e-Learning

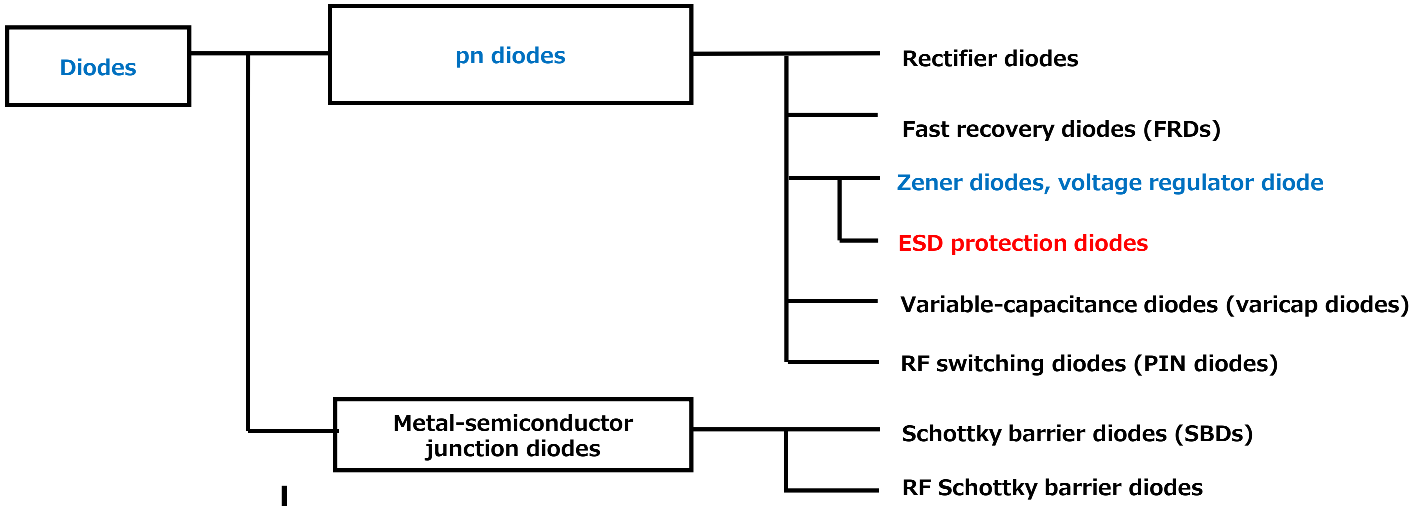
Basics of TVS Diodes (ESD protection diodes)

Toshiba Electronic Devices & Storage Corporation

1. What is a TVS diode (ESD protection diode)?

An ESD protection diode is a type of Zener diode.
When a diode is reverse-biased, little current flows from cathode to anode. However, when the reverse bias exceeds a certain point (called the reverse breakdown voltage), the reverse current suddenly increases. As the reverse bias is increased, the diode reaches a region of a constant voltage regardless of the current flowing through the diode. The breakdown voltage (Zener voltage) characteristics of Zener diodes are utilized to compose a constant-voltage regulator and suppress surge voltage. Zener voltage regulator diodes are used to maintain a constant voltage whereas ESD protection diodes are used to absorb ESD energy in order to protect an electronic circuit.

TVS: Transient voltage suppressor



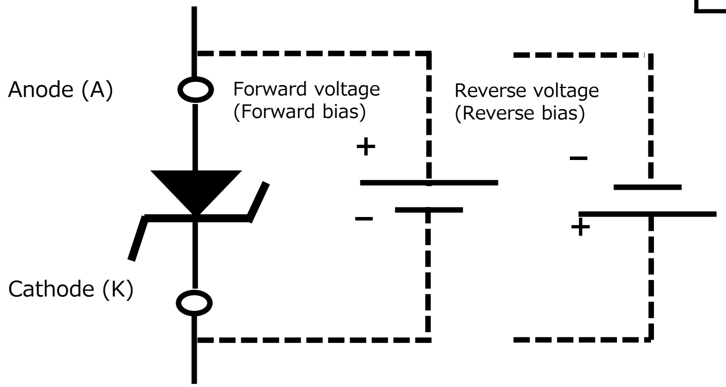


Figure 1.1 Forward and reverse biases across a Zener diode

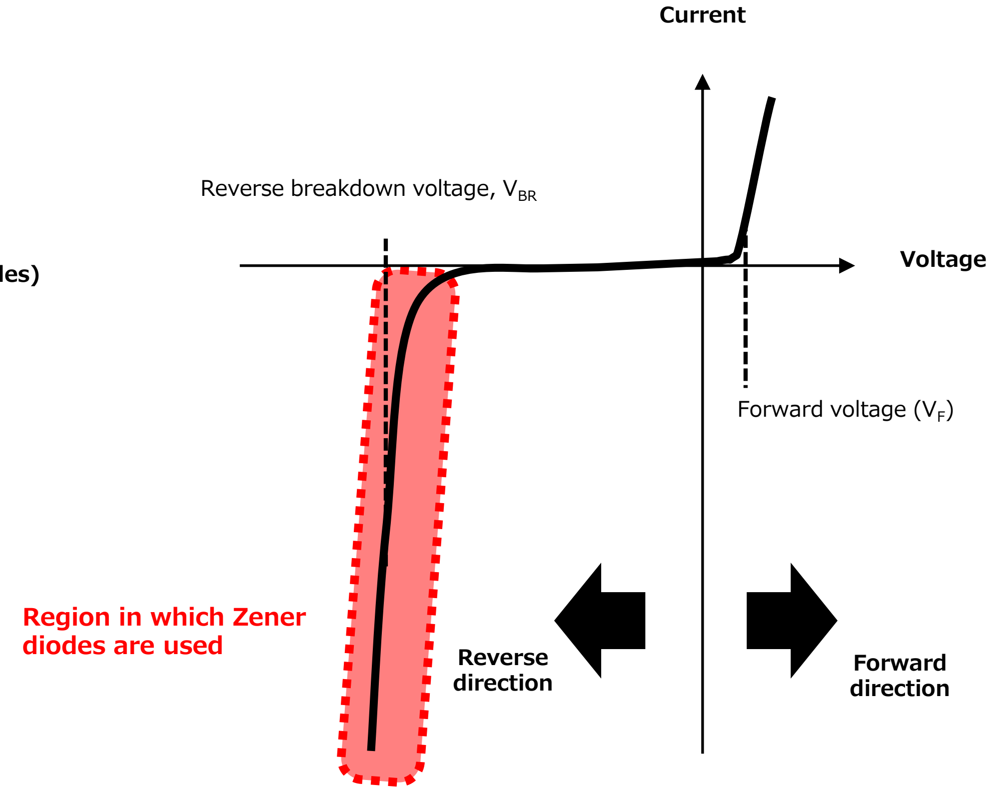


Figure 1-2. Diode characteristics

1-1. Reverse breakdown voltage

The reverse breakdown voltage is determined by Zener breakdown or avalanche breakdown.

Zener breakdown

When a pn junction is reverse-biased, a depletion layer extends across the pn junction. An electric field causes a gap between the valence band of the p-type region and the conduction band of the n-type region to decrease inside the depletion layer. As a result, electrons tunnel from the valence band of the p-type region to the conduction band of the n-type region because of quantum tunneling. Zener breakdown is a phenomenon in which the tunneling of electrons across the depletion region causes a sudden increase in reverse current. Figure 1.3 illustrates Zener breakdown.

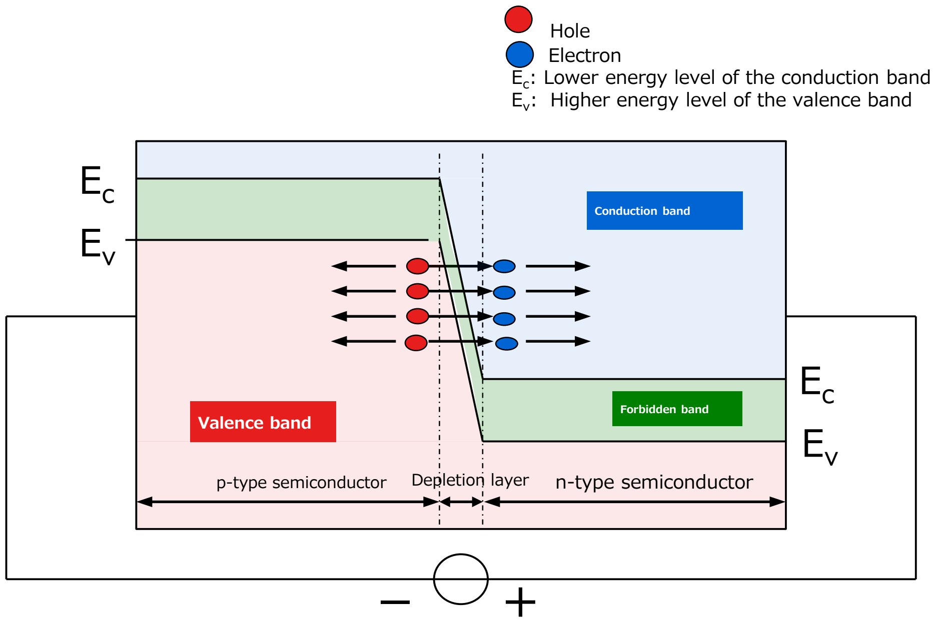


Figure 1.3 Zener breakdown

1-1. Reverse breakdown voltage

The reverse breakdown voltage is determined by Zener breakdown or avalanche breakdown.

Avalanche breakdown

When a pn junction is reverse-biased, a small quantity of electrons passes through the pn junction. These electrons are accelerated in the depletion layer by an electric field, acquiring large kinetic energy. The accelerated electrons collide with the atoms in a crystal lattice, ionizing them and creating electron holes. The electrons of these atoms are excited to the conduction band and knocked out, becoming free electrons. The free electrons are also accelerated and collide with other atoms, creating more electron-hole pairs and leading to further knocking-out processes. This phenomenon is called avalanche breakdown.

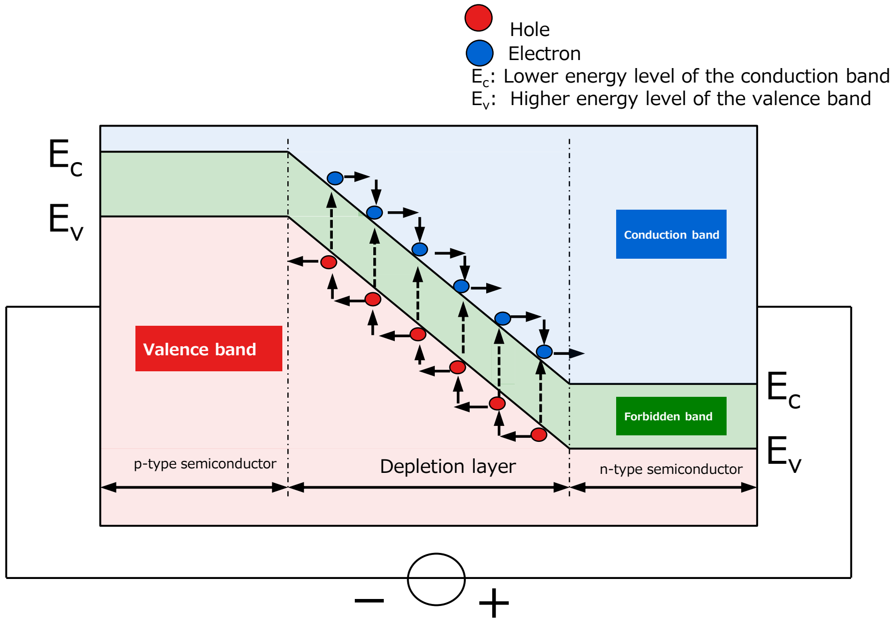


Figure 1.4 Avalanche breakdown

1-1. Reverse breakdown voltage

The reverse breakdown voltage is determined by Zener breakdown or avalanche breakdown.

<u>Comparison of avalanche breakdown and Zener breakdown</u>

Since diodes with high breakdown voltage are lightly doped, they form a wide depletion layer (forbidden band). Conversely, since diodes with low breakdown voltage are heavily doped, they form a thin depletion layer (forbidden band). When a diode has a wide depletion layer, electron tunneling (Zener breakdown) is less likely to occur, causing avalanche breakdown to become more predominant. In the case of a heavily doped diode with a thin depletion layer, Zener breakdown is more like to occur. As temperature increases, the width of the forbidden band (E_g) decreases, contributing to the Zener effect. In addition, as temperature increases, the lattice vibration of a semiconductor increases, causing its carrier mobility to decrease. As a result, avalanche breakdown becomes less likely to occur. Zener breakdown voltage decreases with temperature whereas avalanche breakdown voltage increases with temperature. Generally, Zener breakdown is predominant below roughly 6 V whereas avalanche breakdown is predominant above roughly 6 V. It should be noted that even diodes of the same product series exhibit different temperature characteristics.

