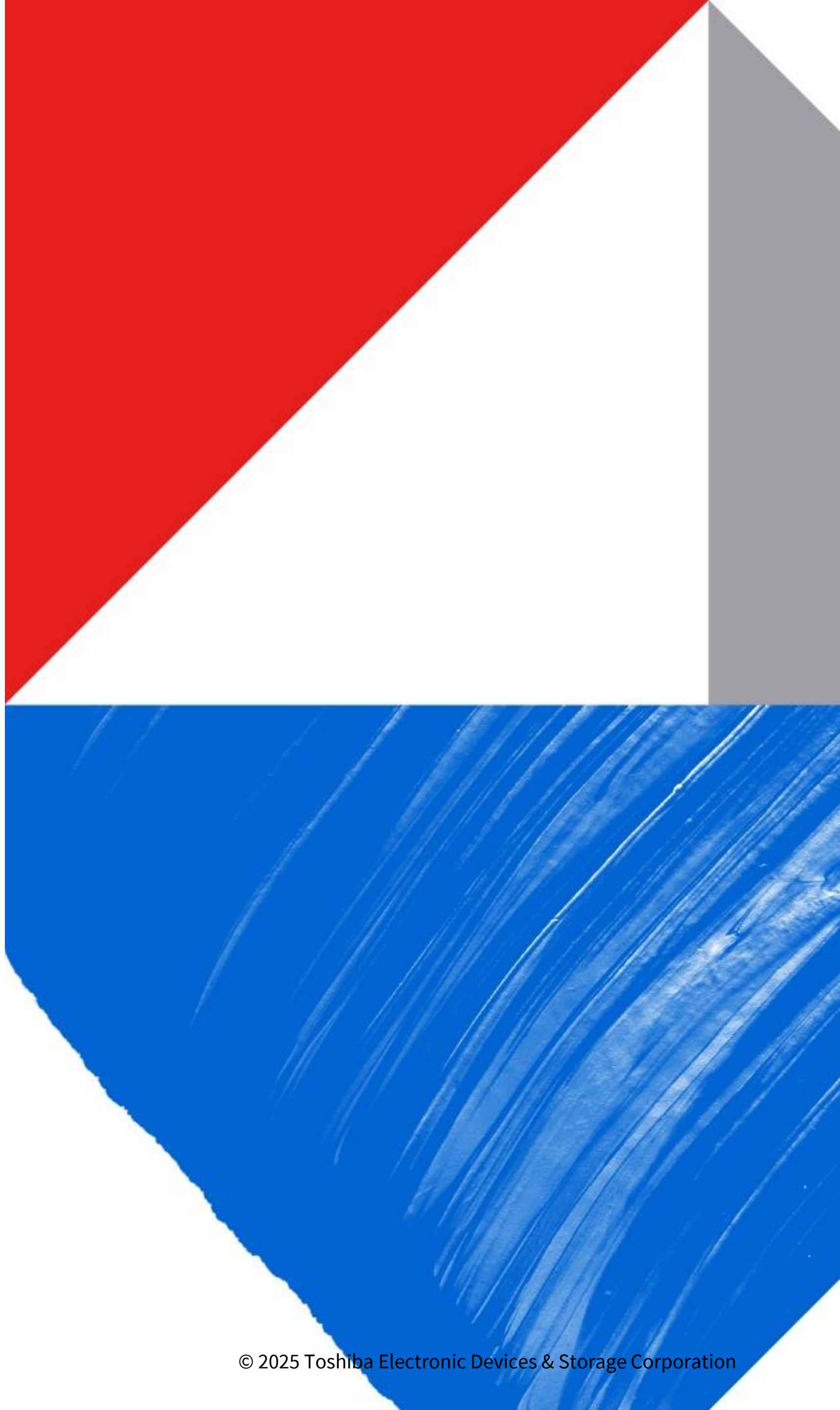
TOSHIBA

Protecting power supply and signal lines

Basics of TVS Diodes—Essential Devices for Circuit Protection

Toshiba Electronic Devices & Storage Corporation



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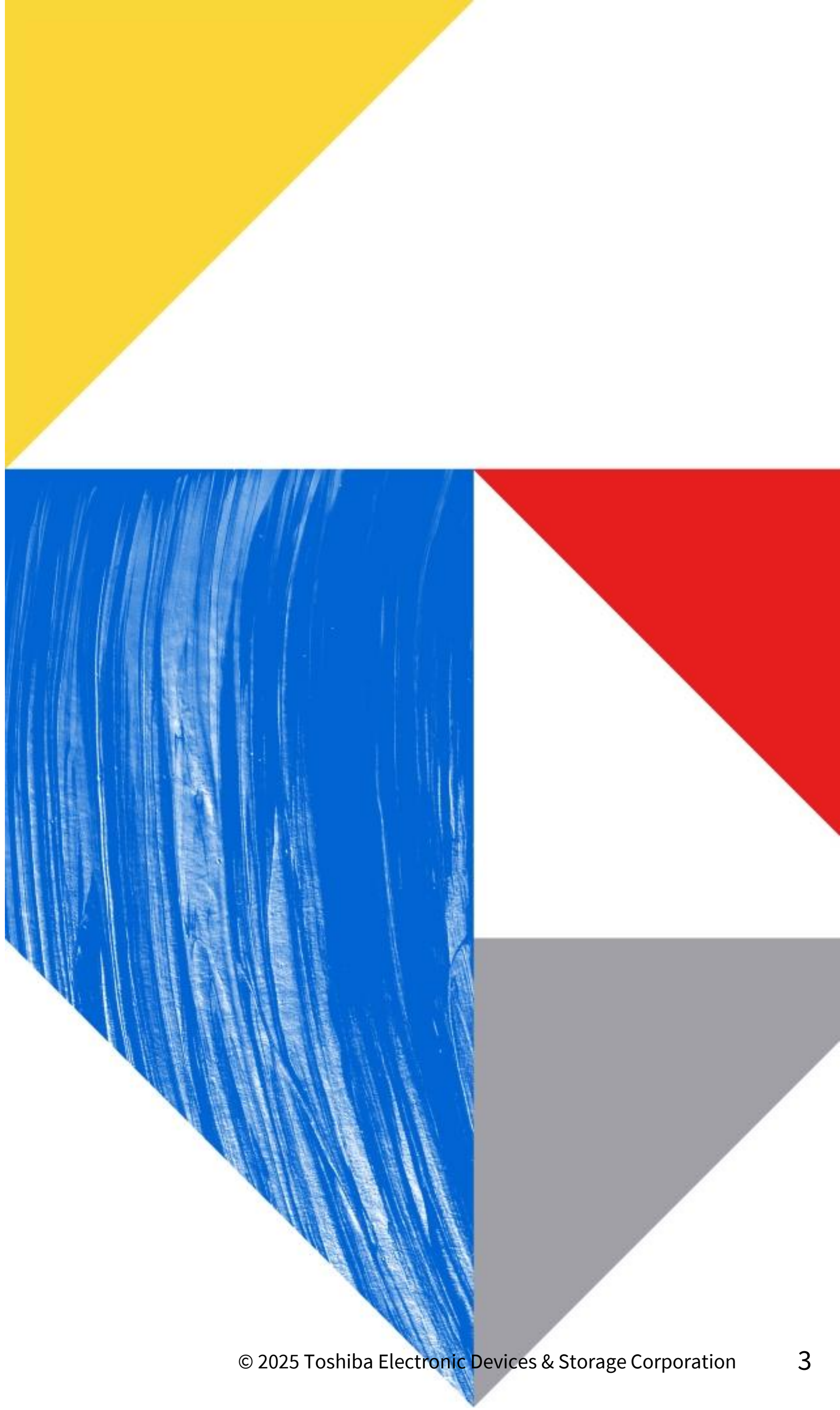
Issues relating to the latest electronic devices and importance of protection devices



Introduction

Electrostatic discharge (ESD) is the voltage surge that you are most familiar with. Static electricity exists everywhere.

Static electricity voltage (V)	Impact
1,000	Not felt at all
2,000	Slight sensation felt on fingers; not painful
3,000	Prickling or slightly stinging sensation
4,000	Slightly painful sensation like needles going deep into fingers
5,000	Pain felt from palm(s) to forearm(s)
8,000	Numbing sensation extending from palm(s) to forearm(s)
10,000	Pain felt over entire arm(s) combined with sensation of electric flow(s)

Source: MIL-HDBK-773A

Means of static generation	Measured voltages	
	10% to 20% RH	65% to 90% RH
Walking across carpet	35,000	1,500
Walking over vinyl floor	12,000	250
Worker at bench	6,000	100
Vinyl envelopes for work instructions	7,000	600
Common poly bag picked up from bench	20,000	1,200
Work chair padded with polyurethane foam	18,000	1,500

Semiconductor components in electronic devices are frequently exposed to surges typified by static electricity.

Issues relating to the latest electronic devices

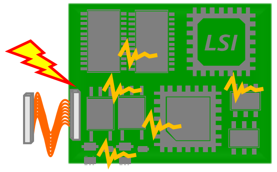
Characteristics of recent electronic devices

- ✓ Small boards and narrow part-to-part spacing
- ✓ Board partitioning due to system size reduction

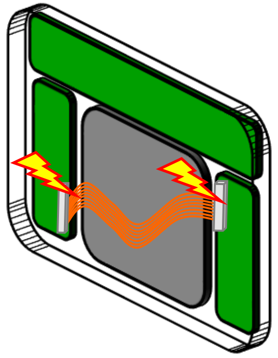
- ✓ Increase in the number of external connectors
- ✓ Increase in the number of peripheral devices connected via connectors

- ✓ Diverse high-performance ICs and LSI chips mounted on board
  (Shrinking processes and differences in surge immunity levels)

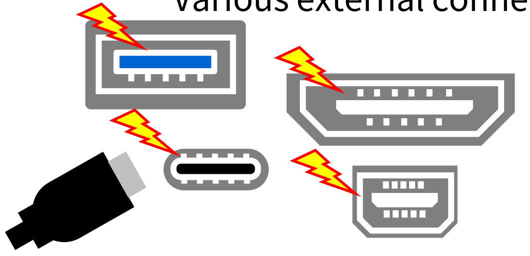
High-density board



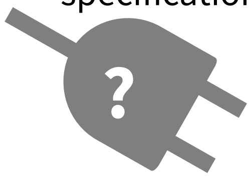
Multiple boards connected via connectors



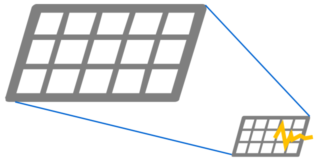
Various external connectors



Charger with unknown specifications



Shrinking process

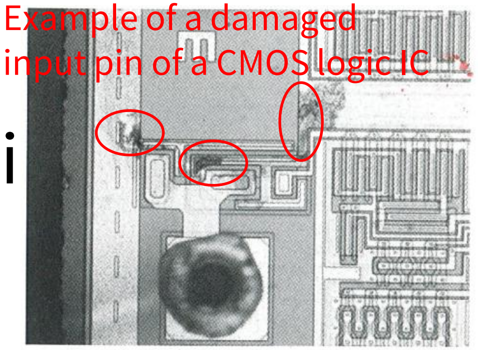


Electronic devices are exposed to an increasing risk of destruction because of an environment susceptible to static electricity and other surge events as well as ever-decreasing surge immunity levels.

Why are protection diodes necessary?
What occurs if a system does not have any protection diodes?

Without surge protection

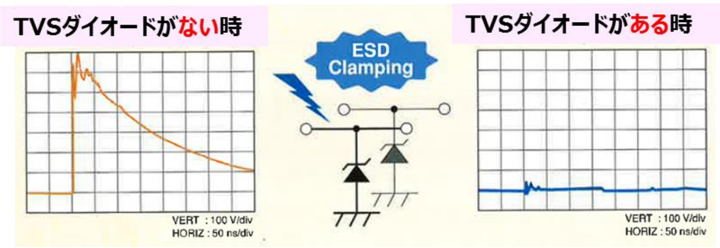
- ✓ Damage to a product
- ✓ Damage to product reputati
- ✓ Damage to brand



Example of a damaged input pin of a CMOS logic IC

➡ It would be time consuming and costly to identify the cause of damage and communicate with customers, hindering the development of new products.

Benefits of protection diodes



- ✓ Reducing the risk of product destruction
- ✓ Enhancing product reliability
- ✓ Enhancing product reputation
- ✓ Enhancing trust in your company

TVS diodes improve the surge immunity of an electronic device and reduce the risk of its destruction.

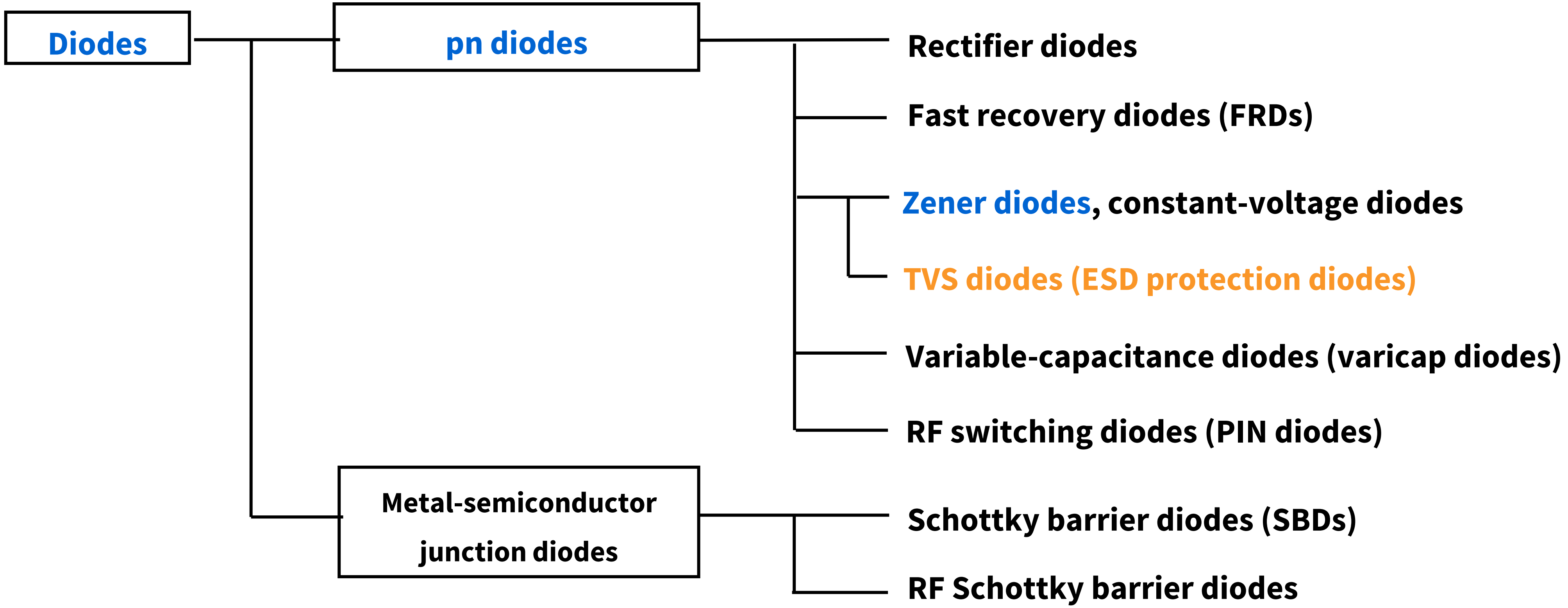
02

Basic operation of TVS diodes

What are TVS diodes?

TVS diodes are designed based on Zener diodes, a type of pn diodes, specifically to protect devices from ESD and other overvoltage transients.

