TOSHIBA

e-Learning

Basics of Schottky Barrier Diodes

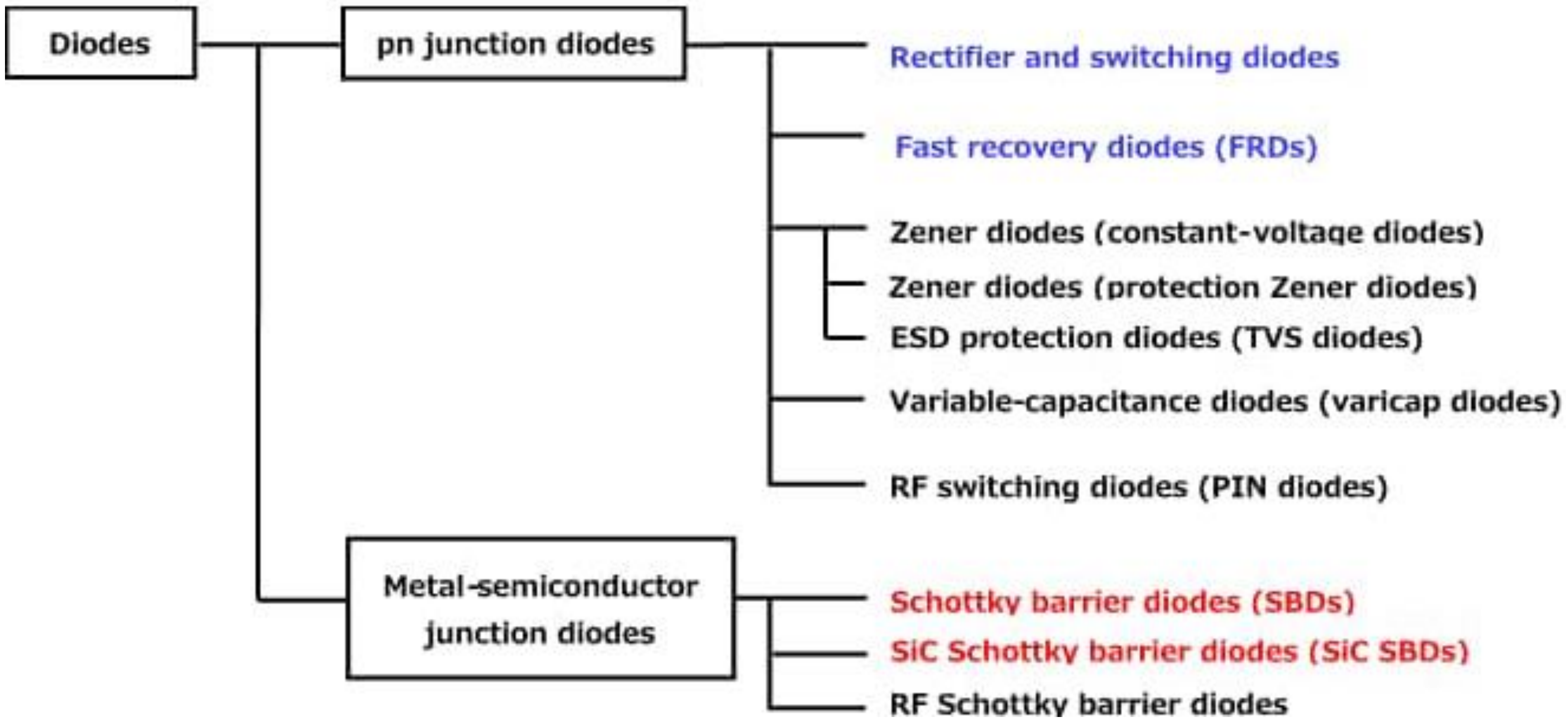
Chapter3 Basics of Schottky Barrier Diodes

Toshiba Electronic Devices & Storage Corporation

3.1. Classification of diodes

Diodes can be broadly categorized into pn junction diodes and metal-semiconductor junction diodes. Figure shows the classification of diodes available from Toshiba.

The next subsection compares Schottky barrier diodes (SBDs) with other types of diodes. Rectifier and switching diodes(*) are the most commonly used pn junction diodes. Fast recovery diodes (FRDs) are rectifier diodes that are doped with a heavy metal to provide a shorter reverse recovery time than typical rectifier diodes.