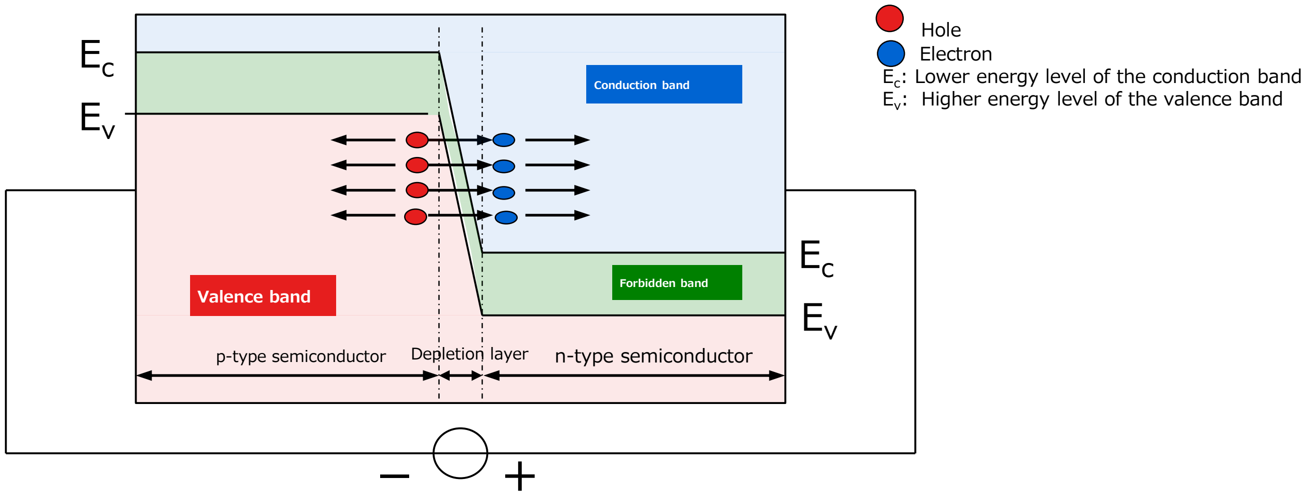


Figure 1.3 Zener breakdown

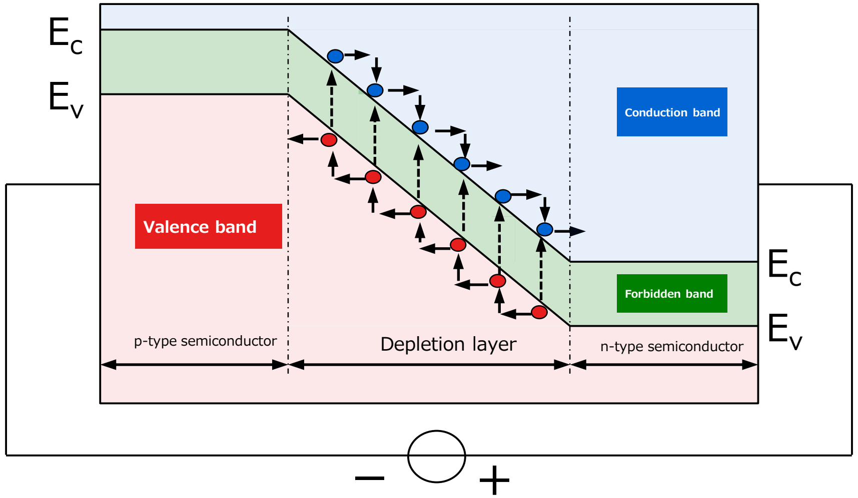


Figure 1.4 Avalanche breakdown

1-2. Using different types of protection diodes (ESD protection diodes and Zener diodes for overvoltage protection)

The ESD protection diode is a type of Zener diode specifically designed to protect electronic circuits from overvoltage surge, particularly electrostatic discharge (ESD) events. ESD protection diodes provide protection mainly against short ESD pulses as well as lightning-induced and switching surge events that last for less than several microseconds. Zener diodes specifically designed for protection from surge events with a pulse duration larger than ESD are called surge protection Zener diodes. These Zener diodes are suitable for protecting electronic circuits from overvoltage pulses due to lightning-induced and switching surge events that last for more than several microseconds.

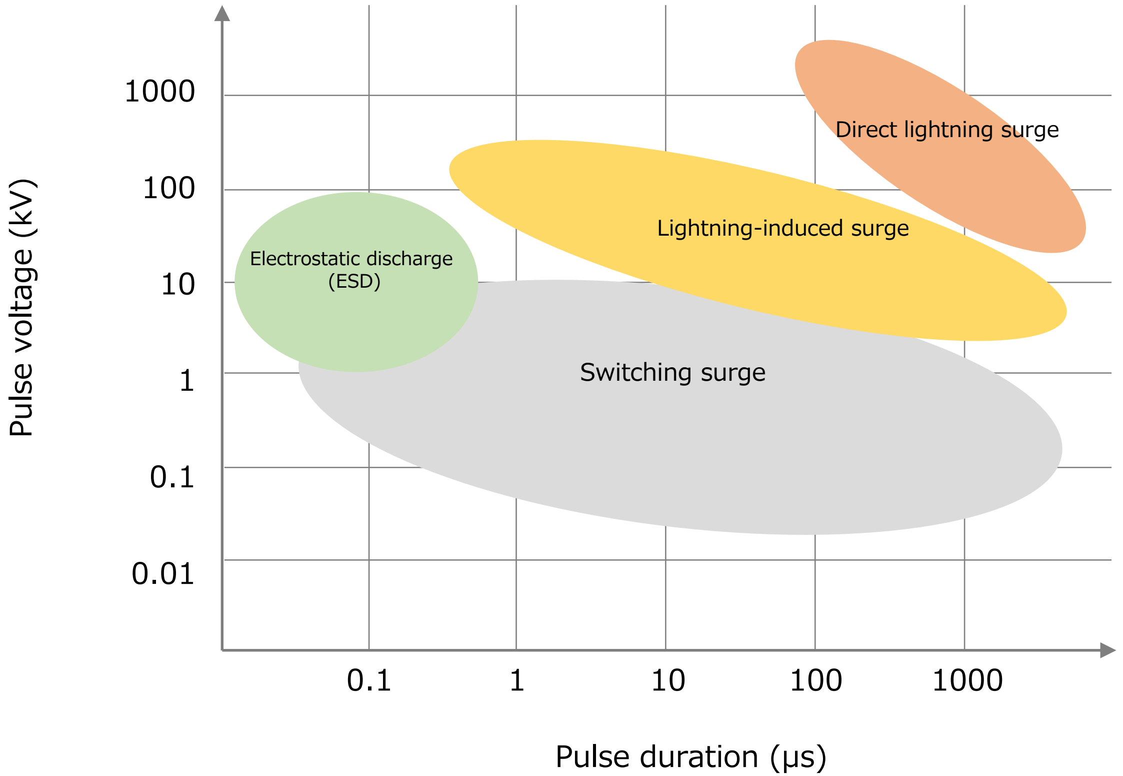


Figure 1.5 Classification of overvoltage pulses

1-2. Using different types of protection diodes (ESD protection diodes and Zener diodes for overvoltage protection)

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Table 1.1 Types of voltage surge

Type	Description
Electrostatic discharge (ESD)	Electrostatic discharge (ESD) is a sudden flow of electricity between two electrically charged objects due to the discharging of stray capacitance that occurs when they are brought into contact or close together. Although ESD events can reach thousands of volts, their pulse duration is on the order of nanoseconds. Because of lower surge energy, ESD events are relatively easier to protect from than lightning-induced and switching surge events. ESD strikes occur frequently at low humidity. Accompanying the prevalence of smartphones and other mobile devices that are prone to malfunction due to an ESD strike, ESD protection is becoming increasingly important.
Lightning-induced surge	Lightning-induced surge is a type of surge that is induced to the inductance of long wires such as power supply and communication lines because of the effect of electromagnetic pulses emitted by lightning strikes. As is the case with ESD events, lightning-induced surge events reach thousands of volts. However, lightning-induced surge events have larger energy because their pulses last for microseconds to milliseconds. Compared to ESD protection devices, surge protection devices become relatively large so as to pass large energy to ground. In contrast to lightning-induced surge, a type of surge caused by a direct lightning strike is called direct lightning surge. It is difficult to protect from a direct lightning surge because of its extremely high energy.
Switching surge	Switching surge is an overvoltage transient induced during the on/off switching of a switch or a relay because of a sharp change in current, circuit inductance, and wire inductance. Since a circuit’s inductance and capacitance cause switching surge, its voltage is lower than that of ESD and lightning surge. However, switching surge pulses last for several nanoseconds to even milliseconds. Switching surge events with a long pulse duration have higher energy than ESD surge events. Protection devices are selected according to the magnitude of a circuit’s inductance and capacitance.

1-2. Using different types of protection diodes (ESD protection diodes and Zener diodes for overvoltage protection)

ESD protection diodes are specifically designed to protect electronic circuits from overvoltage surge, particularly from ESD events, without affecting the waveforms of signal lines. ESD protection diodes are available with a capacitance of 0.12 to 100 pF. Surge protection Zener diodes provide a wide junction so as to absorb large surge energy. With a total capacitance of 100 to 600 pF, these diodes are suitable for protection against lightning-induced and switching surge events. Table 1.2 shows the suitability of ESD protection diodes and surge protection Zener diodes for different types of overvoltage surge pulses:

Table 1.2 Effects on surge protection

	Total capacitance	Purpose	Protection			
			ESD	Switching surge	Lightning-induced surge	Direct lightning surge
ESD protection Diodes	C_t: 0.12 to 100 pF	Protection from overvoltage surge of a duration on the order of microseconds or less	**Excellent**	Poor	Poor	Very poor
Surge protection Zener diodes	C_t: 100 to 600 pF	Protection from overvoltage surge longer than microseconds (and from ESD strikes as well)	Good	Excellent	Good	Very poor

Note: Comparison of Toshiba’s diodes

1-3. Differences between protection diodes (ESD protection diodes and surge protection Zener diodes) and diodes for constant-voltage regulation

A protection diode is a type of Zener diode. Zener diodes can be used not only as protection diodes but also as constant-voltage regulators. Protection diodes are specifically designed to protect electronic circuits from ESD and other transient pulses. In contrast, Zener diodes for constant-voltage regulation remain conducting in breakdown mode.

Protection diodes

Protection diodes are used as voltage clampers for surge protection. These diodes are designed to conduct in the event of excessive voltage being applied to a circuit.

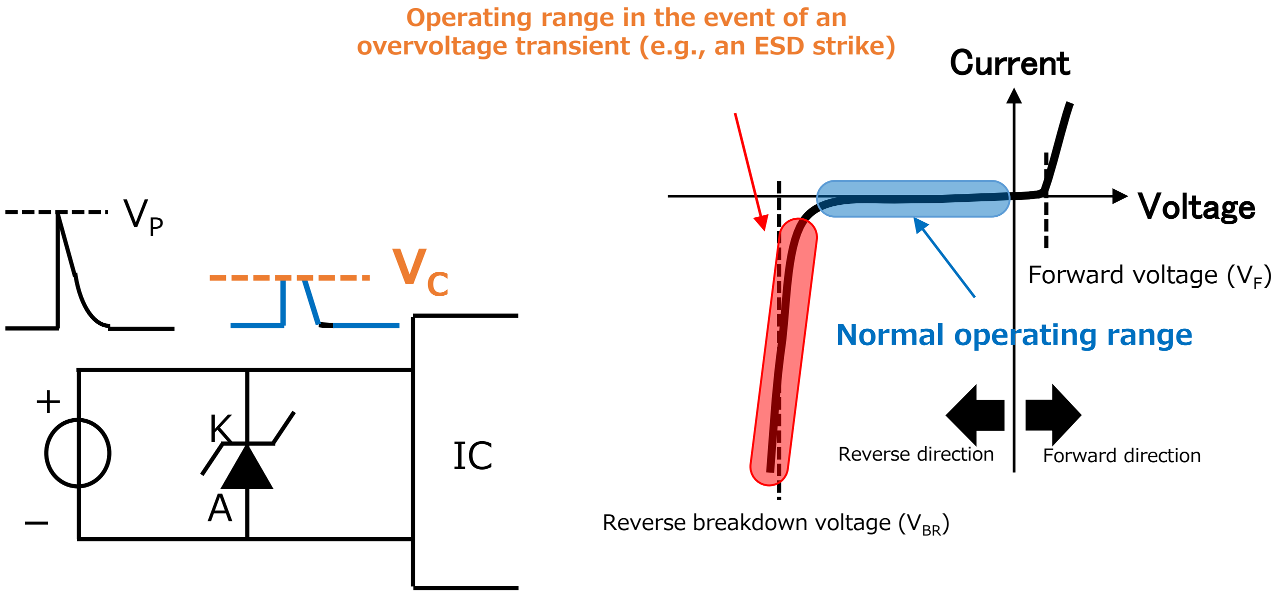


Figure 1.6 Operation of a protection diode
(Example of a Zener diode application)

1-3. Differences between protection diodes (ESD protection diodes and surge protection Zener diodes) and diodes for constant-voltage regulation

A protection diode is a type of Zener diode. Zener diodes can be used not only as protection diodes but also as constant-voltage regulators. Protection diodes are specifically designed to protect electronic circuits from ESD and other transient pulses. In contrast, Zener diodes for constant-voltage regulation remain conducting in breakdown mode.

Diodes for constant-voltage regulation

The voltage that appears across a diode when a small current (I_Z) is passed from cathode (K) to anode (A) is used as a constant-voltage source (V_Z). The amount of power that can be applied is constrained by the permissible power dissipation of the diode and the board on which it is mounted.