TVS: transient voltage suppressor



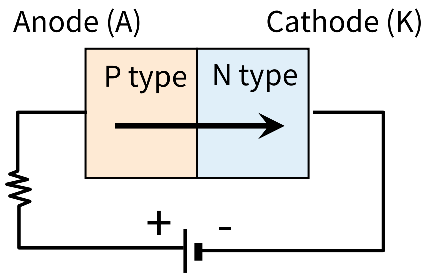
Diodes

- **pn diodes**
  - **Rectifier diodes**
  - **Fast recovery diodes (FRDs)**
  - **Zener diodes, constant-voltage diodes**
    - **TVS diodes (ESD protection diodes)**
  - **Variable-capacitance diodes (varicap diodes)**
  - **RF switching diodes (PIN diodes)**
- **Metal-semiconductor junction diodes**
  - **Schottky barrier diodes (SBDs)**
  - **RF Schottky barrier diodes**

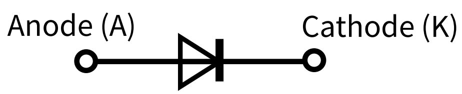
Review of pn diodes

A pn diode is a type of diode formed by the junction of a p-type semiconductor and an n-type semiconductor.
A pn diode conducts current in one direction, but not the other, depending on the direction of the voltage applied.

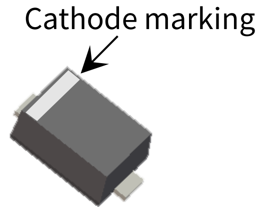
■ Polarity (forward direction)



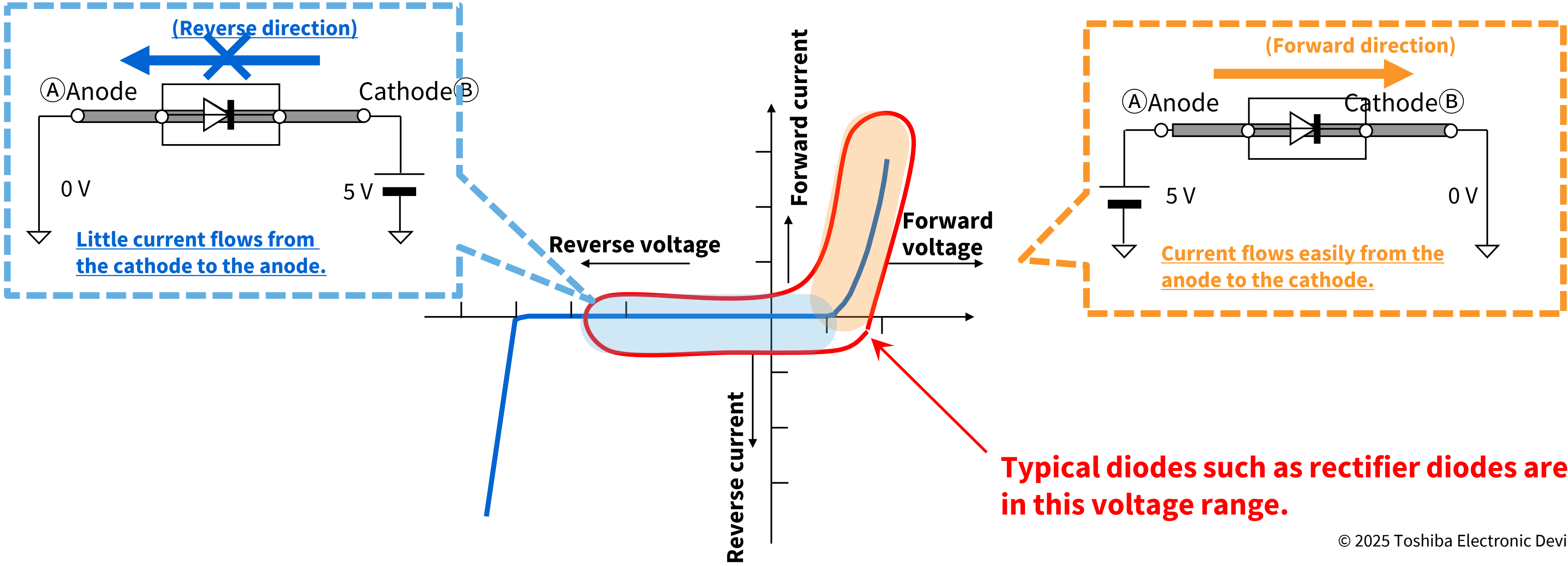
■ Symbol



■ Example of external appearance



■ Electrical characteristics

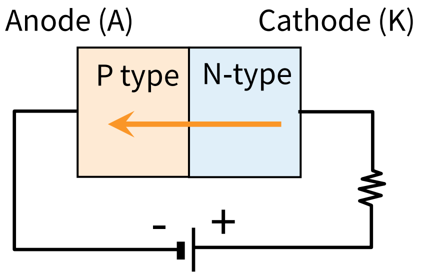


Typical diodes such as rectifier diodes are used in this voltage range.

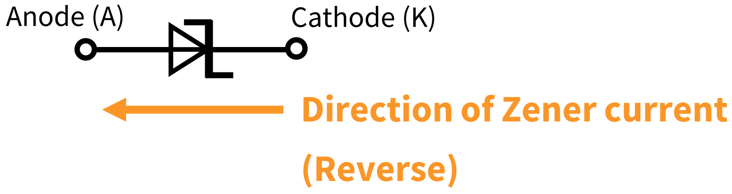
Zener and TVS diodes

A Zener diode is a type of diode designed to be used in the reverse-biased condition.
As the reverse bias across the pn junction is increased, a Zener diode conducts suddenly at a certain point. This breakdown voltage is called Zener voltage. From this point on, the voltage across the Zener diode remains constant, regardless of the amount of current flowing through it. Zener diodes are widely used because of this reverse conduction characteristic.

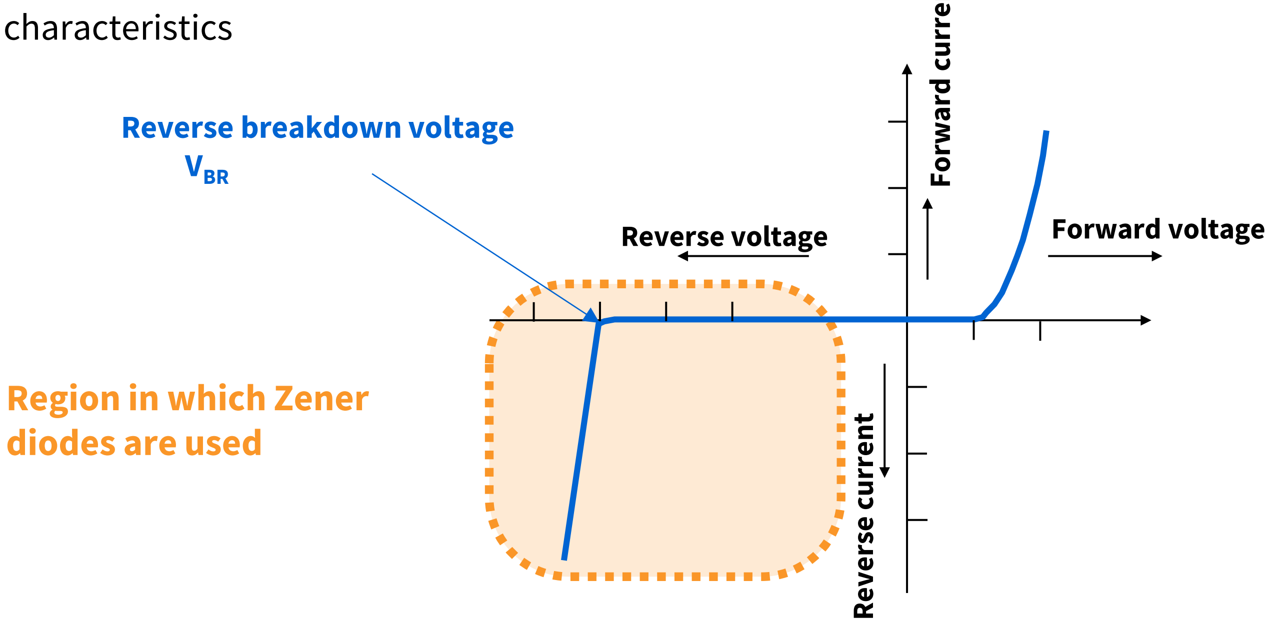
■ Polarity



■ Symbol



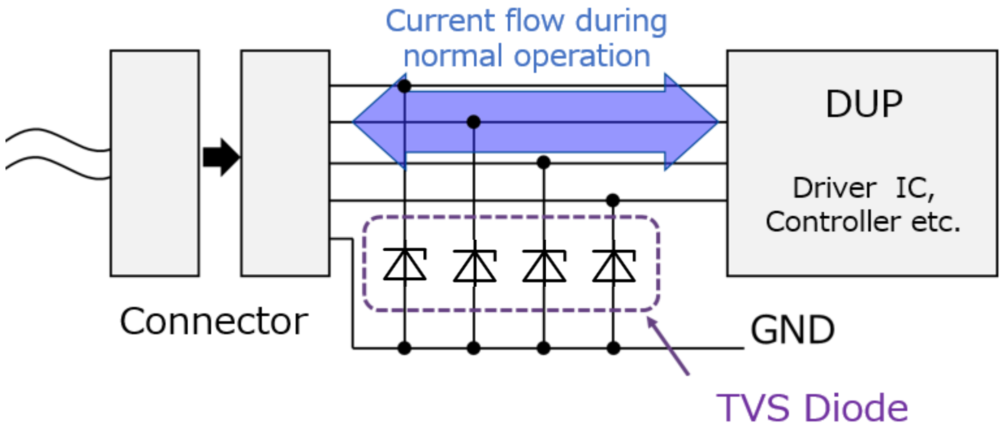
■ Electrical characteristics



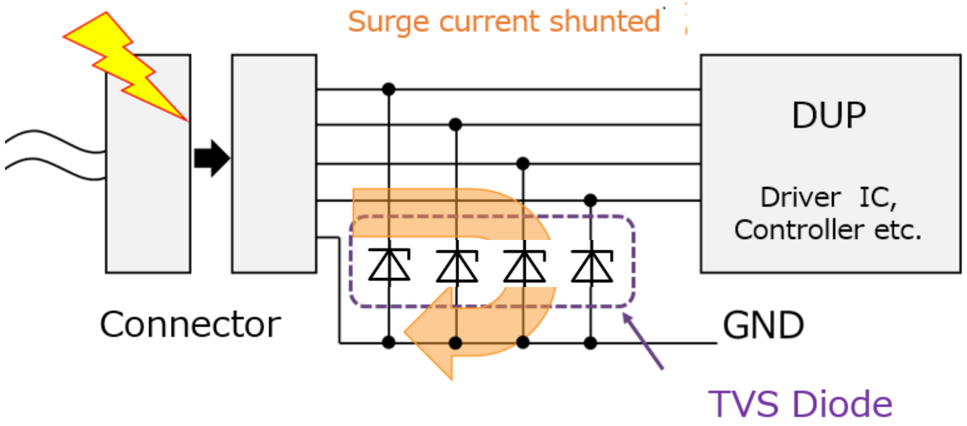
Basic operation of TVS diodes

TVS diodes operate in different current-voltage regions during normal operation and in the event of an overvoltage transient.

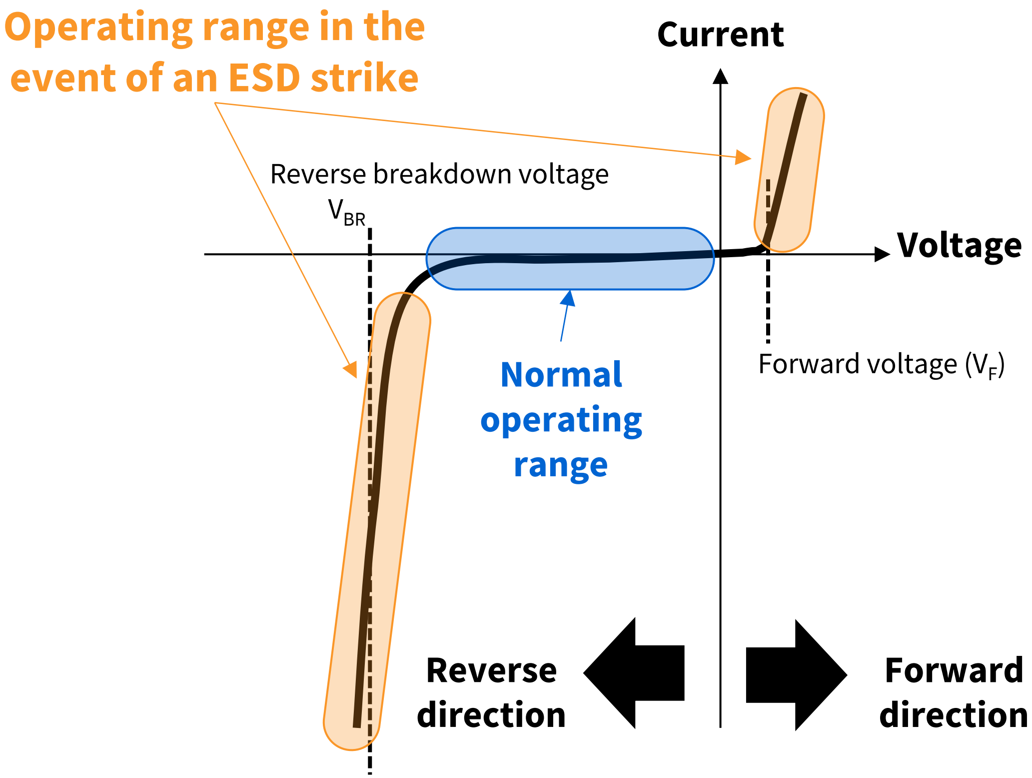
During normal operation (without a surge event)



In the event of a surge



Operating range of TVS diodes



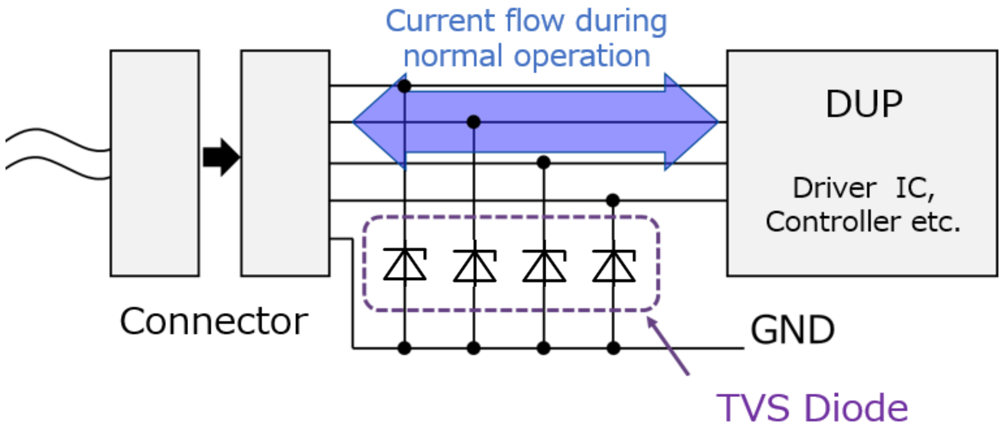
03

Characteristics important for TVS diodes

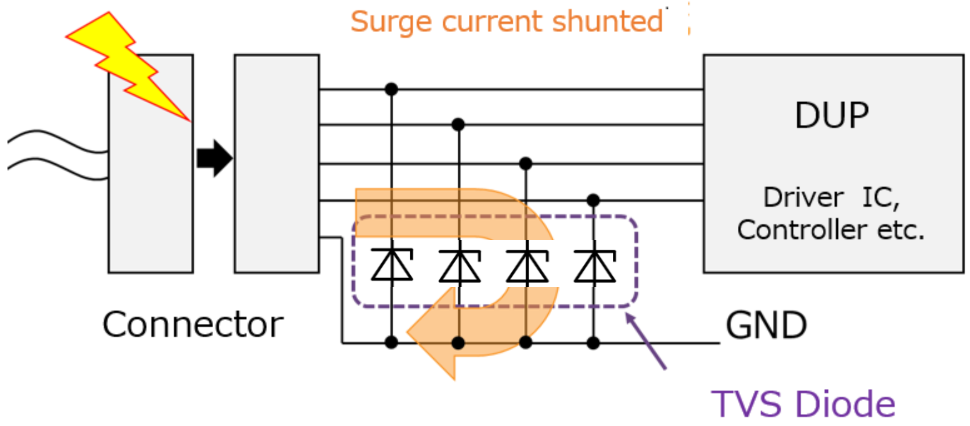
Characteristics important for TVS diodes

Important electrical characteristics differ during normal operation and in the event of an overvoltage transient.

