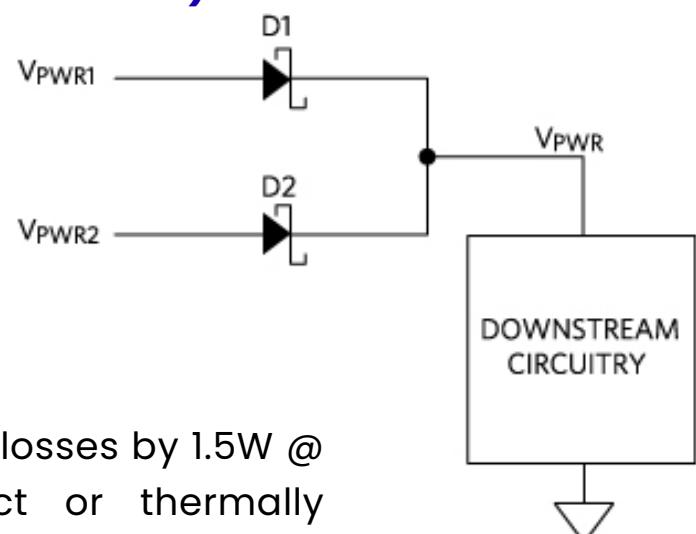
In systems requiring redundant or backup power supplies, power OR-ing diodes are used to prevent backfeeding and to ensure seamless switching between sources. Schottky diodes are preferred due to their lower forward voltage drop, which minimizes power loss and heat.

OR-ing Circuit Function:

- D1 and D2 isolate two voltage sources (V_{PWR1} , V_{PWR2})
- The source with the higher voltage automatically supplies the load
- Prevents reverse current from one supply into another
- Used in server motherboards, battery/adapter switchover, and UPS systems

Silicon vs Schottky Comparison (at 5A load):

Parameter	SIL	SCH
Forward Drop	1.1V	0.8V
Power Loss	5.5W	4.0W
Efficiency	-27% loss	-19% loss
Thermal Impact	HIGH	MODERATE



Even a 0.3V V_f improvement reduces losses by 1.5W @ 5A — a critical gain in compact or thermally constrained systems.

Why Schottky in OR-ing?

- Lower $V_f \rightarrow$ reduced I^2R loss
- No reverse recovery delay \rightarrow cleaner transitions
- Faster switchover time \rightarrow better uptime in backup systems
- Less heat \rightarrow reduced heatsink size or BOM cost

SCHOTTKY DIODES

High-Frequency Rectification

RF Power Detection Using Schottky Diodes

Schottky diodes play a critical role in detecting and rectifying RF signals in communication and sensing systems. Their low forward voltage, fast response, and minimal junction capacitance make them ideal for small-signal and high-frequency applications like RF energy harvesting, power meters, and envelope detection.

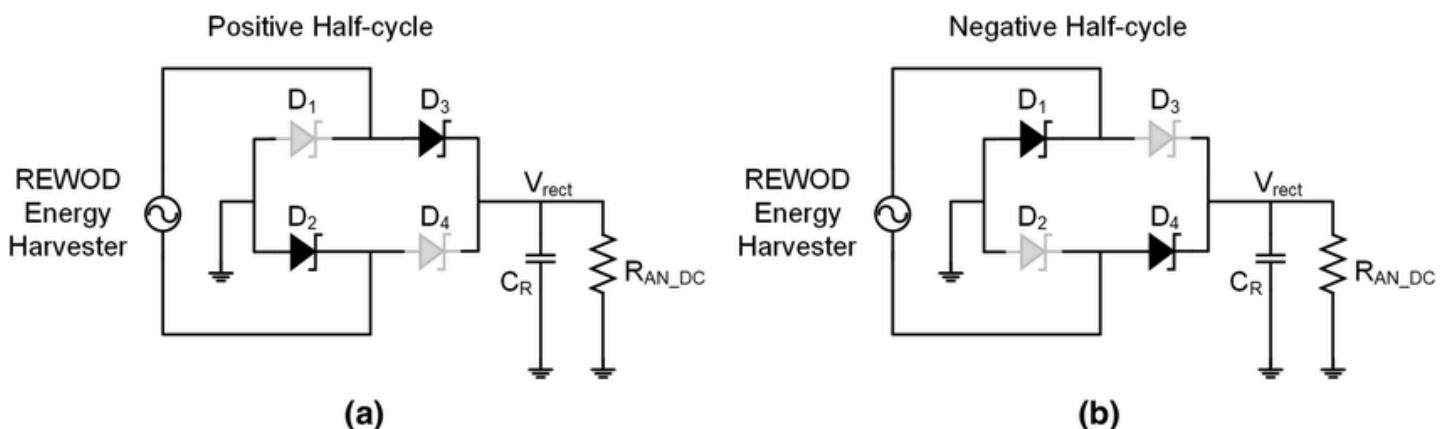
Key Requirements for RF Detection:

- Low forward voltage drop: Enables detection of millivolt-level signals
- High switching speed: Allows tracking of fast RF waveforms
- Low parasitic capacitance: Reduces distortion and improves detection fidelity
- Square-law response: Enables accurate RF power-to-voltage conversion

Application Example: RF Energy Harvester Rectifier

In the diagrams shown:

- D1-D4 form a high-frequency full-wave rectifier topology
- Output voltage (V_{rect}) represents rectified RF energy
- CR smooths the rectified signal, while RANT_DC provides load or measurement path



- (a) During the positive half-cycle: D1 & D2 conduct, charging the capacitor
- (b) During the negative half-cycle: D3 & D4 conduct, maintaining current flow

SCHOTTKY DIODES

Selection Criteria

Choosing the right Schottky diode depends on current rating, application domain (power or signal), and environmental constraints. Below is a categorized guideline to assist in effective part selection.

Power Applications (>1A)

Use these guidelines when selecting Schottky diodes for high-current or power conversion circuits:

- Forward Current Rating: Choose a diode rated at least $1.5 \times$ the max expected load current.
- Reverse Voltage (V_{RRM}): Should be at least $2 \times$ the peak reverse voltage seen in circuit.
- Forward Voltage (V_f): Lower V_f results in better efficiency and lower heat.
- Thermal Resistance (R_{θJA}): Impacts heat dissipation – critical in continuous operation.
- Package Selection: Consider options like TO-220 (with heatsink) or DPAK (SMD with copper pour) based on space and thermal budget.

Signal Applications (<100mA)

For RF, logic, or small-signal detection, these parameters matter most:

1. Speed Requirements: Ensure fast recovery time for high-frequency signals.
2. Leakage Current: Choose low-leakage types for precision or low-power circuits.
3. Forward Voltage: Impacts detection threshold in analog or RF circuits.
4. Package Size: Compact packages like SOT-23, SOD-123 are ideal for dense PCBs.
5. Cost: Balance performance with volume and reliability needs.