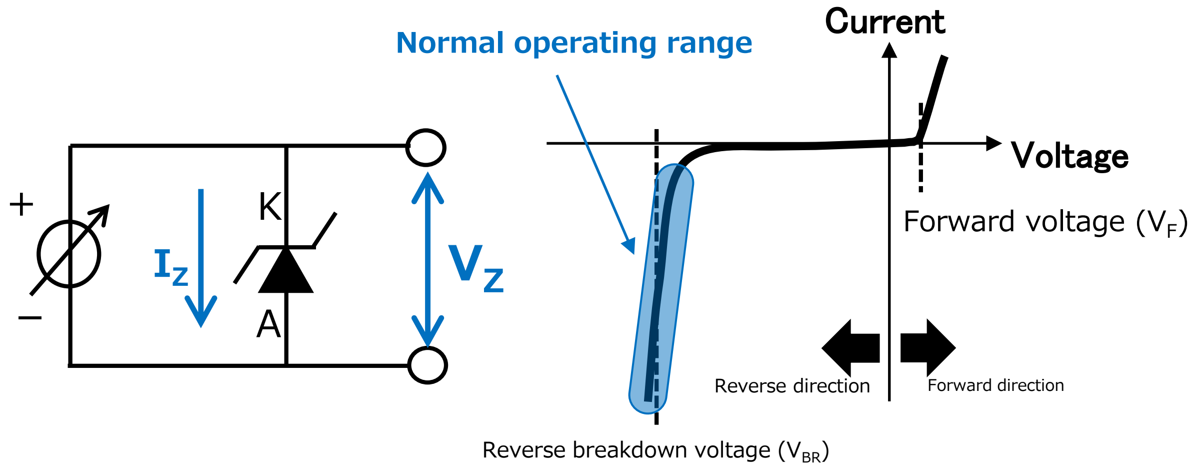


Figure 1.7 Operation of a diode for constant-voltage regulation

2. Basic operations of TVS diodes (ESD protection diodes)

ESD protection diodes are inserted between signal lines and GND in order to protect a device under protection (DUP) from voltage surge. In normal operating mode (i.e., in the absence of an ESD surge), little current flows through the ESD protection diodes, except a very small amount of current (I_R) that flows through the diodes that sets their reverse breakdown voltage (V_{BR}) to a level higher than a signal line. When a voltage surge higher than the reverse breakdown voltage (V_{BR}) is introduced into a signal line, the ESD protection diodes shunt excessive current to GND, suppressing the surge voltage below the reverse breakdown voltage (V_{BR}).

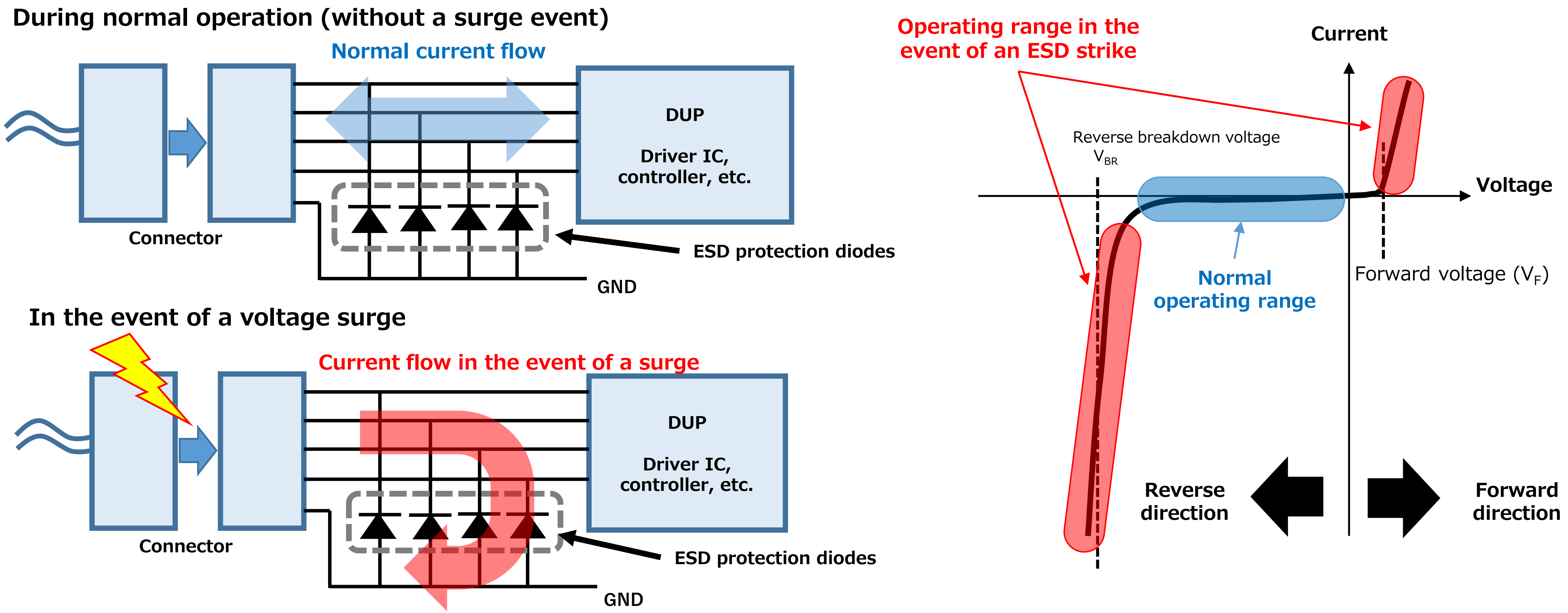


Figure 2.1 Application example and basic operations of ESD protection diodes

2-1. Equivalent circuits and benefits

During normal operation

ESD protection diodes are normally placed between signal lines and GND. Therefore, these diodes act as capacitors in a steady state. Since their capacitance and the resistance of the signal lines form lowpass filters (LPFs), ESD protection diodes cause an insertion loss (I_L), degrading the quality of signals, depending on their speed (especially the quality of high-speed signals such as USB 3.0 and USB 3.1).

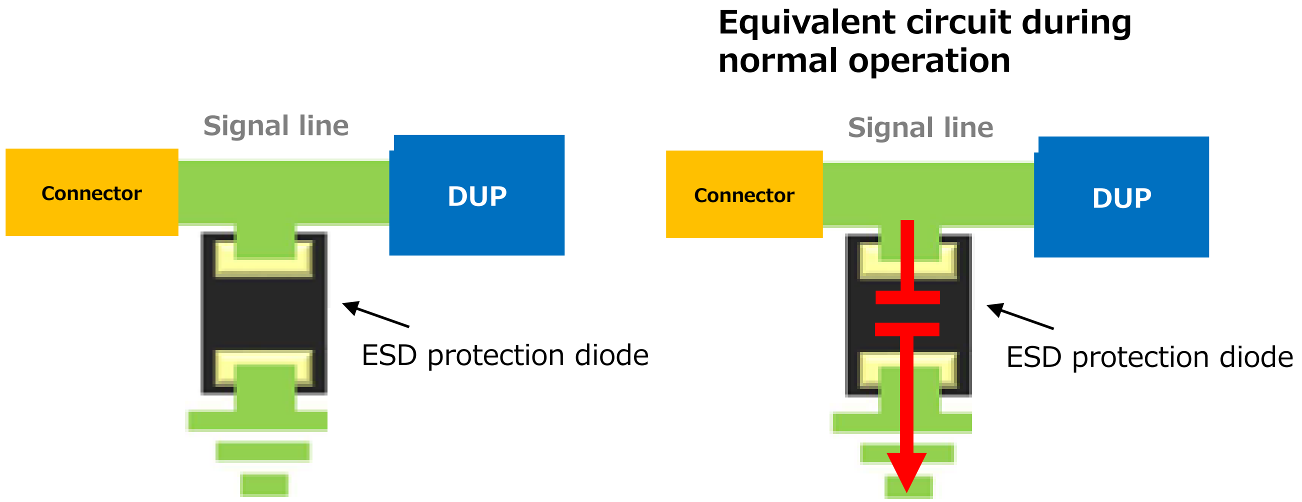


Figure 2.2 Equivalent circuits of ESD protection diodes

2-1. Equivalent circuits and benefits

In the event of a voltage surge

When a surge or external noise enters a system via a connector, its impact on the subsequent device (e.g., an IC) greatly depends on the presence or absence of ESD protection diodes. Without ESD protection diodes, all of the surge current flows directly to a sensitive device, causing a malfunction or device destruction. If a circuit has ESD protection diodes, much of the surge current is shunted to GND through them. The dynamic resistance (R_{dyn}) of an ESD protection diode represents the ease of shunting surge current to GND. ESD protection diodes with lower dynamic current shunt more of the surge current to GND. Such diodes also help reduce the voltage across their dynamic resistance, i.e., the resistance between their terminals (known as clamp voltage). Therefore, ESD protection diodes with lower dynamic resistance allow less surge current to flow to the device under protection (DUP), providing more robust protection for the DUP.

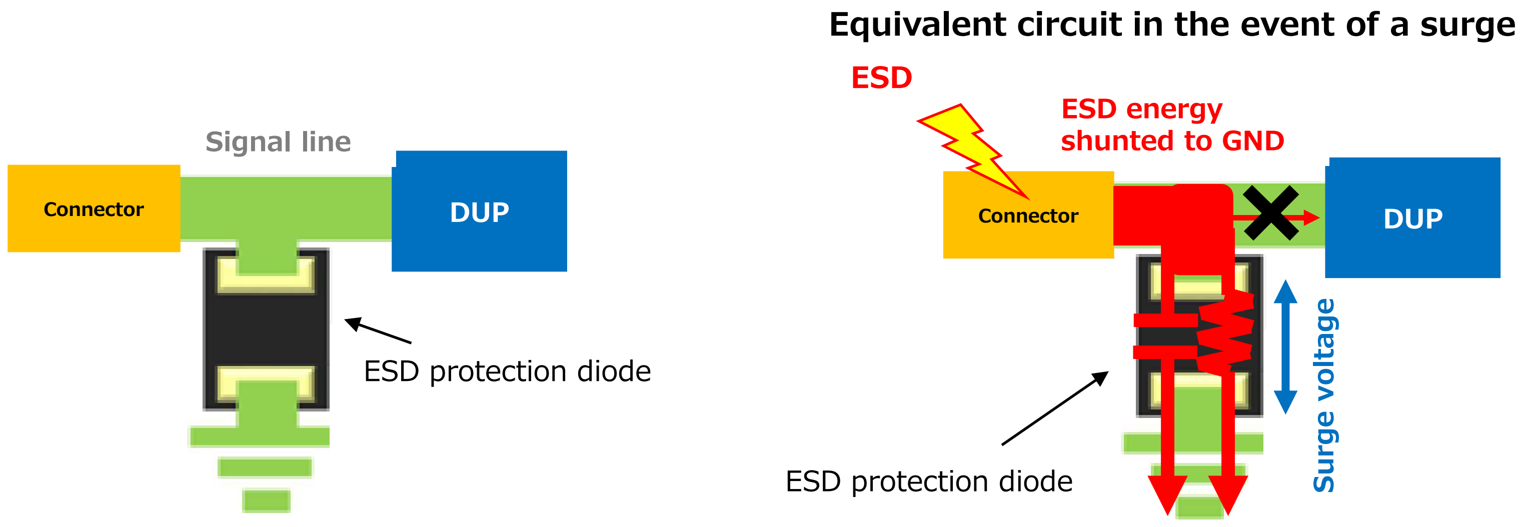


Figure 2.2 Equivalent circuits of ESD protection diodes

3. Key electrical characteristics of TVS diodes (ESD protection diodes)

3-1. Key characteristics for normal operation (in the absence of an ESD event)

Since an ESD protection diode is connected in the reverse direction, the voltage across it is lower than the reverse breakdown voltage (V_{BR}) during normal operation. Therefore, the ESD protection diode does not conduct during normal operation. At this time, a depletion layer is formed across the pn junction, causing the diode to act as a capacitor. The following three considerations apply to normal operation when selecting ESD protection diodes:

3-1-1 Whether the reverse breakdown voltage (V_{BR}) of an ESD protection diode is sufficiently higher than the amplitude (maximum voltage) of the signal line to be protected