During normal operation (without a surge event)



In the event of a surge



Important characteristics

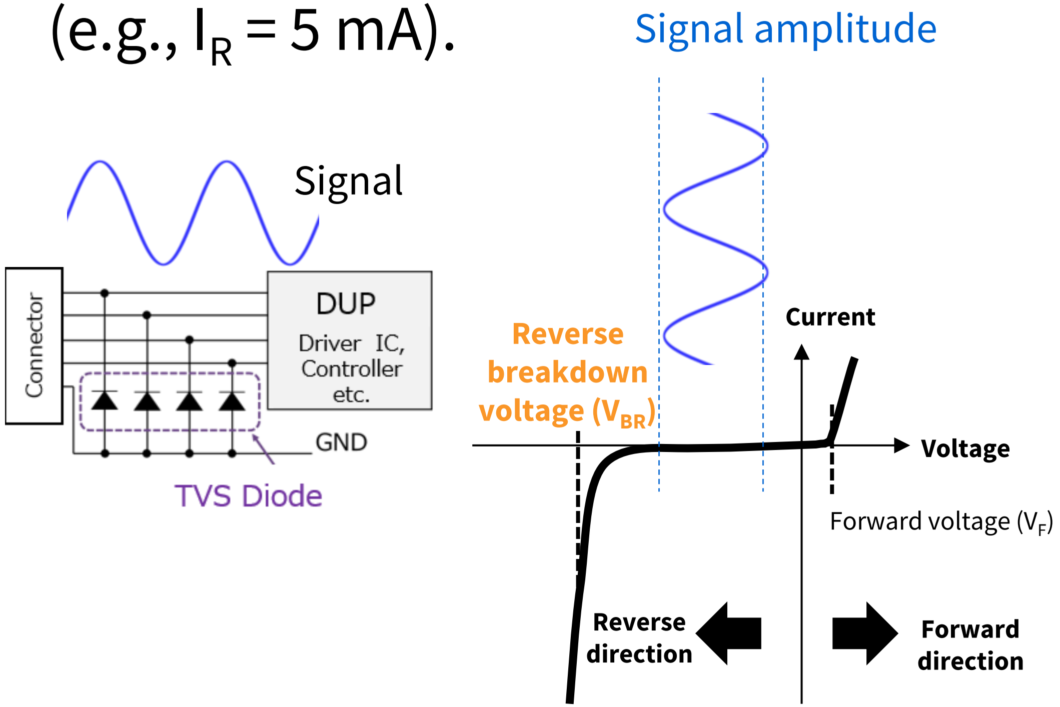
1. Reverse breakdown voltage, V_{BR} (Zener voltage, V_Z)
2. Signal polarity
3. Total capacitance, C_T

4. Dynamic resistance, R_{DYN}
5. Clamp voltage, V_C

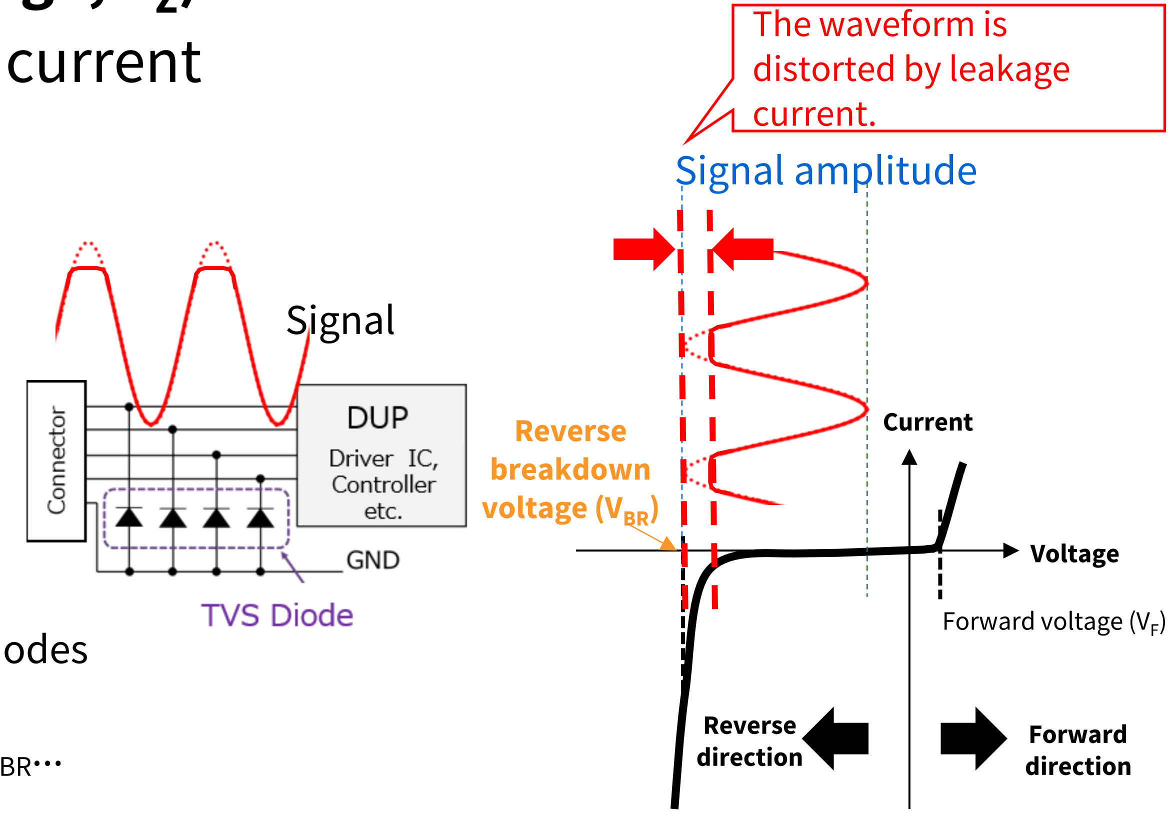
Characteristics important for TVS diodes:
1. Reverse breakdown voltage, V_{BR} (Zener voltage, V_Z)

1. Reverse breakdown voltage, V_{BR} (Zener voltage, V_Z)

V_{BR} is the reverse voltage at the specified reverse current (e.g., I_R = 5 mA).



If you do not choose TVS diodes with an appropriate V_{BR}…

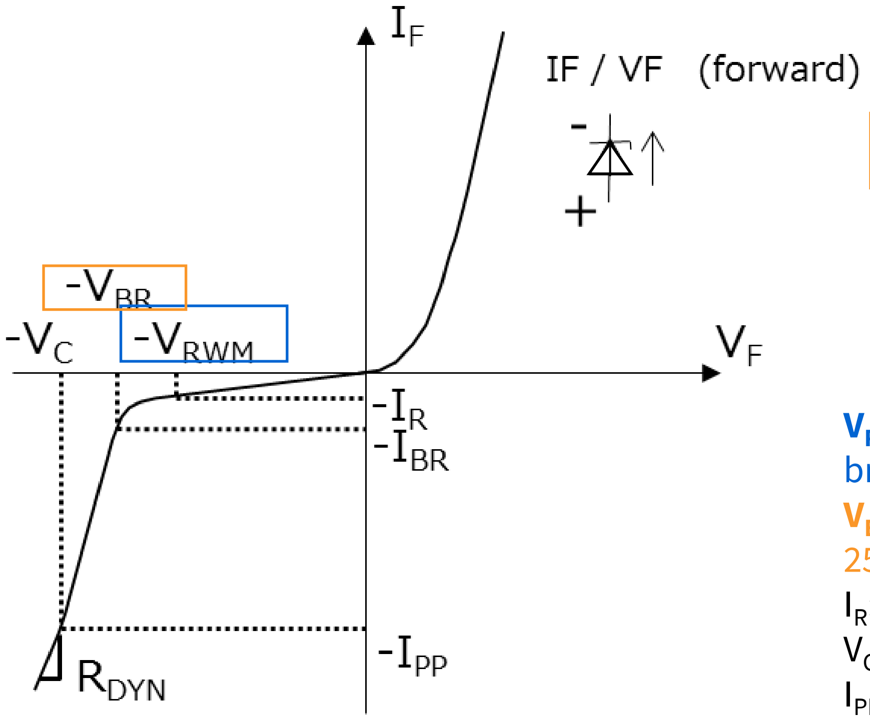


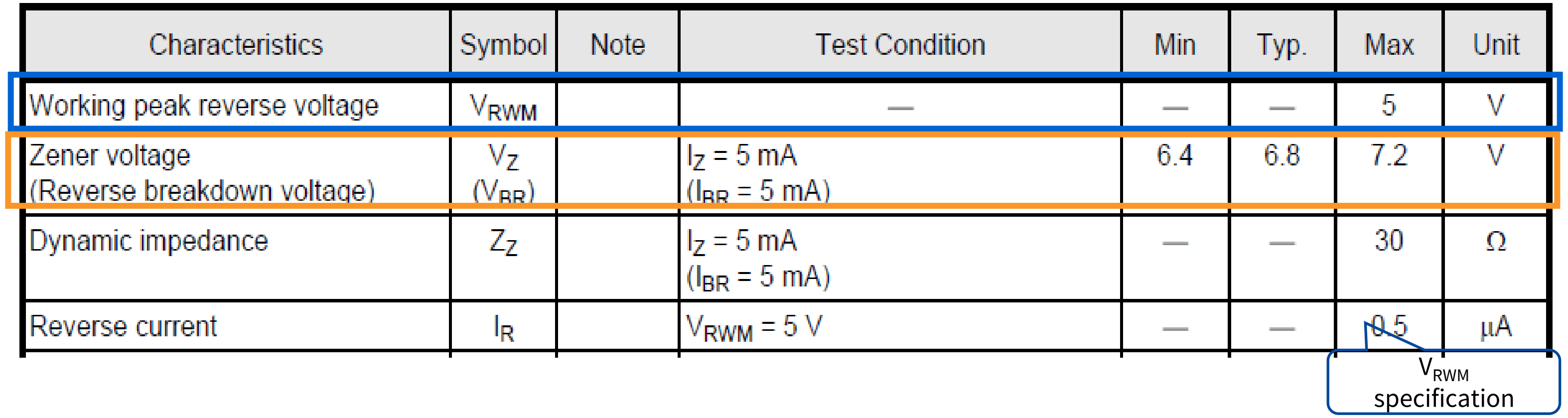
Select TVS diodes with a V_{BR} (V_Z) value higher than the high-level voltage of the signal lines to be protected. When the high-level voltage is 5 V, TVS diodes with a V_{BR} (V_Z) of 6.2 V or 6.8 V are recommended.

Characteristics important for TVS diodes:
1. Reverse breakdown voltage, V_{BR} (Zener voltage, V_Z)

1. Reverse breakdown voltage, V_{BR} (Zener voltage, V_Z)

Example of a V_{BR} specification shown in an actual datasheet





Characteristics	Symbol	Note	Test Condition	Min	Typ.	Max	Unit
Working peak reverse voltage	V_{RWM}		—	—	—	5	V
Zener voltage (Reverse breakdown voltage)	V_Z (V_{BR})		I_Z = 5 mA (I_{BR} = 5 mA)	6.4	6.8	7.2	V
Dynamic impedance	Z_Z		I_Z = 5 mA (I_{BR} = 5 mA)	—	—	30	Ω
Reverse current	I_R		V_{RWM} = 5 V	—	—	0.5	μA

V_{RWM} specification

V_{RWM}: Working peak reverse voltage (maximum voltage at which a TVS diode does not enter into breakdown at T_a = 25°C)

V_{BR}: Reverse breakdown voltage (voltage range in which a TVS diode enters into breakdown at T_a = 25°C)

I_R: Reverse current
V_C: Clamp voltage
I_{PP}: Peak pulse current
R_{DYN}: Dynamic resistance

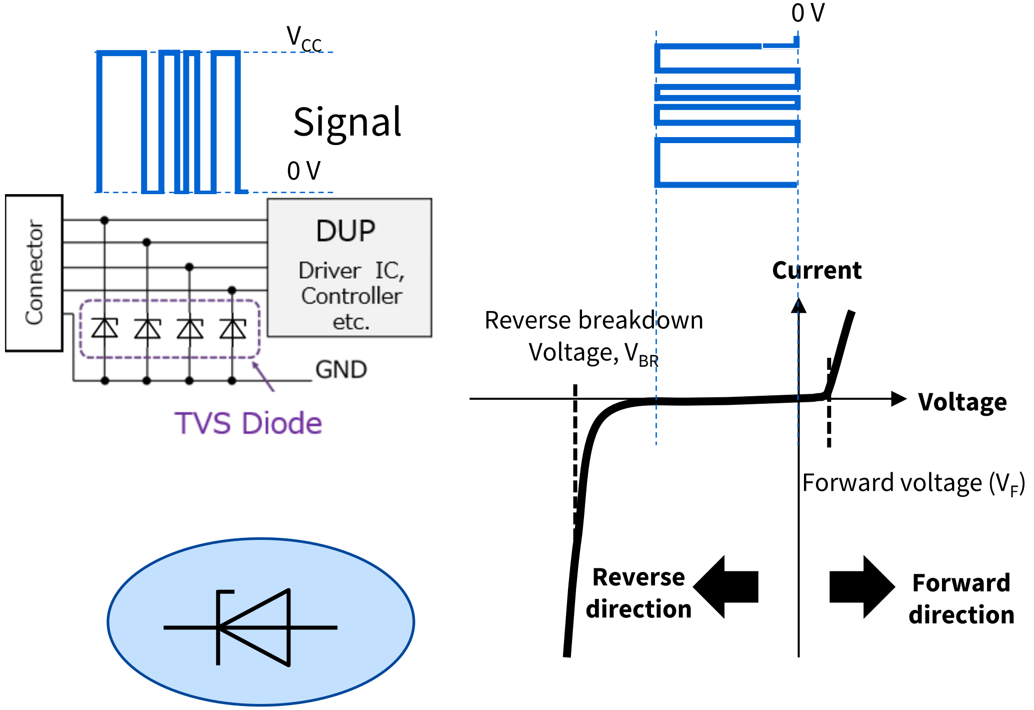
For some TVS diodes, the working peak reverse voltage (V_{RWM}) is specified.
Select TVS diodes with a V_{RWM} value higher than the amplitude of the signal lines to be protected.

Characteristics important for TVS diodes: 2. Signal polarity

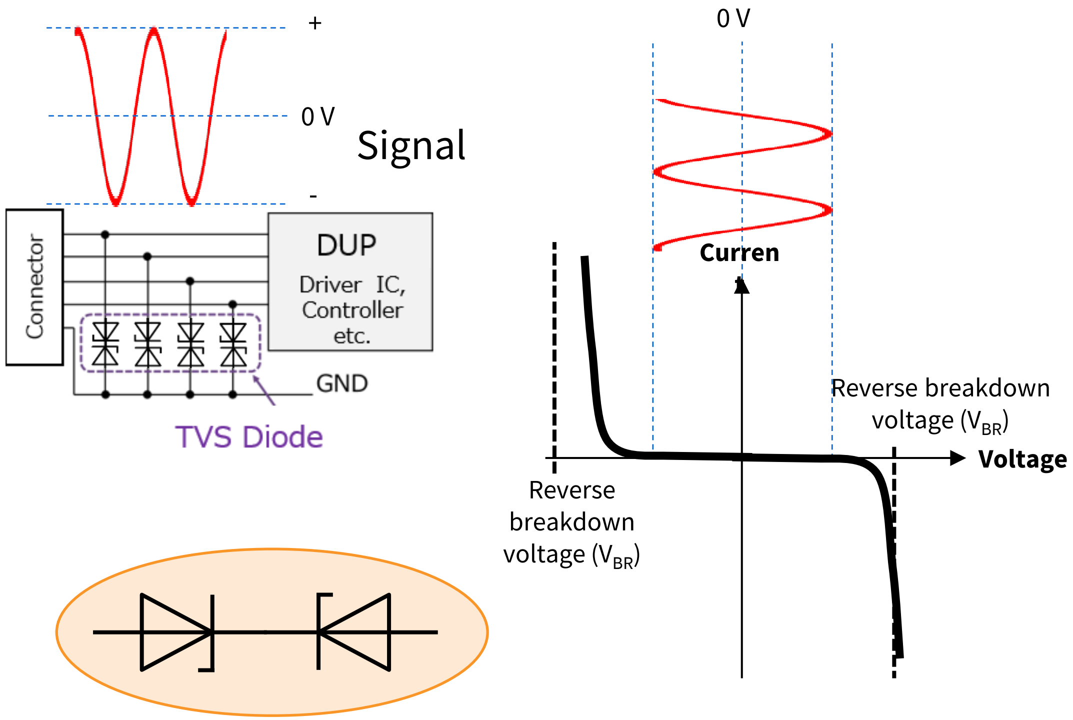
2. Signal polarity

Determine whether the signal lines to be protected cross the GND level like analog signals.