Environmental Considerations

When designing for industrial, automotive, or rugged environments, account for:

- Temperature Range: Ensure device can operate from -40°C to +85°C or beyond.
- Humidity: Plastic vs. ceramic packages influence moisture ingress and long-term reliability.
- Vibration: Through-hole offers stronger mechanical hold; SMD requires proper anchoring.

Tip: Always cross-check derating curves, package thermal limits, and manufacturer test conditions for real-world safety margins.

ZENER DIODES

Introduction

Zener diodes are specially designed semiconductor devices that allow current to flow in the reverse direction when the applied voltage reaches a specified breakdown point. This controlled reverse breakdown makes them ideal for voltage regulation, over-voltage protection, and voltage reference circuits.

Unlike standard diodes, Zener diodes operate safely and reliably in the breakdown region without damage, as long as power dissipation limits are observed.

Principle of Operation

A Zener diode behaves like a normal diode under forward bias. Under reverse bias, it blocks current until the applied voltage reaches the Zener breakdown voltage (V_z). Beyond this point, it conducts in reverse, clamping the voltage to a fixed value.

Two breakdown mechanisms:

- 1. Zener Breakdown ($V_z < \sim 5.6V$):** Dominated by quantum tunneling
- 2. Avalanche Breakdown ($V_z > \sim 5.6V$):** Caused by impact ionization

Note: Both mechanisms are safe and stable for Zener diode operation.

Key Parameters and Ratings

Parameter	Description
Zener Voltage (V_z)	Nominal breakdown voltage (1.8V – 200V)
Test Current (I_{zT})	Current at which V_z is specified
Zener Impedance (Z_z)	Dynamic resistance in breakdown region
Max Power (P_{max})	Maximum power the diode can safely dissipate
Reverse Leakage (I_R)	Small current before breakdown
Temperature Coefficient	Voltage shift per °C (important in precision circuits)

ZENER DIODES

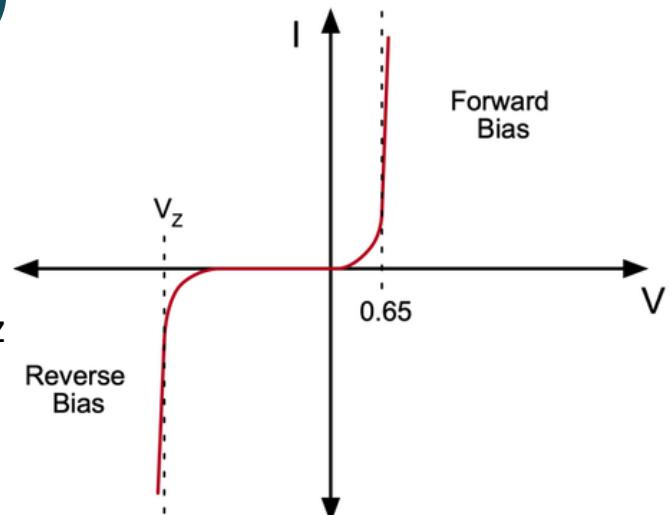
Applications

- **Voltage Regulation:** Keeps voltage stable across load by clamping at V_z
- **Overvoltage Protection:** Protects sensitive ICs from transient voltage spikes
- **Voltage Reference:** Stable V_z makes it suitable for analog reference design
- **Waveform Clipping and Clamping:** Used in signal conditioning circuits to limit peaks
- **Logic Level Shifting:** Provides offset for interfacing mismatched voltage domains

Advantages & Limitations

✓ Advantages

- Simple voltage regulation
- Inexpensive and compact
- Wide range of voltage ratings
- Good temperature stability (low V_z types)



⚠ Limitations

- Limited load current capability
- Requires proper resistor selection
- Not suitable for tight regulation under varying load
- Efficiency decreases with high current draw

Common Part Numbers

Part Number	V_z (V)	Pmax (W)	Package	Notes
1N4728A	33	1	DO-41	General-purpose
1N4733A	51	1	DO-41	Popular for 5V regulation
BZX79C12	12	5	DO-35	Compact signal clamping
MMSZ5231B	51	35	SOD-123	SMD version for compact PCBs

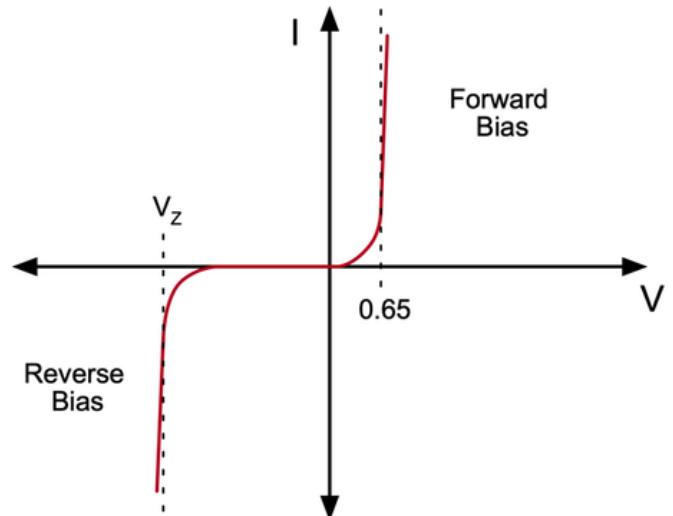
ZENER DIODES

Zener Behavior

Zener diodes don't switch instantly at their rated breakdown voltage – they exhibit a “knee” characteristic, where conduction begins gradually.

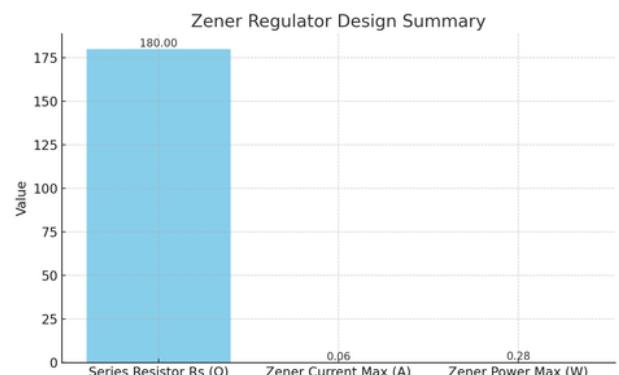
Critical Parameters

- **Knee Current:** Minimum current needed for proper regulation
- **Test Current:** Defined point where V_Z is measured (typically 5–20 mA)
- **Maximum Current:** Limited by power dissipation and thermal specs
- **Voltage Regulation ($\Delta V/\Delta I$):** Voltage change across current variation (also called dynamic resistance)



Zener Regulator Design

- Series Resistance:
$$R_s = \frac{(V_{IN_{max}} - V_Z)}{(I_{L_{max}} + I_{Zmin})}$$
- Power Dissipation:
$$P_Z = V_Z \times I_Z$$
- Worst Case Zener Current:
$$I_{Z_{max}} = \frac{(V_{IN_{max}} - V_Z)}{R_s} - I_{L_{min}}$$



Design Example:

Goal: Generate 5V reference from 12V source

- Load Current: 0 to 50 mA
- Input Voltage Range: 10V to 15V
- Zener Diode: 5.1V, 1W (e.g., 1N4733A)

Tip: Always ensure I_Z stays within the safe operating window, even under worst-case V_{IN} and load conditions.

