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Basic Knowledge of Discrete Semiconductor Device

Chapter II

Diodes

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Toshiba Electronic Devices & Storage Corporation

Types of Diodes

Diodes are two-terminal semiconductor devices with a pn junction or an alternative junction. Table 2-1 shows an example of classification of diodes. They are classified into rectifier diodes, Zener diodes, etc. by structure and usage. Diodes are widely used.

Table 2-1 Example of classification of diodes

- **Diodes**
  - **PN junction diodes**
    - **Rectifier diodes**
    - **Fast recovery diodes (FRD)**
    - **TVS diode (ESD protection diode)**
    - **Zener diodes**
    - **Variable-capacitance diodes**
    - **High-frequency diodes**
  - **Metal-semiconductor junction diodes**
    - **Schottky barrier diodes (SBD)**
    - **High-frequency Schottky barrier diodes**

Diodes are sometimes classified not only as in the above figure, but also by usage.

Functions of Rectifier Diodes

A characteristic of diodes is that current flows (forward direction) or current does not flow (reverse direction) depending on the direction of applied voltage. This works to convert alternating current (AC) voltage to direct current (DC). The electrode terminals are called the anode (A) and the cathode (K), and current flows when the anode electrode is at positive potential. Note: The cathode "K" comes from the German "Kathode."

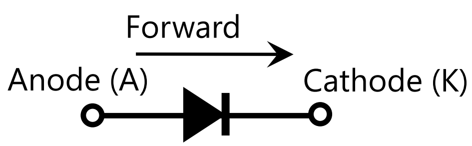


Fig. 2-1(a) Symbol of diode and names of its electrodes

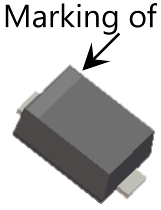


Fig. 2-1(b) Example of appearance of diode

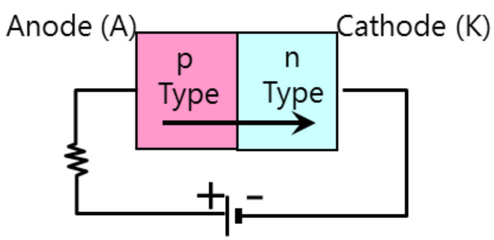


Fig. 2-1(c) Polarity of diode

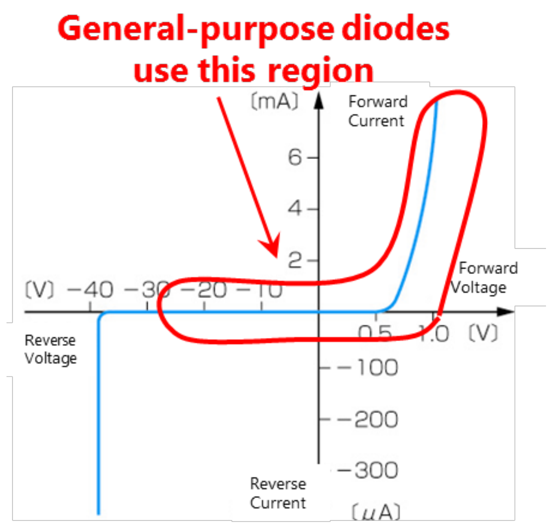


Fig. 2-1(d) Typical characteristic of diode

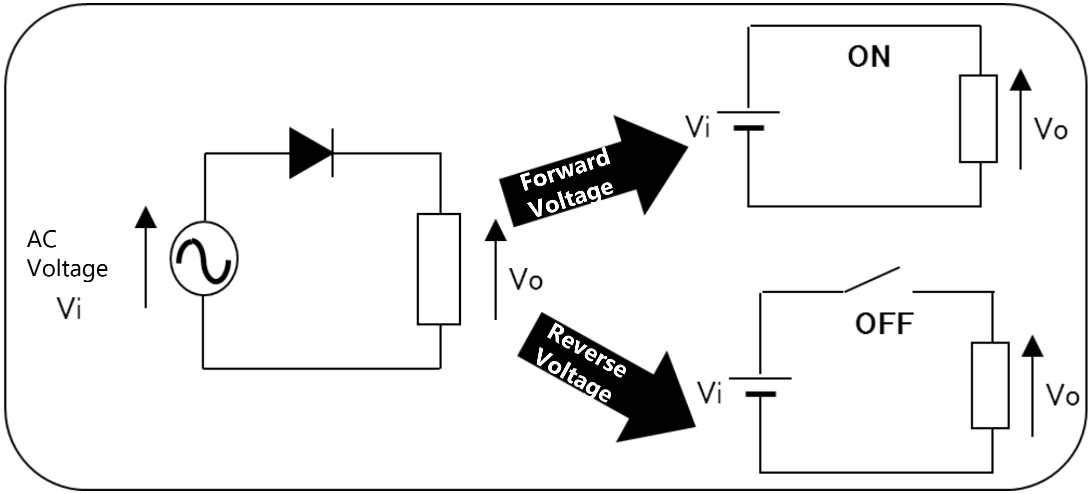
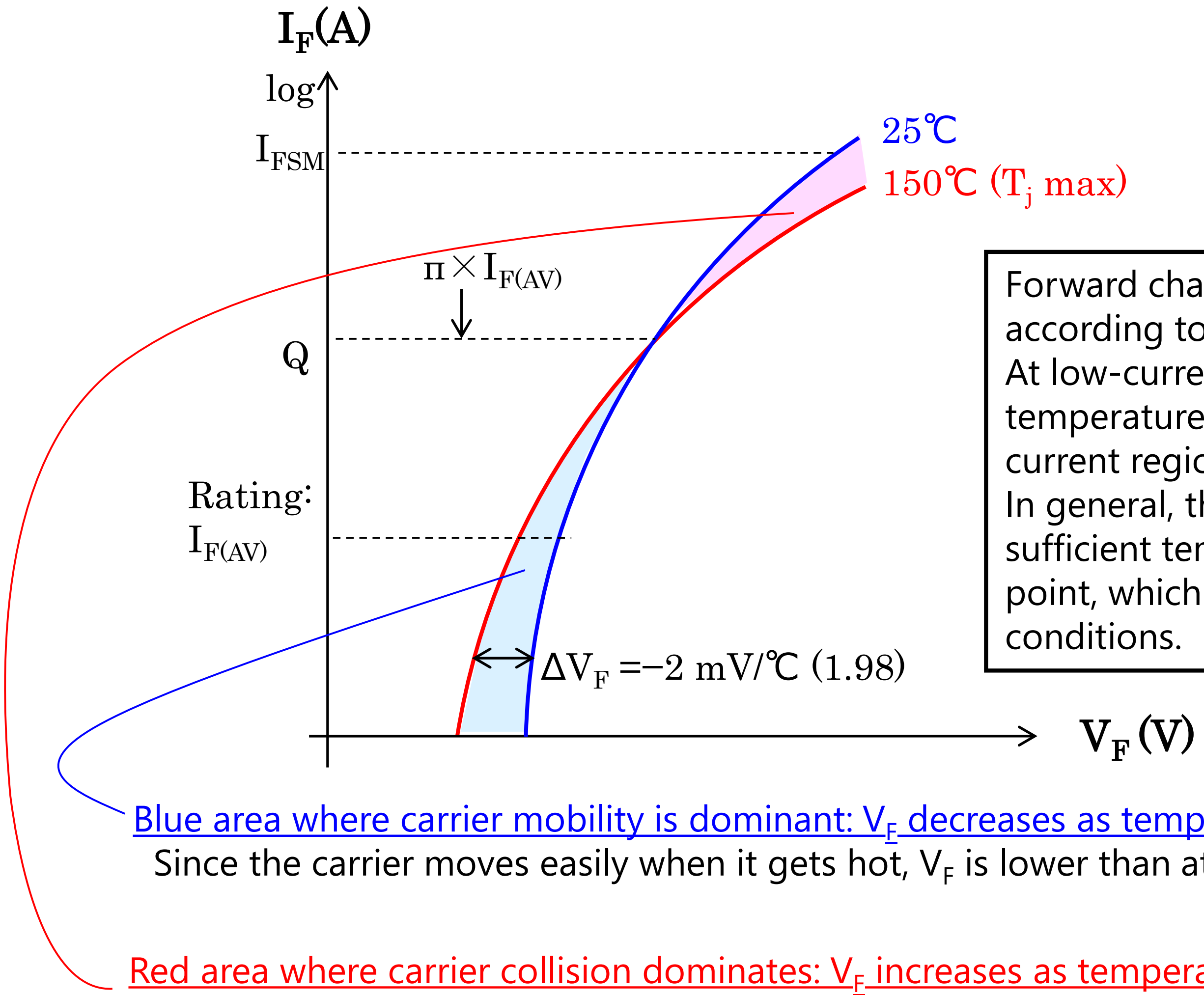