Digital signal swinging between logic Low and logic High



Analog signal symmetrical around GND

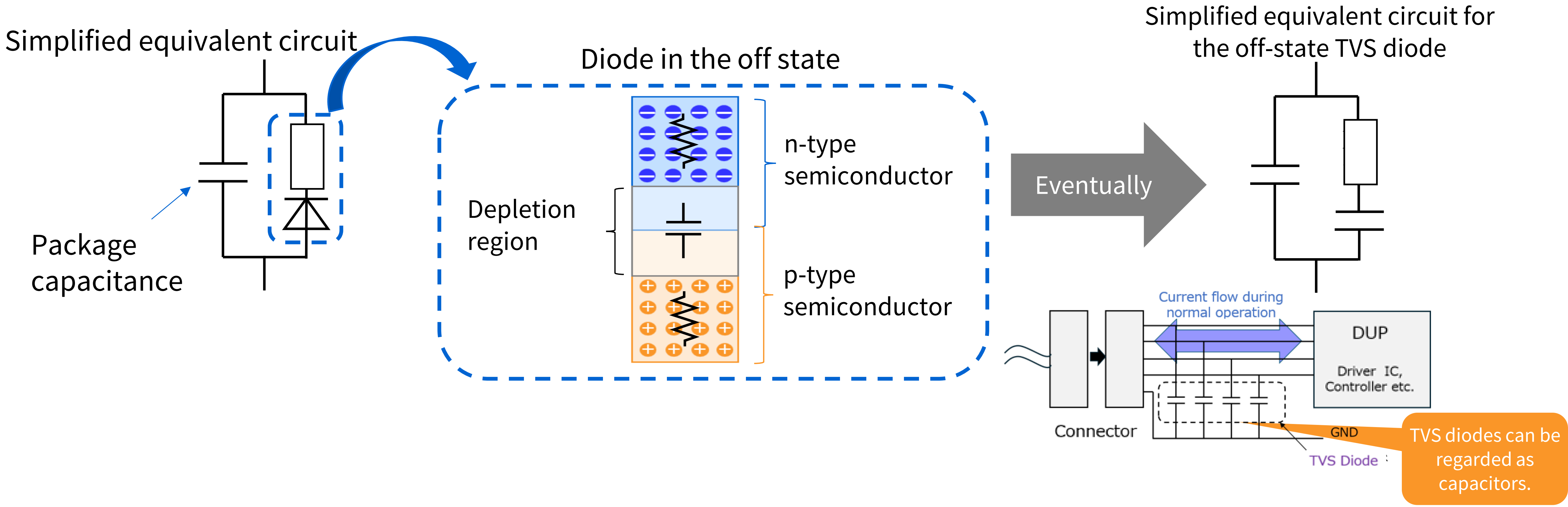


Select bidirectional TVS diodes for bipolar signals.

Characteristics important for TVS diodes: 3. Total capacitance, C_T

3. Total capacitance, C_T

Equivalent circuit of the TVS diode during normal operation



TVS diodes can be regarded as capacitors.

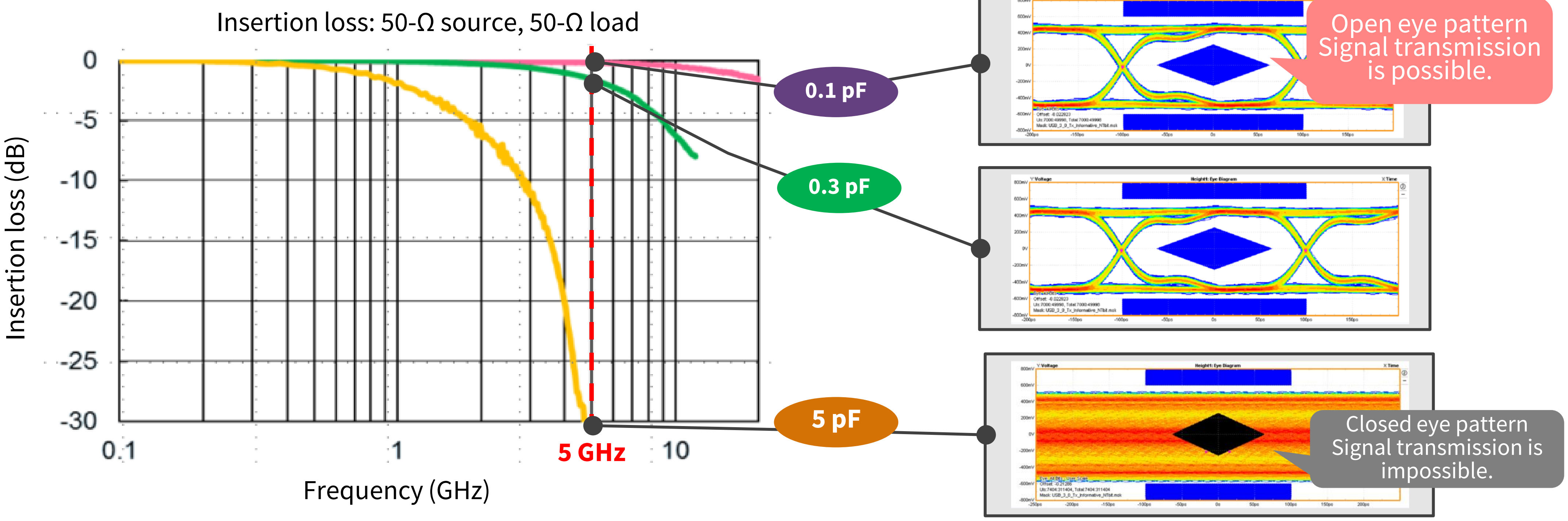
The depletion region of a diode acts as a capacitor, affecting signal waveforms.

Characteristics important for TVS diodes: 3. Total capacitance, C_T

Rounding of rising waveforms

Total capacitance of TVS diodes vs. insertion loss

Eye patterns (when USB 3.1 signals are applied)



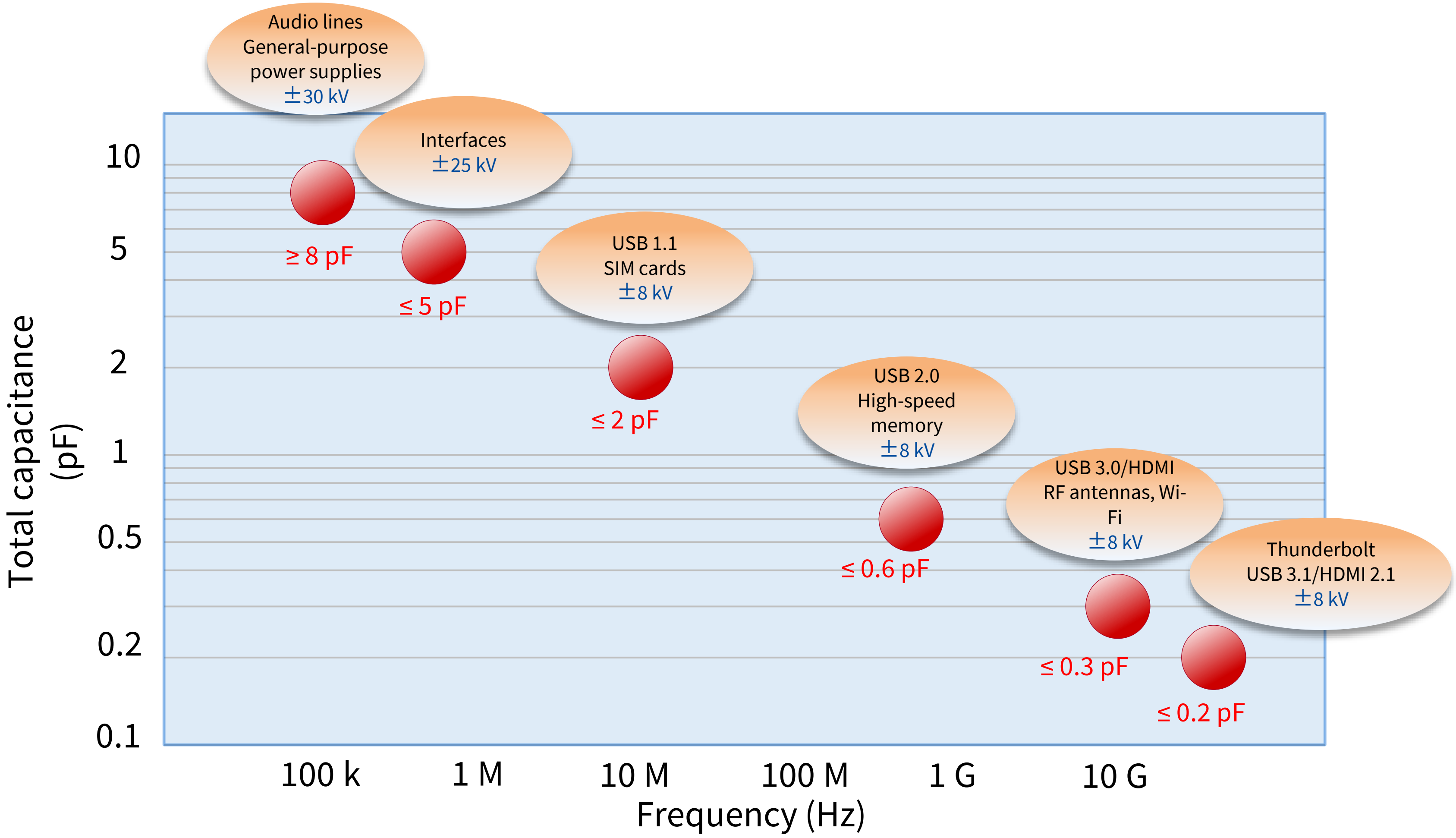
Open eye pattern
Signal transmission is possible.

Closed eye pattern
Signal transmission is impossible.

The signal quality is degraded if you do not choose the right TVS diode, considering the frequency of the signal lines to be protected.

Characteristics important for TVS diodes: 3. Total capacitance, C_T

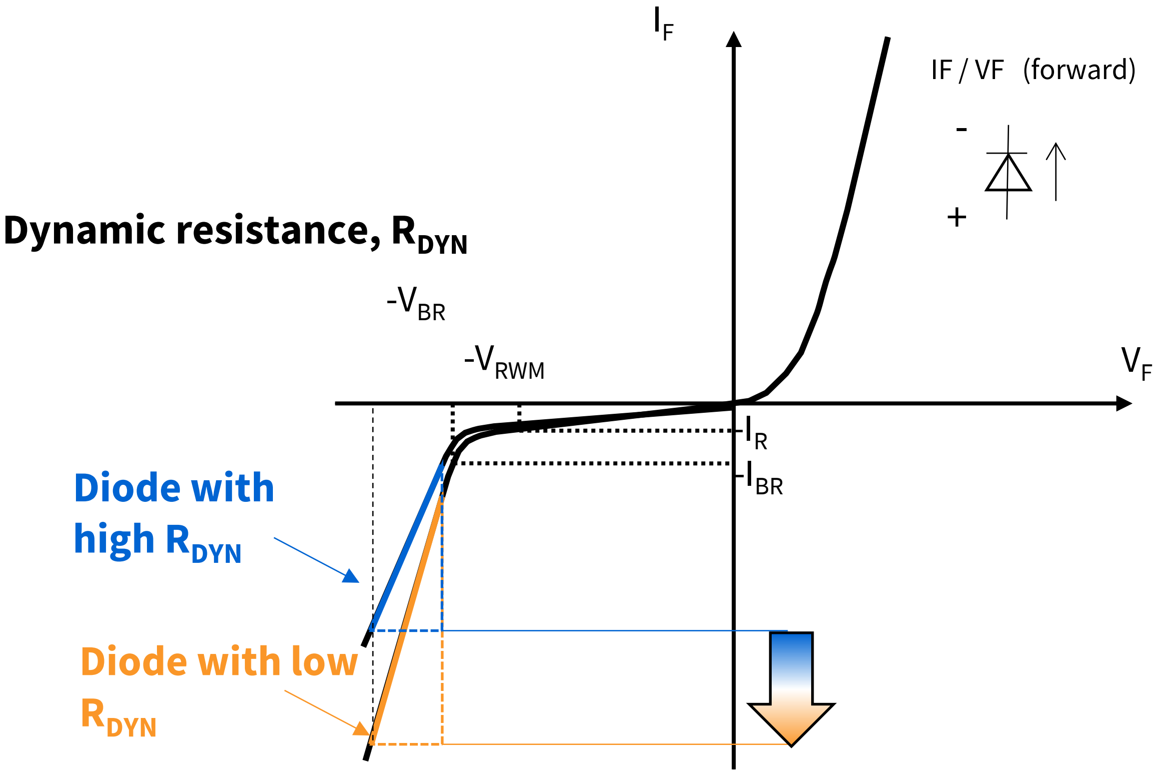
Selecting TVS diodes according to the signal frequency



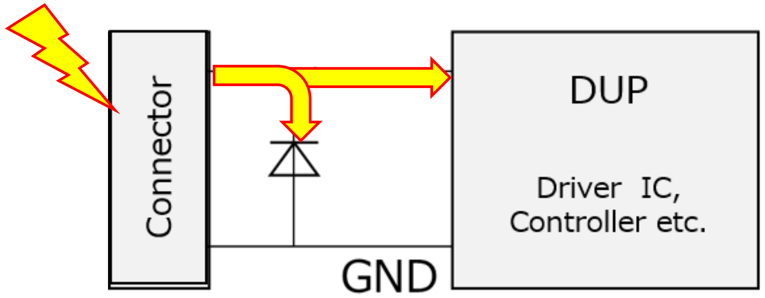
Characteristics important for TVS diodes: 4. Dynamic resistance, R_{DYN}

4. Dynamic resistance, R_{DYN}

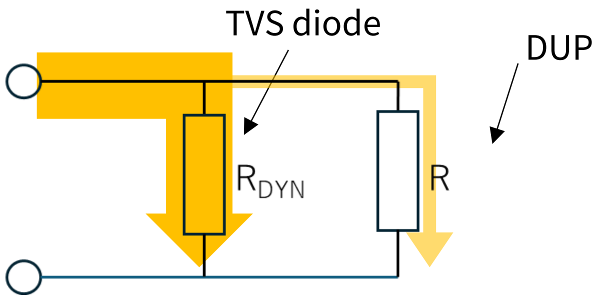
R_{DYN} is the impedance of a TVS diode when it is conducting as a result of a surge.



Where does more surge current flow?



A TVS diode with low R_{DYN} reduces the current that flows to the device under protection (DUP).