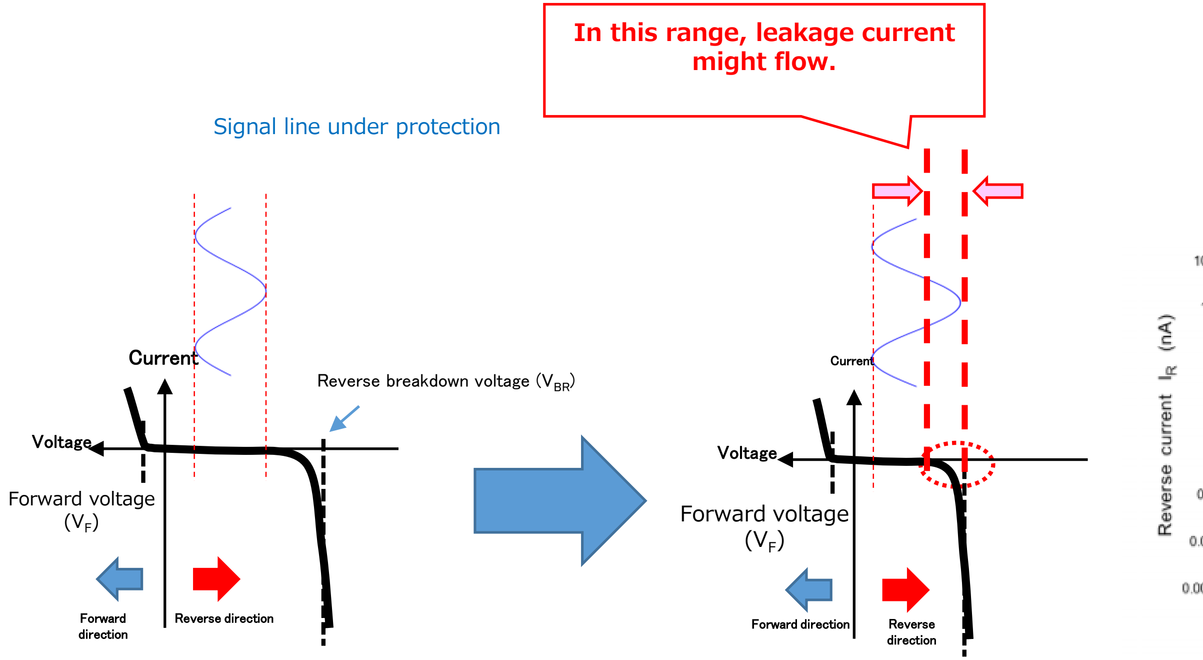
3-1-2 Whether the total capacitance (C_T) of an ESD protection diode is sufficiently low with respect to the frequency of the signal line to be protected

3-1-3 Signal polarity (i.e., whether the signal voltage crosses the GND potential like an analog signal)

3-1. Key characteristics for normal operation (in the absence of an ESD event)(1)

3-1-1. Whether the reverse breakdown voltage (V_{BR}) of an ESD protection diode is sufficiently higher than the amplitude (maximum voltage) of the signal line to be protected

As the voltage across an ESD protection diode approaches its reverse breakdown voltage (V_{BR}), leakage current increases. At a voltage close to V_{BR}, the leakage current might distort the waveform of the signal line to be protected. Reverse current (I_R) increases exponentially with reverse voltage (V_R). It is important to select ESD protection diodes with V_{RWM} higher than the amplitude of the signal lines to be protected.



When V_{BR} has a sufficient margin relative to the signal line under protection

When V_{BR} has no margin relative to the signal line under protection

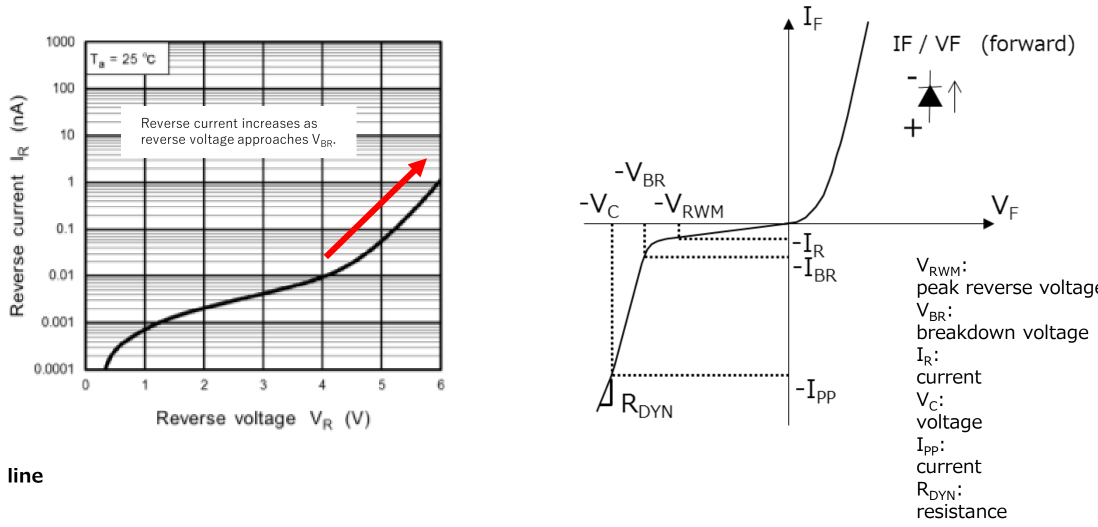
Figure 3.1 Reverse breakdown voltage vs signal line voltage

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}

V_{BR}

Definition of V_{RWM}



V_{RWM}: Working peak reverse voltage
V_{BR}: Reverse breakdown voltage
I_R: Reverse current
V_C: Clamp voltage
I_{PP}: Peak pulse current
R_{DYN}: Dynamic resistance

Figure 3.2 Leakage current of an ESD protection diode

3-1-2. Whether the total capacitance (C_t) of an ESD protection diode is sufficiently low with respect to the frequency of the signal line to be protected

Figure 3.3 shows an equivalent circuit of an ESD protection diode. The diode does not conduct during normal operation. At this time, a depletion layer is formed at the interface of the pn junction as shown in Figure 3.3. The depletion layer electrically acts as a capacitor. Therefore, the signal quality is degraded unless appropriate ESD protection diodes are selected, considering the frequency of the signal lines to be protected.

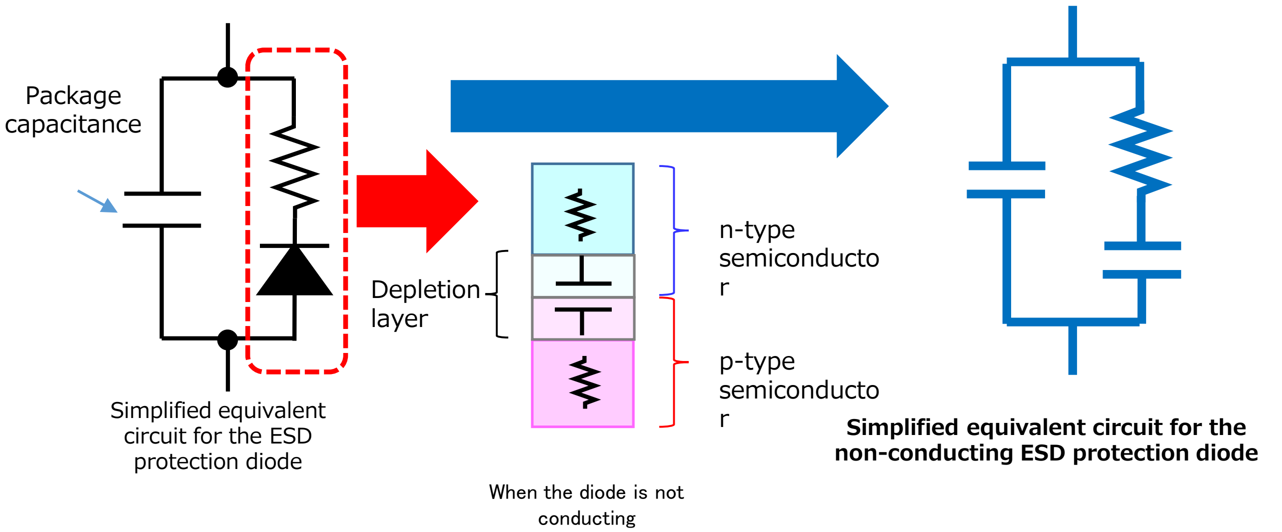


Figure 3.3 Total capacitance of an ESD protection diode

3-1. Key characteristics for normal operation (in the absence of an ESD event)(2)

3-1-2. Whether the total capacitance (C_t) of an ESD protection diode is sufficiently low with respect to the frequency of the signal line to be protected

Figure 3.4 shows the insertion loss characteristics of ESD protection diodes with a total capacitance (C_T) of 5 pF, 0.3 pF, and 0.1 pF. Diodes with a larger capacitance cause higher insertion loss (as indicated by a larger negative change in the characteristics curve), restricting the frequency range in which they can be used. For example, in the case of Thunderbolt (with a bandwidth of 10 Gbps, which is equivalent to a frequency of 5 GHz), ESD protection diodes with a small capacitance (0.1 to 0.3 pF) cause a small insertion loss and hardly affect the signal passing through the diode whereas an ESD protection diode with a capacitance of 5 pF causes a large insertion loss, considerably decaying the signal that passes through the diode.

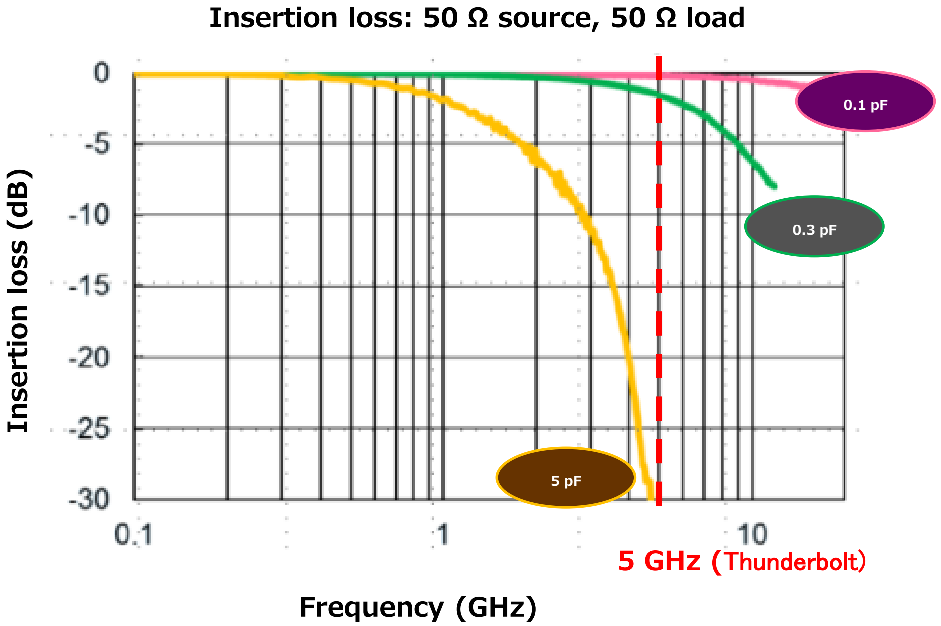


Figure 3.4 Total capacitance of ESD protection diodes vs insertion loss

3-1. Key characteristics for normal operation (in the absence of an ESD event)(2)

3-1-2. Whether the total capacitance (C_t) of an ESD protection diode is sufficiently low with respect to the frequency of the signal line to be protected

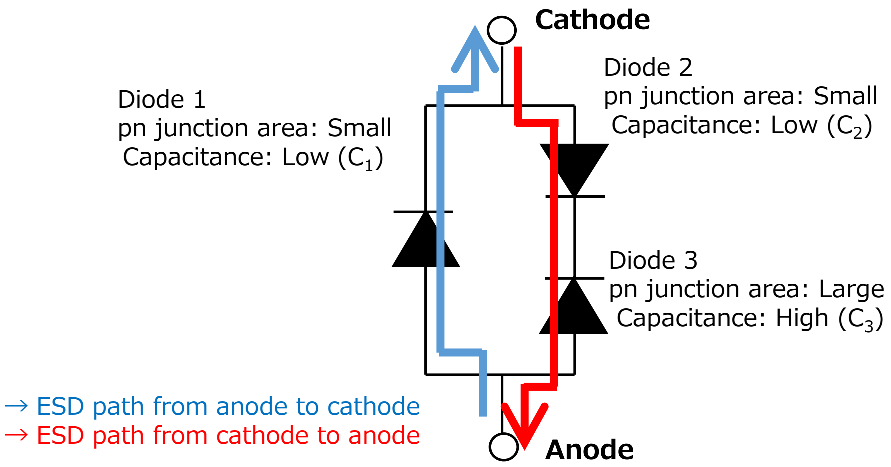
Reduction in total capacitance

(Total capacitance consists of the junction capacitance of a diode and the parasitic capacitance of the package in which it is housed. The junction capacitance constitutes a large proportion of a diode's total capacitance.)

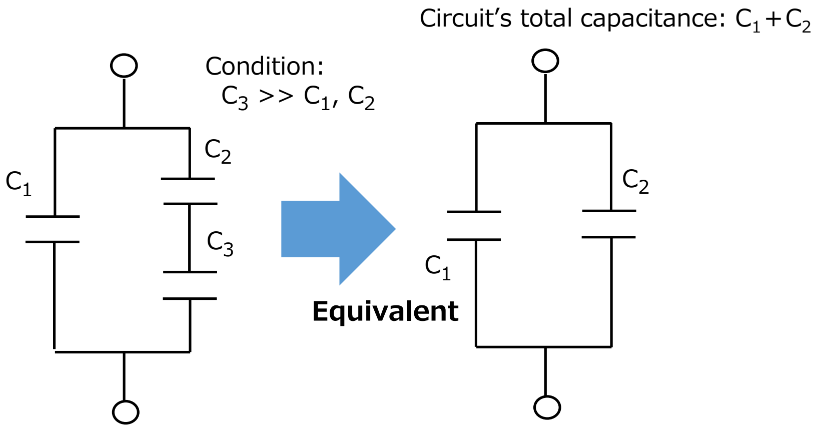
A diode has capacitance because of the depletion layer that is formed across the pn junction (p: p-type semiconductor, n: n-type semiconductor) when it is reverse-biased. In contrast to the capacitance, the depletion layer acts as an insulating layer where minority carriers do not exist. Reducing the dopant concentration of the semiconductor regions causes an increase in the width of the depletion layer. Therefore, in order to reduce the capacitance of a diode, it is necessary to reduce the area of the pn junction or increase the reverse breakdown voltage (V_{BR}), but either way results in the degradation of its ESD immunity. When two diodes are connected in series, their combined capacitance decreases. Also, diodes are less tolerant of ESD energy in the reverse direction than in the forward direction. Toshiba's low-capacitance (C_t) ESD protection diodes are fabricated using a process called the ESD diode array process (EAP), which combines multiple diodes to reduce capacitance without compromising the ESD immunity.