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

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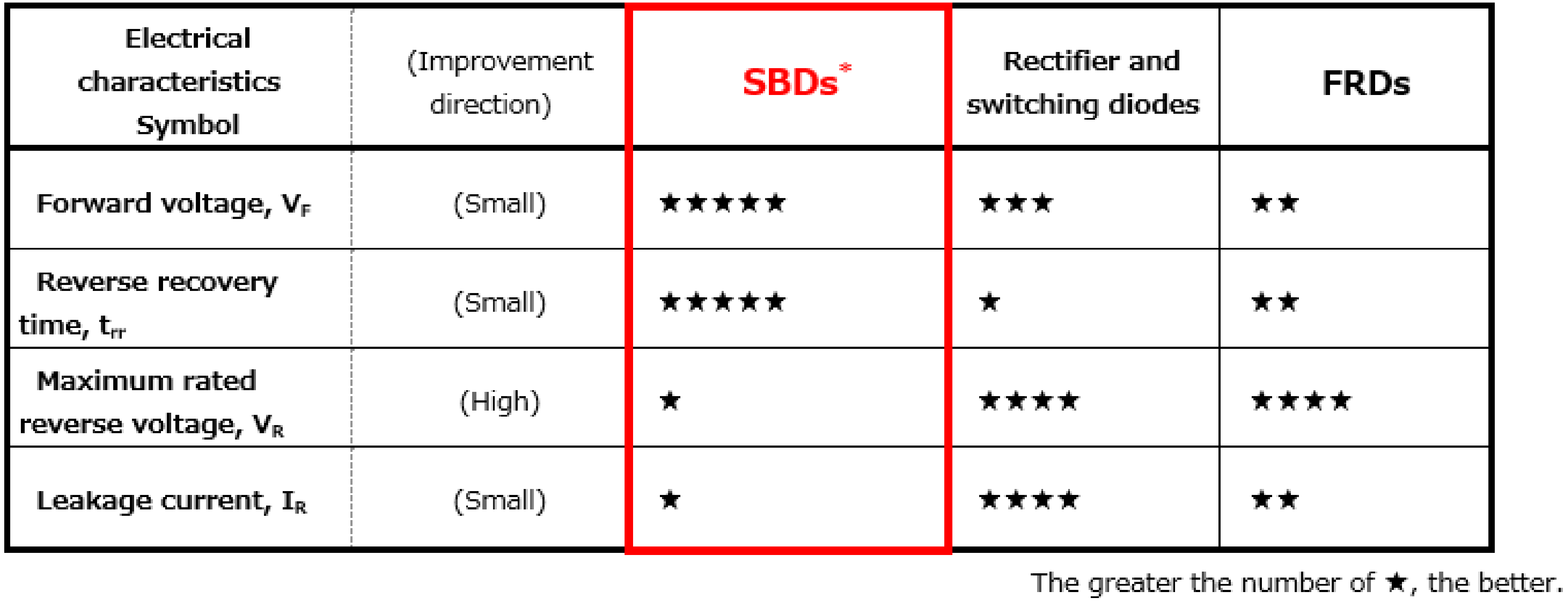
* Switching diodes are a type of pn junction diodes suitable for switching a small signal (up to 100 mA and 50 V). Most switching diodes are housed in a small surface-mount package.

3.2. Comparison between SBDs and pn junction diodes

The following table compares SBDs with rectifier diodes, switching diodes, and FRDs.
Reverse recovery time can be a limiting factor for the turn-off of a diode. SBDs offer advantages of low forward voltage and short reverse recovery time whereas their disadvantages include low maximum rated reverse voltage (V_R) and large leakage under V_R.



Electrical characteristics Symbol	(Improvement direction)	SBDs*	Rectifier and switching diodes	FRDs
Forward voltage, V_F	(Small)	★★★★★	★★★	★★
Reverse recovery time, t_{rr}	(Small)	★★★★★	★	★★
Maximum rated reverse voltage, V_R	(High)	★	★★★★	★★★★
Leakage current, I_R	(Small)	★	★★★★	★★

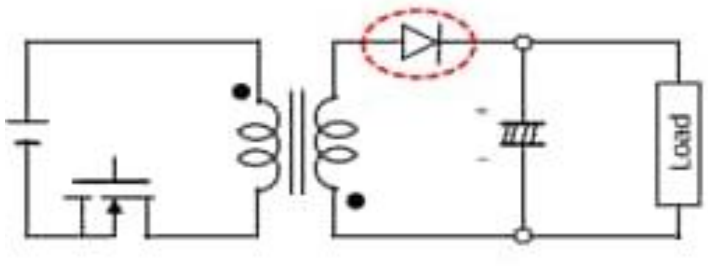
The greater the number of ★, the better.

3.3. Applications of SBDs

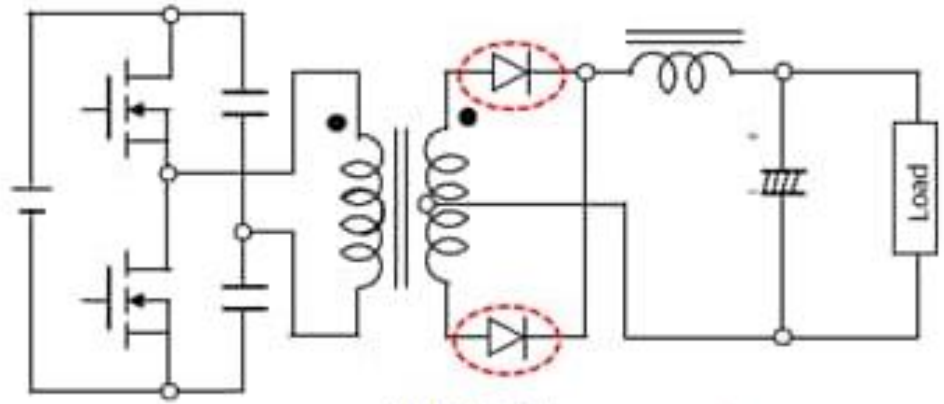
SBDs are used for applications requiring low forward voltage (V_F) and short reverse recovery time (t_{rr}).

Rectification on the secondary side of a power supply circuit

SBDs are used for rectification on the secondary side of various step-down voltage converters such as flyback, forward, push-pull, half-bridge, and full-bridge converters. SBDs pass electrical power while they are conducting. Therefore, when an SBD is on, a power loss occurs because of a voltage drop equal to its forward voltage (V_F). An SBD also suffers a large switching loss during a reverse recovery time (t_{rr}), i.e., during a transition from the on-state to the off-state. SBDs with low V_F and low t_{rr} are ideally suited for converter applications where the voltage applied to an SBD on the secondary side is lower than its maximum rated reverse voltage (V_R).