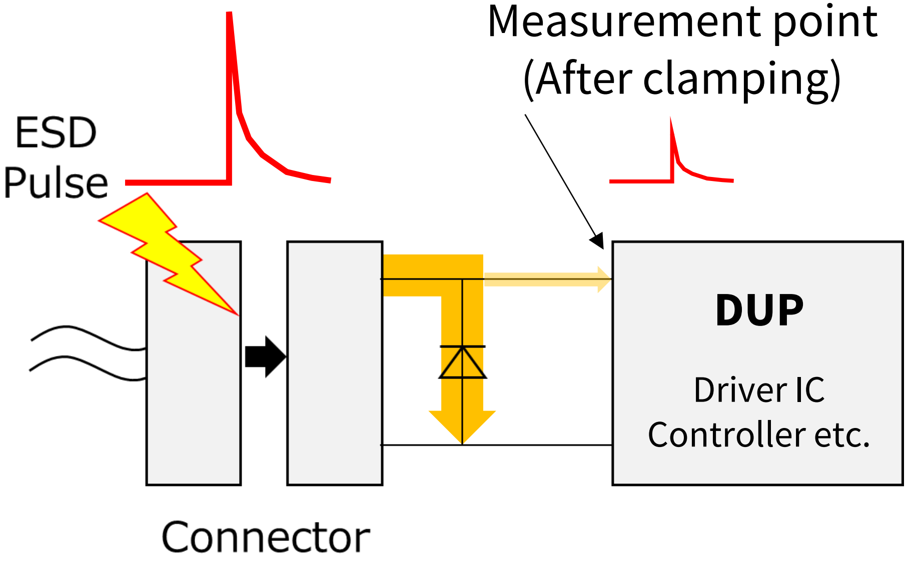


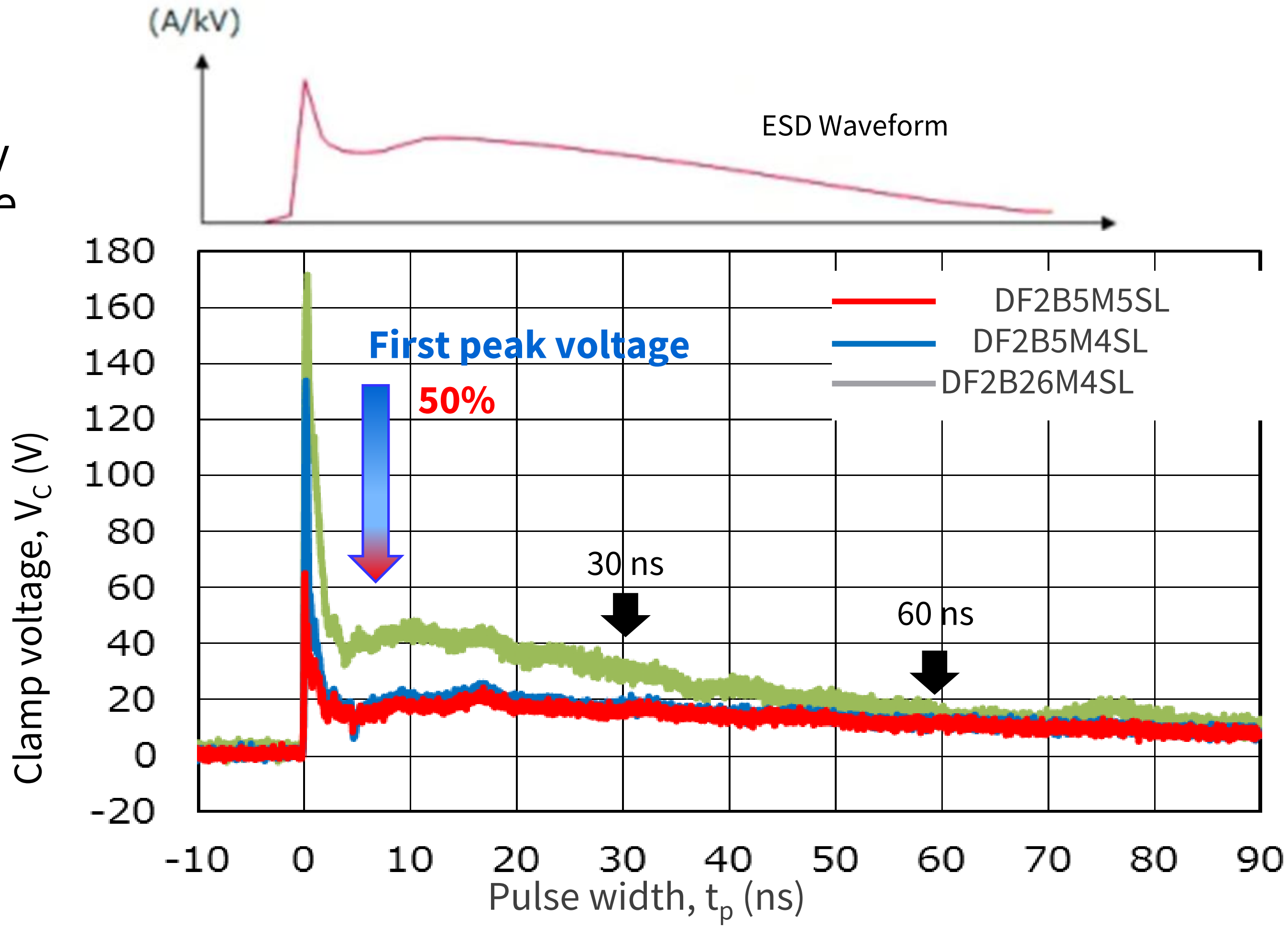
If the TVS has low impedance (i.e., dynamic resistance), most of the surge current is shunted through the TVS diode, reducing the current that flows to the DUP.

Characteristics important for TVS diodes: 5. Clamp voltage, V_C

5. Clamp voltage, V_C

A TVS diode clamps the transient voltage to a safe level specified as V_C. It indicates the ability of the TVS diode to absorb ESD and other surge energies.





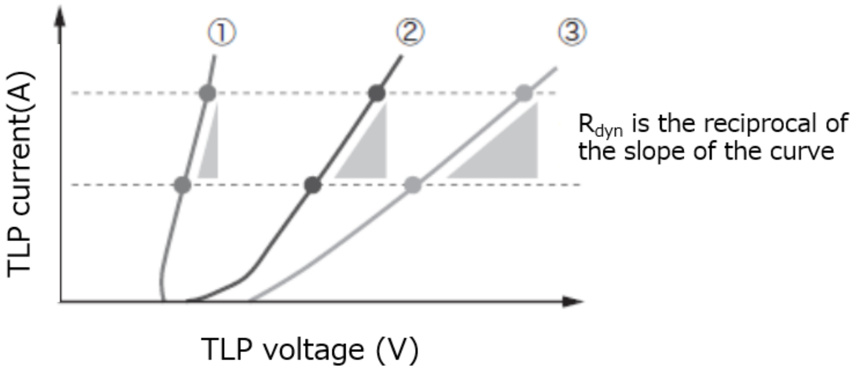
The smaller the area under the curve of the ESD waveform, the less damage the DUP suffers.

Supplement to the descriptions of important characteristics of TVS diodes
Measurement of dynamic resistance and clamp voltage

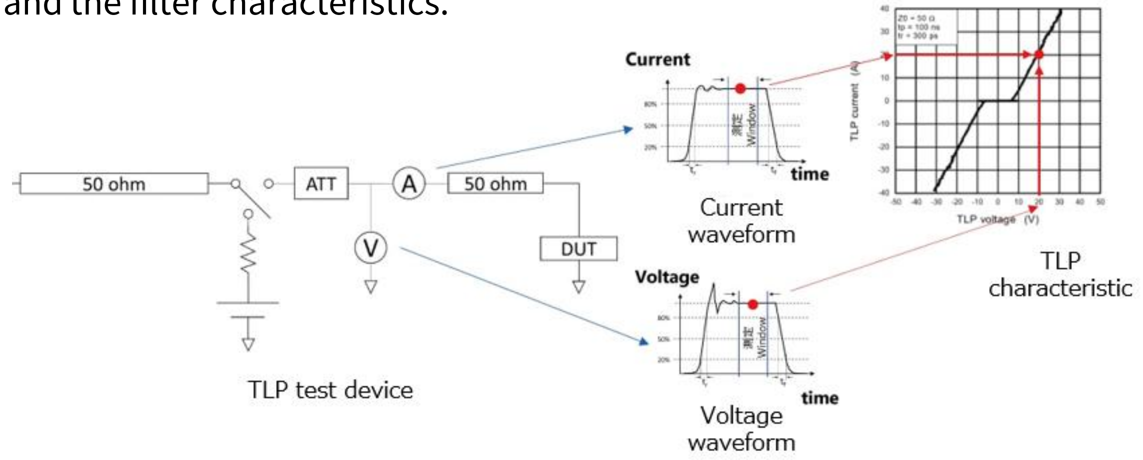
What is a transmission line pulse (TLP) test?

A TLP test shows changes in transient current over time after a surge is applied.

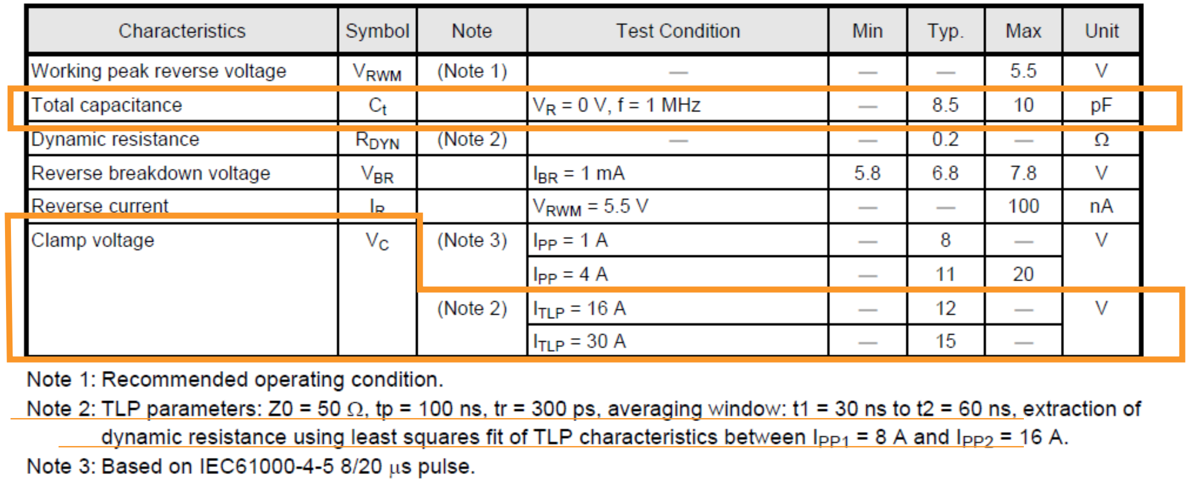
The TLP test uses a short pulse on the order of nanoseconds to obtain the I-V characteristics of a TVS diode in the high-current region without destroying it.



Measurement example:
The pulse width and the rise time are varied by changing the cable length and the filter characteristics.



Example of an electrical characteristics table in a datasheet



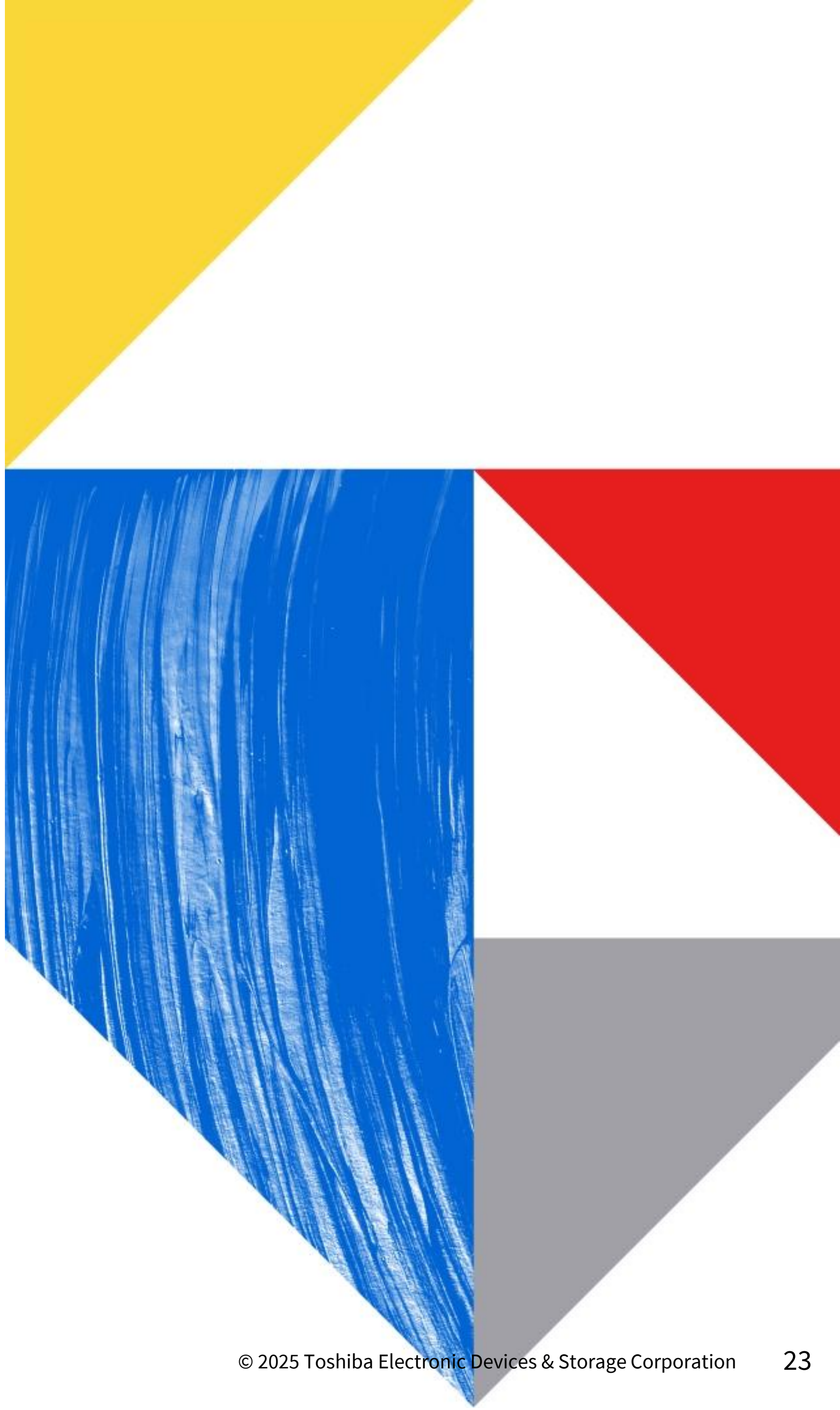
Characteristics	Symbol	Note	Test Condition	Min	Typ.	Max	Unit
Working peak reverse voltage	V_{RWM}	(Note 1)	—	—	—	5.5	V
Total capacitance	C_t		V_R = 0 V, f = 1 MHz	—	8.5	10	pF
Dynamic resistance	R_{DYN}	(Note 2)	—	—	0.2	—	Ω
Reverse breakdown voltage	V_{BR}		I_{BR} = 1 mA	5.8	6.8	7.8	V
Reverse current	I_R		V_{RWM} = 5.5 V	—	—	100	nA
Clamp voltage	V_C	(Note 3)	I_{PP} = 1 A	—	8	—	V
			I_{PP} = 4 A	—	11	20	
		(Note 2)	I_{TLP} = 16 A	—	12	—	V
			I_{TLP} = 30 A	—	15	—	

Note 1: Recommended operating condition.
Note 2: TLP parameters: Z0 = 50 Ω, tp = 100 ns, tr = 300 ps, averaging window: t1 = 30 ns to t2 = 60 ns, extraction of dynamic resistance using least squares fit of TLP characteristics between I_{PP1} = 8 A and I_{PP2} = 16 A.
Note 3: Based on IEC61000-4-5 8/20 μs pulse.

The TLP test serves as an aid for ESD design because it makes it possible not only to compare the ESD protection performance of different TVS diodes but also to compare the ESD tolerance of a TVS diode with the I-V curve of an IC to be protected.

04

Tips for selecting the right TVS diode and circuit design considerations



Selecting TVS diodes

Select the optimum TVS diode based on the following important characteristics.