3-1-2. Whether the total capacitance (C_t) of an ESD protection diode is sufficiently low with respect to the frequency of the signal line to be protected

Figure 3.5 shows the circuit diagram of a low-capacitance ESD protection diode in an EAP configuration. It consists of three diodes: low-capacitance Diode 1 and Diode 2 (with a capacitance of C_1 and C_2 respectively) and high-capacitance Diode 3 (with a capacitance of C_3). Diode 1 and Diode 2 have a small pn junction area and high V_{BR} whereas Diode 3 has a large pn junction area and adequate V_{BR}. The ESD current applied to the anode flows through Diode 1 in the forward direction whereas the one applied to the cathode flows through Diode 2 in the forward direction and then through Diode 3 in the reverse direction since the V_{BR} of Diode 3 is lower than that of Diode 1. Typically, diodes are less tolerant of ESD energy in the reverse direction than in the forward direction. Since the pn junction area of Diode 1 and Diode 2 is small, they are even less tolerant of ESD energy in the reverse direction. However, when an ESD protection diode is configured as shown in Figure 3.6(a), ESD current does not flow through Diode 1 and Diode 2 in the reverse direction. Therefore, this circuit provides high ESD immunity as a whole. Figure 3.6(b) shows the equivalent capacitance circuit of this ESD protection diode. The combined capacitance can be reduced by connecting low-capacitance Diode 2 and high-capacitance Diode 3 in series. Also, since the V_{BR} of this circuit is determined by the V_{BR} of Diode 3, ESD immunity can be increased by adjusting the V_{BR} of Diode 3 according to the signal line to be protected.



(a) Circuit diagram



(b) Equivalent capacitance circuits

Figure 3.5 EAP circuit configuration

3-1-2. Whether the total capacitance (C_t) of an ESD protection diode is sufficiently low with respect to the frequency of the signal line to be protected

Rough total capacitance versus signal frequency

Figure 3.6 can be used as guide when selecting ESD protection diodes according to the signal frequency.

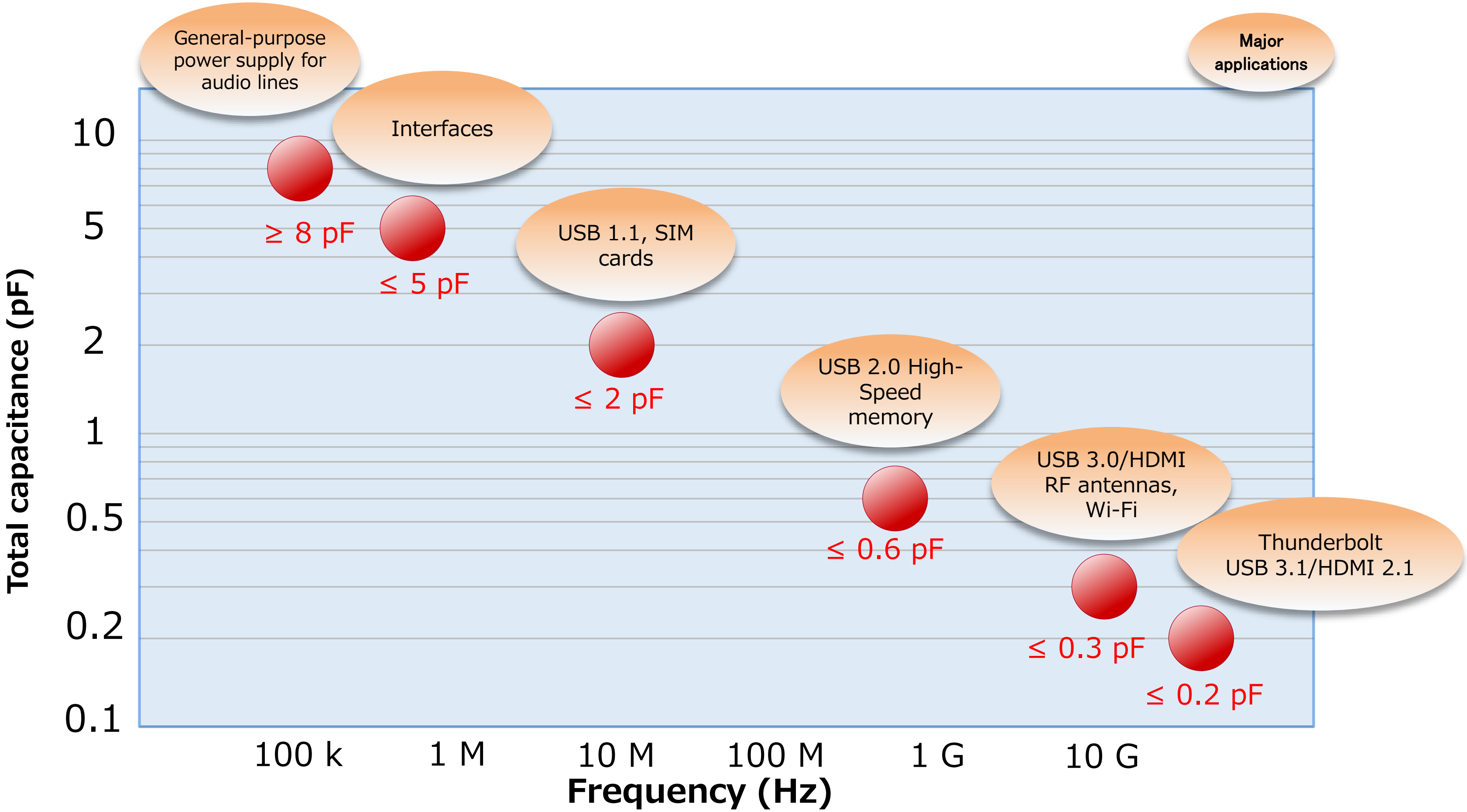


Figure 3.6 Rough total capacitance vs signal frequency

3-1-3. Signal polarity (i.e., whether the signal voltage crosses the GND potential like an analog signal)

It is necessary to select either unidirectional or bidirectional ESD protection diodes, considering the polarity of signal lines to be protected. Different types of diodes are used for unmodulated digital signals that swing only in the positive direction (e.g., between 0 V (logic Low) and 5 V (logic High)) and unbiased analog signals whose voltage can be positive and negative. Bidirectional ESD protection diodes should be used for signals that range above and below GND as shown below. (Both unidirectional and bidirectional diodes can be used for signals whose voltage can only be positive or negative.)

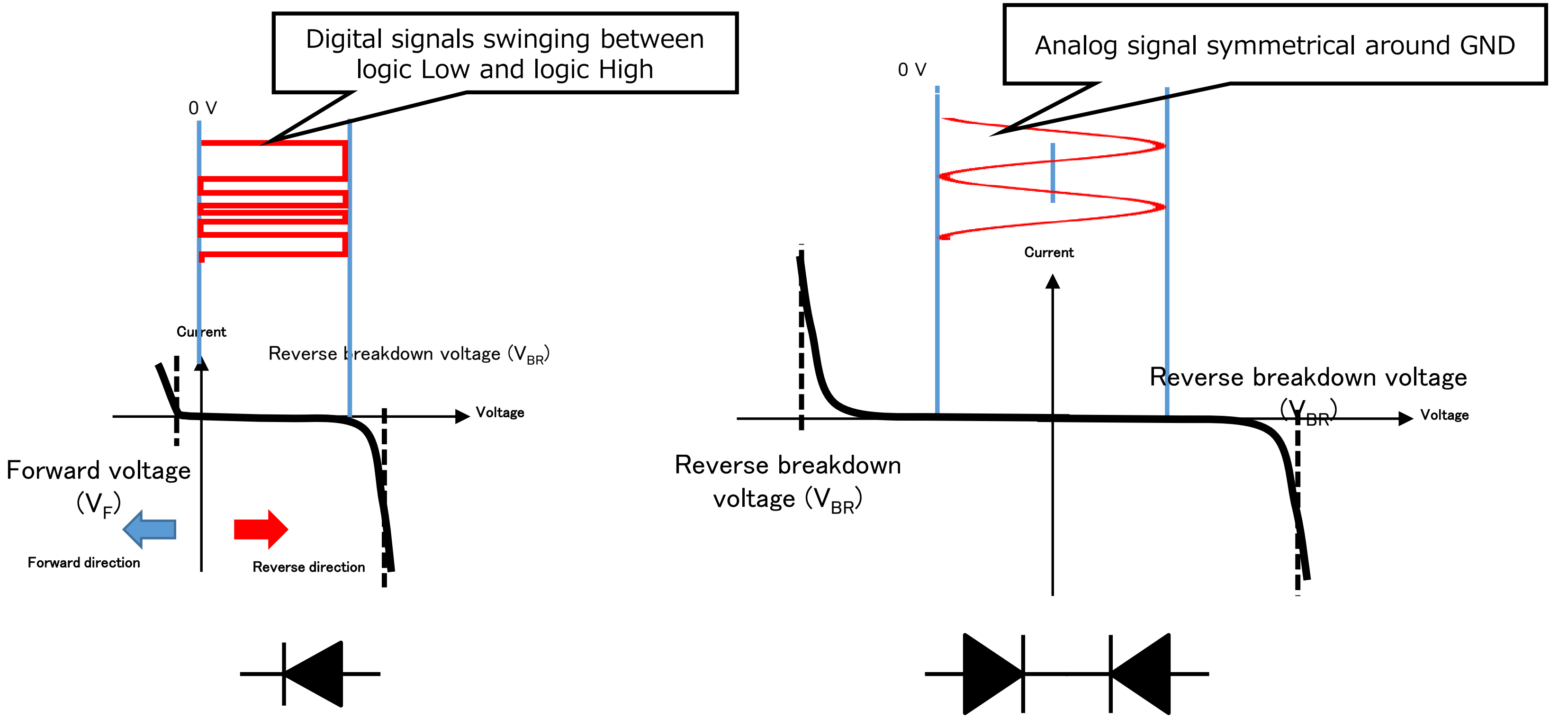


Figure 3.7 Unidirectional vs bidirectional polarity

3. Key electrical characteristics of TVS diodes (ESD protection diodes)

Key characteristics for protection against ESD events

When an ESD is introduced into a system, ESD protection diodes either conduct or enter reverse breakdown. A unidirectional ESD protection diode absorbs ESD energy by entering reverse breakdown in the event of a positive ESD strike and by going into conduction in the event of a negative ESD strike. There are three points to note to prevent the DUP from being destroyed by an ESD pulse:

3-2-1 Low dynamic resistance (R_{DYN})

3-2-2 Low clamp voltage (V_C) and first peak voltage

3-2-3 Operations of an ESD protection diode to absorb ESD pulses with different polarities

3-2-1. Low dynamic resistance (R_{DYN})

In the event of an ESD strike, the ESD current flows to both the ESD protection diode and the device under protection (DUP). It is important to reduce the current flowing to the DUP (i.e., increase the current shunted through the ESD protection diodes). Nowadays, the datasheets for ESD protection diodes show their dynamic resistance (R_{DYN}). R_{DYN} is the slope of the V_F–I_F curve in reverse conduction mode. In the event of an ESD strike, ESD protection diodes with lower dynamic resistance conduct more current at a given voltage.
From the connector side, the impedances of the ESD protection diode and the DUP can be regarded as being connected in parallel. If the ESD protection diode has low impedance (i.e., dynamic resistance), most of the surge current is shunted through the ESD protection diode, reducing the current that flows to the DUP and therefore the possibility of its destruction.