Fig. 2-2 Typical function of diode

Forward Characteristic of Rectifier Diodes (I_F-V_F Characteristic)



Forward characteristic of rectifier diode varies according to current level and temperature.
At low-current region, V_F is low at high temperature, and the opposite is true at high-current region.
In general, the diode should be used with a sufficient temperature margin below the Q point, which is the cross point of the above two conditions.

Blue area where carrier mobility is dominant: V_F decreases as temperature increases.
Since the carrier moves easily when it gets hot, V_F is lower than at low temperature.

Red area where carrier collision dominates: V_F increases as temperature increases.
When a large current flows, a lot of carriers move. In the case of high temperature, the probability of collision between carriers increases and V_F becomes higher than at low temperature.

FRDs (Fast Recovery Diodes)

The structure and function of fast recovery diodes (FRDs) are the same as those of rectifier diodes. Rectifier diodes are used for low-frequency applications below 500 Hz, whereas FRDs are used for high-frequency switching from a few kHz to 100 kHz. Therefore, the reverse recovery time (t_{rr}) of the diode characteristic, which is important for high-speed switching, is short. FRDs are also referred to as S-FRDs, HEDs, etc. according to the trr value.
t_{rr} of a general rectifier diode is several µs to several tens of µs. On the other hand, t_{rr} of an FRD is several tens of ns to several hundred ns and is about 1/100 of that of the rectifier diode. It is used in switching power supplies, inverters, DC/DC converters, etc.

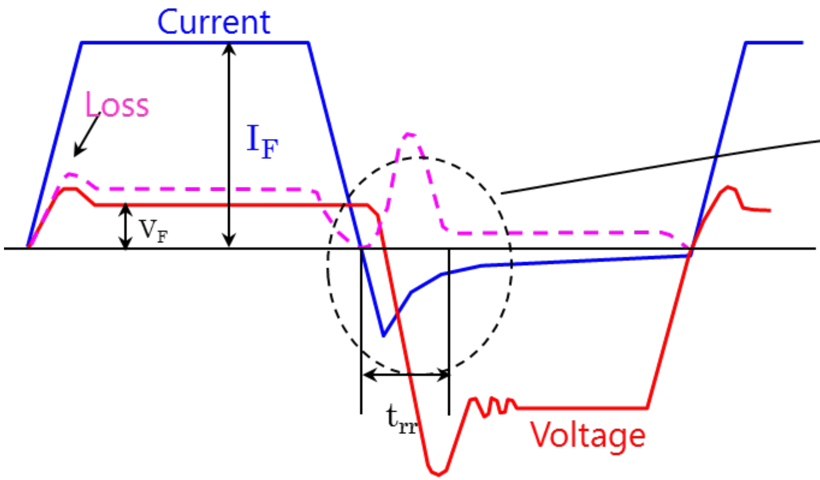


Fig. 2-3(a) Example of diode switching waveform and loss

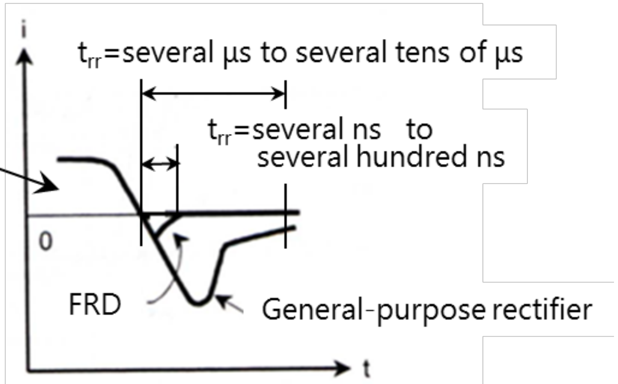


Fig. 2-3(b) Comparison of t_{rr} between general-purpose rectifier and FRD

The loss due to t_{rr} (reverse recovery loss) is negligible when the frequency is low, but this loss increases with frequency, and it cannot be ignored if it becomes several kHz or more.