ZENER DIODES

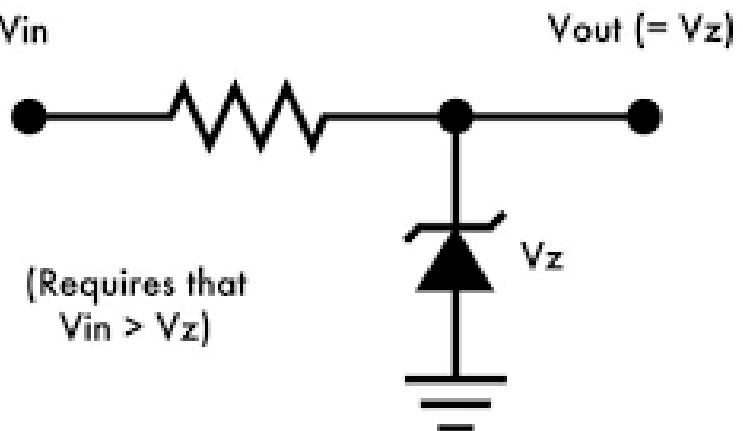
Zener as Voltage Clamps

Overvoltage Protection

Zener diodes excel at clamping excessive voltages before they damage circuits.

Clamp Design Guidelines

- **Zener Voltage (V_z):** Choose 20% above the normal signal maximum.
- **Series Resistance (R_s):** Limits fault current to within Zener rating.
- **Response Time:** Must be faster than the damage threshold of the protected circuit.



Common Zener Faults

1. Insufficient Knee Current

- **Cause:** Zener doesn't regulate properly at light loads.
- **Solution:** Ensure $I_Z > I_{ZK}$ under all conditions.

2. Excessive Power Dissipation

- **Cause:** Zener overheats and fails.
- **Solution:** Calculate worst-case power properly, use adequate heatsinking.

3. Wrong Voltage Selection

- **Cause:** Zener voltage too close to normal operating level.
- **Solution:** Use 10–20% higher margin above normal voltage.

4. Ignoring Dynamic Resistance

- **Cause:** Poor regulation under varying loads.
- **Solution:** Choose Zener with low R_z for precision applications.

5. Temperature Drift Ignorance

- **Cause:** Reference voltage varies too much with temperature.
- **Solution:** Use temperature-compensated Zeners for critical circuits.

FAST DIODES

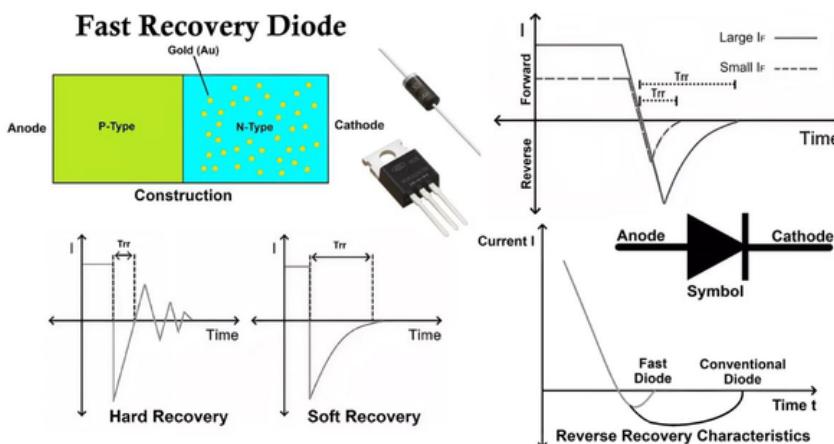
Fast Diodes – Diode Speed Limitations

Stored Charge Problem:

Standard silicon diodes suffer from stored charge in the depletion region during forward conduction. When switching direction, this stored charge must first be removed, creating reverse recovery current.

This leads to

- **Switching loss at high frequencies**
- **Current spikes that stress devices**
- **EMI generation due to abrupt cutoffs**
- **Reduced efficiency in power converters**



Reverse Recovery Process:

- Forward conduction: Carriers injected across junction.
- Reverse bias applied: Stored carriers begin to discharge.
- Reverse current flows: Until stored charge is depleted.
- Blocking begins: Diode can finally block reverse voltage.

Critical Speed Parameters:

Parameter	Symbol	Impact	Typical Range
Reverse Recovery Time	TRR	Switching Loss	1 ns – 10 ms
Forward Recovery Time	TFR	Turn-On Delay	50 ns – 500 ns
Stored Charge	QRR	Current Spike	1 nC – 1 μ C
Softness Factor	S	di/dt at Turn-Off	0.1 – 10

Recovery Types:

- **Hard Recovery:** Abrupt cutoff, generates spikes & EMI.
- **Soft Recovery:** Controlled fall, reduces EMI, improves stability.

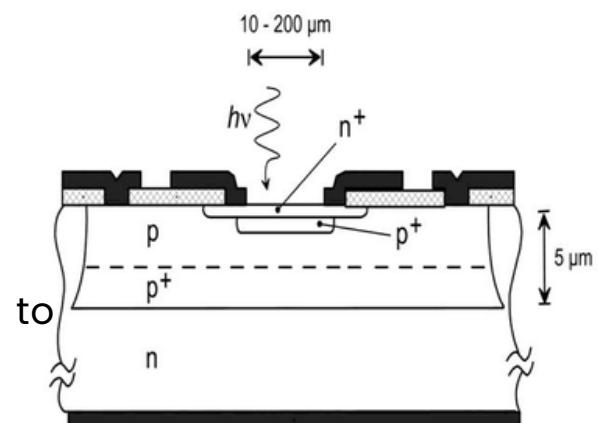
FAST DIODES

Fast Recovery (Epitaxial) Diodes

Fast recovery diodes are built on epitaxial silicon layers with controlled carrier lifetimes. This engineering reduces stored charge and accelerates switching.

