TOSHIBA

Basic Knowledge of Discrete Semiconductor Device

Chapter II

Diodes

February 2022
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 diodes (TVS diodes)**
    - **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. Utilizing this property, the diode works to rectify the AC voltage. 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."

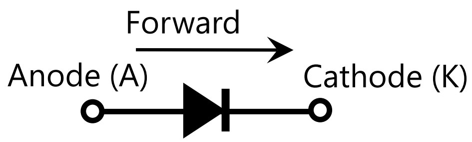


Fig. 2-1(a) Symbol of diode and names of its electrodes

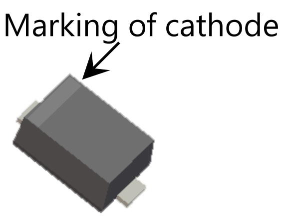


Fig. 2-1(b) Example of appearance of diode

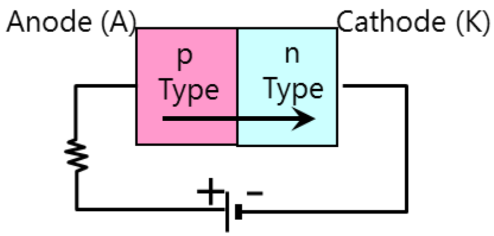


Fig. 2-1(c) Polarity of diode

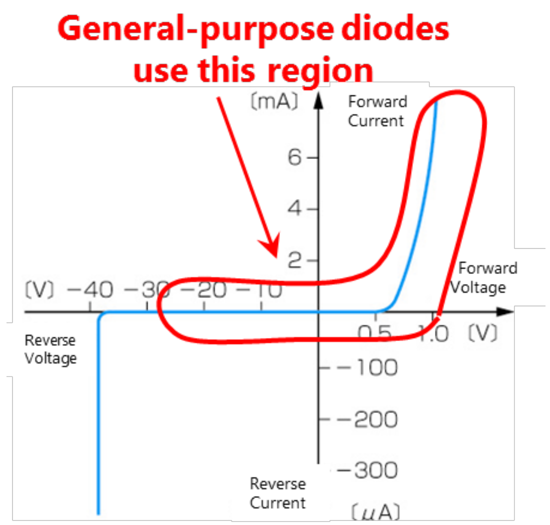


Fig. 2-1(d) Typical characteristic of diode

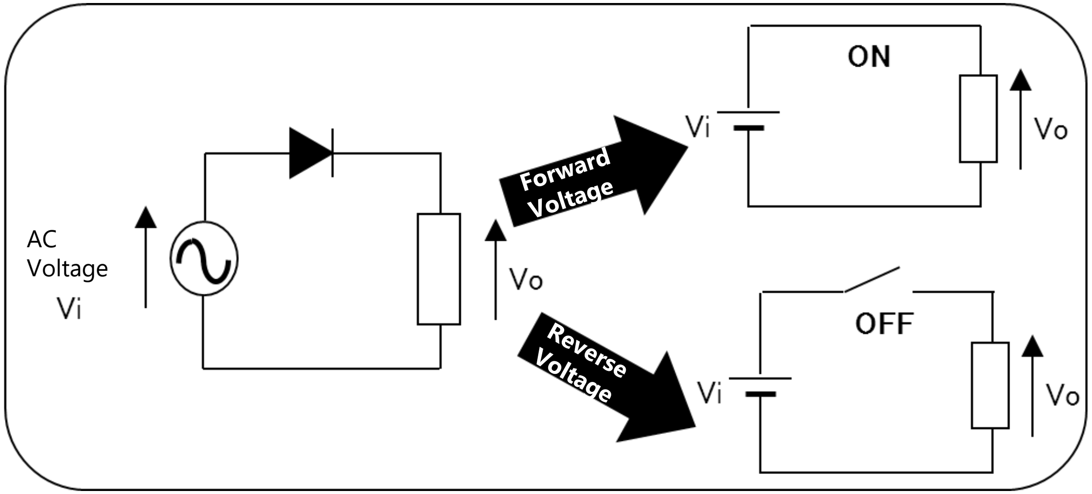
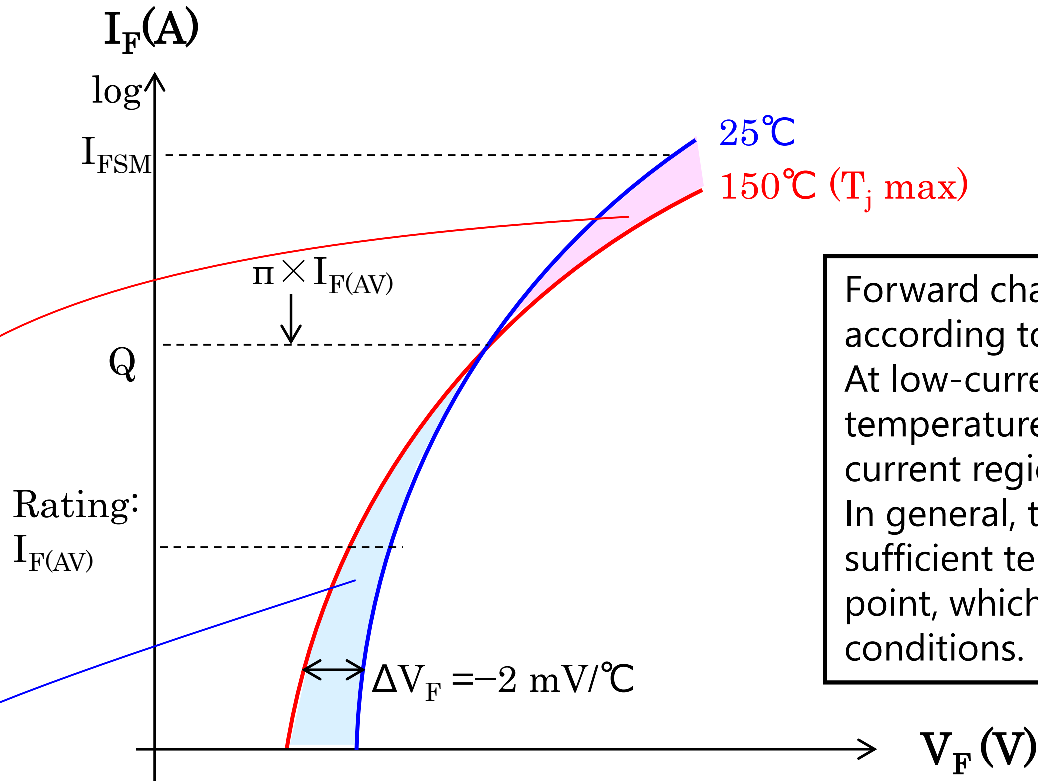


Fig. 2-2 Typical function of diode

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.