Voltage Regulator Diodes (Zener Diodes)

Voltage regulator diodes utilize the reverse characteristics of a pn junction. When raising reverse voltage of pn junction diodes, high current starts flowing at a certain voltage, and constant voltage can be obtained. (This phenomenon is called breakdown and this voltage is called breakdown voltage.)

Voltage regulator diodes actively use this characteristic. Since this breakdown voltage is also called Zener voltage, voltage regulator diodes are also called Zener diodes. This voltage may be used as a constant voltage power supply or a reference voltage for electronic circuits.

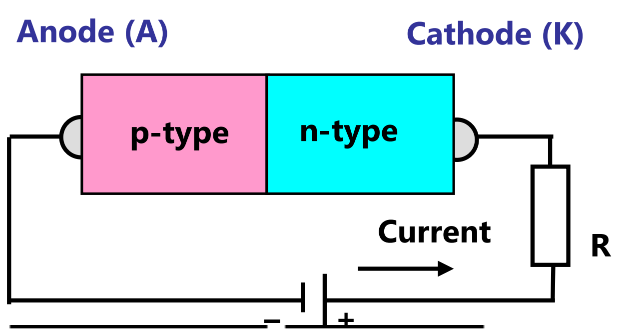


Fig. 2-4(a) Structure and connection of Zener diode

(Note: Generally, the Zener phenomenon is observed when the voltage is 6 V or less. If it exceeds 6 V, the avalanche phenomenon becomes dominant over the Zener phenomenon. Zener voltage and avalanche voltage have different temperature characteristics; the former has a negative temperature coefficient and the latter has a positive one.)

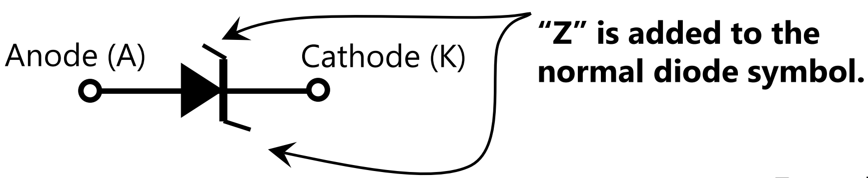


Fig. 2-4(b) Symbol of Zener diode

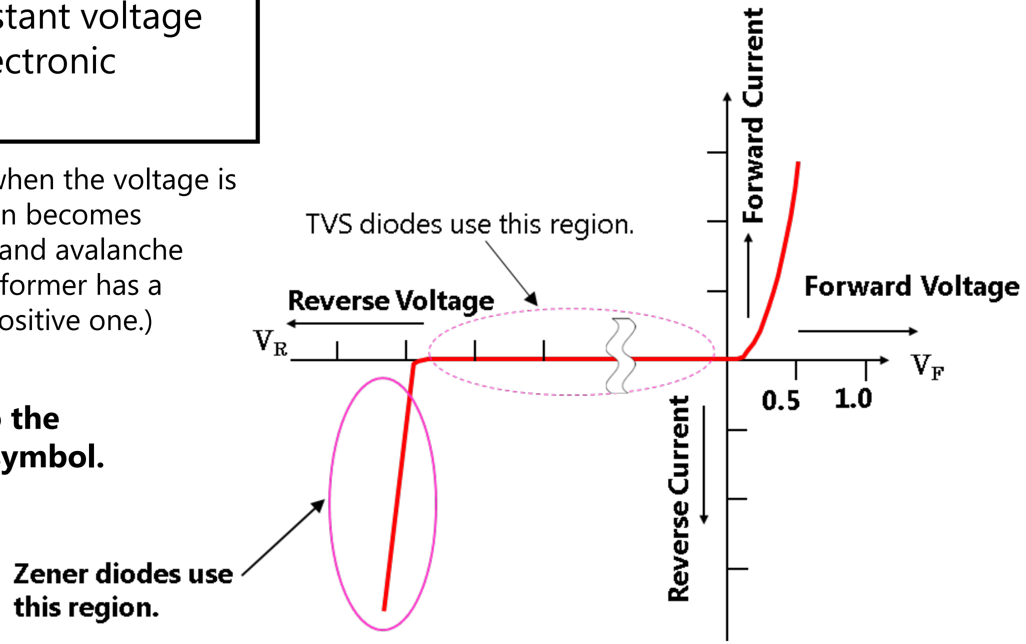
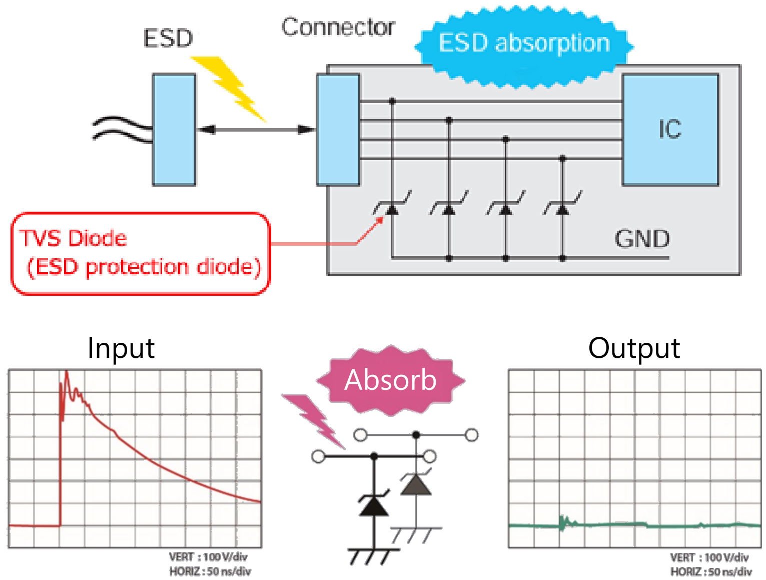


Fig. 2-4(c) Electrical characteristic of Zener diode

TVS Diodes (ESD protection diode)

A TVS diode (ESD protection diode) is a kind of Zener diode. It is a diode that is mainly used for static electricity (ESD) countermeasures. It protects integrated circuits and others from high-voltage ESD entering from a USB line etc.
TVS diodes absorb abnormal voltage from interfaces, external terminals, etc., prevent malfunction of circuits and protect devices. They are suitable for absorbing and suppressing static electricity or short-pulse voltage.