Advantages:

- Predictable recovery time
- Soft recovery for low EMI
- Higher reverse voltage ratings
- Moderate cost increase compared to standard diodes



Popular Devices:

Part Number	Voltage	Current	TRR	Application
UF4007	1000V	1A	75 ns	General Purpose
MUR460	600V	4A	35 ns	Switching Supplies
BYV26C	1000V	1A	150 ns	Rectification
RHRP460	600V	4A	15 ns	High Frequency

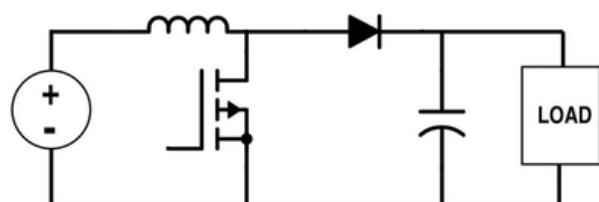
Switching Power Supply Applications

Boost Converter Main Diode

In boost converters, the diode must handle fast repetitive switching at high frequencies.

Design Considerations:

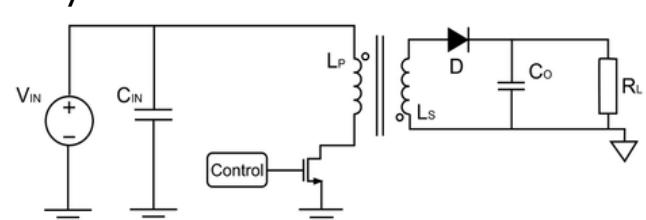
- Voltage rating $\geq 1.5 \times$ maximum input
- Current rating $\geq 1.25 \times$ load current
- TRR $\leq 1/10$ switching period



Boost Converter Main Diode

Transformer isolation requires a secondary rectifier diode with:

- High blocking voltage capability
- Very fast recovery to prevent ringing
- Low forward drop for efficiency
- Avalanche energy handling for transients



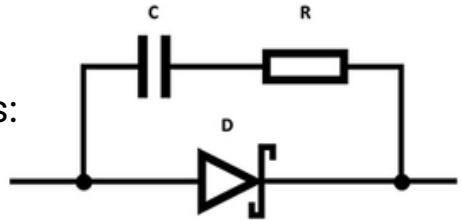
FAST DIODES

Snubber Circuits

Function:

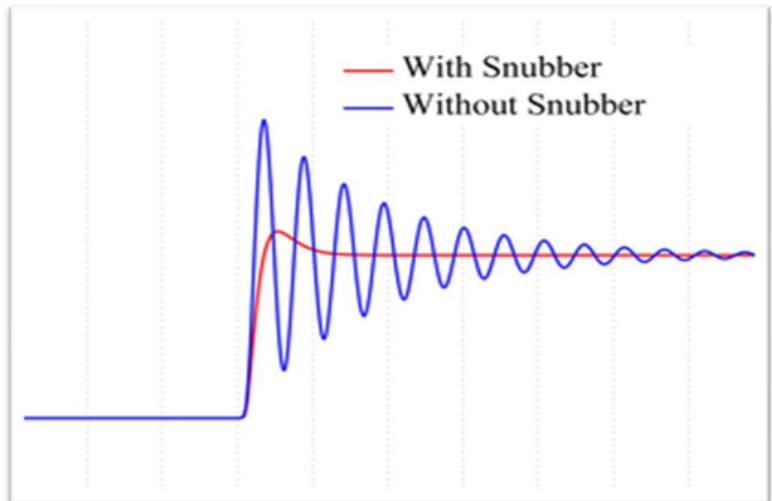
Snubber networks (RC or RCD) across fast diodes:

- Absorb switching transients
- Reduce EMI
- Protect semiconductors from over-voltage stress
- Improve efficiency and stability



Effect on Waveforms:

- **With snubber:** Lower overshoot and damped ringing.
- **Without snubber:** Severe oscillations, risk of device failure.



Practical Design Notes:

- **Forward Voltage (V_f):** Trade-off between conduction loss (lower V_f preferred) and leakage current.
- **Thermal Design:** At high frequency, switching losses dominate – ensure heatsinking or derating.
- **Application Split:**
 - SMPS Boost/Flyback: Ultrafast epitaxial diodes (15–75 ns TRR).
 - Inverters & UPS: Soft recovery diodes preferred (low EMI).
 - Snubber Networks: TRR must be faster than switching edge.
- **Failure Mode:** Thermal runaway from excess switching loss → always derate current & verify TRR.

TVS DIODES

Physics & Advantages

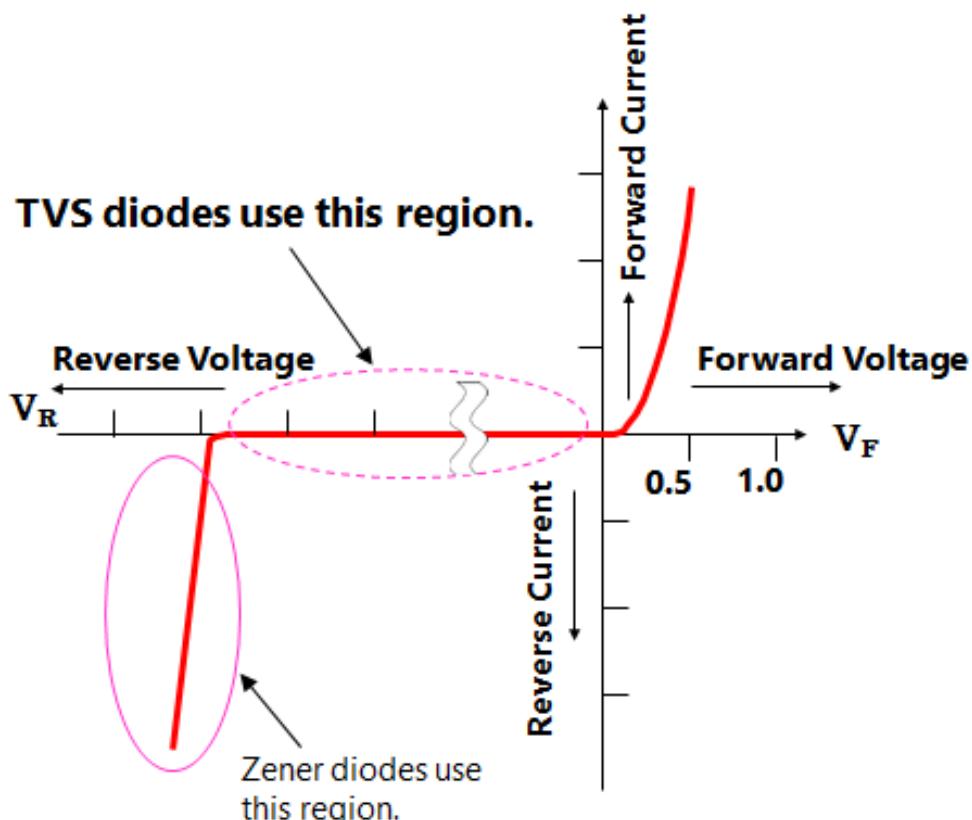
TVS (Transient Voltage Suppression) diodes are specialized avalanche diodes optimized for absorbing high-energy transient pulses. Unlike Zener diodes, they are designed for fast response, sharp clamping, and high surge capability.