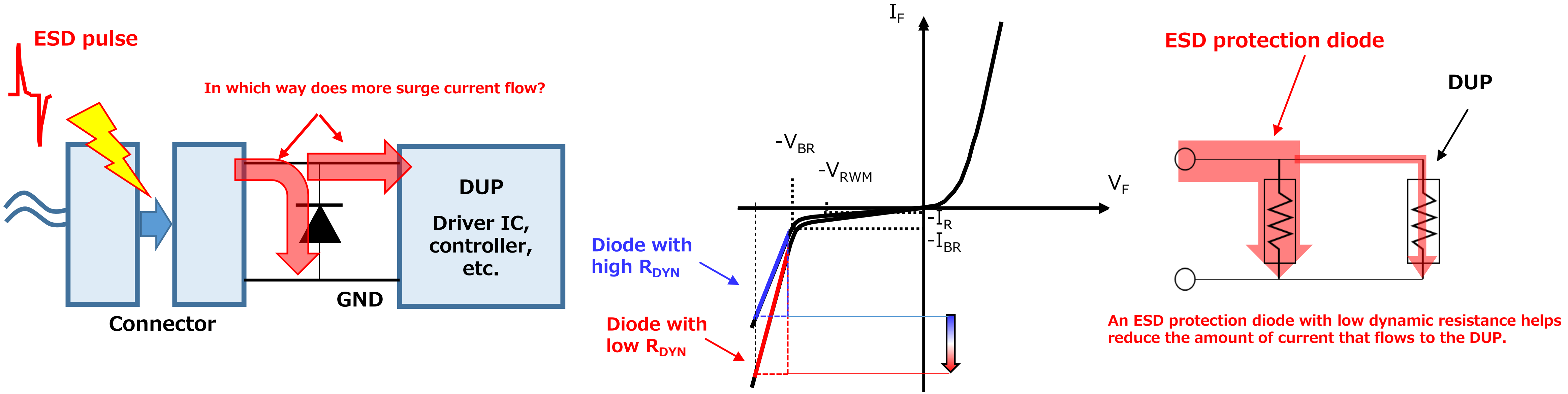


Figure 3.8 Dynamic resistance of ESD protection diodes vs current flowing to the DUP

3-2-1. Low dynamic resistance (R_{DYN})

Figure 3.9 illustrates how to calculate dynamic resistance (R_{DYN}) of an ESD protection diode. A transmission line pulse (TLP) test applies short pulses with a duration on the order of nanoseconds to study the current-voltage (I-V) characteristics of a diode based on the current-voltage relationship over time. In the following graph, TLP I and TLP V represent current and voltage, respectively.

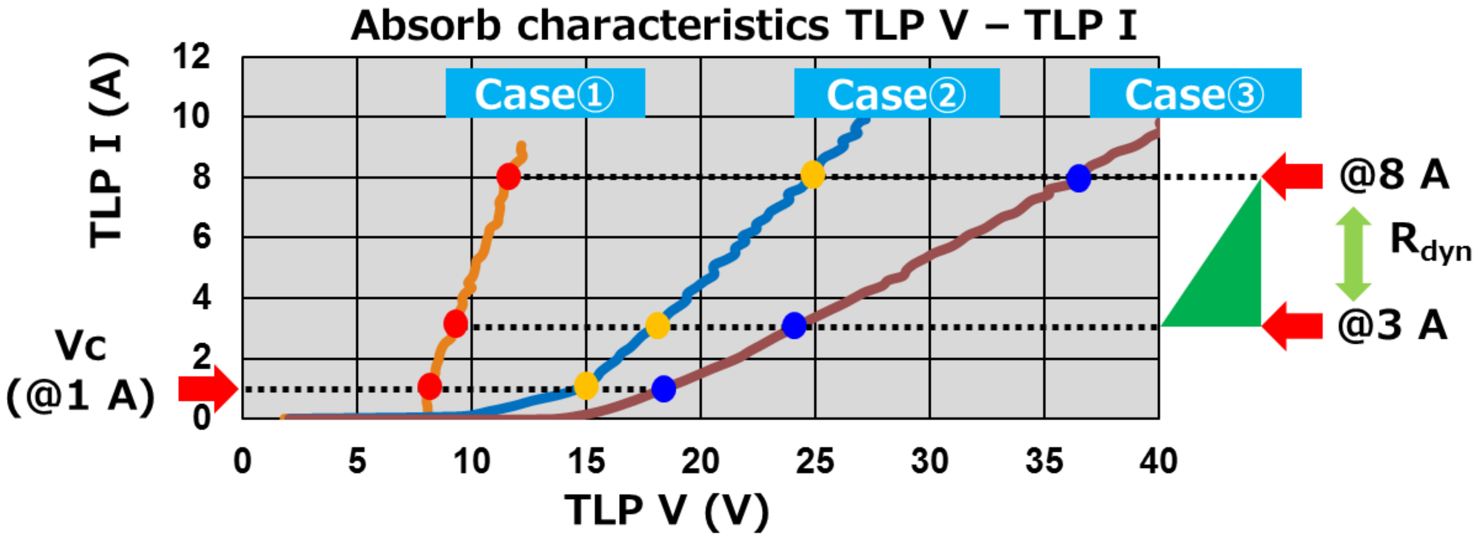


Figure 3.9 Role of the dynamic resistance of an ESD protection diode

3-2. Key characteristics for protection against ESD events(1)

3-2-1. Low dynamic resistance (R_{DYN})

Figure 3.9 illustrates where surge current flows in the event of an ESD strike. If the ESD protection diode has low impedance (i.e., dynamic resistance), most of the surge current is shunted to GND through the ESD protection diode, reducing the current that flows to the DUP. Therefore, the ESD protection diode helps prevent the destruction of the DUP due to an ESD strike.

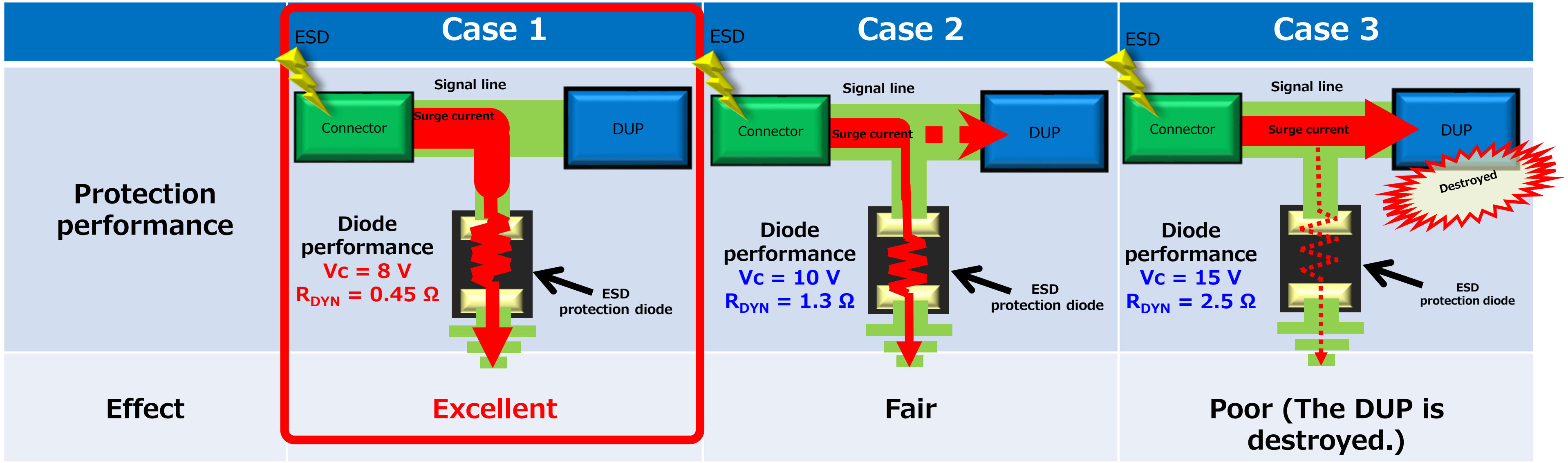


Figure 3.9 Role of the dynamic resistance of an ESD protection diode

3-2. Key characteristics for protection against ESD events(2)

3-2-2 Low clamp voltage (V_C) and first peak voltage

Figure 3.10 shows the response waveforms of ESD protection diodes with high and low clamp voltages (V_C) when an ESD waveform stipulated in IEC 61000-4-2 was applied to them. These waveforms were taken at the input of a device under protection (DUP). The ESD protection diode with a lower V_C exhibits lower clamp voltage at 30 ns and 60 ns than the one with a higher V_C. The smaller the area under the curve of the ESD waveform, the less damage the DUP suffers. Therefore, ESD protection diodes with low V_C provide better protection against ESD pulses. In addition, some ESD protection diodes do not respond immediately after the ESD entry. Therefore, if the first peak of the ESD pulse is higher than the V_C of the ESD protection diode, it might be applied to the DUP, leading to its malfunction or destruction. ESD protection diodes are designed to provide faster response than other types of protection devices. In addition, Toshiba is working on the optimization of the chip process and the internal device structure in order to further reduce the first peak voltage and therefore provide more rugged protection against the peak ESD voltage during the initial period.

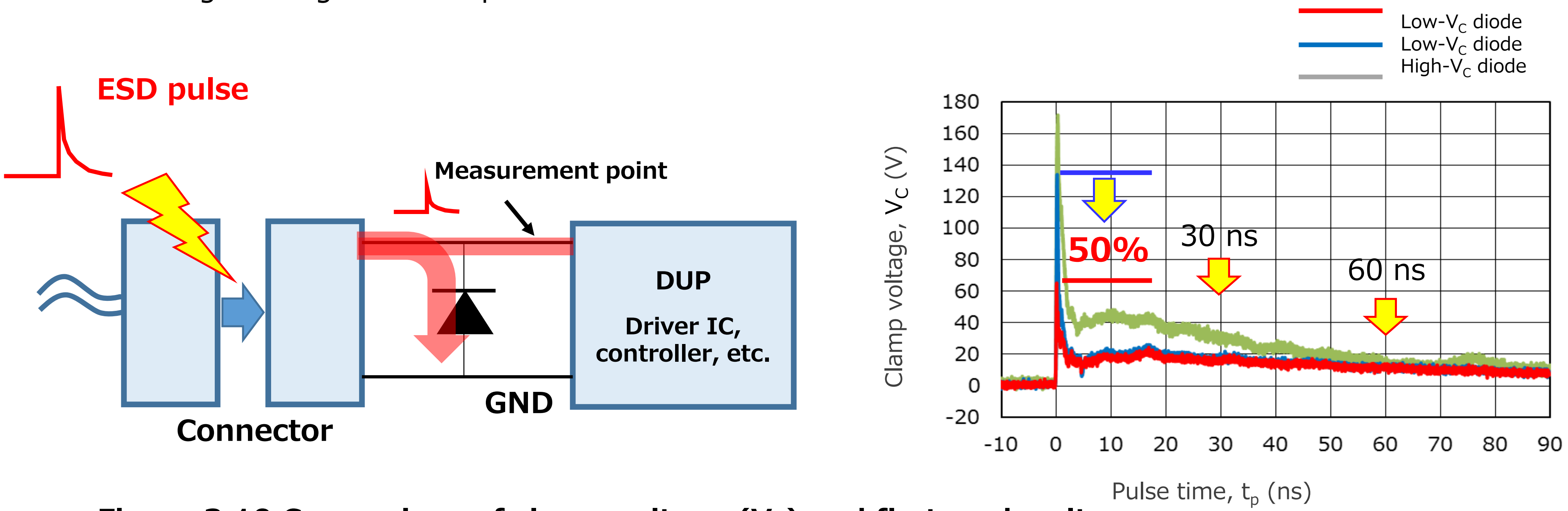


Figure 3.10 Comparison of clamp voltage (V_C) and first peak voltage

3-2. Key characteristics for protection against ESD events(3)

3-2-3 Operations of an ESD protection diode to absorb ESD pulses with different polarities

Both unidirectional and bidirectional ESD protection diodes can absorb positive and negative ESD pulses.

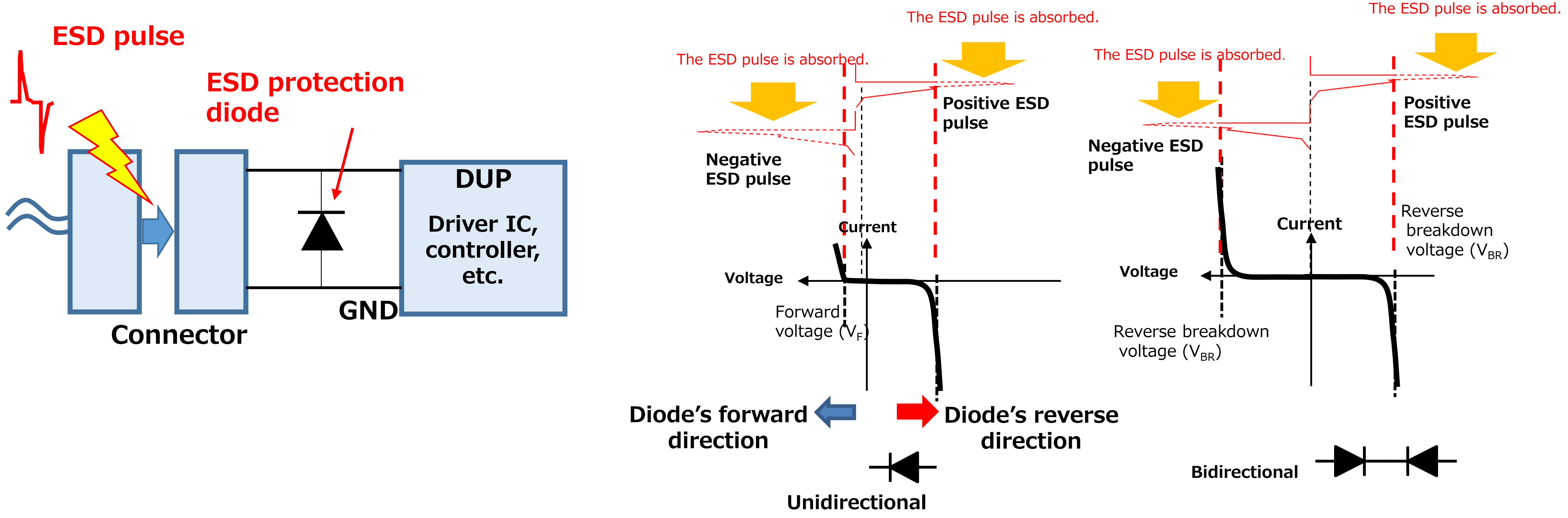


Figure 3.11 Surge absorption operations of an ESD protection diode

4. Selection guidelines for TVS diodes (ESD protection diodes)

In order to choose the right ESD protection diode, pay attention to the key electrical characteristics described in Section 3.