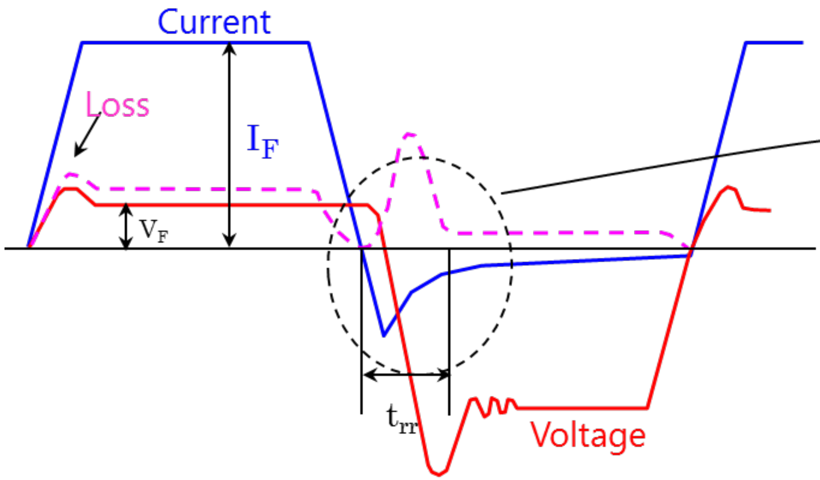


Fig. 2-3(a) Example of diode switching waveform and loss

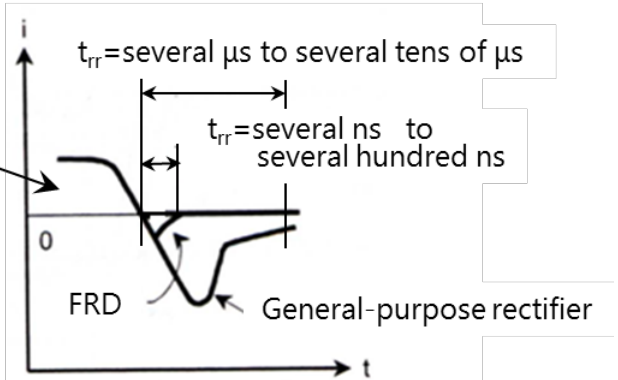


Fig. 2-3(b) Comparison of t_{rr} between general-purpose rectifier and FRD

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.

(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.)