Flyback converter

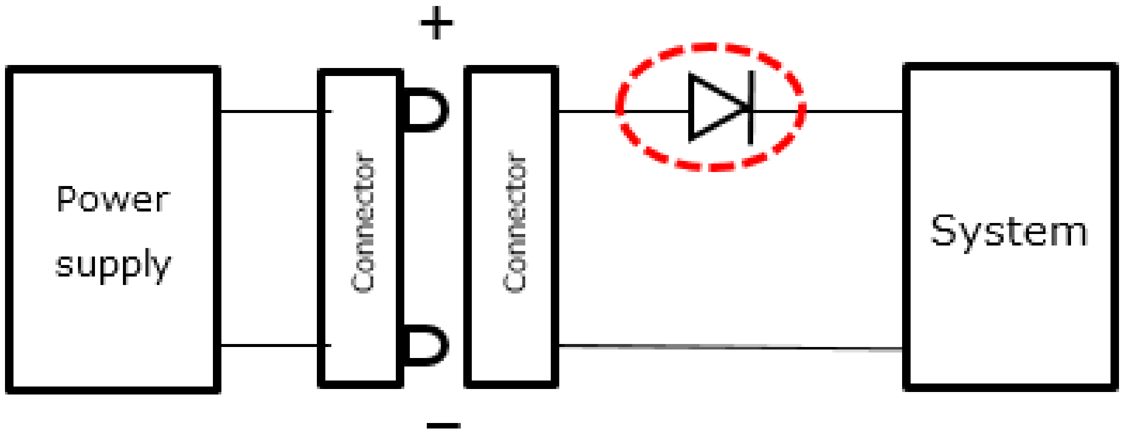


Half-bridge converter

3.3. Applications of SBDs

Reverse-connection protection

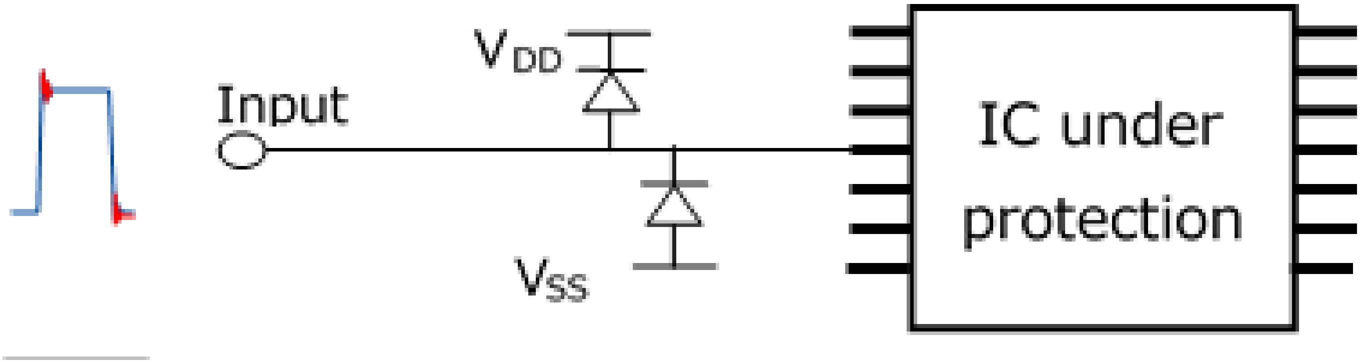
A diode is inserted in series with a power line when there is a possibility that the user of a mobile device might place a charger or a battery in the wrong direction. When a diode is connected in the right direction, a voltage drop that occurs across the diode causes a power loss. A low-V_F SBD is the ideal choice when the voltage across a reverse-connected SBD is lower than its V_R.



3.3. Applications of SBDs

IC protection

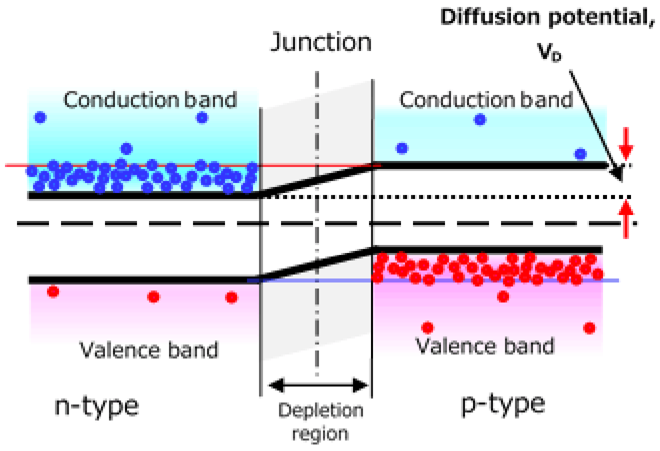
Some ICs have a maximum input voltage rating of GND-0.3 V to V_{DD} + 0.3 V. A low-V_F SBD is the ideal choice when its input voltage might exceed the maximum rated voltage because of ringing.



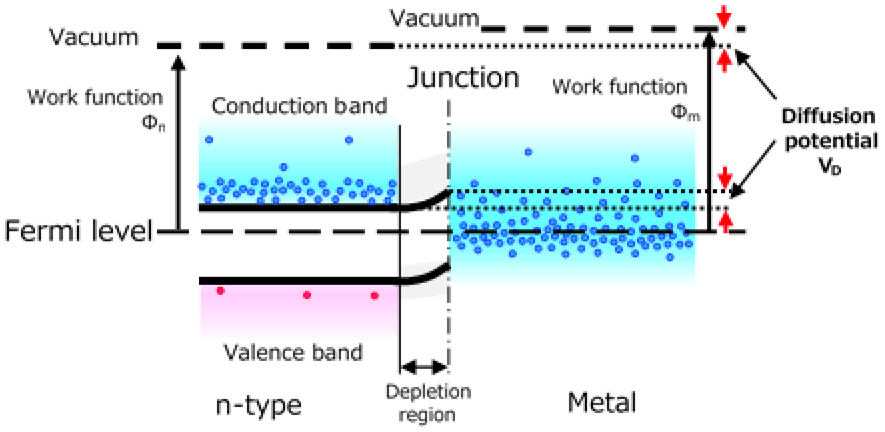
SBDs are also used in various devices to support the recent trend toward low operating voltage and low power consumption. For example, SBDs are used to compose low-voltage (e.g., 1.5-V) diode logic and undervoltage detection circuits (voltage monitoring circuits).