1. Maintaining the quality of the signals to be protected

a) Signal line voltage
Select ESD protection 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.
b) Signal polarity
Use bidirectional ESD protection diodes for signals that cross the GND level such as analog signals.
c) Signal speed
Select ESD protection diodes with appropriate total capacitance (C_T) according to the maximum frequency of the signal lines to be protected.

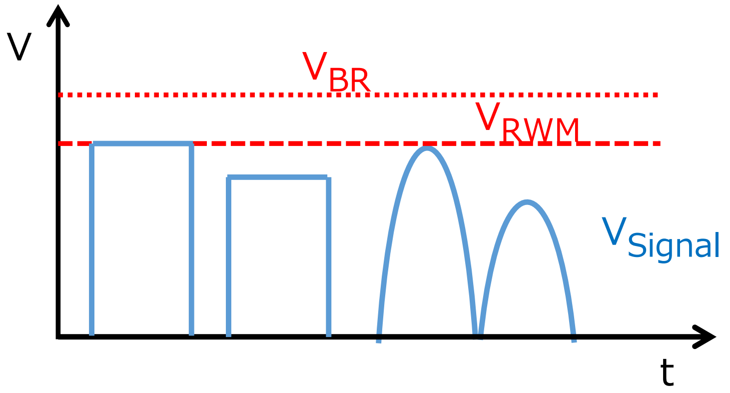


Figure 4.1 V_{RMW}, V_{BR}, and signal line voltage (V_{Signal})

4. Selection guidelines for TVS diodes (ESD protection diodes)

In order to choose the right ESD protection diode, pay attention to the key electrical characteristics described in Section 3.

2. Enhancing ESD protection performance

d) Dynamic resistance
Select ESD protection diodes with dynamic resistance (R_{DYN}) as low as possible.
e) Clamp voltage
Select ESD protection diodes with the minimum clamp voltage (V_C) according to the V_{RWM} required.
Be sure to choose diodes with V_C lower than the withstand voltage of the device under protection.

3. ESD tolerance of ESD protection diodes

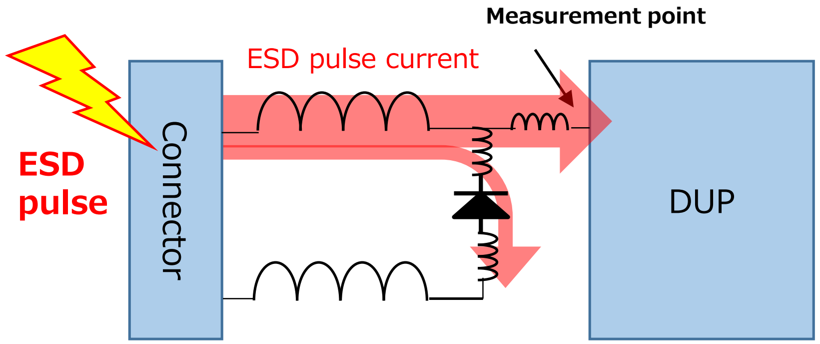
f) IEC 61000-4-2
Select ESD protection diodes with a guaranteed ESD performance higher than a system’s ESD immunity requirement.
Note, however, that the ESD performance of the ESD protection diode is generally proportional to its total capacitance.
g) IEC 61000-4-5
Select ESD protection diodes with electrical ratings higher than the peak pulse power and peak pulse current requirements.

5. Layout considerations for TVS diodes (ESD protection diodes)

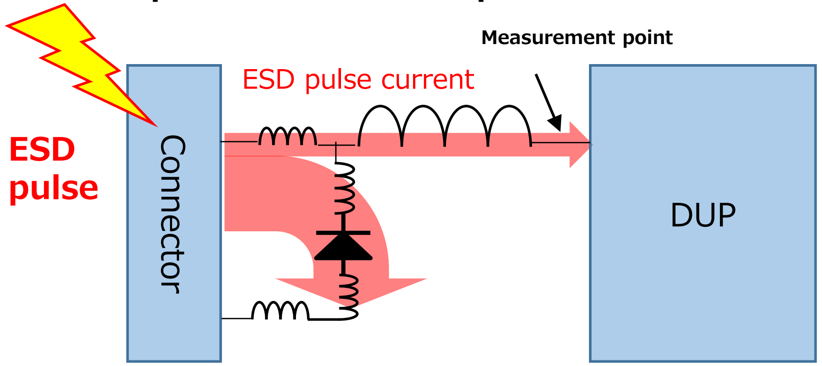
Note that the placement of ESD protection diodes affects their ESD protection performance.

1. Place ESD protection diodes close to the ESD entry point.
2. Minimize trace inductance in series with ESD protection diodes including GND after the board traces originating from the connector diverge into two paths leading to ESD protection diodes and the DUP.

When an ESD protection diode is placed near the DUP



When an ESD protection diode is placed near the connector



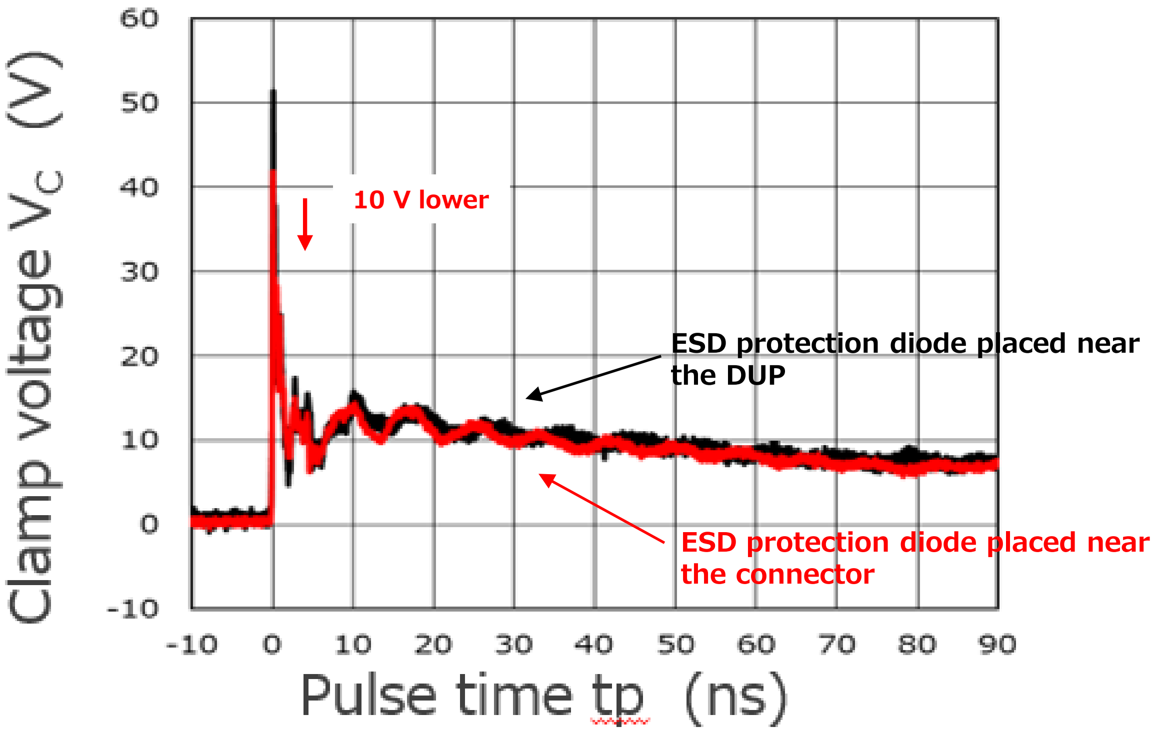


Figure 5.1 Difference in clamp voltage depending on the placement of ESD protection diodes

5. Layout considerations for TVS diodes (ESD protection diodes)

3. Do not run any board trace in parallel with a signal trace to which an ESD pulse might be introduced. In particular, avoid running board traces leading to a device with low ESD immunity in parallel with a board trace that could be exposed to an ESD event.

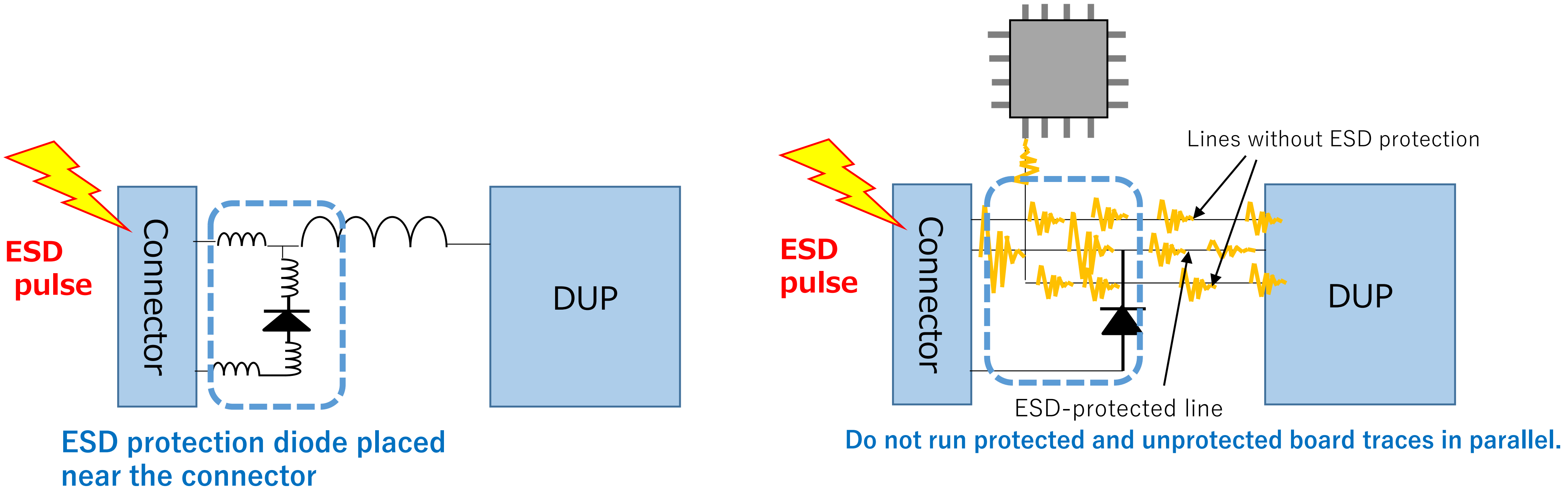


Figure 5.2 Board traces for ESD protection diodes

6. Absolute maximum ratings of TVS diodes (ESD protection diodes)

Absolute maximum ratings

Definition

For ESD protection diodes, the maximum allowable current, voltage, power dissipation, and other characteristics are specified as maximum ratings. In circuit design, understanding maximum ratings is crucial in order to obtain the best performance from ESD protection diodes and maintain the device reliability throughout their target operating life. In order to guarantee the lifespan and reliability of ESD protection diodes, maximum ratings must not be exceeded. For ESD protection diodes, maximum ratings are defined in accordance with the absolute maximum rating system. The absolute maximum ratings are the highest values that must not be exceeded even instantaneously under any conditions. If a stress exceeding the specified rating is applied, a device might be permanently degraded. None of the absolute maximum ratings may be exceeded. Therefore, care should be exercised as to supply voltage bounces, variations in the characteristics of electronic devices, possible exposure to stress higher than maximum ratings during circuit adjustment, changes in ambient temperature, input signal fluctuations, and so on. The major ratings that should be considered include the ESD tolerance, peak pulse power, junction temperature, and storage temperature of ESD protection diodes. These parameters are interrelated and cannot be considered separately. They also depend on external circuit conditions. Although the absolute maximum ratings are generally specified at an ambient temperature (T_a) of 25°C, some parameters are specified at different temperatures.

Electrostatic discharge voltage (IEC 61000-4-2) (contact), V_{ESD}

This is the ESD tolerance to a contact discharge, i.e., a discharge through direct contact with equipment under protection. The ESD tolerance is measured according to the method and ESD waveform specified in the IEC 61000-4-2 standard from the International Electrotechnical Commission (IEC). The specified V_{ESD} value is the peak value of the test waveform.

Electrostatic discharge voltage (IEC 61000-4-2) (air), V_{ESD}

This is the ESD tolerance to an air discharge, i.e., a discharge that occurs between equipment under test (EUT) and a discharge gun through an air layer. The test method and the ESD waveform are specified in IEC 61000-4-2.

6. Absolute maximum ratings of TVS diodes (ESD protection diodes)

Peak pulse power (t_p = 8/20 μs), P_{PK}

P_{PK} is the maximum surge power that can be shunted before an ESD protection diode itself is damaged. The peak pulse power is measured using an 8/20 μs pulse waveform shown in Figure 6.1. (8/20 μs means that it takes 8 μs for the waveform to rise to 100% and 20 μs to fall from 100% to 50%.)