By using TVS diode (ESD protection diode),
it can absorb intrusive ESD, prevent malfunction of the circuit, protect device such as IC !

Fig. 2-5(a) Example of usage of TVS diodes

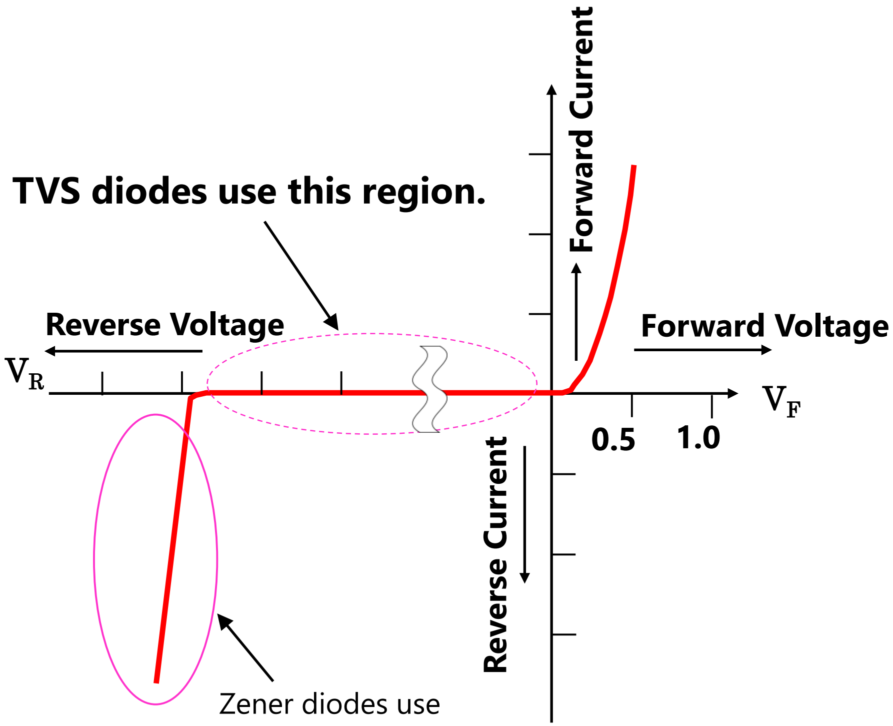


Fig. 2-5(b) Electrical characteristic of TVS diode

Difference between TVS Diodes and Zener Diodes (1)

As shown in Fig. 2-6(a), a TVS diode (ESD protection diode) absorbs very high overvoltage in a short time and works so as not to apply excessive voltage to other semiconductor devices. On the other hand, as shown in Fig.2-6(b), a Zener diode clamps input voltage to a constant voltage and supplies clamped voltage to other semiconductor devices.
Thus, a TVS diode absorbs surge voltage to protect other semiconductor devices, whereas a Zener diode provides constant voltage to other semiconductor devices.

TVS diode

Absorbing and controlling static electricity and short-time pulse

Zener diode

Constant voltage control
Standard voltage

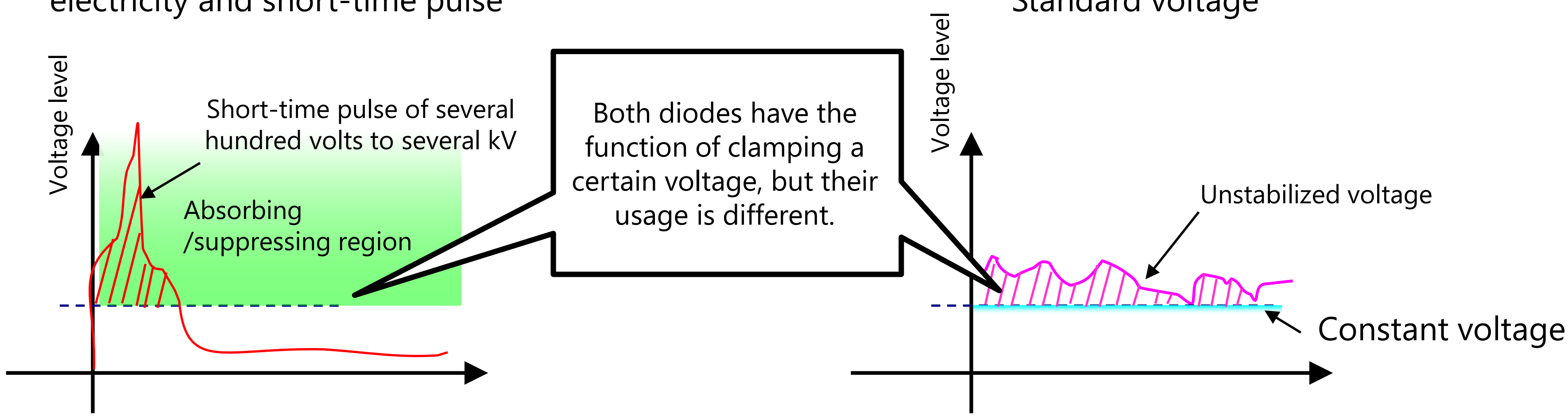


Fig. 2-6(a) Usage of TVS diode

Fig. 2-6(b) Usage of Zener diode

Difference between TVS Diodes and Zener Diodes (2)