Key Benefits:

- **Ultra-Fast Response:** < 1 ns
- **High Peak Power:** 400 W to 30 kW+
- **Sharp Clamping:** Precise overvoltage limiting
- **Low Capacitance:** Minimal signal distortion (ideal for high-speed data lines)
- **Self-Resetting:** Automatic recovery after transient

Trade-offs

- Higher cost than regular diodes
- Higher standby leakage current
- Breakdown voltage varies with temperature (temperature drift)
- Limited continuous power capability (pulse operation only)



TVS DIODES

Reference Tables

Standard TVS Voltage Ratings:

6.8V, 8.2V, 9.1V, 10V, 11V, 12V, 13V, 15V, 16V, 18V, 20V, 22V, 24V, 28V, 30V, 33V

Trade-offs

Package	Power Rating	Size (mm)	Applications
SOD-323	200W	1.3 × 0.8	Mobile devices
SOD-523	230W	1.2 × 0.8	Ultra-portable
SOT-23	300W	2.9 × 1.3	General purpose
SMB	600W	4.3 × 2.6	Power circuits
SMC	1500W	6.1 × 3.6	High power
P600	5000W	9.5 × 6.6	Industrial systems

Common TVS Part Numbers

Part Number	VWM	VC	PPP	Package	Application
SMAJ5.0A	5V	9.2V	400 W	SMA	USB/Logic rails
SMBJ33A	33V	53V	600 W	SMB	Automotive/Industrial
SMCJ58A	58V	95V	1500 W	SMC	Telecom surge
1.5KE200A	200V	344V	1500 W	DO-201	Power line protection
P6KE400A	400V	650V	600 W	DO-15	General AC protection

Communication Line Protection

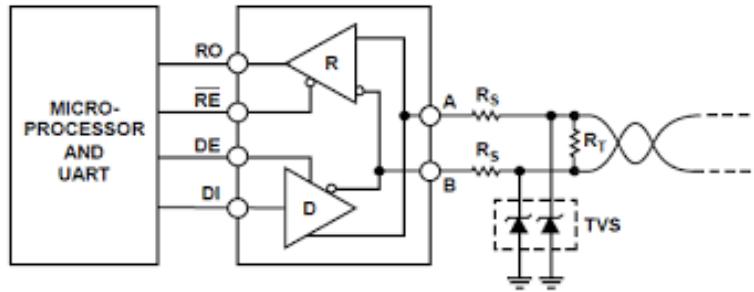
Sources of Transients

- Lightning strikes (indirect coupling)
- Power line switching
- Motor startup surges
- Switching power supplies

TVS DIODES

ITU-T K.20/K.21 Requirements

- Longitudinal Voltage: 1kV / 10 μ s
- Metallic Voltage: 100V / 10 μ s
- Current Capability: \geq 5 A
- Insulation Coordination: 1500 V



Performance Example (SP3003-04HTG TVS):

Parameter	Requirement	Device Spec
Data Rate	Up to 20 Mbps	20 Mbps+
ESD Protection	± 15 kV	± 30 kV
Capacitance	< 50 pF	12 pF
Leakage Current	< 1 mA	0.01 mA

Selection Criteria

Power Applications (>1W)

- Peak Pulse Power: 2x expected transient energy
- Clamping Voltage: 20% below damage threshold
- Working Voltage: 15% above normal system voltage
- Thermal Management: Consider repetitive pulse heating
- Package Selection: Must support power dissipation

Signal Line Protection (<1W)

- **Capacitance:** Keep low to minimize distortion
- **Leakage Current:** Critical in high-impedance circuits
- **ESD Rating:** Must exceed system-level requirements
- **Response Time:** Faster than system damage threshold
- **Package Size:** Small SMD (SOT-23, SOD-323) for portable devices

Environmental Considerations

- **Temperature Range:** -40°C to +150°C (Automotive-grade)
- **Humidity:** Conformal coating may be required
- **Altitude:** Derating above 2000 m elevation
- **Mechanical Stress:** Must withstand thermal cycling & vibration

DIODE SPECIFICATIONS & PARAMETERS

1. Forward Voltage Drop (V_F) and Impact on Efficiency

The Forward Voltage Drop (V_F) is the minimum voltage required across a diode to make it conduct in the forward-biased condition. It represents the energy barrier that charge carriers must overcome at the PN junction.

Typical VF Values by Diode Type:

Diode Type	Typical VF Range
Silicon Diode	0.6V – 0.7V
Germanium Diode	~0.3V
Schottky Diode	0.15V – 0.45V
LED	1.6V – 3.3V (depends on color)
Fast Recovery Diode	0.7V – 1.2V

Why VF Matters:

- **Power Loss:**

$$P = V_F \times I_F$$

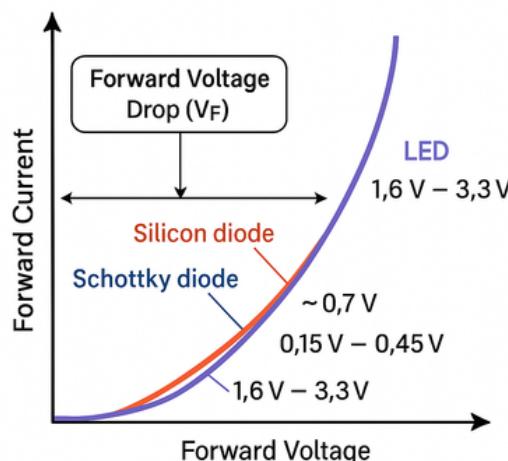
- Higher VF leads to greater energy loss as heat, especially in high-current circuits (e.g., power supplies).

- **Efficiency Impact:**

- In low-voltage systems (e.g., 3.3V logic or battery-powered designs), a 0.7V drop may result in significant performance degradation or functional issues.

- **Thermal Management:**

- VF contributes directly to thermal load on the diode and surrounding PCB. It must be considered in power dissipation calculations.



DIODE SPECIFICATIONS & PARAMETERS

Design Considerations:

- Prefer Schottky diodes in low-voltage or efficiency-critical designs (e.g., USB, battery, SMPS).
- In LED circuits, VF determines the resistor value for current limiting.
- VF decreases with temperature ($\sim 2\text{mV}/^\circ\text{C}$ for silicon), which can help or hinder depending on circuit sensitivity.