Peak pulse current (t_p = 8/20 μs), I_{PP}

I_{PP} is the peak pulse current that can be shunted before an ESD protection diode itself is damaged.
The peak pulse current is measured using a test waveform shown in Figure 6.1 compliant with IEC 61000-4-5.

Junction temperature, T_j

T_j is the maximum junction temperature at which an ESD protection diode can operate without degradation or self-damage.

Storage temperature, T_{stg}

T_{stg} is the ambient temperature range in which an ESD protection diode can be stored and transported without voltage application.

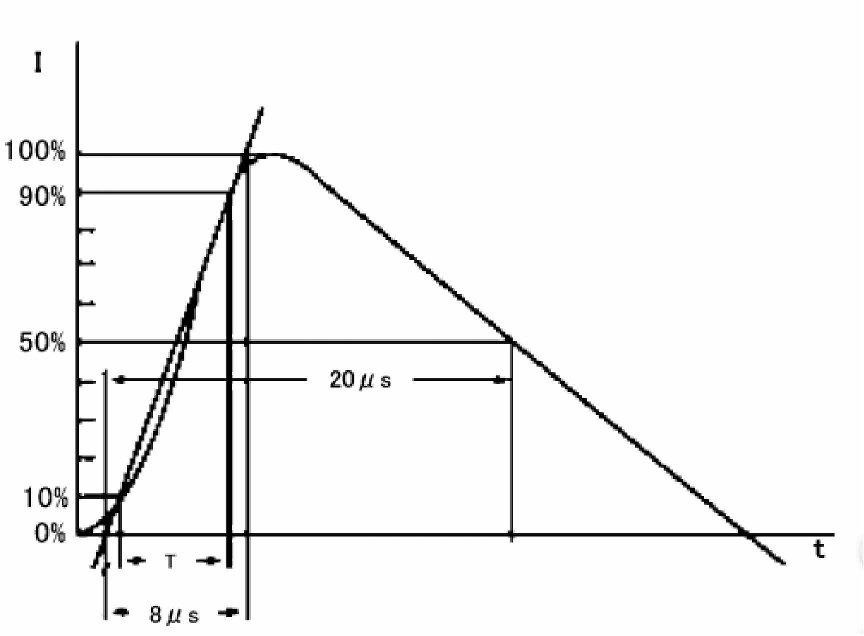


Figure 6.1 Pulse waveform of the ESD protection diode

Supplemental information: IEC61000-4-2 and IEC 61000-4-5

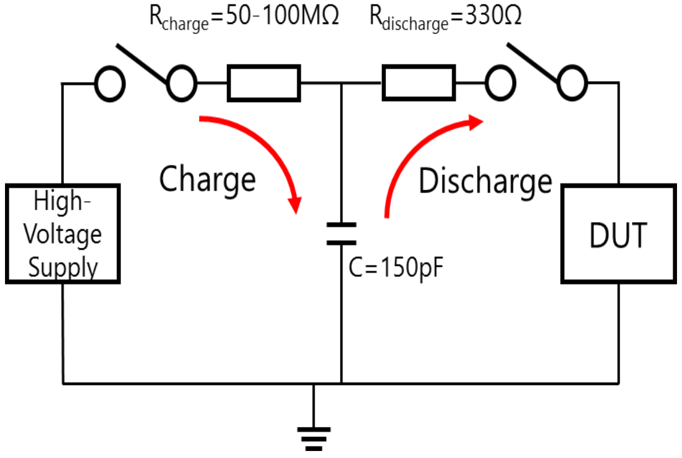
IEC61000-4-2 and IEC 61000-4-5 are designed to ensure that electronic systems will not be degraded or destroyed by ESD in the everyday environment.

1. IEC 61000-4-2 test (ESD immunity test: Human body model)

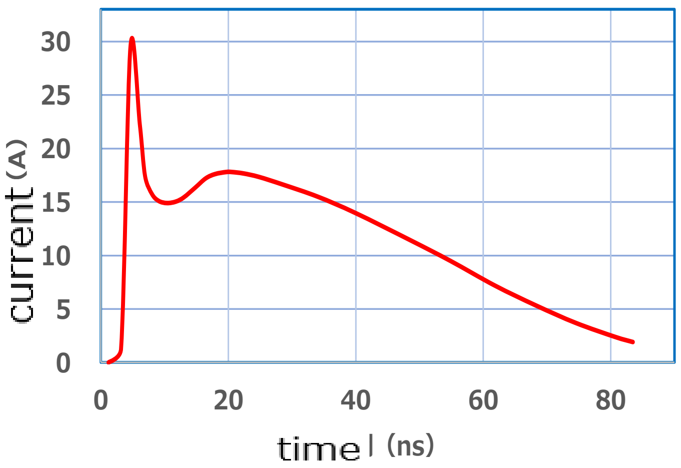
As is the case with the HBM, this test simulates a discharge that might be released from a charged human body. Two methods are used for ESD testing:

- Direct discharge: Tests a discharge that might occur when a human directly touches an exposed metal surface of a system or a device.
- Air discharge: Tests a discharge that might occur between equipment under test (EUT) and a discharge gun through an air layer when the surface of the EUT is coated with resin or other coating materials.

These ESD tests are stipulated in IEC 61000-4-2 from the International Electrotechnical Commission (IEC).
Toshiba’s ESD protection diodes are tested using both direct and air discharge methods.



Example of a test circuit



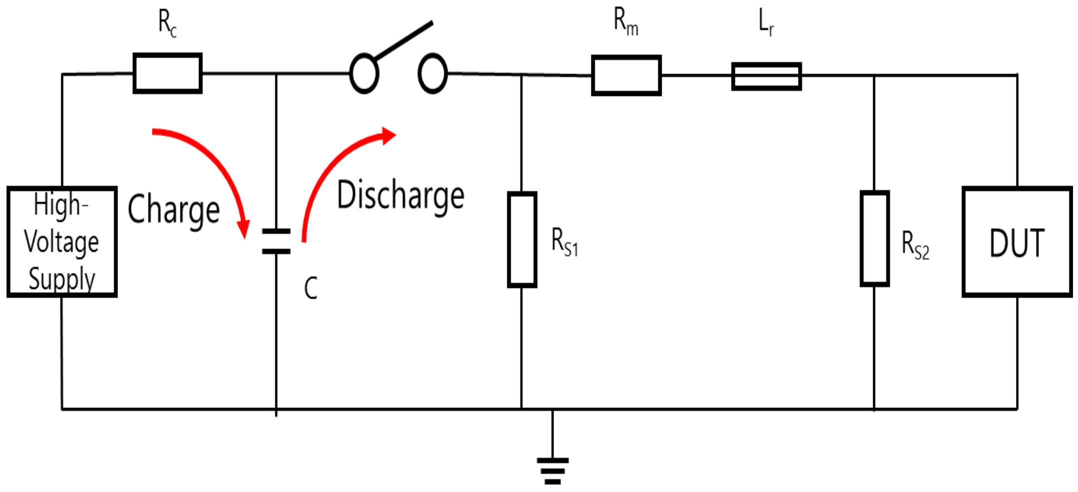
Example of a test waveform

Figure 6.2 IEC 61000-4-2 test

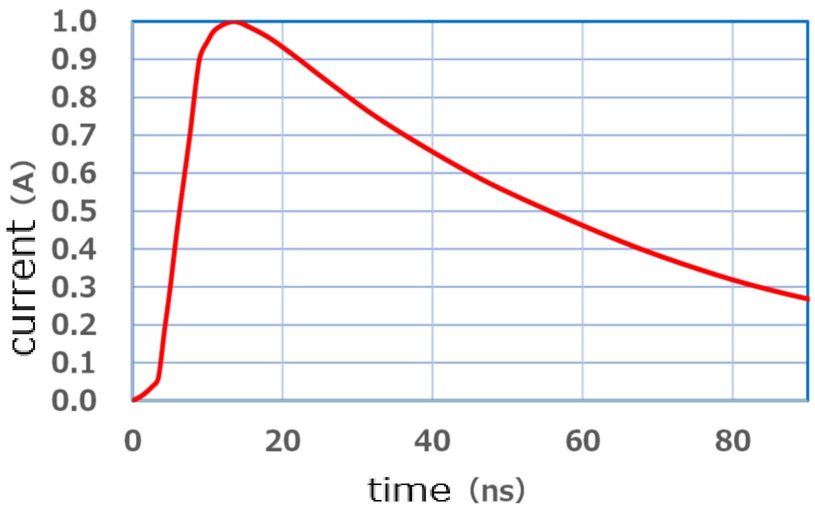
2. IEC 61000-4-5 test (Surge immunity test: Lightning surge test)

Also known as a lightning surge test, a surge immunity test models transient phenomena caused by a direct lightning strike as well as voltage and current surges induced by a nearby lightning strike. This test also includes transient switching phenomena such as a sharp load variation and a load short-circuit that might occur when the power switch of a large machine is turned on. The IEC 61000-4-5 test is the most stringent system-level surge immunity test in terms of the level and cycle time of the surge current applied.

The surge immunity test is stipulated in IEC 61000-4-5.



Example of a test circuit



Example of a test waveform

Figure 6.3 IEC 61000-4-5 test

Electrical characteristics

Working peak reverse voltage, V_{RWM}

At a voltage lower than the working peak reverse voltage, an ESD protection diode exhibits a very high impedance. (Even if the working peak reverse voltage is applied, only a current less than the specified leakage current flows.) The designer can use this parameter as a guide to ensure that it is above the maximum operating voltage of the signal line to be protected.

Total capacitance, C_t

C_T is the equivalent capacitance across a diode's terminals when a small signal is applied at the specified reverse voltage and frequency. The total capacitance is the sum of the junction capacitance of a diode and the parasitic capacitance of its package. Junction capacitance decreases as reverse voltage increases.

Dynamic resistance, R_{DYN}

The dynamic resistance is the current slope of the V_F–I_F curve between V_{BR} and V_C when an ESD protection diode goes into reverse breakdown as reverse voltage is increased. The dynamic resistance and the clamp voltage described below represent the ESD performance of an ESD protection diode.

Reverse breakdown voltage, V_{BR}

Reverse breakdown voltage is the voltage at which an ESD protection diode begins to conduct the specified amount of current under specified conditions (defined typically at 1 mA, although this differs from device to device). V_{BR} is originally a parameter defined for Zener diodes. V_{BR} is defined as the voltage at which an ESD protection diode turns on.

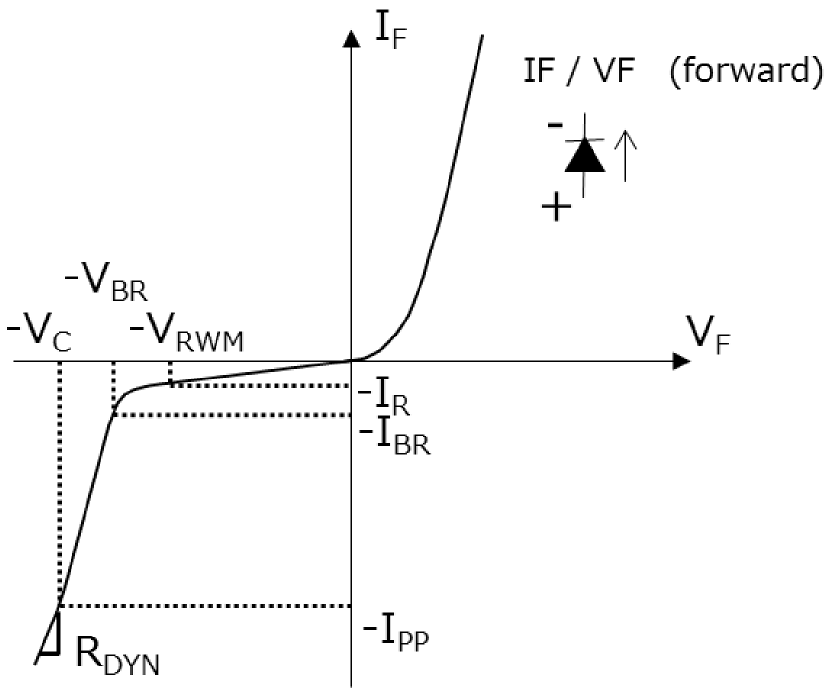
7. Electrical characteristics of TVS diodes (ESD protection diodes)

Reverse current, I_R

Reverse current is the leakage current that flows in the reverse direction when an ESD protection diode is reverse-biased at the specified voltage. In the case of ESD protection diodes, I_R is defined at the working peak reverse voltage (V_{RWM}).

Clamp voltage, V_C

Clamp voltage is the maximum voltage to which an ESD protection diode is clamped when exposed to the specified peak pulse current. V_C is generally measured at multiple peak pulse current points. As shown in Section 6 (Figure 6.1), an 8/20 μs waveform is used for the peak pulse current. The dynamic resistance and the clamp voltage represent the ESD performance of an ESD protection diode.



V_{RWM}: **Working peak reverse voltage**

Voltage at which an ESD protection diode does not enter into breakdown at T_a = 25°C

V_{BR}: **Reverse breakdown voltage**

Voltage at which an ESD protection 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

Figure 7.1 Voltage-vs-current curve of ESD protection diodes

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