3.4. Forward voltage

The forward voltage is the voltage across a diode that occurs when it is conducting in the forward direction. The current and voltage characteristics of a diode are determined by its diffusion barrier (diffusion potential). The forward voltage, especially in the small current region, is proportional to the diffusion potential. (The forward voltage in the high-current region is also affected by series resistance as described in Section 3.6.) In the case of a pn junction, the diffusion potential is equal to a difference in potential between the lower edges of the conduction bands of the n-type and p-type semiconductors. In the case of a metal-semiconductor junction, the diffusion potential is equal to a difference between the work functions of the n-type (or p-type) semiconductor and the metal. Figure shows unbiased pn and metal-semiconductor junctions. The diffusion potential of the pn junction changes with the dopant concentration, but only slightly. In contrast, the diffusion potential of a metal-semiconductor junction depends on the metal joined with the n-type semiconductor. Generally, the diffusion potential of the metal-semiconductor junction is lower than that of the pn junction.



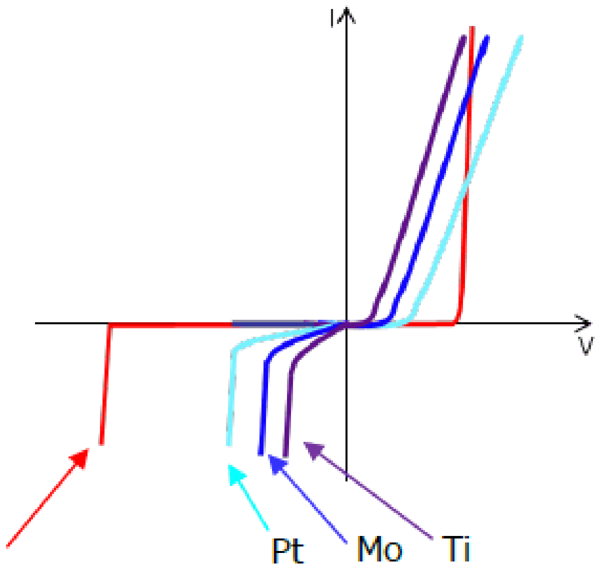
pn junction diode



Metal-semiconductor junction
(Schottky junction / Schottky contact)

3.4. Forward voltage

Left figure shows the V_F–I_F curves of metal-semiconductor junctions with different metals.
Right figure compares the V_F–I_F curves of the 1SS427 switching diode (V_R = 80 V) and the 1SS416 SBD (V_R = 30 V). The SBD provides a larger forward current than the switching diode at the same forward voltage.

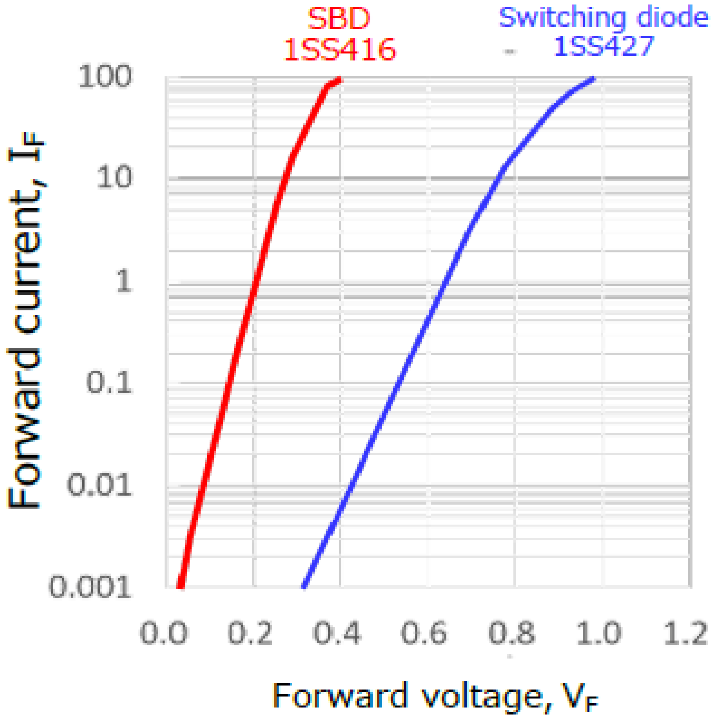


pn junction diode:

Maximum rated reverse voltage:
Up to 600 V

Silicon SBD:

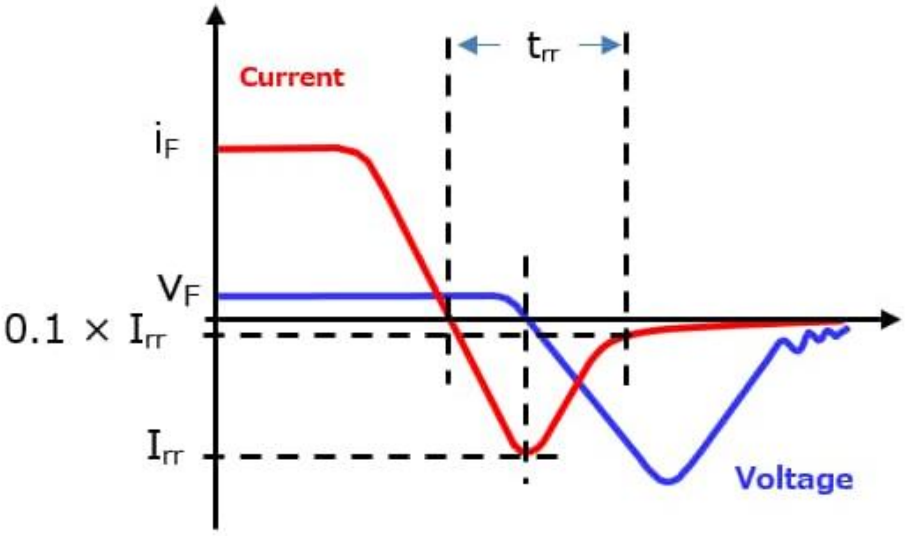
Maximum rated reverse voltage:
20 to 60 V
Forward voltage (V_F):
Ti: 0.4 V
Mo: 0.55 V
Pt: 0.6 to 0.7 V