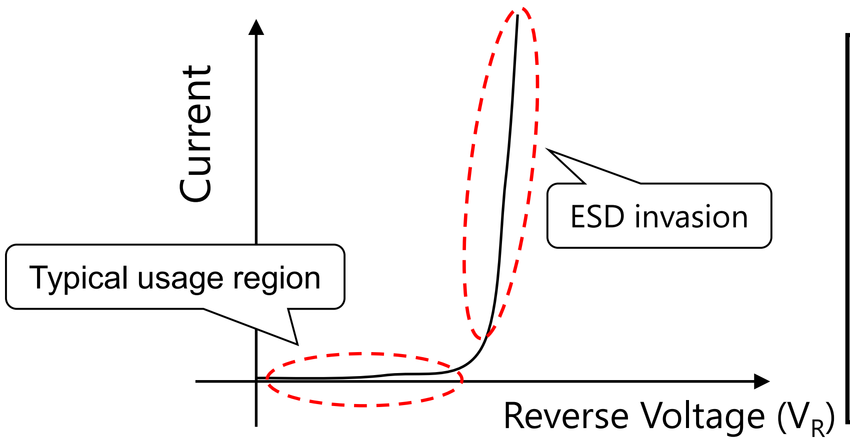


Fig. 2-7(a) TVS diode usage region

[TVS diode: See Fig. 2-7(a).]
TVS diodes are typically used under reverse blocking status. (Virtually no current flows and only voltage is applied.)
Breakdown (clamp) occurs only when voltage exceeding a certain voltage (clamp voltage) is applied to a TVS diode.

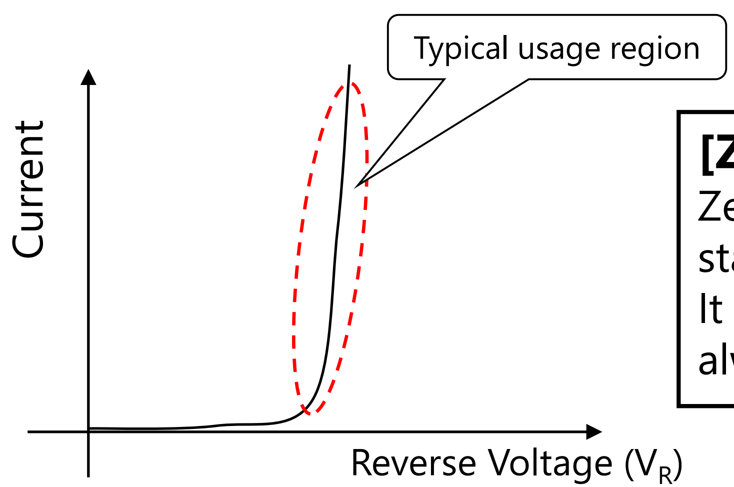


Fig. 2-7(b) Zener diode usage region

[Zener diode: See Fig 2-7(b).]
Zener diodes normally used in the breakdown state.
It is assumed that a breakdown (Zener) current always flows in normal state.

Variable-capacitance Diodes (Varicap Diodes)

The variable-capacitance diode is a product that makes use of the capacity characteristics of the depletion layer. The depletion layer occurs in the pn junction of the diode when the voltage is applied in the reverse direction, and the thickness varies in proportion to the reverse voltage.
Therefore, as the reverse voltage applied increases, the capacitance decreases. This is the same function as increasing the distance between the two electrodes of the capacitor. Conversely, if the reverse voltage becomes low, the capacitance increases.
It is used for tuning circuits etc. Since the frequency characteristics are changed by this capacitance change, a large capacity change ratio is required as compared with a normal diode.

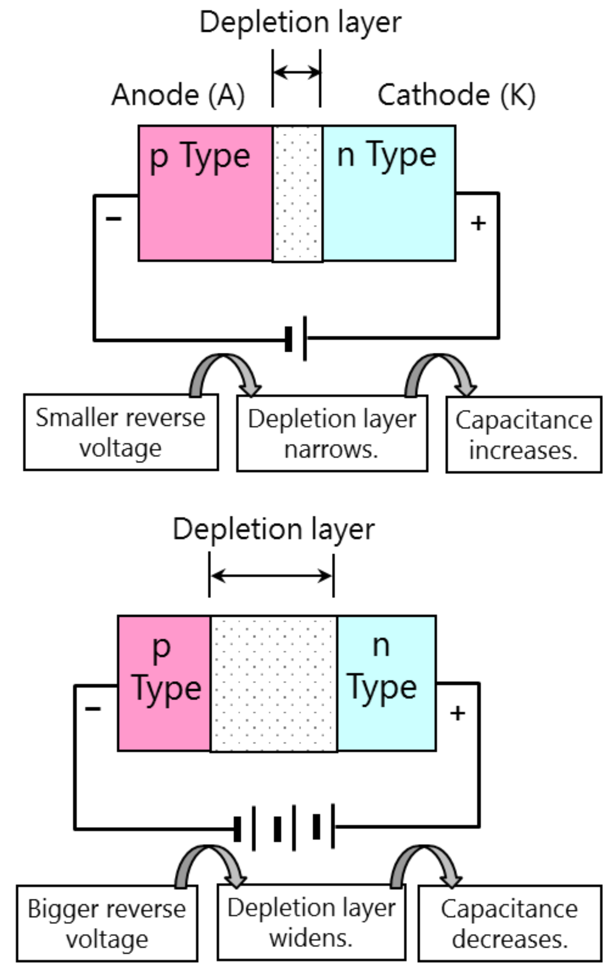


Fig. 2-8(c) Relation between depletion layer and capacitance of variable-capacitance diode