Maintaining the integrity of the signal lines to be protected

1. Signal line voltage

Select TVS diodes with appropriate reverse breakdown voltage (V_{BR}) or working peak reverse voltage (V_{RWM}) according to the maximum voltage of the signal lines to be protected.

2. Signal polarity

Use bidirectional TVS diodes for signals that cross the GND level such as analog signals.

3. Signal speed

Select TVS diodes with appropriate total capacitance (C_T) according to the maximum frequency of the signal lines to be protected.

These considerations are unnecessary for power supply lines.

Enhancing ESD protection performance

4. Dynamic resistance

Select TVS diodes with dynamic resistance (R_{DYN}) as low as possible.

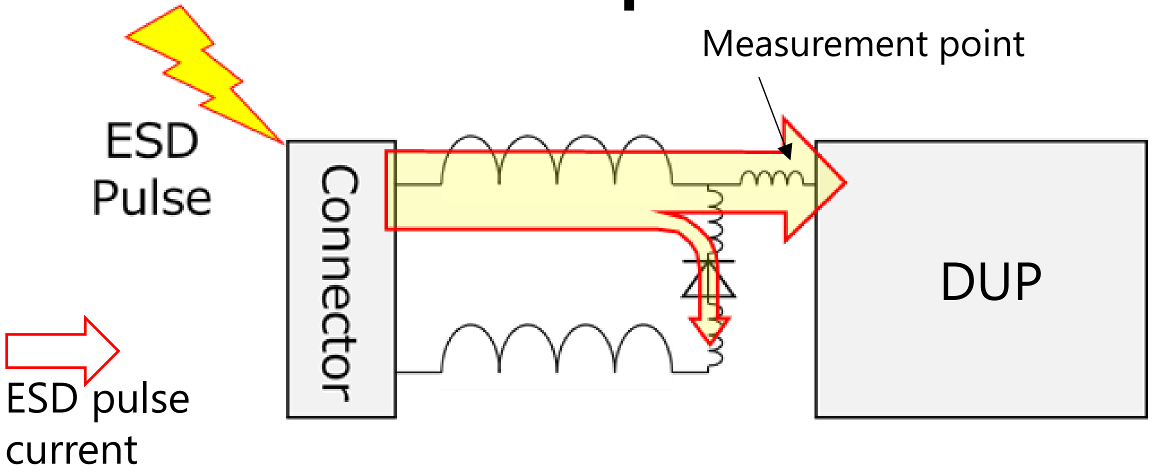
5. Clamp voltage

Select TVS diodes with the minimum clamp voltage (V_C) according to the V_{RWM} required.

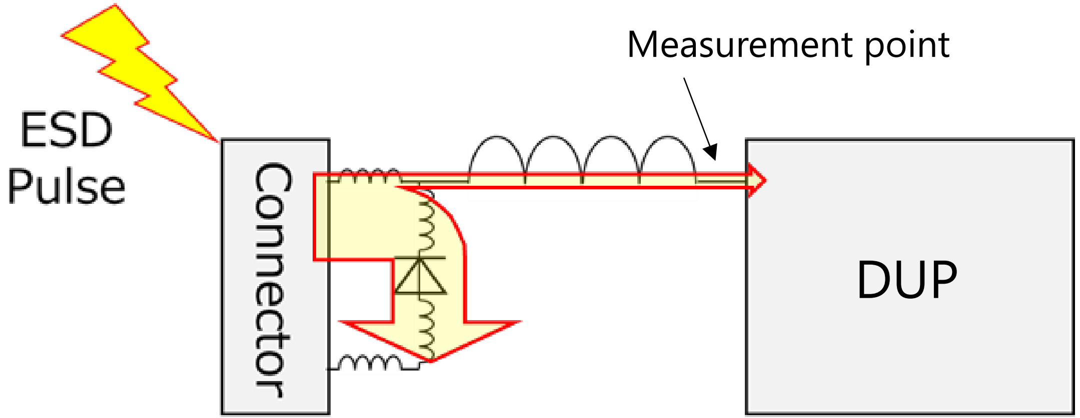
Board layout considerations for TVS diodes

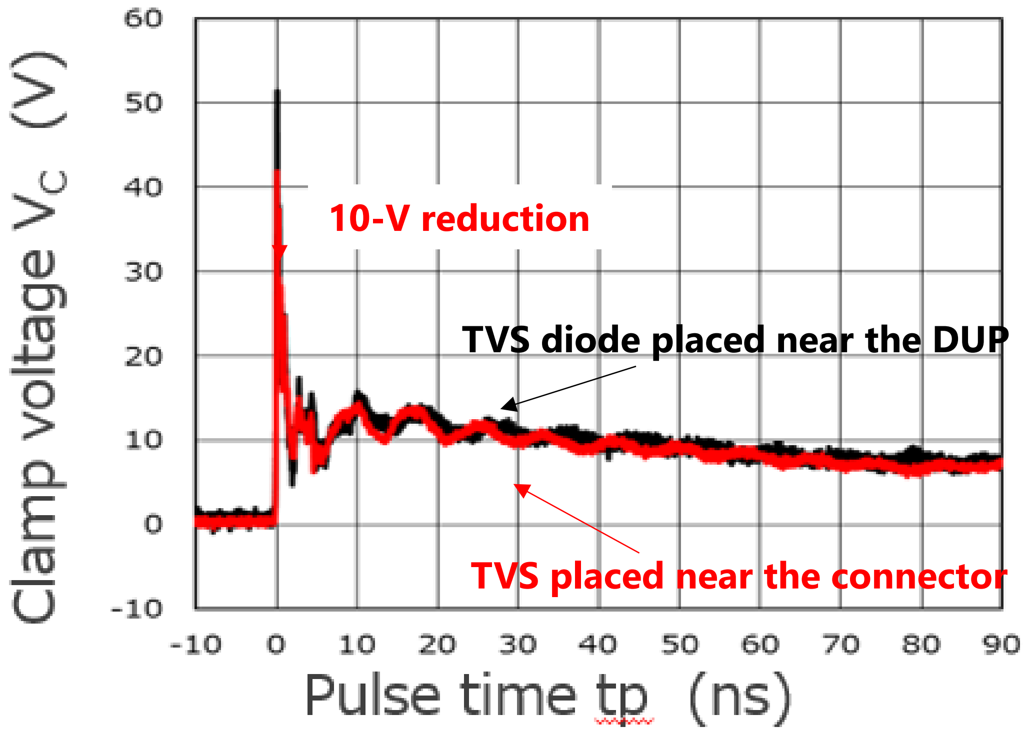
The placement of TVS diodes affects ESD protection performance.

When a TVS diode is placed near the DUP



When a TVS diode is placed **near the connector.**

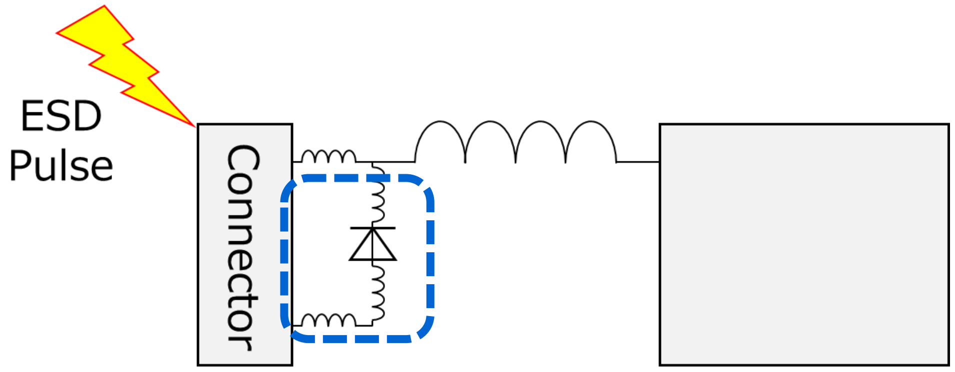




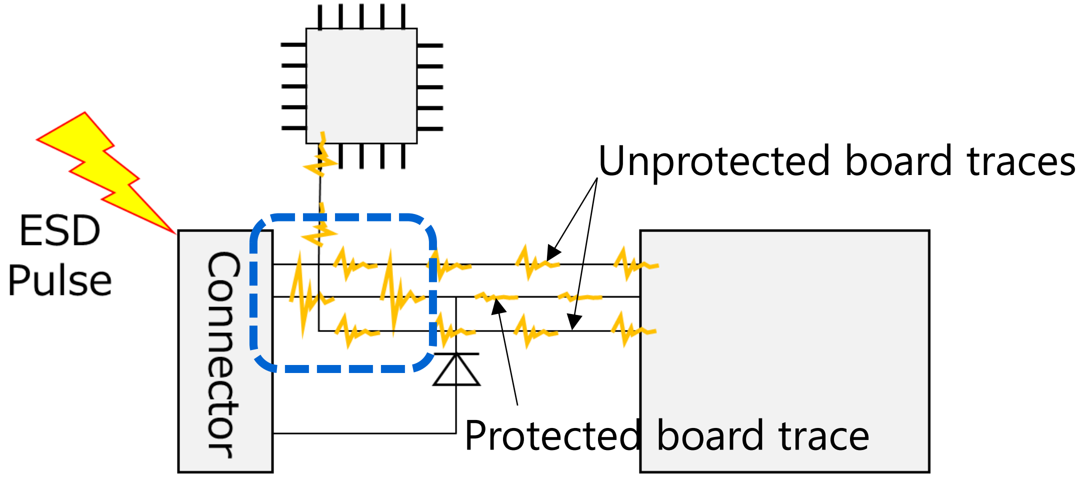
Board layout considerations for TVS diodes

Layout considerations

1. Place TVS diodes close to the ESD entry point.
2. Minimize trace inductance in series with TVS diodes including GND after the board traces originating from the connector diverge into two paths leading to TVS diodes and the DUP.
3. Do not run any board trace in parallel with a signal trace to which an ESD pulse might be introduced. Pay attention particularly to the traces that are only internally connected.



TVS diode placed near the connector

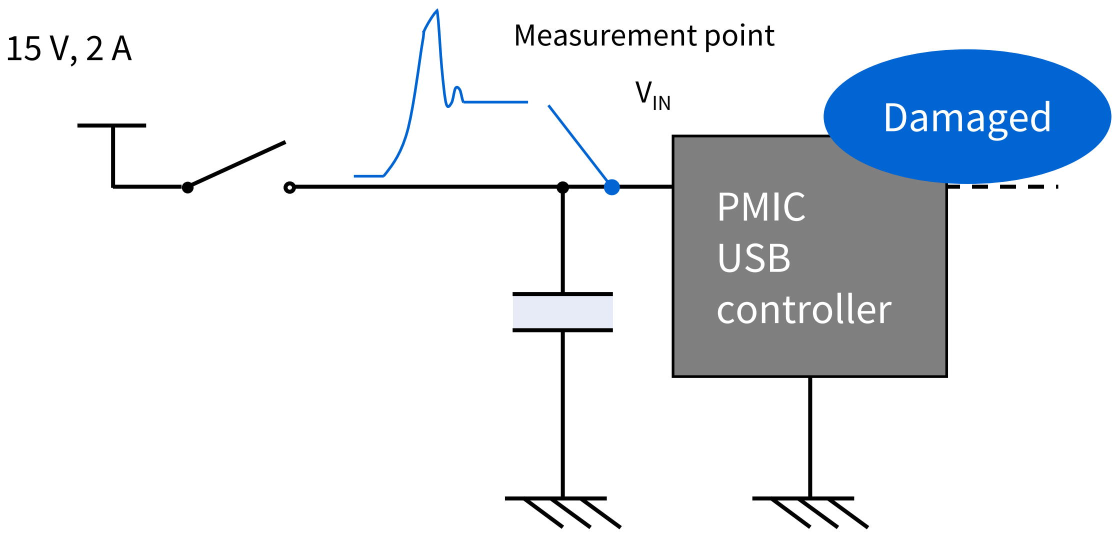


Do not run protected and unprotected board traces in parallel.

Overvoltage protection of power supply lines

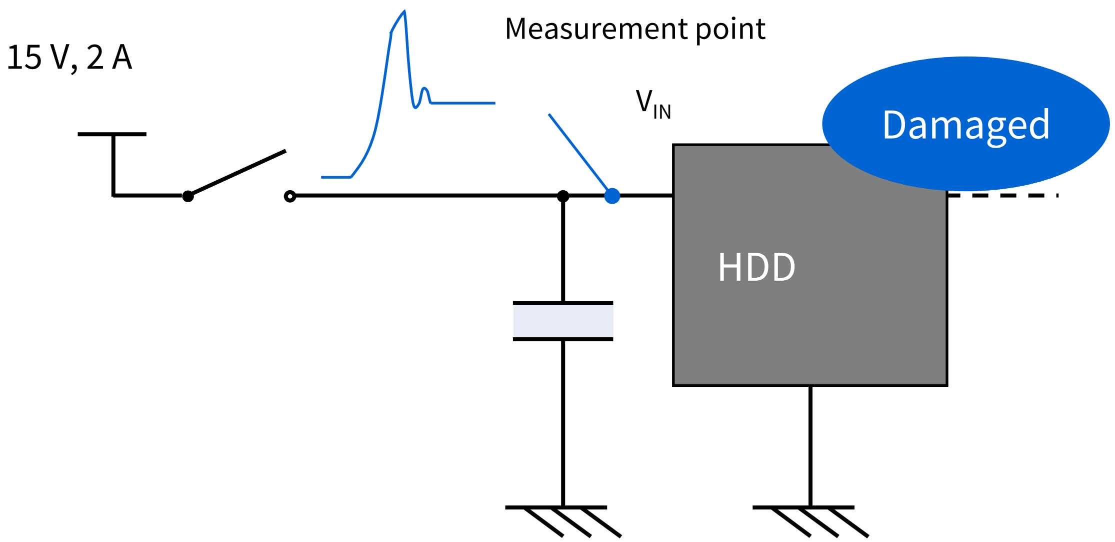
Protect power supply lines not only from ESD but also from overvoltage transients.

Notebook PC



- The power supply fails to turn on.
- A communication link is interrupted.

Server



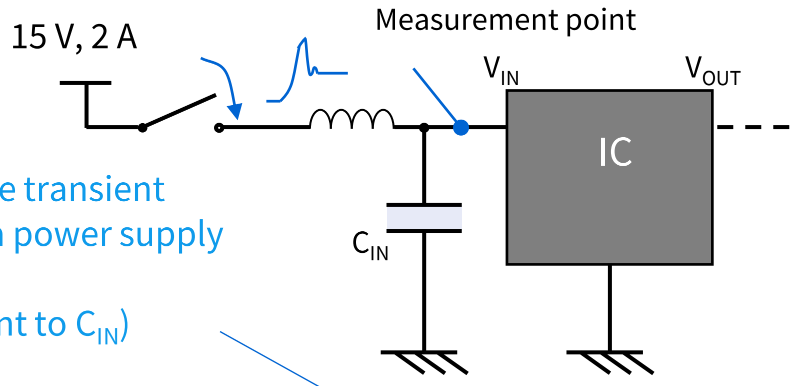
- Important data become corrupted.

Overvoltage protection of power supply lines

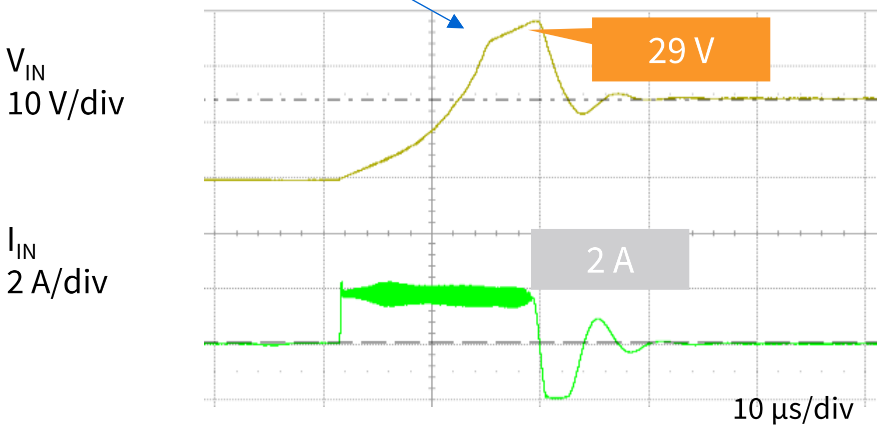
You can easily protect internal circuitry and ICs from overvoltage transients using Zener protection diodes.