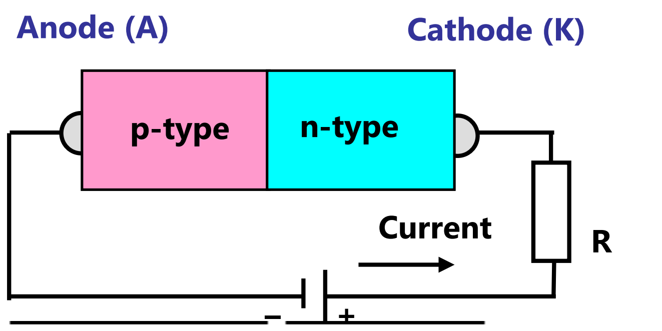


Fig. 2-4(a) Structure and connection of Zener diode

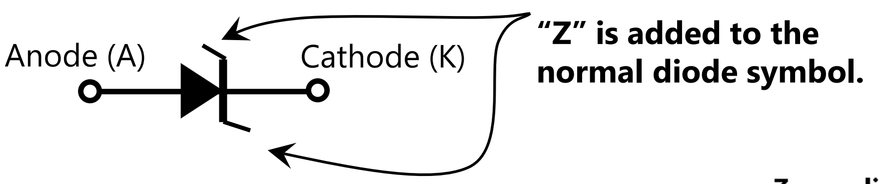


Fig. 2-4(b) Symbol of Zener diode

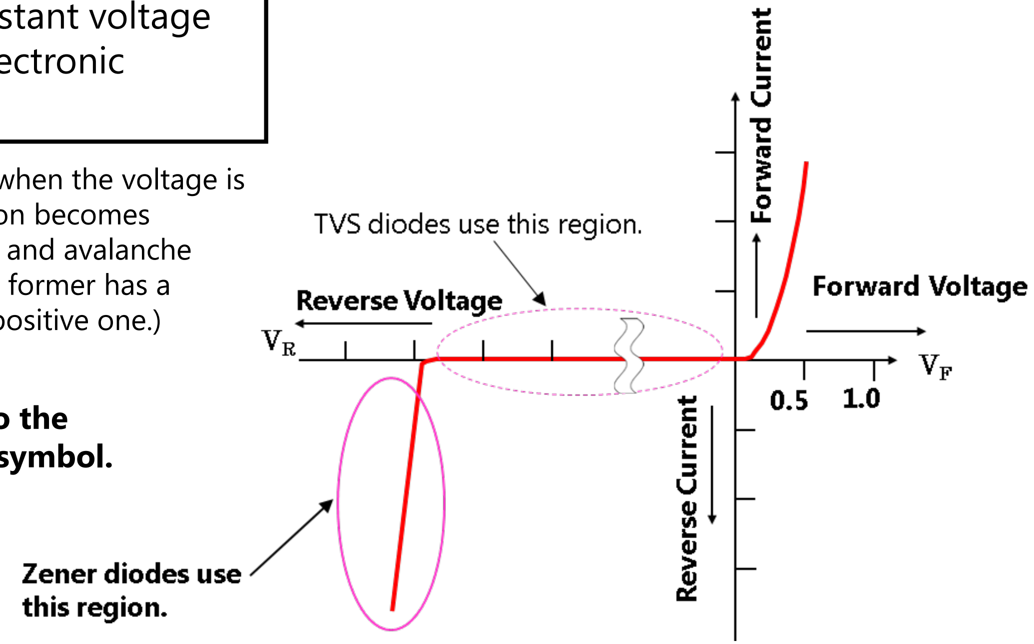
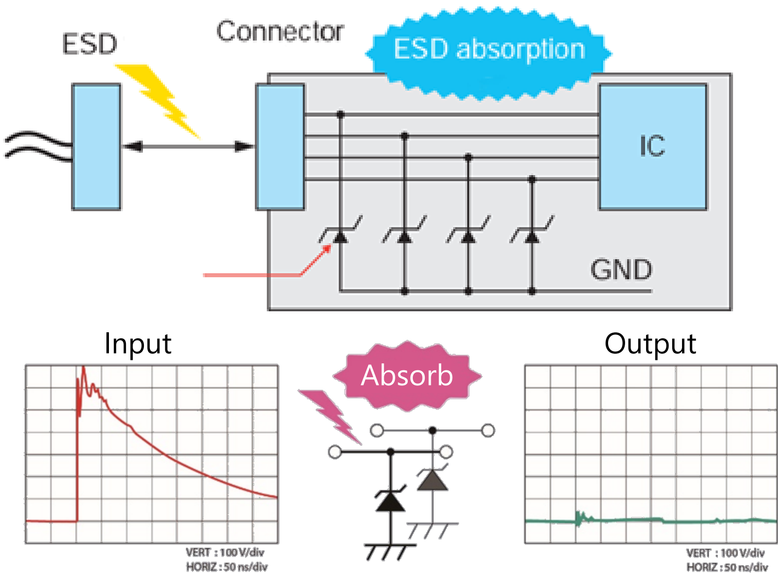


Fig. 2-4(c) Electrical characteristic of Zener diode

TVS Diodes (TVS Diodes)