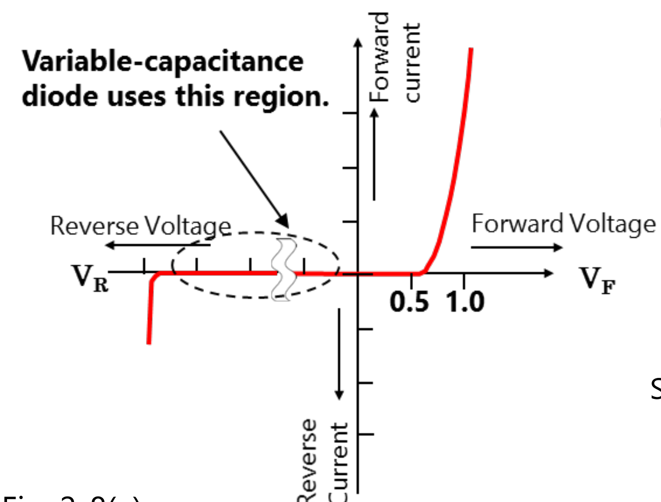


Fig. 2-8(a)
Electrical characteristic of variable-capacitance diode

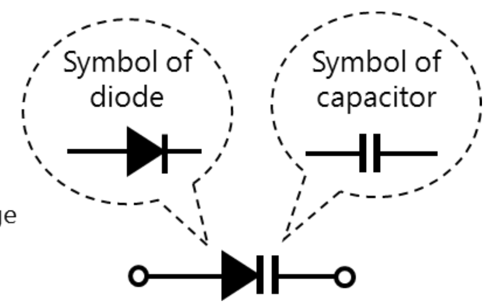


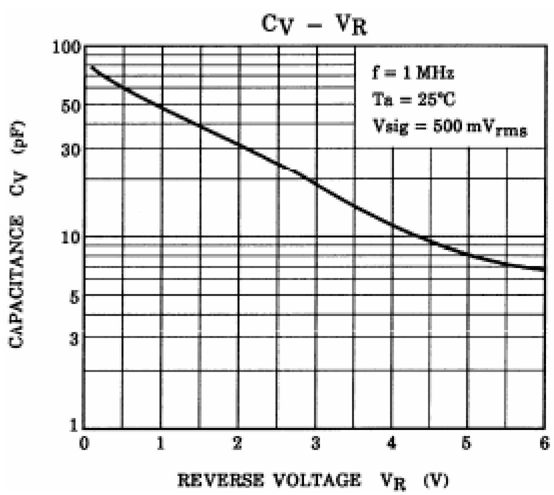
Fig. 2-8(b)
Symbol of variable-capacitance diode

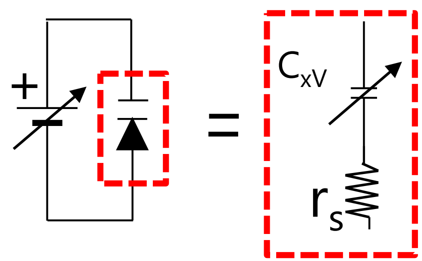
Variable-capacitance Diodes (Varicap Diodes)

Electrical Characteristics (Ta = 25°C)

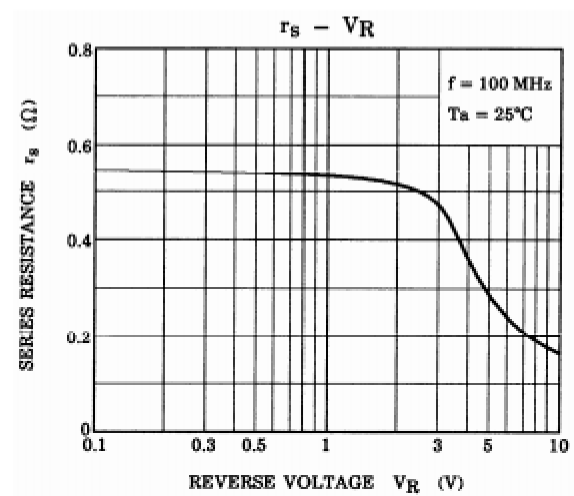
Characteristics	Symbol	Test Condition	Min	Typ.	Max	Unit
Reverse voltage	V_R	$I_R = 1\ \mu A$	10	—	—	V
Reverse current	I_R	$V_R = 10$ V	—	—	3	nA
Capacitance	C_{1V}	$V_R = 1$ V, f = 1 MHz	44	—	49.5	pF
Capacitance	C_{6V}	$V_R = 6$ V, f = 1 MHz	5.4	—	7.3	pF
Capacitance ratio	C_{1V} / C_{6V}	—	6.3	7.5	—	—
Series resistance	r_s	$V_R = 4$ V, f = 100 MHz	—	0.4	0.8	Ω

The important characteristics of a variable-capacitance diode are not the forward voltage V_F and switching characteristics as in the case of a general diode, but the capacitance value and its variation (voltage dependence).





r_s: serial equivalent resistance



Schottky Barrier Diodes (SBDs)

A Schottky barrier diode (SBD) is a device in which a semiconductor and a metal such as molybdenum are bonded instead of a pn junction. In general, semiconductors in which metals are bonded to n-type layers have been commercialized. It is suitable for high-speed switching applications, because of small forward voltage and short reverse recovery time.

For the SBD there is a tradeoff between forward voltage (V_F) and reverse leakage current.
Depending on the metal used, in general, the reverse withstand voltage is about 20 to 150 V and the V_F is about 0.4 to 0.7 V, which is lower than that of the pn junction diode.

SBDs with a new structure with low forward voltage but low leakage current have also been commercialized. (Toshiba has achieved low V_F and low leakage current characteristics by adopting a trench structure for SBD.)