3.5. Reverse recovery time

When diodes and other semiconductor devices are on, current flows because of free electrons and holes (carriers). In addition, these carriers are accumulated as electric charge in the depletion region formed across a junction or in a parasitic capacitor and also accumulated in the lightly doped region as excess carriers. (This causes the above-mentioned conductivity modulation.) When these devices transition from the on state to the off state, they release electrons just like a capacitor. The resulting flow of electrons is observed as a current flow in the opposite direction.

The forward voltage (V_F) is positive while the current (i_F) is between zero and the peak reverse recovery current (I_{rr}). During this period, the electric charge in the depletion region and the parasitic capacitor is mainly released, causing negative current to flow. Once i_F reaches I_{rr}, the excessive carriers (electrons and holes) that contributed to the conductivity modulation disappear because they recombine. Therefore, the time required for this recombination depends on the carrier lifetime.



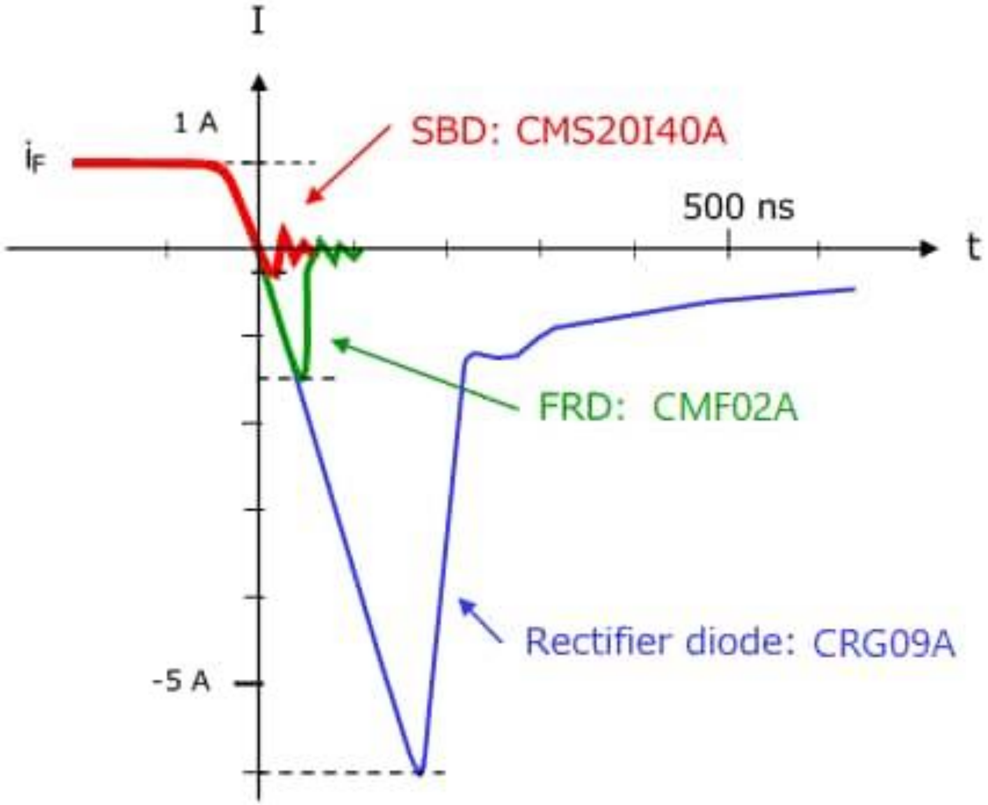
Diode's on-off switching waveform

The reverse recovery time is defined as the time required for the reverse recovery current to decay until a diode recovers as shown in this figure. t_{rr} is defined as the time between the instant at which the forward current (i_F) become zero and the instant at which the reverse recovery time decays to 10% of peak reverse current (I_{rr}).