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

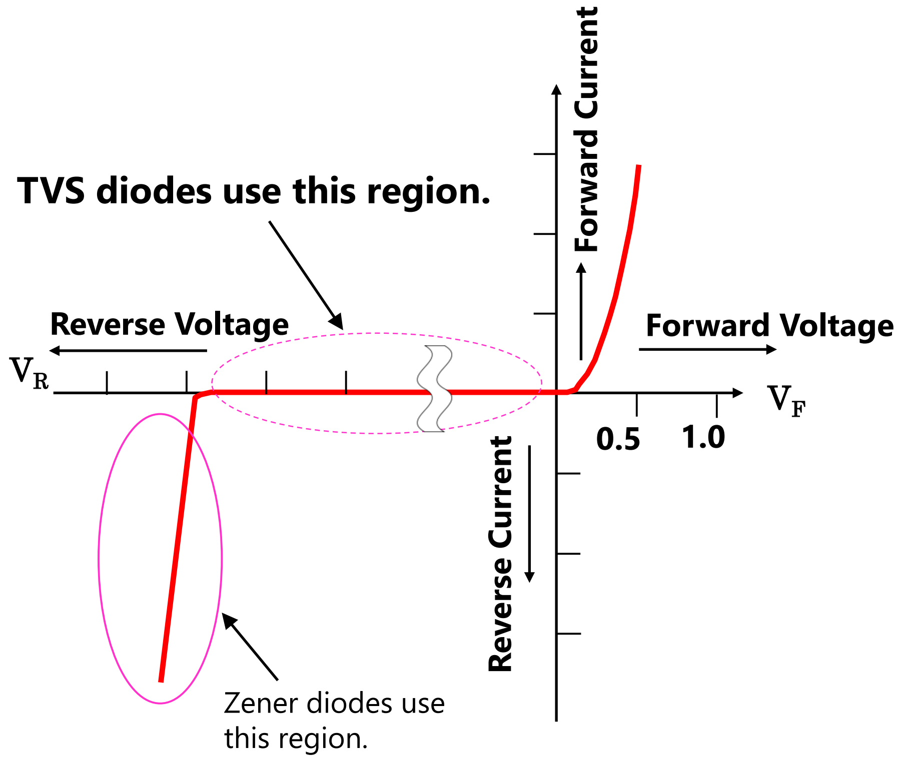


Fig. 2-5(b) Electrical characteristic of TVS diode

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

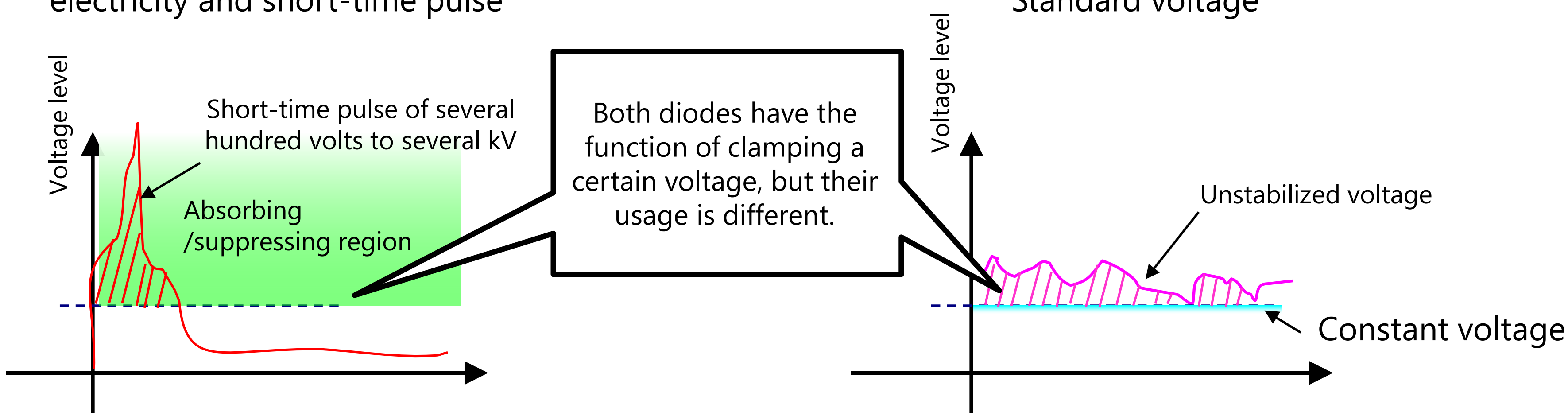


Fig. 2-6(a) Usage of TVS diode

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

Difference between TVS Diodes and Zener Diodes (2)

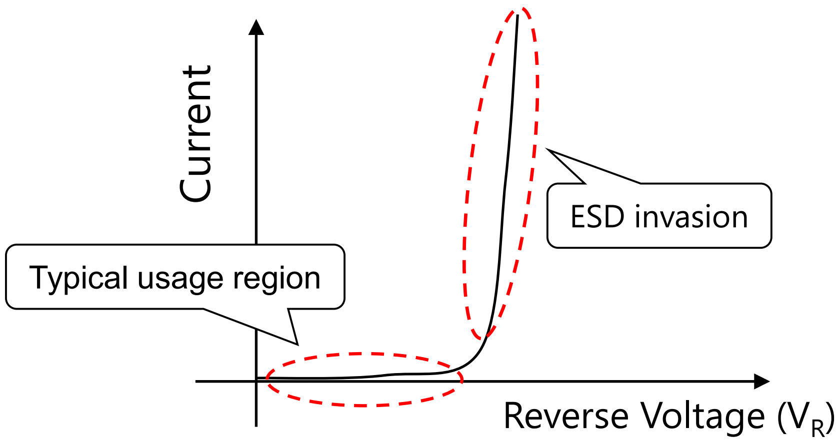


Fig. 2-7(a) TVS diode usage region

[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.

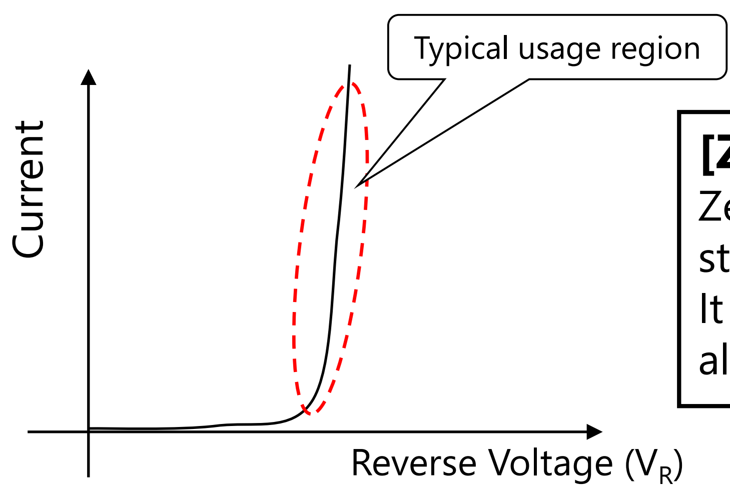


Fig. 2-7(b) Zener diode usage region

[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.