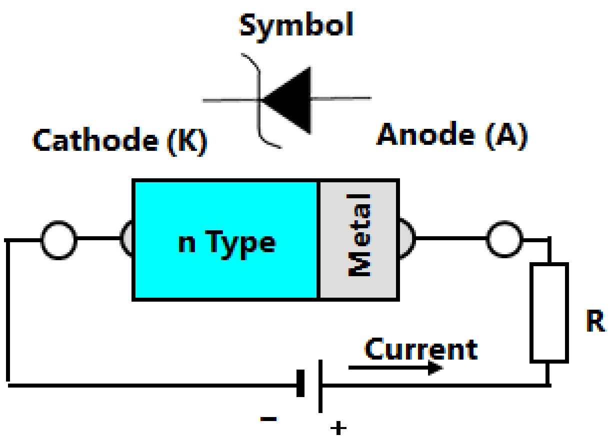


Fig. 2-9(a) Symbol and structure of Schottky barrier diode

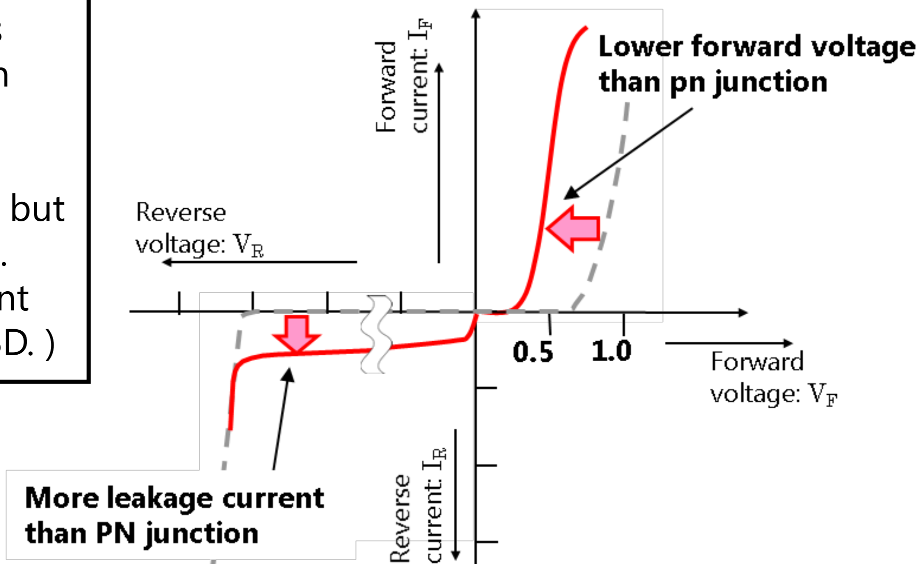
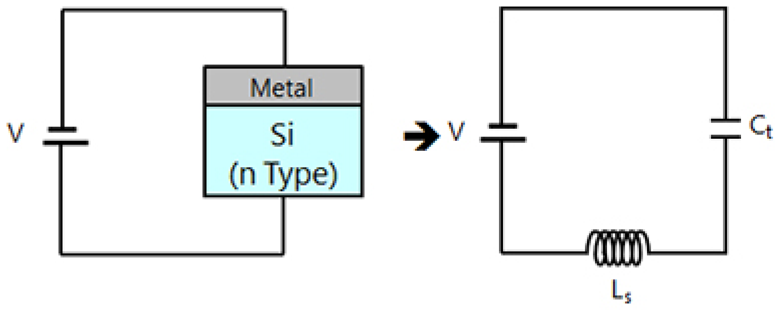


Fig. 2-9(b) Electrical characteristic of Schottky barrier diode

Reverse Recovery Characteristic of Schottky Barrier Diodes (SBDs)



C_t: Junction capacitance

L_s: Stray inductance of circuit

Fig. 2-10(a) Equivalent circuit when reverse voltage is applied to SBD

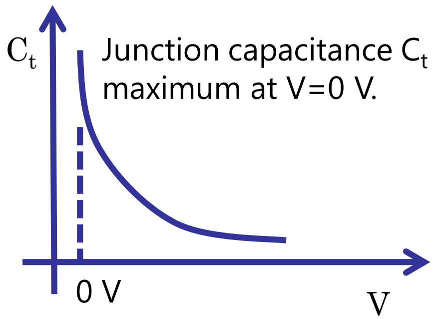


Fig. 2-10(b) Characteristic of junction capacitance of SBD

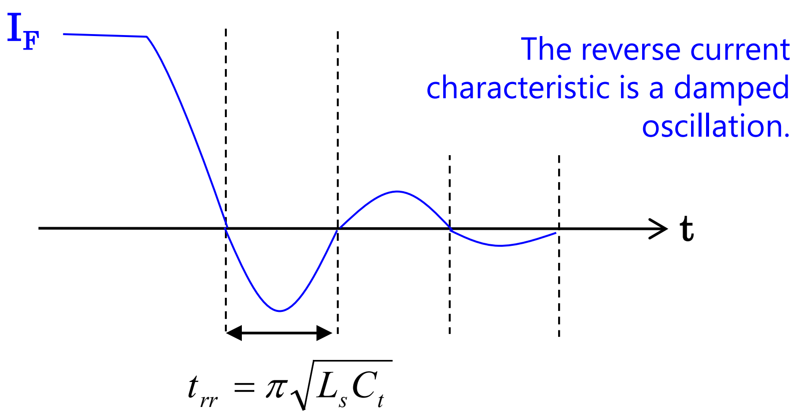
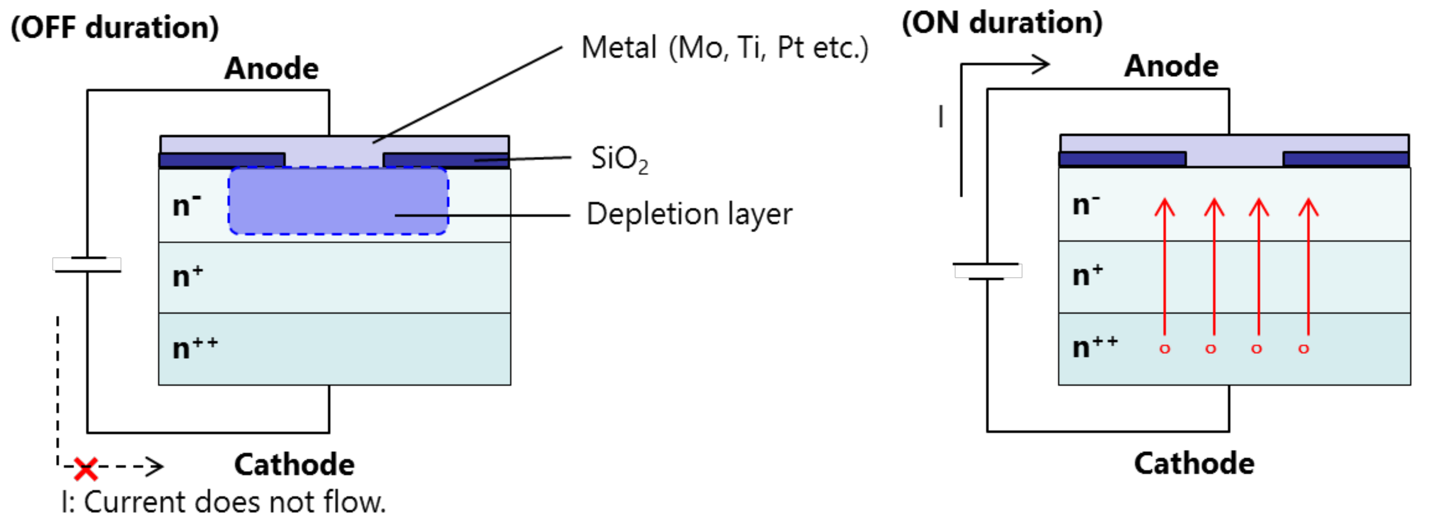