3.5. Reverse recovery time

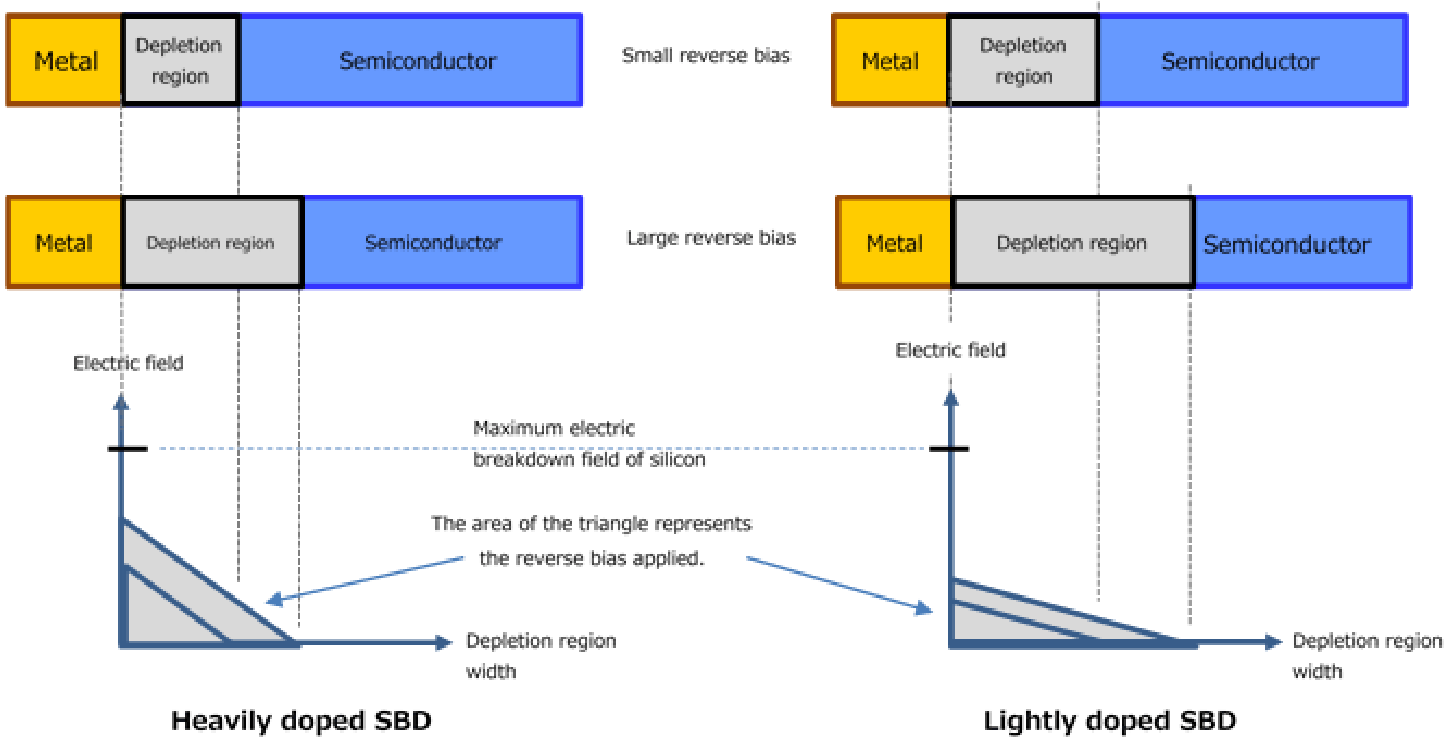
As described above, conductivity modulation occurs in bipolar devices such as pn junction diodes whereas theoretically it does not occur in unipolar devices such as SBDs. Therefore, SBDs exhibit almost zero reverse recovery time.

Figure compares the reverse recovery characteristics of two typical pn junction diodes—the CRG09A rectifier diode (V_R=400 V, I_F=1 A) and the CMF02A fast recovery diode (V_R = 600 V, I_F=1 A)—with the CMS20I40A SBD (V_R=40 V, I_F=2 A). Although it is difficult to make simple comparisons because their maximum rated reverse voltages are different, the reverse recovery time of the fast recovery diode (FRD) is much smaller than that of the rectifier diode whereas the reverse recovery time of the SBD is nearly zero.



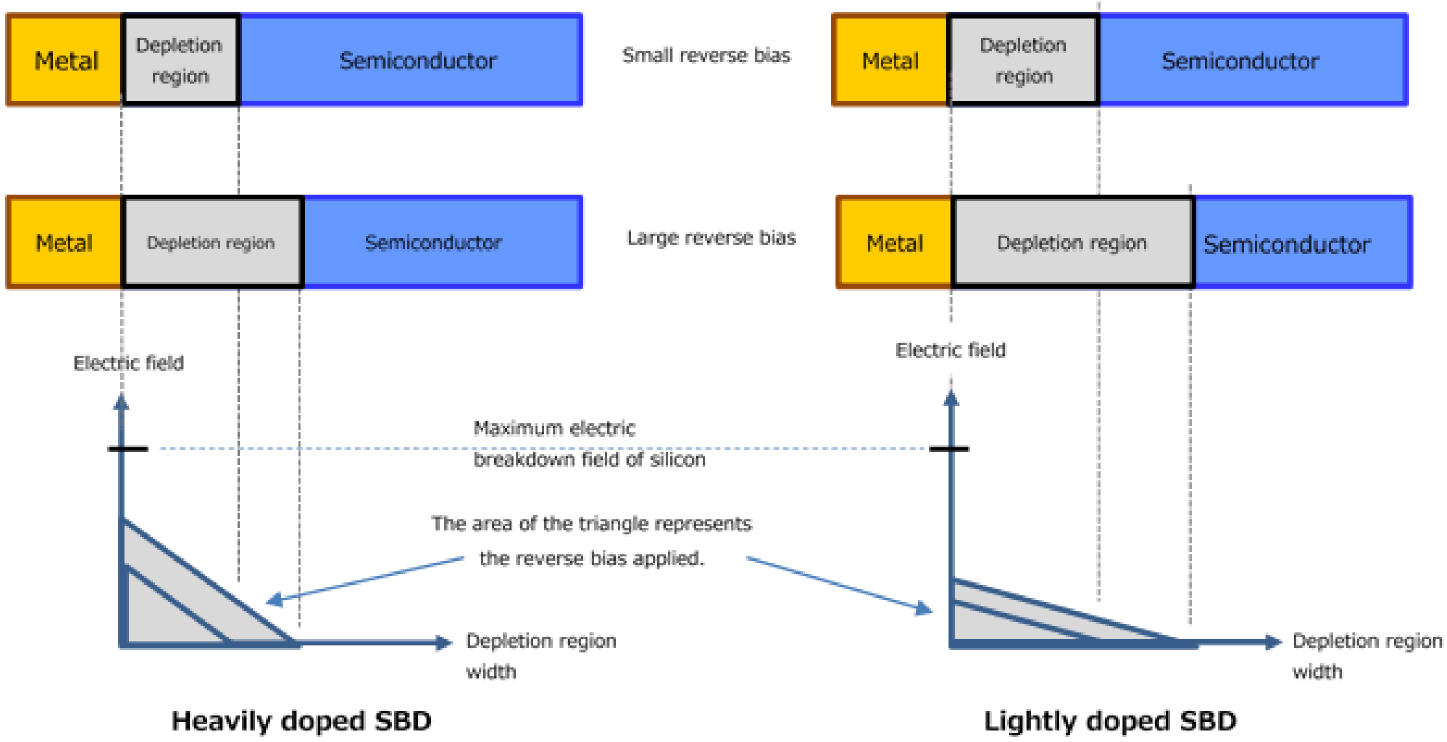
3.6. Maximum rated reverse voltage (V_R)

V_R is the maximum rated reverse voltage that can be applied across an SBD.
When an SBD is reverse-biased, it is applied across the depletion region that extends from the junction into the semiconductor. The width of the depletion region depends on the dopant concentration; the higher the dopant concentration, the narrower the depletion region. Increasing or decreasing the reverse bias causes the depletion region to expand or shrink.