Reference

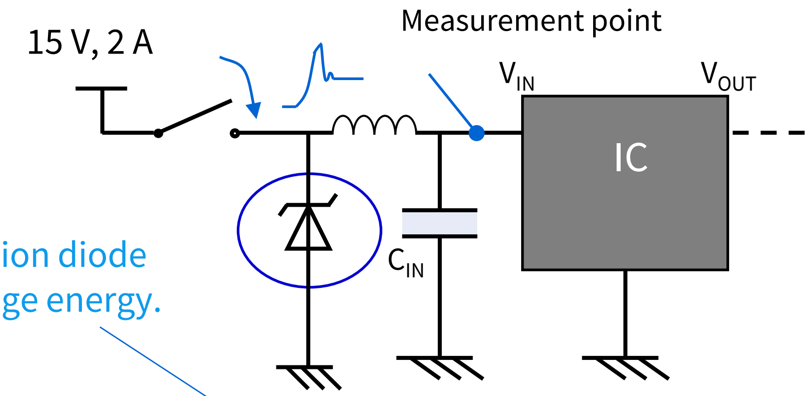
Without a Zener protection diode



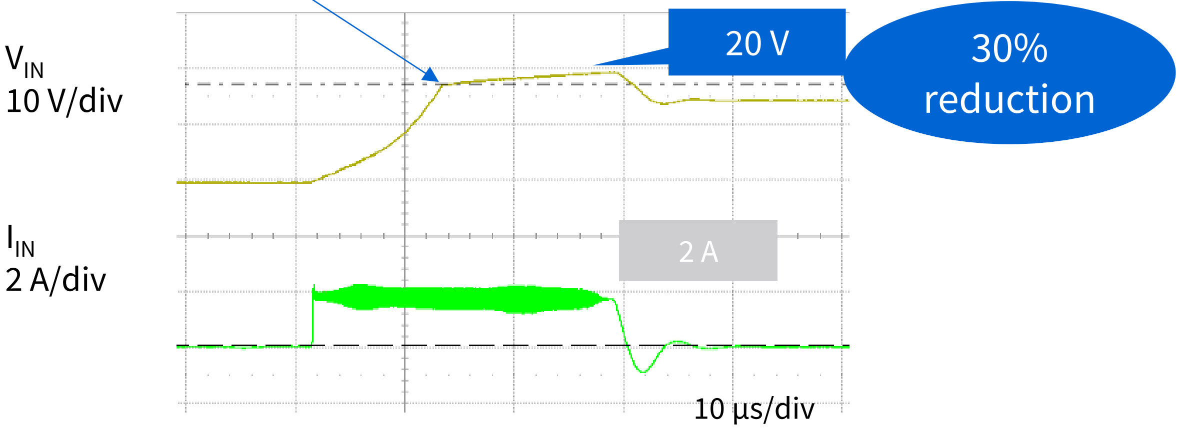
An overvoltage transient occurs when a power supply is turned on.
(In-rush current to C_{IN})



With a Zener protection diode



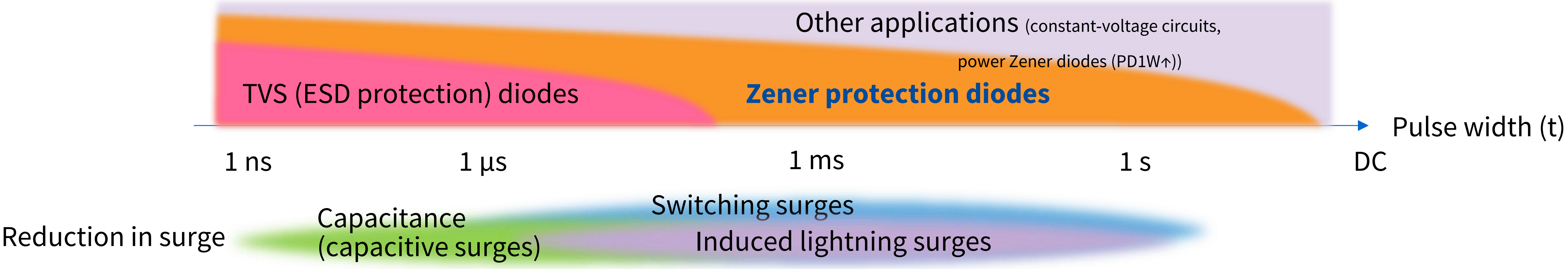
The Zener protection diode absorbs overvoltage energy.



Zener diodes suitable for overvoltage protection of power supply lines

Zener protection diodes protect circuits from surges of various durations.

Causes of surges and protection devices suitable for surge protection



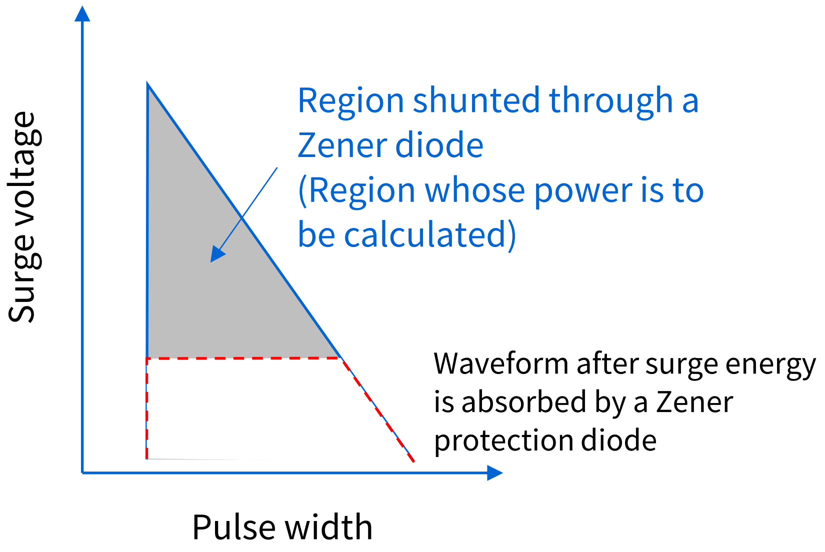
Characteristics of protection diodes

	TVS (ESD protection) diodes	Zener protection diodes
Major applications	Protection from overvoltage transients of a duration on the order of microseconds or less	Protection from overvoltage transients longer than microseconds (Also usable for ESD protection*1)
Total capacitance	≥0.12 pF	100 pF to 600 pF
Locations (examples)	USB, HDMI, and other connectors	Power supply lines, power supply control lines
Remarks	Available with 1 pF and lower capacitance	Protection against near-DC overvoltage transients within permissible power dissipation

Considerations for using Zener diodes for power supply lines overvoltage protection

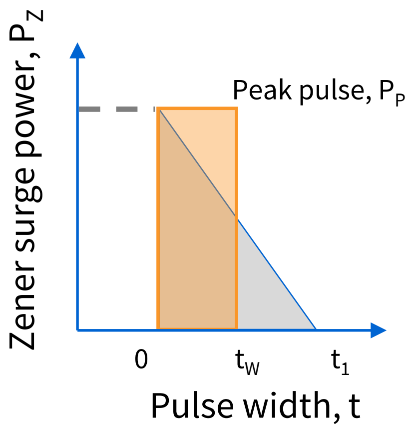
To protect a DUP from long overvoltage transients, choose a Zener diode capable of absorbing surge energy that could possibly occur.

Overvoltage transient waveform

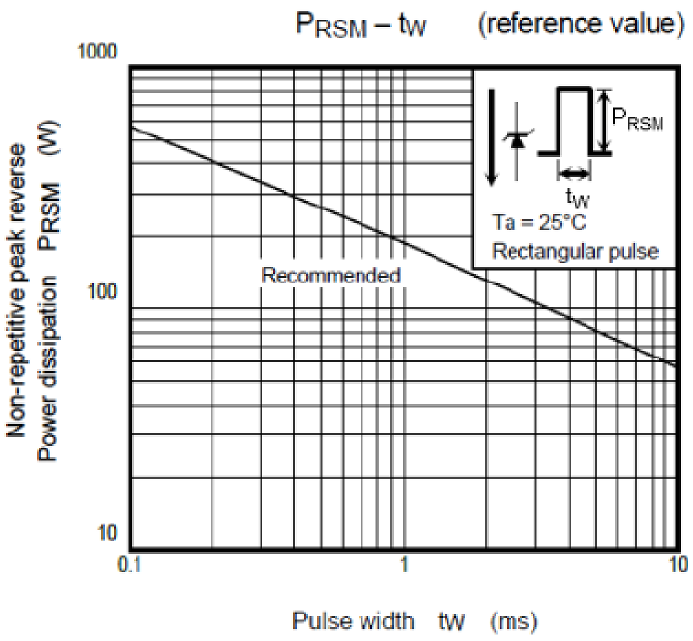


Approximation of diode power dissipation

$$t_W = \frac{1}{P_P}\int_0^{t_1} P_{Z(t)}dt$$

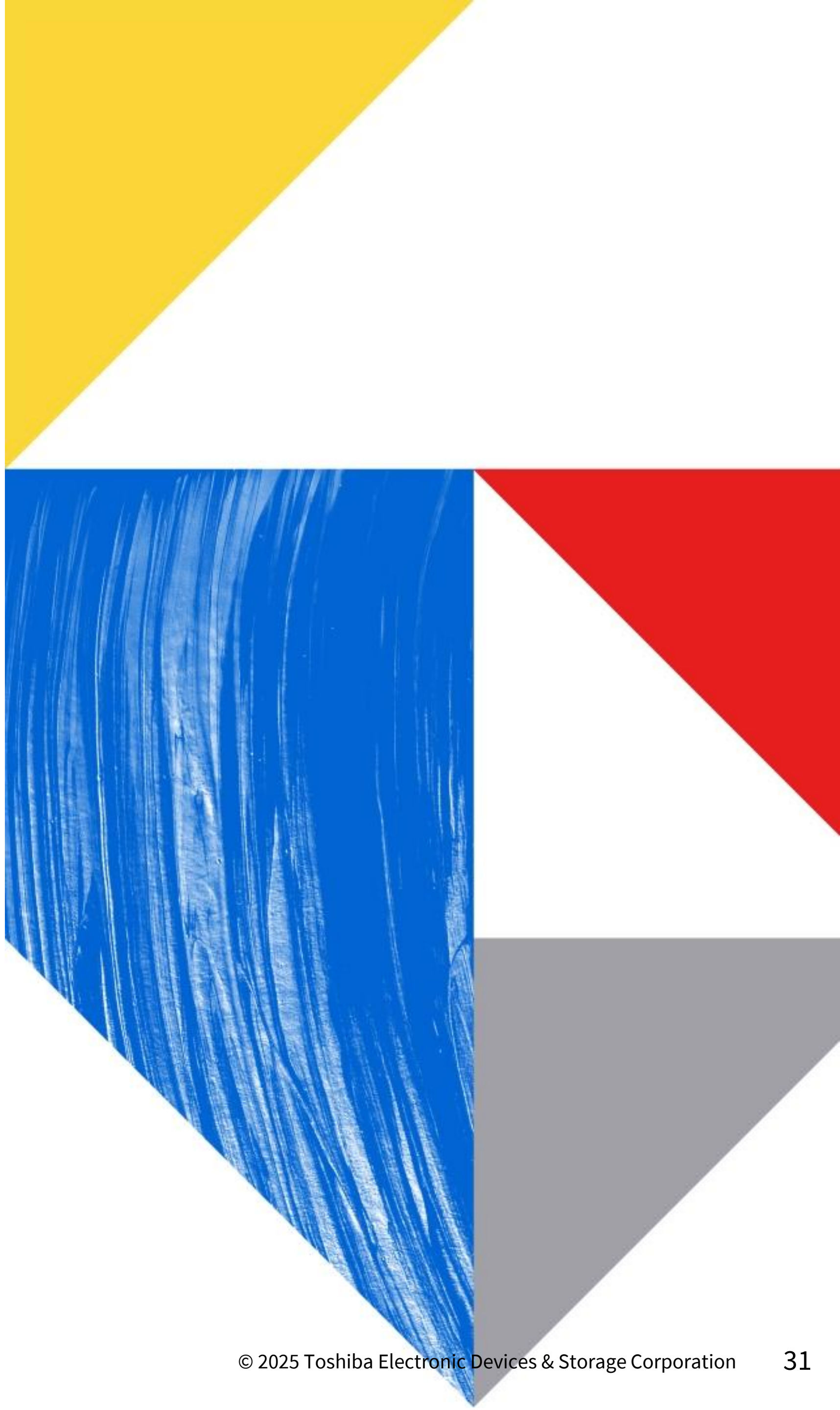


Non-repetitive peak power dissipation



05

Latest TVS diodes



Technological roadmap for TVS diodes

	~2017	2018	2019	2020	2021	2022	2023	2024	2025〜

Process generation

EAP：ESD Diode Array Process

Rdyn：0.7Ω
Vc　　：13V
ESD：±12kV

Low R_{dyn}: 0.5 Ω
Low V_c: 7.5 V
High ESD: ±20 V

Product and package lineups

SOD-962 (SL2)
0.62×0.32 mm

SOD-882 (CST2)
1.0×0.6 mm

SOD-923
1.0×0.6 mm

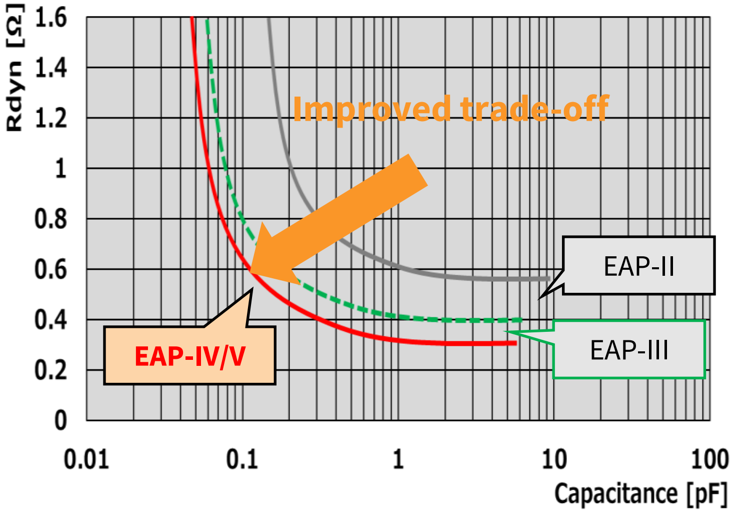
Low first peak voltage
Low R_{dyn}: 0.5 Ω
High ESD: ±20 V

Next

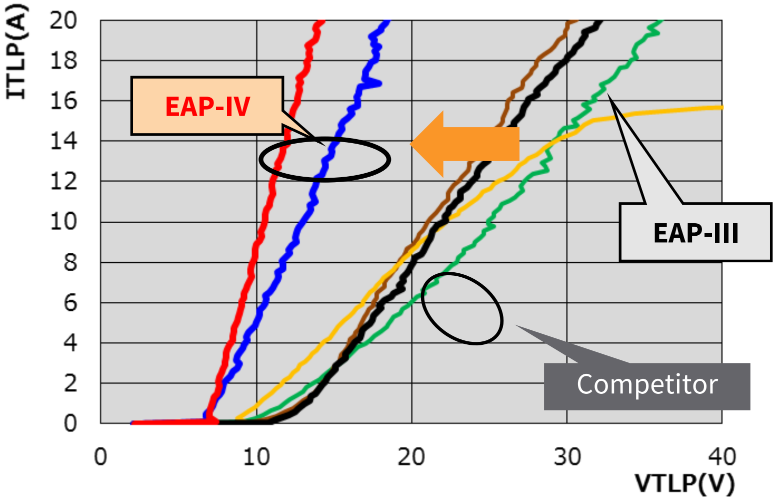
Deep snapback devices
Ultralow clamp voltage (V_C) technology