Example:

If a silicon diode conducts 2A with a VF of 0.7V:

$$P = 0.7V \times 2A = 1.4W$$

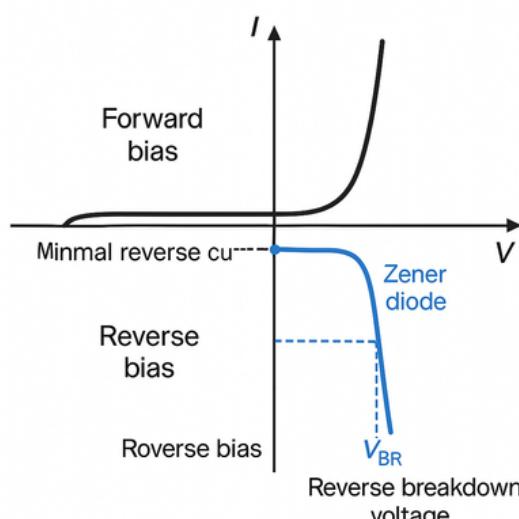
This 1.4W must be dissipated as heat, which might require heat sinking or thermal relief in the PCB layout.

2. Reverse Breakdown Voltage (V_{BR})

Reverse Breakdown Voltage (V_{BR}) is the minimum reverse voltage at which a diode begins to conduct heavily in reverse direction. Beyond this point, the diode enters avalanche or Zener breakdown depending on construction.

Importance in Design

- Acts as the maximum allowable reverse voltage under normal operation.
- Exceeding V_{BR} in non-Zener diodes leads to irreversible damage due to excessive reverse current and heat.
- In Zener diodes, V_{BR} (often called V_Z) is the operating voltage used intentionally for voltage regulation.



DIODE SPECIFICATIONS & PARAMETERS

Typical Values:

Diode Type	V _{br} Range
General PN Diode	50V – 1000V+
Zener Diode	2.4V – 200V
Schottky Diode	20V – 200V (lower limit)
TVS Diode	5V – 600V (transient)

Design Guidelines:

- Choose $V_{br} \geq 2 \times$ the maximum reverse voltage expected in circuit.
- Use TVS or Zener diodes for controlled breakdown applications (clamping, protection).
- For signal diodes, keep reverse voltage well below rated V_{br} .

Failure Risks if Ignored

- **Thermal Runaway:** High reverse current causes rapid heating.
- **Junction Breakdown:** Permanent damage or short circuit failure.
- **Circuit Malfunction:** Voltage leaks across reverse-biased paths.

Example

If a power line has a possible reverse spike of 50V:

Choose a diode with $V_{br} \geq 100V$ to ensure safe operation.

DIODE SPECIFICATIONS & PARAMETERS

3. Forward Current & Peak Surge Current Ratings

Understanding diode current ratings is essential to ensure safe and reliable circuit operation under both steady-state and transient conditions.

Average Forward Current (IFAV)

- Maximum continuous current the diode can conduct in forward bias without exceeding thermal limits.
- **Typical Range:** 1A (e.g., 1N4007) to 20A+ (e.g., MBR2045).
- **Impact:** Determines diode's ability to handle normal operating load.
- **Power Dissipation:**
- **Design Rule:** Use at least 1.5× safety margin; derate if elevated ambient temperatures or power $P = V_f \times I_{FAV}$

Peak Forward Surge Current (IFSM)

- Maximum current the diode can withstand for a short pulse (e.g., 8.3 ms) without damage.
- **Use Case:** Handles inrush currents, capacitor charging, or inductive switching.
- **Typical IFSM:** Up to 200A for a 3A diode (e.g., 1N5408).
- **Non-Repetitive:** Usually rated for a single event or very low duty cycle.

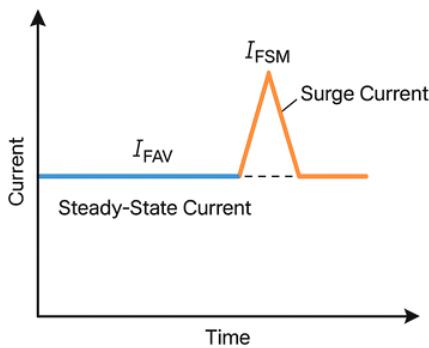
Why Both Matter:

Rating	Function	Exceeding Risk
IFAV	Sustained current handling	Overheating, thermal failure
IFSM	Temporary surge tolerance	Instant junction damage or burnout

Selection Guidelines

- Ensure IFAV ≥ max operating current (with margin).
- Ensure IFSM ≥ worst-case surge current.
- Use heat sinking or copper pours to manage thermal load.
- Add surge limiting elements (e.g., NTC thermistor, inrush controller) for protection.

DIODE SPECIFICATIONS & PARAMETERS



4. Reverse Leakage Current & Precision Circuit Impacts

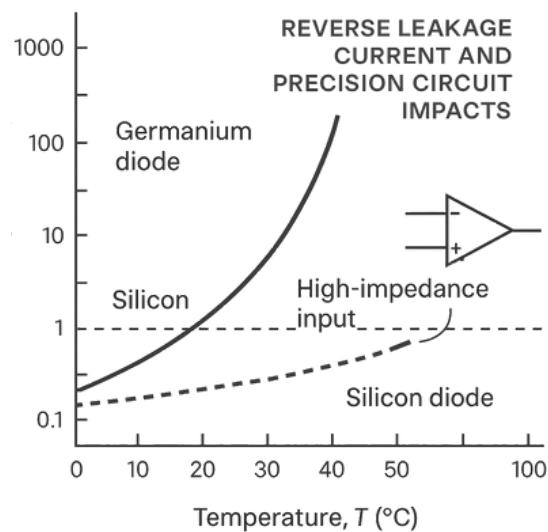
What is Reverse Leakage Current?

- A small amount of current that flows through a diode even when reverse-biased, due to minority carriers.
- **Symbol:** I_R
- **Typical Range:**
 - **Silicon PN Diodes:** Nanoamperes (nA) to microamperes (μA)
 - **Schottky Diodes:** Up to milliamperes (mA), especially at high temperatures

Why It Happens?

- Reverse-biased diodes should ideally block current, but minority carriers in the junction allow a tiny trickle current to flow.
- Thermally activated – increases exponentially with temperature:

- Worsens under:
 - High reverse voltage
 - High junction temperature
 - Low-quality diode fabrication



DIODE SPECIFICATIONS & PARAMETERS

Impact on Precision Circuits

Reverse leakage current, while small, can have significant consequences in sensitive analog or high-impedance circuits:

Application	Effect of IR
Precision ADC inputs	Causes offset errors and voltage drift
High-impedance sensors	Introduces leakage path, distorting measurement
Low-current bias networks	Alters bias points or feedback behavior
Capacitor timing circuits	Discharges timing capacitor, altering timebase

Even nanoamp-level leakage can corrupt performance in circuits with megaohm resistances or picoamp-level signals.

Design Recommendations

- Use low-leakage diodes (e.g., 1N4148, specially rated diodes).
- Avoid Schottky in precision applications unless specifically rated for low IR.
- Keep junction temperature low — use thermal management if needed.
- Choose glass-passivated or high-quality surface-mount packages for lower IR.
- Use guard rings in PCB layout to prevent leakage across surfaces.