3.6. Maximum rated reverse voltage (V_R)

Figure shows the relationship between the depletion region width and the electric field. The area of the triangle formed by the depletion region width and the electric field represents the reverse bias voltage applied.
As the reverse bias is increased, the electric field increases. When the electric field exceeds a certain value (the maximum electric breakdown field of silicon), an SBD is destroyed by the resulting excessive current. V_R is defined as the maximum reverse bias that does not cause the electric breakdown field to be exceeded.
Therefore, the less heavily an SBD is doped, the higher its rated V_R.

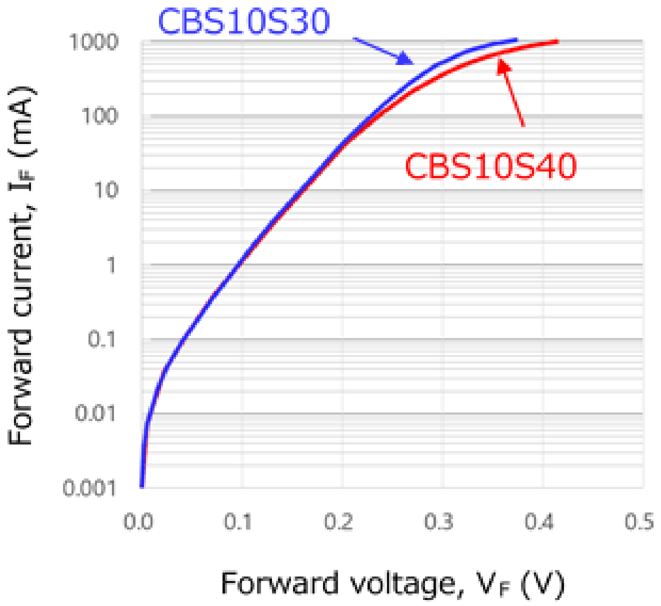


3.6. Maximum rated reverse voltage (V_R)

The dopant concentration also affects the series resistance of a diode directly. The more heavily doped a diode is, the smaller its series resistance becomes. In the case of pn junction diodes, excessive carriers due to the conductivity modulation effect described above reduce the effect of the dopant concentration. However, SBDs do not have the conductivity modulation effect since they are unipolar devices.

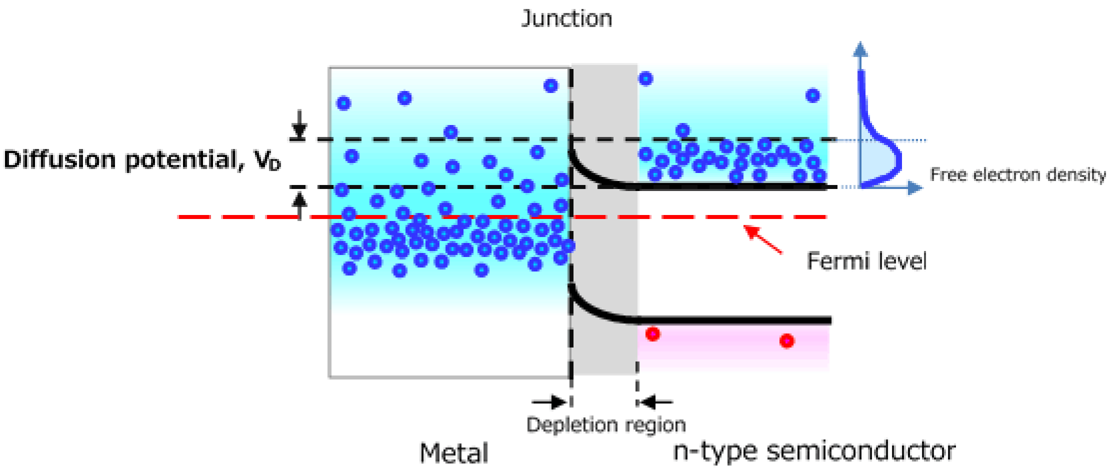
Figure compares the I_F-V_F curves of the SBDs with a V_R of 30 V and 40 V. (CBS10S30 and CBS10S40). In the low-current region, both the CBS10S30 and CBS10S40 exhibit the same I_F-V_F curve. As the forward current approaches the maximum rated current (1 A), the CBS10S40 with a higher V_R conducts less forward current than the CBS10S30 at the same forward voltage.

This is because the CBS10S40 is less heavily doped and thus has a higher series resistance than the CBS10S30. This tendency becomes more marked as the V_R is increased. It is therefore difficult to increase the maximum rated reverse voltage (V_R) of silicon SBDs.