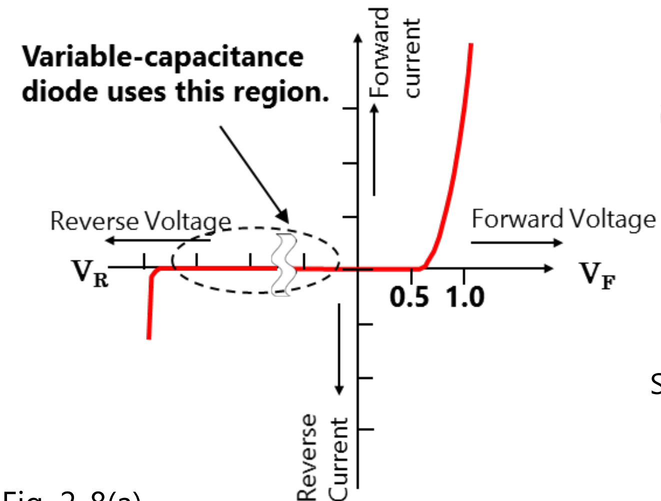


Fig. 2-8(a)
Electrical characteristic of variable-capacitance diode

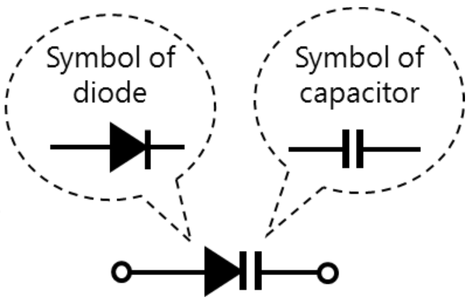


Fig. 2-8(b)
Symbol of variable-capacitance diode

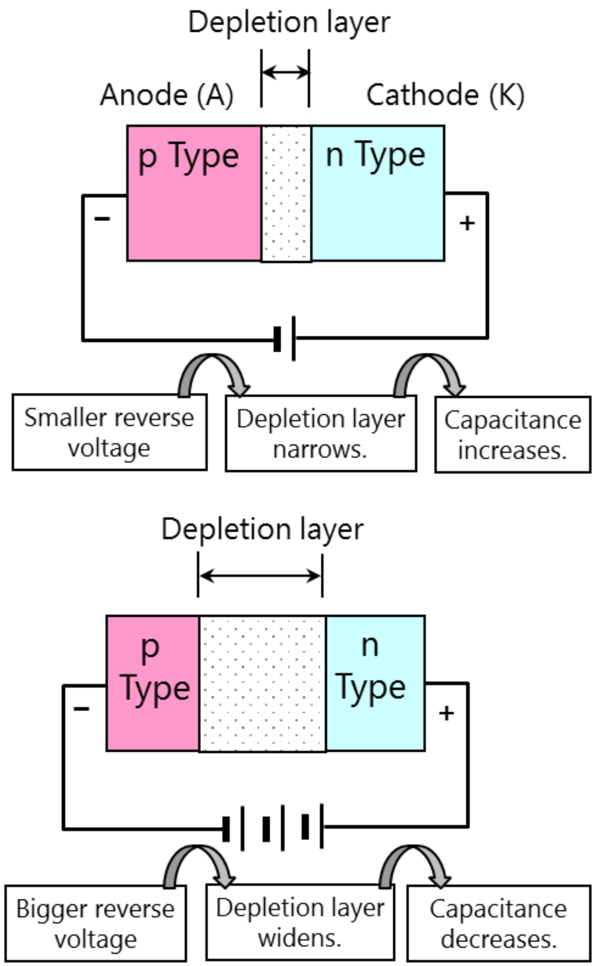


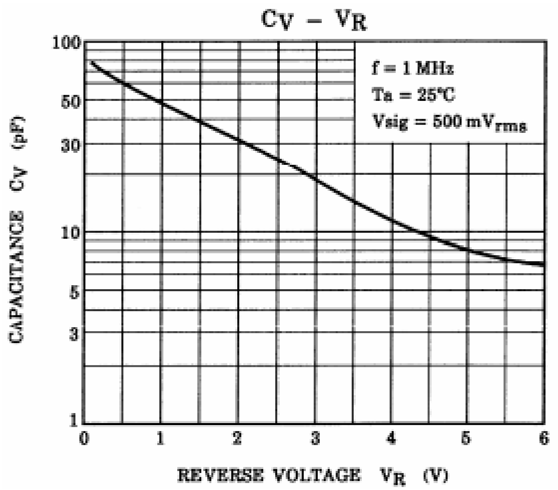
Fig. 2-8(c) Relation between depletion layer and capacitance of variable-capacitance diode

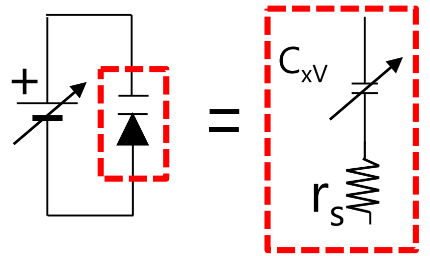
Variable-capacitance Diodes (Varicap Diodes)

Electrical Characteristics (Ta = 25°C)

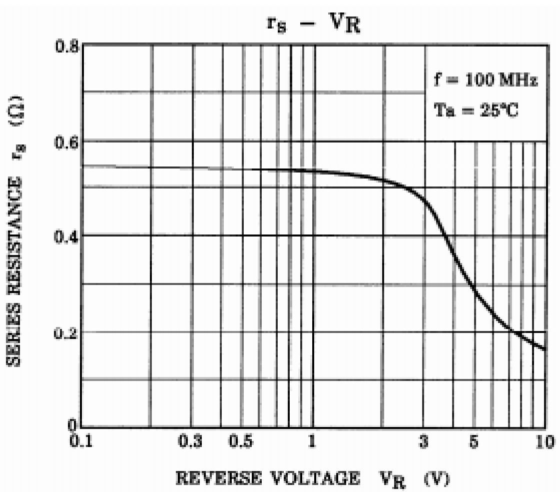
Characteristics	Symbol	Test Condition	Min	Typ.	Max	Unit
Reverse voltage	V_R	I_R = 1 μA	10	—	—	V
Reverse current	I_R	V_R = 10 V	—	—	3	nA
Capacitance	C_{1V}	V_R = 1 V, f = 1 MHz	44	—	49.5	pF
Capacitance	C_{6V}	V_R = 6 V, f = 1 MHz	5.4	—	7.3	pF
Capacitance ratio	C_{1V} / C_{6V}	—	6.3	7.5	—	—
Series resistance	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, SBDs of n-type semiconductor and metal junctions are commercialized. It is suitable for high-speed switching applications, because of small forward voltage and short reverse recovery time[Note].

For the SBD there is a tradeoff between forward voltage (V_F) and reverse current.
Depending on the metal used, in general, the breakdown 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 reverse current have also been commercialized. (Toshiba has achieved low V_F and low reverse current characteristics by adopting a trench structure for SBD.)

Note: Since SBD is a unipolar device, it does not have reverse recovery time due to carrier recombination like pn junction diodes. However, the current waveform charging the capacity between the terminals of SBD is observed like the reverse recovery time of the p-n junction diode.
Therefore, it is described as reverse recovery time in this document.