DIODE SPECIFICATIONS & PARAMETERS

5. Reverse Recovery Time (Tr_r), Switching Speed, & EMI

What is Reverse Recovery Time (Tr_r)?

- Tr_r is the time it takes for a diode to stop conducting after switching from forward bias to reverse bias.
- **Why it matters:**
 - During Tr_r, the diode continues to conduct in reverse direction due to stored charge carriers, causing undesirable current spikes, power loss, and electromagnetic interference (EMI).

Behavior During Switching:

1. Forward Conduction:

- Charge carriers are injected across the PN junction.

2. Switch to Reverse Bias:

- These stored charges must be removed before blocking begins.

3. Reverse Recovery Phase:

- A brief reverse current flows → current snaps off → voltage overshoot and EMI may occur.

Typical Tr_r Values:

Diode Type	Tr _r (Typical)	Use Case
Standard Silicon	1 µs – 30 µs	Low-frequency rectification
Fast Recovery	35 ns – 150 ns	Switching regulators, snubbers
Ultra-Fast / Soft	< 35 ns	High-speed switching
Schottky Diode	~0 ns (no Tr _r)	Ideal for SMPS, RF, logic clamps

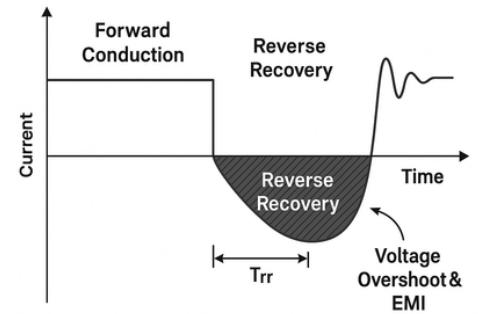
Impact of Slow Tr_r

Issue	Effect
Power Loss	Wasted energy during reverse conduction
EMI/Ringing	Sharp cut-off causes radiated noise
Voltage Overshoot (di/dt)	Stress on MOSFETs and sensitive components
Reduced Efficiency	Especially in SMPS, inverters, flyback converters

DIODE SPECIFICATIONS & PARAMETERS

Design Recommendations

- Use fast recovery or Schottky diodes in high-speed circuits (SMPS, PWM, digital switching).
- Minimize circuit inductance near switching paths to limit overshoot.
- Add snubber circuits (RC or RCD) to absorb reverse spikes.
- Choose soft recovery diodes to reduce EMI in sensitive designs.



6. Junction Capacitance Effects

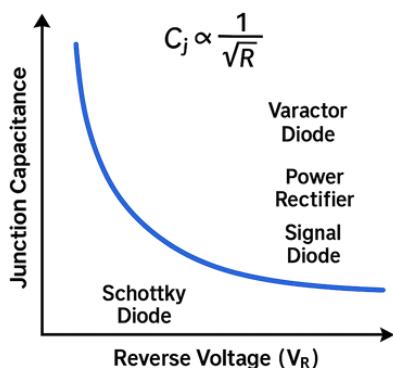
What is Junction Capacitance?

- Junction capacitance (also called transition capacitance or C_j) is the inherent capacitance formed across the depletion region of a reverse-biased PN junction.
- **Analogy:**
 - The PN junction behaves like a variable capacitor, with the P and N regions acting as plates and the depletion layer as the dielectric.

How It Varies:

- Capacitance is inversely proportional to reverse voltage:
$$C_j \propto \frac{1}{\sqrt{V_R}}$$
- As reverse voltage increases, the depletion width widens $\rightarrow C_j$ decreases.
- High-frequency signals see this capacitance as a path to ground, causing signal attenuation or phase shift.

C_j changes with reverse voltage



Diode Type	Junction Capacitance (C_j)	Remarks / Applications
Signal Diodes (e.g. 1N48)	2 – 10 pF	General signal processing logic level protection
Schottky Diodes (1N5819)	10 – 50 pF	Fast switching Low VF-appl
Power Rectifiers (1N4007)	50 – 500 pF	RF-tuning Voltage-controlladors
TVS Diodes (Standard)	≥ 100 pF	Surge and ESD protection Low-speed lines
Low-Cap TVS (Low-Cap)	< 5 pF	Surge an/ESD protect low-speed lines
TVS	< 5 pF	High-speed data

DIODE SPECIFICATIONS & PARAMETERS

Typical Capacitance Ranges:

Application	Effect of High C _j
High-speed digital lines	Signal distortion, slower edge transitions
RF circuits	Frequency detuning, loss of signal power
Precision analog	Increased settling time, phase shift
High-impedance inputs	Signal loading and leakage

Impact on Circuits:

Application	Effect of High C _j
High-speed digital lines	Signal distortion, slower edge transitions
RF circuits	Frequency detuning, loss of signal power
Precision analog	Increased settling time, phase shift
High-impedance inputs	Signal loading and leakage

Typical Capacitance Ranges

- Use low-capacitance diodes in RF, high-speed, or ADC input circuits.
- Prefer SOD-323 or SOT-23 TVS diodes with ultra-low C_j for USB, Ethernet, HDMI.
- Use varactor diodes deliberately in voltage-controlled tuning circuits.
- Avoid Schottky diodes where junction capacitance affects timing or bandwidth.
- Ensure PCB trace lengths are minimized to reduce additional parasitic capacitance.

Notes:

- Capacitance decreases with increasing reverse voltage.
- Use low-C_j diodes in high-speed or precision circuits.
- Capacitance is often not listed for general diodes unless relevant to application (e.g., RF).

DIODE SPECIFICATIONS & PARAMETERS

7. Power Dissipation, Thermal Resistance, & Packaging

Power Dissipation (PD)

- Power dissipation is the heat generated inside a diode due to the voltage drop across it while conducting current.
- **Formula:** $P_D = V_F \times I_F$
- **Importance:**
 - Excessive power leads to thermal buildup, which can damage or shorten diode life if not properly managed.
- **Example:**
 - A diode conducting 2A with a 0.7V drop $\rightarrow P_D = 0.7V \times 2A = 1.4W$

Thermal Resistance (θ_{JA} & θ_{JC}):

- Units: °C/W
- **Purpose:** Determines how well the diode can dissipate heat to the environment or heatsink.
- Formula to estimate junction temperature: $T_J = T_A + (P_D \times \theta_{JA})$
- **Design Note:** Lower thermal resistance = better cooling = safer operation.