Fig. 2-10(c) Typical reverse characteristic of SBD

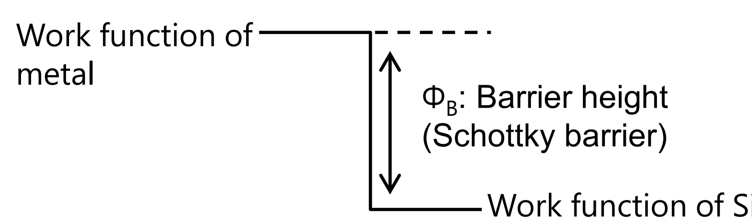
The reverse recovery time (t_{rr}) of the SBD is determined by the LC resonance circuit based on the junction capacitance and the inductance of the external wiring. (Since the junction capacitance is hardly influenced by temperature, t_{rr} is the same from room temperature to high temperature.)
For pn junction diodes, t_{rr} becomes longer as the temperature rises. As a result, the switching characteristics of the SBD become more and more advantageous, which makes it suitable for higher-frequency switching.

Difference Depending on Metal of Schottky Barrier Diodes (SBDs)

In the case of the SBD, the semiconductor consists of n-type layers, and so the metal acts as the anode of the diode. Likewise, only electrons are carriers, and the SBD becomes a unipolar element just like a MOSFET.
The energy level of silicon differs from metal (energy gap). This energy level differs depending on the metal element. Φ_B is the symbol for this difference. Pt (platinum) is a metal with a large energy gap. V (vanadium) or Ti (titanium) are metals with small energy gaps. Adopting a metal with a large ΦB makes leakage current small, but makes forward voltage V_F big. For metals with small Φ_B, the opposite tendency are obtained.



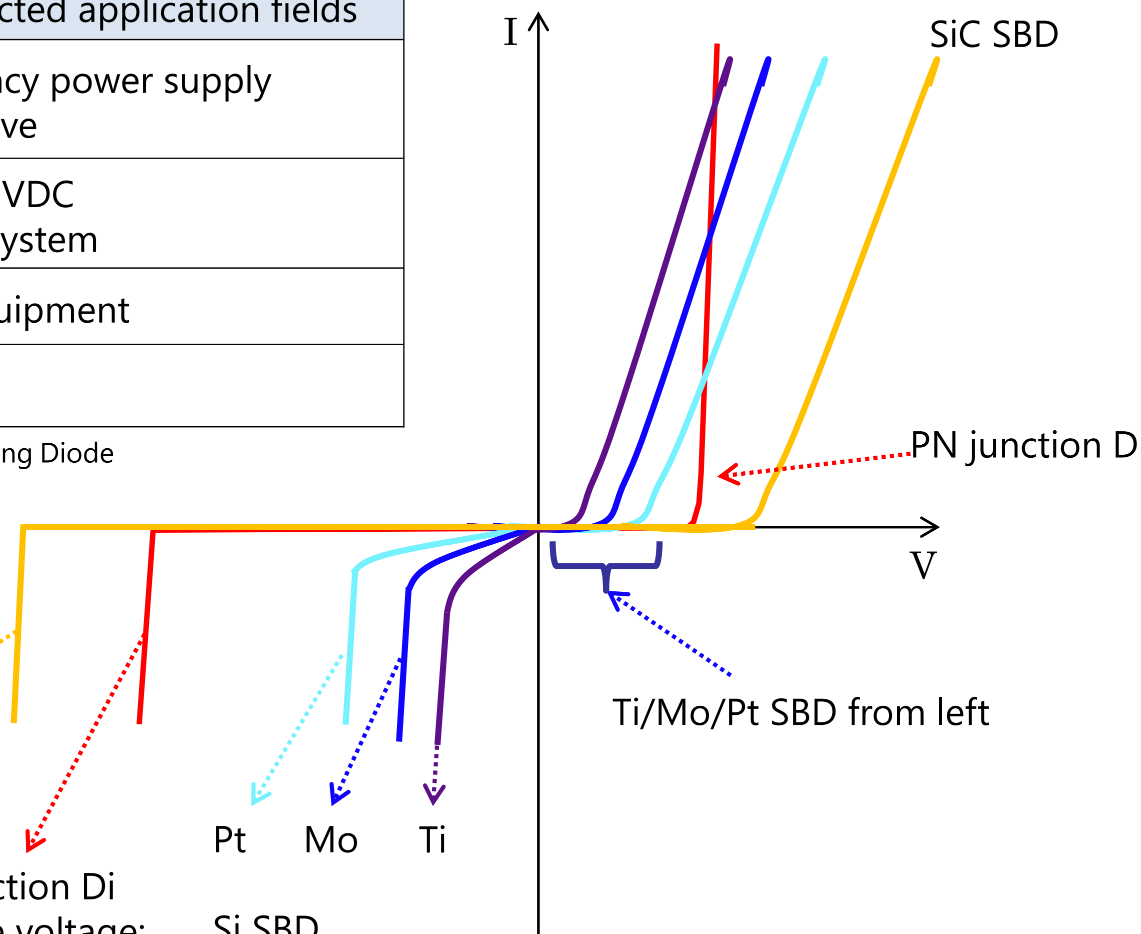
	Pt	Mo	V	Ti
Φ_B	Big ←		Small	
V_F	Big ←		Small	
I_{RRM}	Small →		Big	



Characteristics Application of Various Diodes

Types of diodes		Application or expected application fields
SiC SBD		• PFC[*1] in high-efficiency power supply • IGBT FWD[*2] in AC drive
SiC, PN junction diode		• DC transmission of HVDC • AC drive of traction system
Si SBD	Mo/V	• Battery of mobile equipment
	Pt/Ti	• Rarely used

*1 : Power Factor Correction, *2 : Free-wheeling Diode



SiC SBD
Reverse voltage:
1200 V
150℃ to 175℃

PN junction Di
Reverse voltage:
600 V
125℃ to 150℃

Si SBD
Reverse voltage: 30 V to 60 V
100℃ to 125℃
Ti: V_F=0.4 V, Mo: V_F=0.55 V, Pt: V_F=0.6 to 0.7 V

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