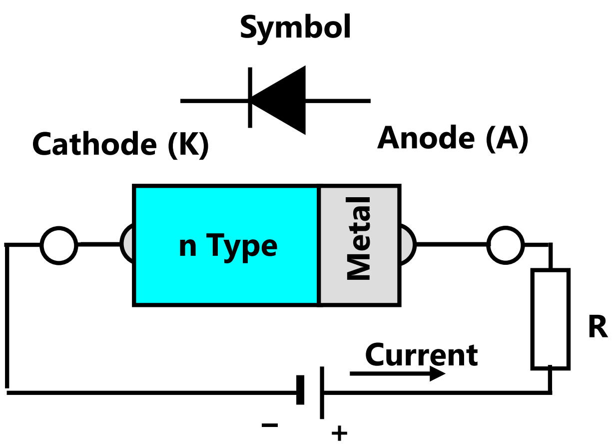


Fig. 2-9(a) Symbol and structure of Schottky barrier diode

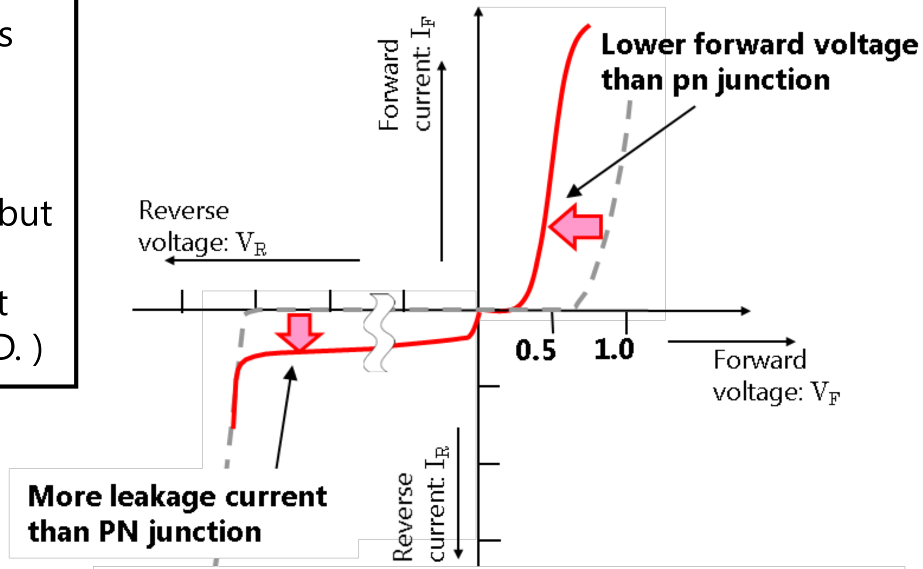


Fig. 2-9(b) Electrical characteristic of Schottky barrier diode

Reverse Recovery Characteristic of Schottky Barrier Diodes (SBDs)

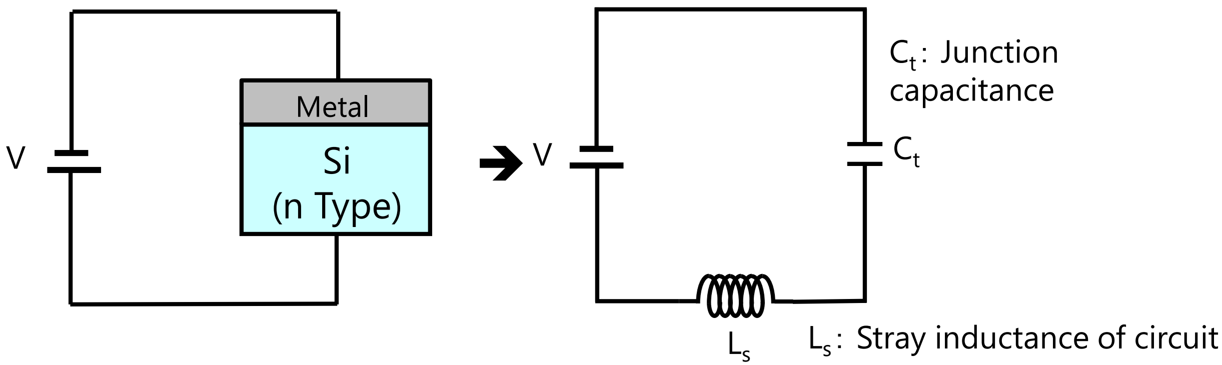


Fig. 2-10(a) Equivalent circuit when reverse voltage is applied to SBD

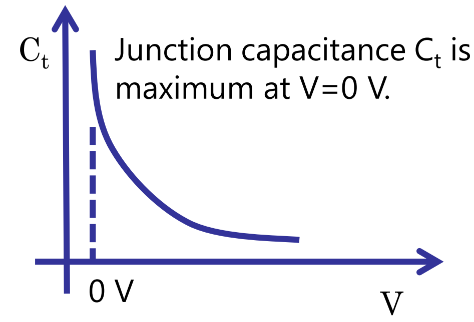
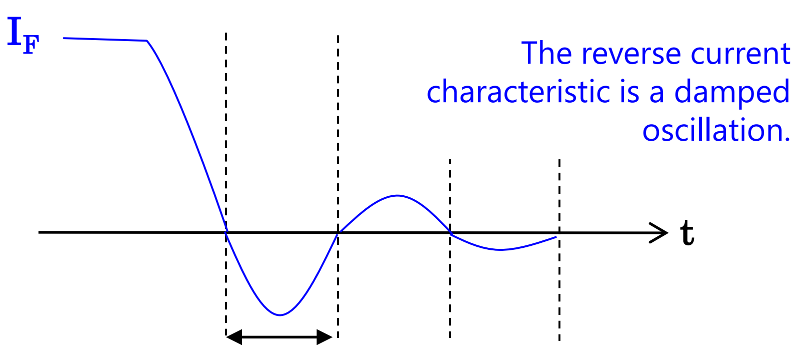