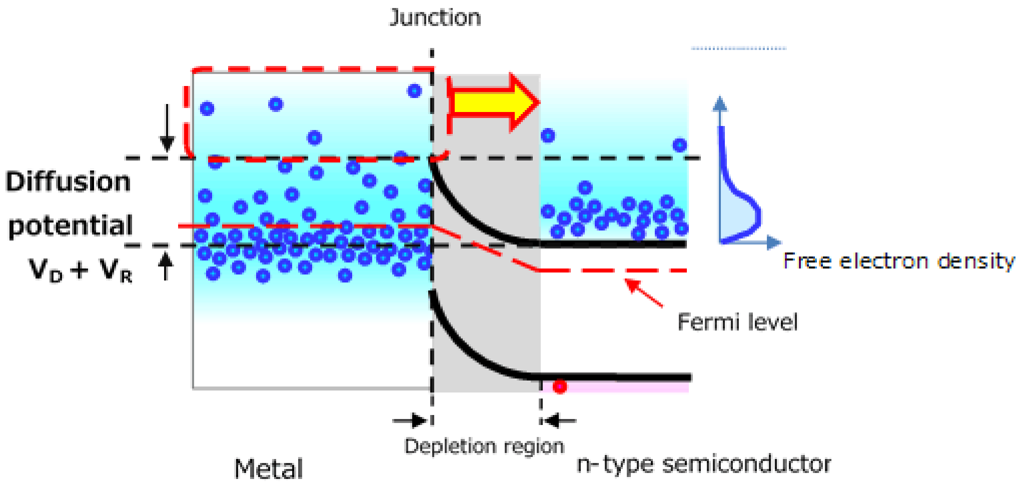


3.7. Leakage current

When forward bias is applied to the barrier, the diffusion potential drops. As a result, electrons in the semiconductor's conduction band diffuse across the depletion region to the metal, resulting in a forward current from the metal to the semiconductor. Carrier diffusion occurs where the density of majority carriers in the semiconductor becomes higher than that of majority carriers in the metal. Therefore, electrons diffuse from the semiconductor to the metal, causing current to flow. When reverse bias is in the range beyond the diffusion potential, the carrier density of the metal becomes higher than that of the semiconductor, causing current to flow in the reverse direction. This current is called leakage current.



SBD (Unbiased)

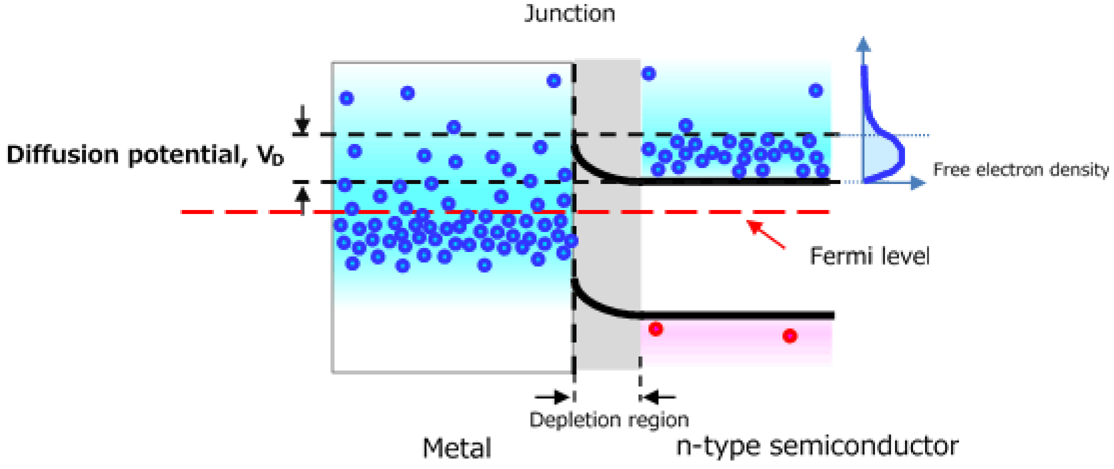


SBD (Reverse-biased)

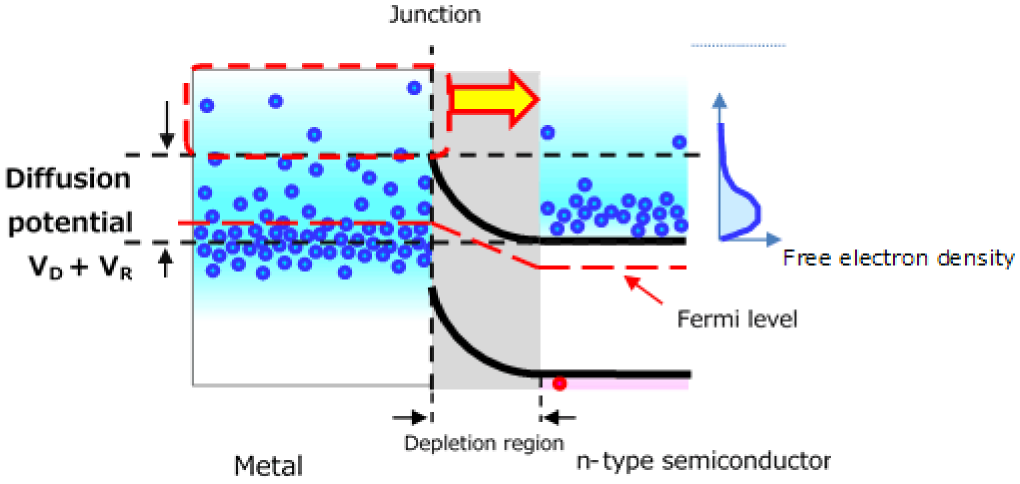
3.7. Leakage current

Since an SBD has a low carrier density at an energy level higher than the diffusion potential, the magnitude of leakage current is much lower than that of the forward current.

Since the diffusion potential of the SBD is lower than that of the pn junction diode, current begins flowing across the SBD at a lower voltage than in the case of the pn junction diode. SBDs tend to exhibit higher leakage current since their crystal structure tends to be disturbed at the heterogeneous junction of a metal and a semiconductor.



SBD（Unbiased）



SBD（Reverse-biased）

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