Low Capacitor For dataline

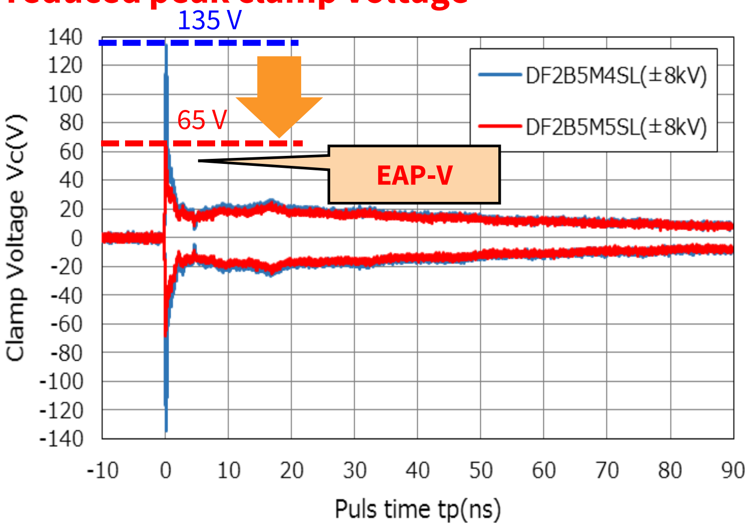
Improved trade-off between dynamic resistance and capacitance



Increased ESD immunity due to reduced clamp voltage



Enhanced protection performance due to reduced peak clamp voltage



Low-capacitance TVS diodes fabricated with a new process (EAP-V)

DF2xxM5 series

Excellent surge protection due to low clamp voltage (C_T)

SL2 (SOD-962)
(0.62×0.32 mm)

SOD-882 (CST2)
1.0×0.6 mm

- **Maximum working peak reverse voltage:**

V_{RWM} = 3.3 V / 5.0 V

- **Ultralow clamp voltage:**

First peak voltage, V_{peak} = 70 V (DF2B6M5SL)

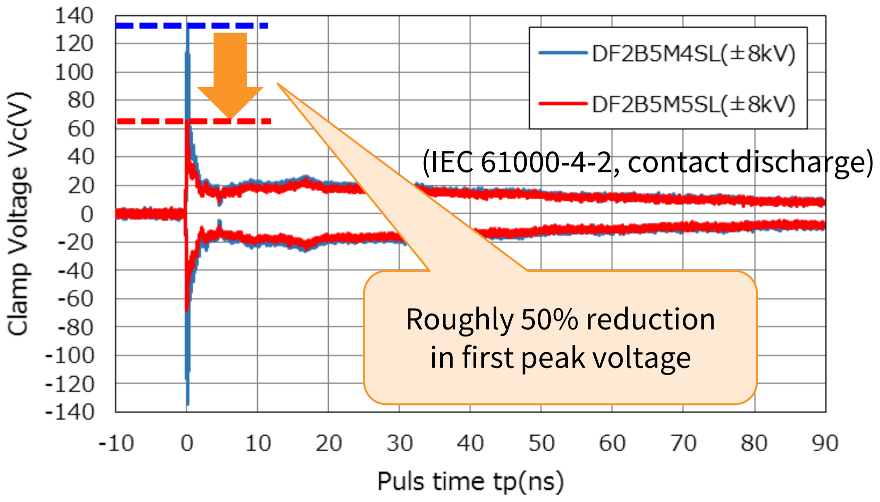
- **Ultralow total capacitance:**

C_T = 0.3 pF (bidirectional) / 0.6 pF (unidirectional)

- **Low dynamic resistance:**

R_{DYN} = 0.3 to 0.5 Ω typical

Note: DF2xxM5SL: SL2 package, DF2xxM5CT: CST2 package



Part Number	Structure	V_{RWM} Max (V)	First V_{peak} Level Typ. (V)	C_T @ 0 V Typ. (pF)	R_{DYN} Typ. (Ω)	V_{ESD} Min (kV) IEC 61000-4-2 (contact discharge)	V_{CL} Max (V) @ I_{pp} = 2 A IEC 61000-4-5 (8/20-µs pulse)	Availability
DF2B5M5SL/CT	Bidirectional	3.3	65	0.3	0.5	±20	15	Available
DF2B6M5SL/CT		5.0	70	0.3	0.5	±20	15	
DF2S5M5SL/CT	Unidirectional	3.3	60	0.6	0.3	±20	15	
DF2S6M5SL/CT		5.0	65	0.6	0.3	±20	15	

Ultralow-capacitance TVS diodes (0.15 pF typical)

DF2B5M4ASL, DF2B5M4ASL

Available with ultralow capacitance for protection of USB 3.1 and other high-speed signal lines

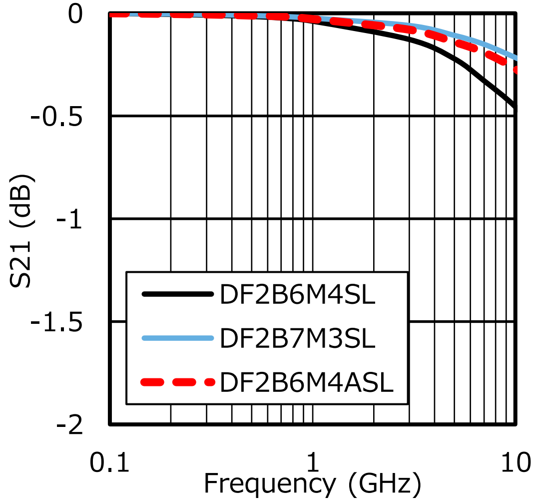
SL2 (SOD-962)
(0.62×0.32 mm)

- **Applications: USB 3.1 and other high-speed signal lines**
- **Ideal for high-speed signal lines: C_T = 0.15 pF typical**
- **Available with two V_{RWM} points:** 3.6 V / 5.5 V
- **High ESD immunity: V_{ESD} = ±15 kV**

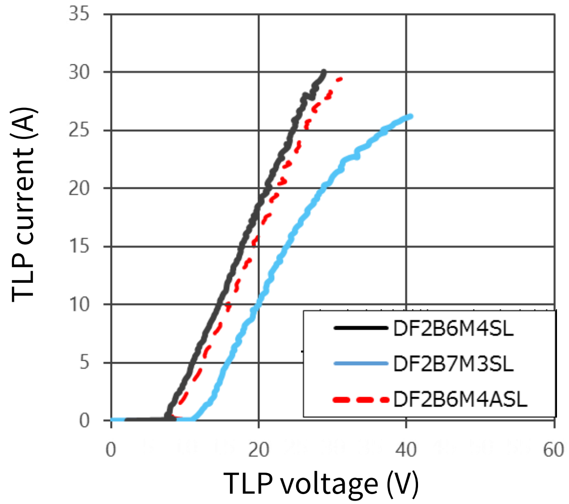
(IEC 61000-4-2, contact discharge)

- **Low clamp voltage:** 20 V at I_{TLP} = 16 A

Estimated insertion loss



TLP performance



Part Number	V_{RWM} Max (V)	C_T at 0 V (pF)		V_{ESD} Min (kV) IEC 61000-4-2 (contact discharge)	V_{CL} Typ. (V) @ I_{TLP} = 16 A	R_{DYN} Typ. (Ω)	Availability
		Typ.	Max.				
DF2B5M4ASL	3.6	**0.15**	**0.20**	**±16**	**20**	0.7	**Available**
DF2B6M4ASL	5.5	**0.15**	**0.20**	**±15**	**20**	0.7	
DF2B7M3SL	5.5	0.12	0.20	±12	(25)	0.7	
DF2B6M4SL	5.5	0.20	0.30	±20	18	0.5	

Zener diodes for general-purpose protection

Small Zener diodes for overvoltage protection

Zener diodes for protection against electrical stress

■ Characteristics

- ➢ **Wide voltage range:**

V_Z (typ.) = 5.6 to 36 V

- ➢ **Packages of various sizes:**

Available in four types of general-purpose packages as well as the small US2H package with high allowable power dissipation

■ Typical applications

- ➢ Home appliances

(PCs, TVs, air conditioners, vacuum cleaners, etc.)

- ➢ Industrial equipment

(Factory automation control equipment, networking equipment, etc.)

■ Package lineup

Category	Package		Series	Power Dissipation
2-pin general-purpose Zener diodes	**ESC** (SOD-523) 1.6×0.8 mm		**CEZ series**	150 mW*1
	USC (SOD-323) 2.5×125 mm		**CUZ series**	200 mW*1
3-pin general-purpose Zener diodes	**USM** (SOT-323) 2.1×2.0 mm		**MUZ series**	150 mW*2
	S-Mini (SOT-346) 2.9×2.5 mm		**MSZ series**	200 mW
2-pin power Zener diodes	**US2H** (SOD-323HE) 2.4×1.4 mm		**CUHZ series**	1000 mW*3

Small package lineup **SL2**(SOD-962) 0.62x0.32mm  **CSLZ series**

*1: FR4 board (20×20 mm, Cu pad: 4×4 mm)
*2: FR4 board (20×20 mm, Cu pads: 0.5 mm^2 x3)
*3: FR4 board (25.4×25.4 mm, Cu pad: 645 mm^2)

■ Typical TVS diodes and their intended applications

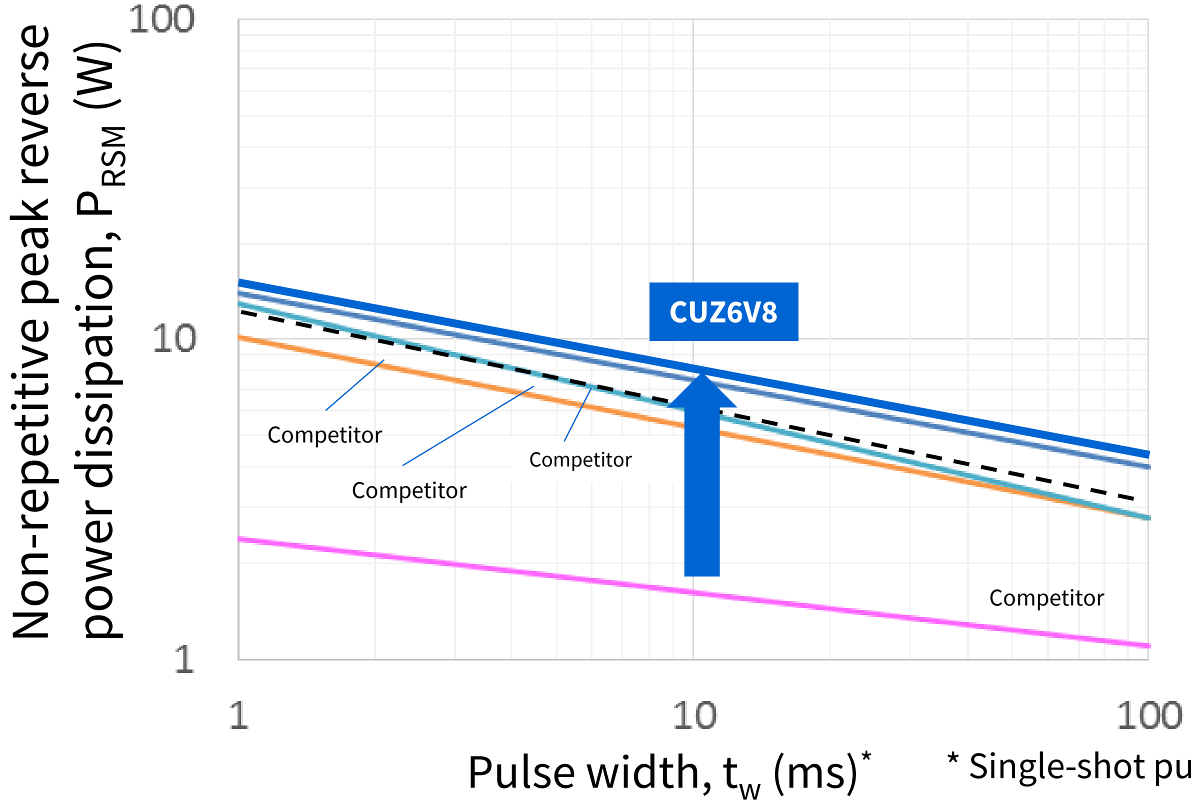
V_Z Typ. (V)	Typical Part (CUZ Series)	Applications	V_Z Typ. (V)	Typical Part (CUZ Series)	Applications
5.6 V	CUZ5V6	Low voltage	16 V	CUZ16V	12-V lines
6.2 V	CUZ6V2	3.3-V lines	20 V	CUZ20V	16-V lines
6.8 V	CUZ6V8	5-V lines	24 V	CUZ24V	20 V
8.2 V	CUZ8V2	5-V lines	30 V	CUZ30V	24 V
12 V	CUZ12V	9-V lines	36 V	CUZ36V	32 V

Comparison of Zener surge power: P_{RSM} vs t_w (reference)

Because of high surge immunity, Toshiba’s small Zener diodes provide protection against high-energy surges.

Reference

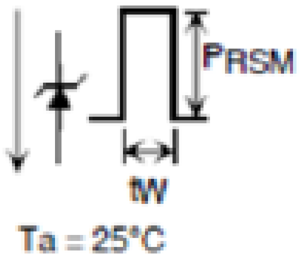
P_{RSM} vs t_w*



* Single-shot pulse

2.5×1.25 mm

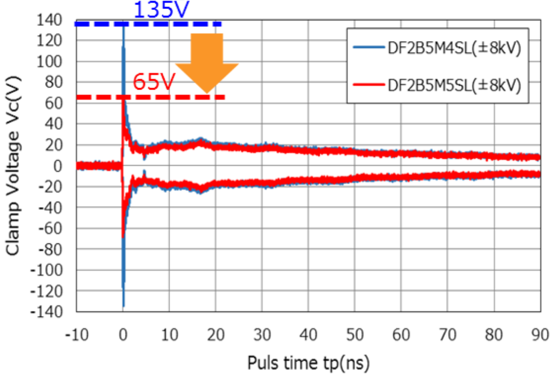
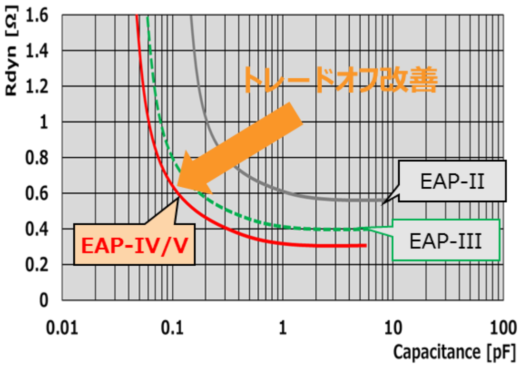
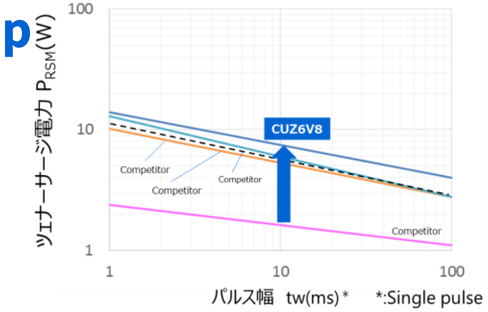
* Test condition



Non-repetitive single-shot pulse

Summary

In response to requests for key characteristics of TVS diodes, Toshiba Diodes will continue to advance new technologies and product development.

Apps	Operating condition	**Key characteristics**	**Summary of TVS Diode Key Features and Toshiba Approach**
Signal Line	Protection (Surge)	**Dynamic Resistance R_{DYN}, Clamping Voltage V_C**	**1st peak voltage reduction, low dynamic resistance and low capacitance**  
	Normal operation (Non surge)	**Reverse Breakdown Voltage V_{BR}, Forward Voltage V_F, Signal Polarity, Terminal Capacitance C_T**	
Power Line	Protection (Surge)	**Clamping Voltage V_C, Maximum Surge Energy Tolerance**	**High surge energy capability and improved permissible loss for package lineup** 

Thank you for your attention.

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