Fig. 2-10(b) Characteristic of junction capacitance of SBD



$$t_{rr} = \pi\sqrt{L_s C_t}$$

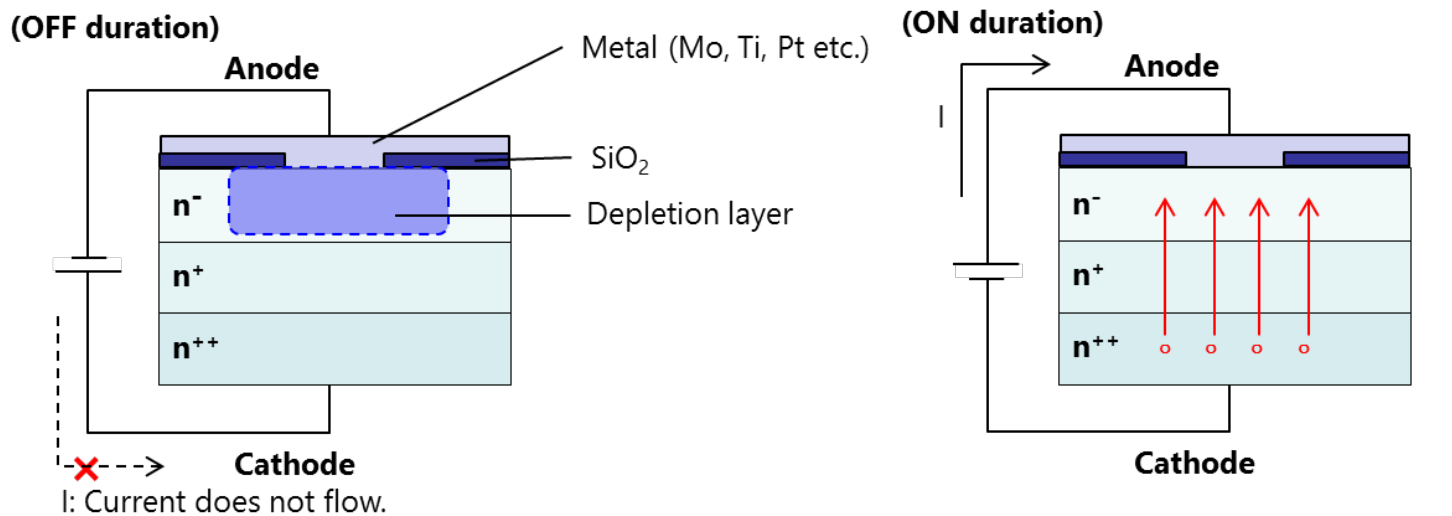
Fig. 2-10(c) Typical reverse characteristic of SBD

The reverse recovery time (t_{rr}) [Note] 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.

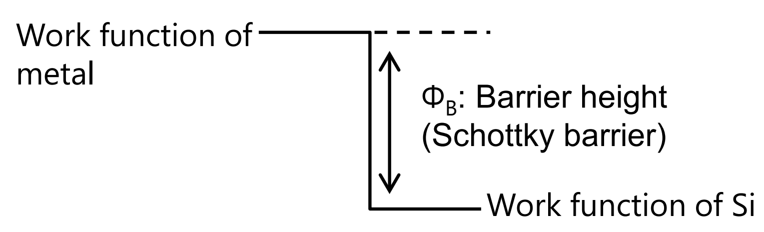
Note: Since SBD is a unipolar device, it does not have reverse recovery time due to carrier recombination like pn junction diodes. However, the current waveform charging the capacity between the terminals of SBD is observed like the reverse recovery time of the p-n junction diode.
Therefore, it is described as reverse recovery time in this document.

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.



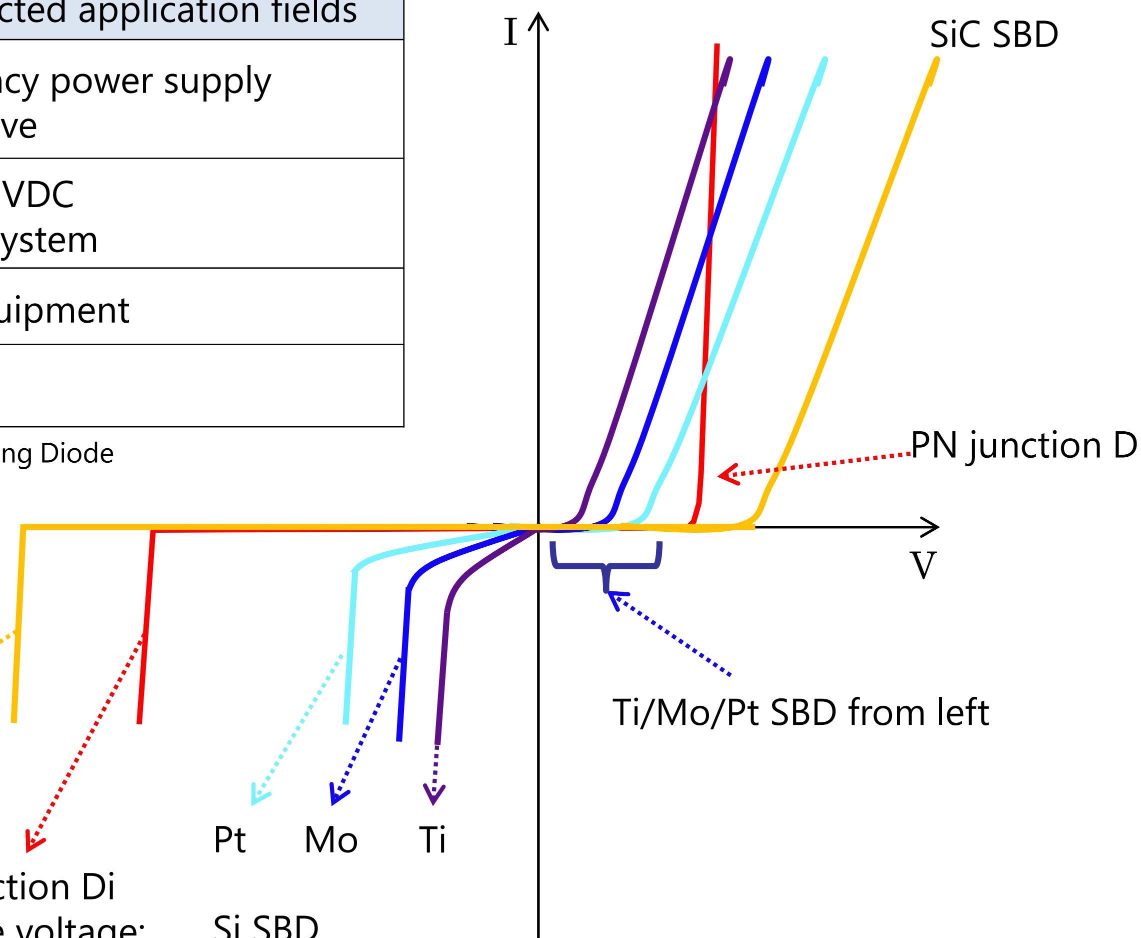
	Pt	Mo	V	Ti
Φ_B	Big ←	←	Small	
V_F	Big ←	←	Small	
I_{RRM}	Small →	→	Big	



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

RESTRICTIONS ON PRODUCT USE

Toshiba Corporation and its subsidiaries and affiliates are collectively referred to as “TOSHIBA”.
Hardware, software and systems described in this document are collectively referred to as “Product”.