Diode Package Types and Heat Handling

Package	θ_{JA} (°C/W)	Power Handling	Remarks
DO-41	~100	~1W	Through-hole, general-purpose
DO-201	~45	~3W	Larger THT for higher current
DO-15	~25	~5W	Used in higher-power rectification
TO-220	~50 (θ_{JA}), ~3 (θ_{JC})	~25W (with heatsink)	High-power, mountable
SOD-123	~200	<0.5W	Small SMD, low-power applications
SMA/SMB/SMC	100–150	0.5W to 2W	SMD TVS or power diodes

DIODE SPECIFICATIONS & PARAMETERS

8. Temperature Effects and Stability

Temperature significantly impacts diode performance, affecting forward voltage, reverse leakage, breakdown behavior, and long-term reliability.

Forward Voltage vs. Temperature

- Forward voltage (V_F) decreases with temperature:
- **Example:** $\Delta V_F \approx -2 \text{ mV}/{}^\circ\text{C}$ (for silicon diodes)
- At $25^\circ\text{C} \rightarrow V_F \approx 0.7\text{V}$
- At $85^\circ\text{C} \rightarrow V_F \approx 0.58\text{V}$
- **Impact:**
 - May affect biasing conditions in analog and reference circuits.
 - Used deliberately in temperature sensing and compensation circuits.

Reverse Leakage Current

$$IR_{highT} \gg IR_{roomT}$$

- IR increases exponentially with temperature:
- Especially significant in Schottky and germanium diodes.
- **Impact:**
 - Introduces error in high-impedance or low-current circuits.
 - Can lead to thermal runaway in high-reverse-voltage applications.

Zener Voltage Drift

- Zener diodes show non-linear temperature behavior:
 - Below 5.6V: Negative tempco (voltage drops with temp)
 - Above 5.6V: Positive tempco
 - Around 5.6V: Near-zero tempco (most stable)
- Impact:
 - Reference stability in voltage regulation and precision analog circuits.

DIODE SPECIFICATIONS & PARAMETERS

Switching Speed and Recovery

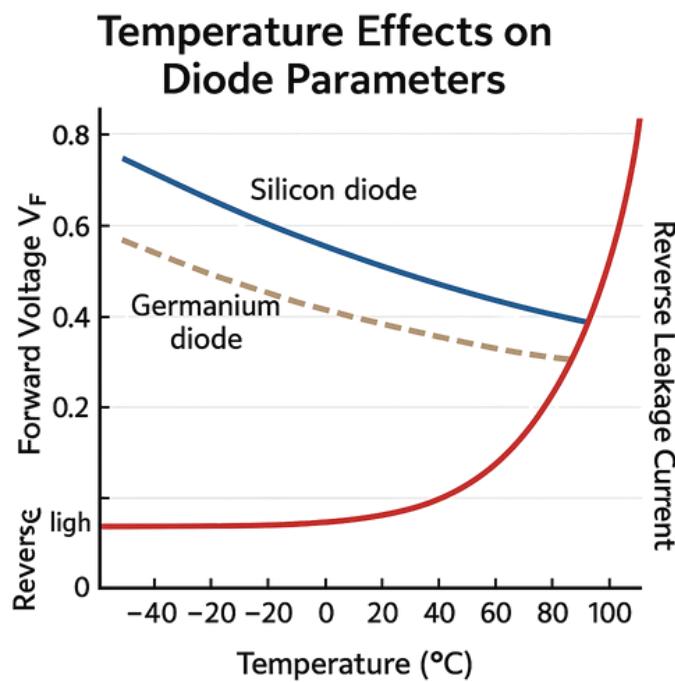
- At higher temperatures:
 - Minority carrier lifetimes increase
 - Recovery times may slow down
 - EMI risk may rise

Long-Term Reliability

- High temps accelerate:
 - Junction degradation
 - Package aging
 - Solder fatigue
- Each 10°C rise cuts device lifetime by ~50% (Arrhenius rule)

Design Guidelines

- Use temperature derating for current and power.
- For precision circuits, select temperature-compensated Zeners or bandgap references.
- Use heat sinks, thermal vias, and airflow for thermal control.
- Refer to manufacturer's derating curves in datasheets.



APPLICATION-BASED SELECTION CRITERIA

Diode Selection

Selecting the right diode depends on the electrical, thermal, switching, and protection requirements of your application. Below is a breakdown of the most common use cases and the appropriate diode types to choose for each.

1. Rectification (AC to DC Conversion)

Application	Recommended Diode	Why
Low-current rectifier	1N4001-1N4007	Reliable, cost-effective
High-current rectifier	1N540x, 6A10, 10A10	Higher IF rating, suitable for power
High-frequency SMPS	UF4007, MUR460, RHRP15120	Fast recovery to reduce switching loss
Ultra-low loss	Schottky (MBR2045, SB5100)	Low VF, high efficiency

2. Voltage Regulation & References

Application	Recommended Diode	Why
Fixed voltage clamp	Zener Diode	Stable reverse breakdown voltage
Precision reference	5.1V Zener	Minimal temperature drift (~0 tempco)
Low-voltage regulation	TL431, Zener < 5.6V	Negative tempco helps thermally balance
High-voltage regulator	Zener > 12V	Tolerant to wider supply ranges

3. Protection Circuits (Surge, ESD, Reverse Polarity)

Application	Recommended Diode	Why
ESD protection (data lines)	Low-cap TVS (e.g., PESD5V)	<1 pF, fast response
Power line surge protection	TVS diode (SMBJ, SMCJ)	High power pulse handling (400W to 1500W+)
Reverse polarity protection	Schottky / MOSFET + Zener	Low VF loss, safe clamping
Relay/motor freewheeling	1N4007 / UF4007	Protects switches from inductive kickback

APPLICATION-BASED SELECTION CRITERIA

4. Signal Conditioning & Logic Interfacing

Application	Recommended Diode	Why
Logic level shifter	Schottky	Fast switching, low VF
Clamping analog inputs	Fast diode / Schottky	Protect ADC from over-voltage
Logic OR function	Standard diode (1N4148)	Simple wired-logic configuration

5. RF, Tuning, and Sensing Applications

Application	Recommended Diode	Why
RF tuning (VCO)	Varactor	Variable capacitance with bias voltage
Light detection	Photodiode	Converts light to current
Temperature sensing	Diode (forward-biased)	-2 mV/°C voltage drop
Fast RF switching	PIN Diode	Acts as variable resistor at RF

6. Power Sharing & Redundancy

Application	Recommended Diode	Why
Dual power source OR-ing	Schottky	Low forward drop, avoids voltage drop
Battery + adapter input	Schottky or Ideal Diode IC	Seamless switchover

General Selection Checklist

Parameter	What to Check
Forward Current (IF)	$\geq 1.5 \times$ max continuous current
Reverse Voltage (VR)	$\geq 2 \times$ peak reverse voltage
Reverse Recovery Time (Tr)	Fast enough for switching circuits
Capacitance (Cj)	Low for high-speed, high-frequency designs
Power Dissipation (PD)	Withstands heat with margin
Package	Matches power and thermal layout constraints