•TOSHIBA reserves the right to make changes to the information in this document and related Product without notice.

•This document and any information herein may not be reproduced without prior written permission from TOSHIBA. Even with TOSHIBA's written permission, reproduction is permissible only if reproduction is without alteration/omission.

•Though TOSHIBA works continually to improve Product's quality and reliability, Product can malfunction or fail. Customers are responsible for complying with safety standards and for providing adequate designs and safeguards for their hardware, software and systems which minimize risk and avoid situations in which a malfunction or failure of Product could cause loss of human life, bodily injury or damage to property, including data loss or corruption. Before customers use the Product, create designs including the Product, or incorporate the Product into their own applications, customers must also refer to and comply with (a) the latest versions of all relevant TOSHIBA information, including without limitation, this document, the specifications, the data sheets and application notes for Product and the precautions and conditions set forth in the "TOSHIBA Semiconductor Reliability Handbook" and (b) the instructions for the application with which the Product will be used with or for. Customers are solely responsible for all aspects of their own product design or applications, including but not limited to (a) determining the appropriateness of the use of this Product in such design or applications; (b) evaluating and determining the applicability of any information contained in this document, or in charts, diagrams, programs, algorithms, sample application circuits, or any other referenced documents; and (c) validating all operating parameters for such designs and applications. **TOSHIBA ASSUMES NO LIABILITY FOR CUSTOMERS' PRODUCT DESIGN OR APPLICATIONS.**

•**PRODUCT IS NEITHER INTENDED NOR WARRANTED FOR USE IN EQUIPMENTS OR SYSTEMS THAT REQUIRE EXTRAORDINARILY HIGH LEVELS OF QUALITY AND/OR RELIABILITY, AND/OR A MALFUNCTION OR FAILURE OF WHICH MAY CAUSE LOSS OF HUMAN LIFE, BODILY INJURY, SERIOUS PROPERTY DAMAGE AND/OR SERIOUS PUBLIC IMPACT ("UNINTENDED USE").** Except for specific applications as expressly stated in this document, Unintended Use includes, without limitation, equipment used in nuclear facilities, equipment used in the aerospace industry, lifesaving and/or life supporting medical equipment, equipment used for automobiles, trains, ships and other transportation, traffic signaling equipment, equipment used to control combustions or explosions, safety devices, elevators and escalators, and devices related to power plant. **IF YOU USE PRODUCT FOR UNINTENDED USE, TOSHIBA ASSUMES NO LIABILITY FOR PRODUCT.** For details, please contact your TOSHIBA sales representative or contact us via our website.

•Do not disassemble, analyze, reverse-engineer, alter, modify, translate or copy Product, whether in whole or in part.

•Product shall not be used for or incorporated into any products or systems whose manufacture, use, or sale is prohibited under any applicable laws or regulations.

•The information contained herein is presented only as guidance for Product use. No responsibility is assumed by TOSHIBA for any infringement of patents or any other intellectual property rights of third parties that may result from the use of Product. No license to any intellectual property right is granted by this document, whether express or implied, by estoppel or otherwise.

•**ABSENT A WRITTEN SIGNED AGREEMENT, EXCEPT AS PROVIDED IN THE RELEVANT TERMS AND CONDITIONS OF SALE FOR PRODUCT, AND TO THE MAXIMUM EXTENT ALLOWABLE BY LAW, TOSHIBA (1) ASSUMES NO LIABILITY WHATSOEVER, INCLUDING WITHOUT LIMITATION, INDIRECT, CONSEQUENTIAL, SPECIAL, OR INCIDENTAL DAMAGES OR LOSS, INCLUDING WITHOUT LIMITATION, LOSS OF PROFITS, LOSS OF OPPORTUNITIES, BUSINESS INTERRUPTION AND LOSS OF DATA, AND (2) DISCLAIMS ANY AND ALL EXPRESS OR IMPLIED WARRANTIES AND CONDITIONS RELATED TO SALE, USE OF PRODUCT, OR INFORMATION, INCLUDING WARRANTIES OR CONDITIONS OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, ACCURACY OF INFORMATION, OR NONINFRINGEMENT.**

•Do not use or otherwise make available Product or related software or technology for any military purposes, including without limitation, for the design, development, use, stockpiling or manufacturing of nuclear, chemical, or biological weapons or missile technology products (mass destruction weapons). Product and related software and technology may be controlled under the applicable export laws and regulations including, without limitation, the Japanese Foreign Exchange and Foreign Trade Law and the U.S. Export Administration Regulations. Export and re-export of Product or related software or technology are strictly prohibited except in compliance with all applicable export laws and regulations.

•Please contact your TOSHIBA sales representative for details as to environmental matters such as the RoHS compatibility of Product. Please use Product in compliance with all applicable laws and regulations that regulate the inclusion or use of controlled substances, including without limitation, the EU RoHS Directive. **TOSHIBA ASSUMES NO LIABILITY FOR DAMAGES OR LOSSES OCCURRING AS A RESULT OF NONCOMPLIANCE WITH APPLICABLE LAWS AND REGULATIONS.**

TOSHIBA