Diode

Diode Types and Applications

Various diode products have been developed for various applications, including rectifier diodes and switching diodes. This application note explains the types of diodes and their applications.

Diode types

Diode types can be classified based on their production processes, characteristics, internal circuits, and shapes.

Figure 1 shows the main categories of diodes based on their production processes and characteristics. The grayed out items among the types indicate diodes that have not been productized by ROHM.

First, the diodes are classified into two large categories based on the production processes. The first category is pn junction diodes, in which a junction of p-type and n-type semiconductors is formed. Based on their characteristics, the pn junction diodes are classified into rectifier diodes, switching diodes, fast recovery diodes, Zener diodes, high-frequency switching diodes, and so on. The Zener diodes include diodes specialized for circuit protection and transient voltage suppressors (TVS), which are higher-performance protective elements. In addition to these, optical semiconductors are also included in the pn junction diodes. Based on their characteristics, LEDs and semiconductor lasers are classified as light emitting elements, while photodiodes are classified as light receiving elements.

The second category is unipolar diodes, in which junction of the n-type or p-type semiconductor joined with metal is formed. Schottky barrier diodes are included in the unipolar diodes based on their characteristics. Furthermore, this category includes diodes for high-power devices using SiC (silicon carbide) for the semiconductor and low-capacitance diodes for high-frequency detection.

Other than the above, there are current regulative diodes, which have junction FET as internal elements. The source and the gate are short-circuited on the cathode side, while the drain side works as the anode.

Next, the classification based on the internal circuits is shown in Figure 2. There are two categories in this classification. The discrete types have one element enclosed in one package, while diode arrays are an integration of multiple diodes. Based on how the internal circuits are connected, the diode arrays are classified into the anode common, cathode common, series, and parallel types. The mounting area of diode arrays can be downsized by adjusting them to individual application circuits. For applications with a large power loss, the thermal design must be considered because the heat generation is concentrated in one element.

Figure 3 shows the classification based on the shapes. Based on the mounting methods on the PCB and the heat dissipation performances, the diodes can be classified into the through-hole type and the surface-mounted type. The through-hole type has the package leads inserted into the holes in the PCB. With the surface-mounted type, the package is mounted on the surface of the PCB. ROHM has released the through-hole and surface-mounted type products.

The number of axial type products has decreased because mounting on the PCB surface has become common. The surface-mounted type includes small packages for small signals and packages equipped with FIN or back electrodes for power applications. Since heat is dissipated to the PCB, the power packages for surface mounting are limited to devices for which the power loss is up to several watts. Devices that require a larger power loss are designed as the through-hole type of the TO series equipped with a heatsink. In addition, some packages of the surface-mounted type have front electrodes, and a heatsink can be mounted.

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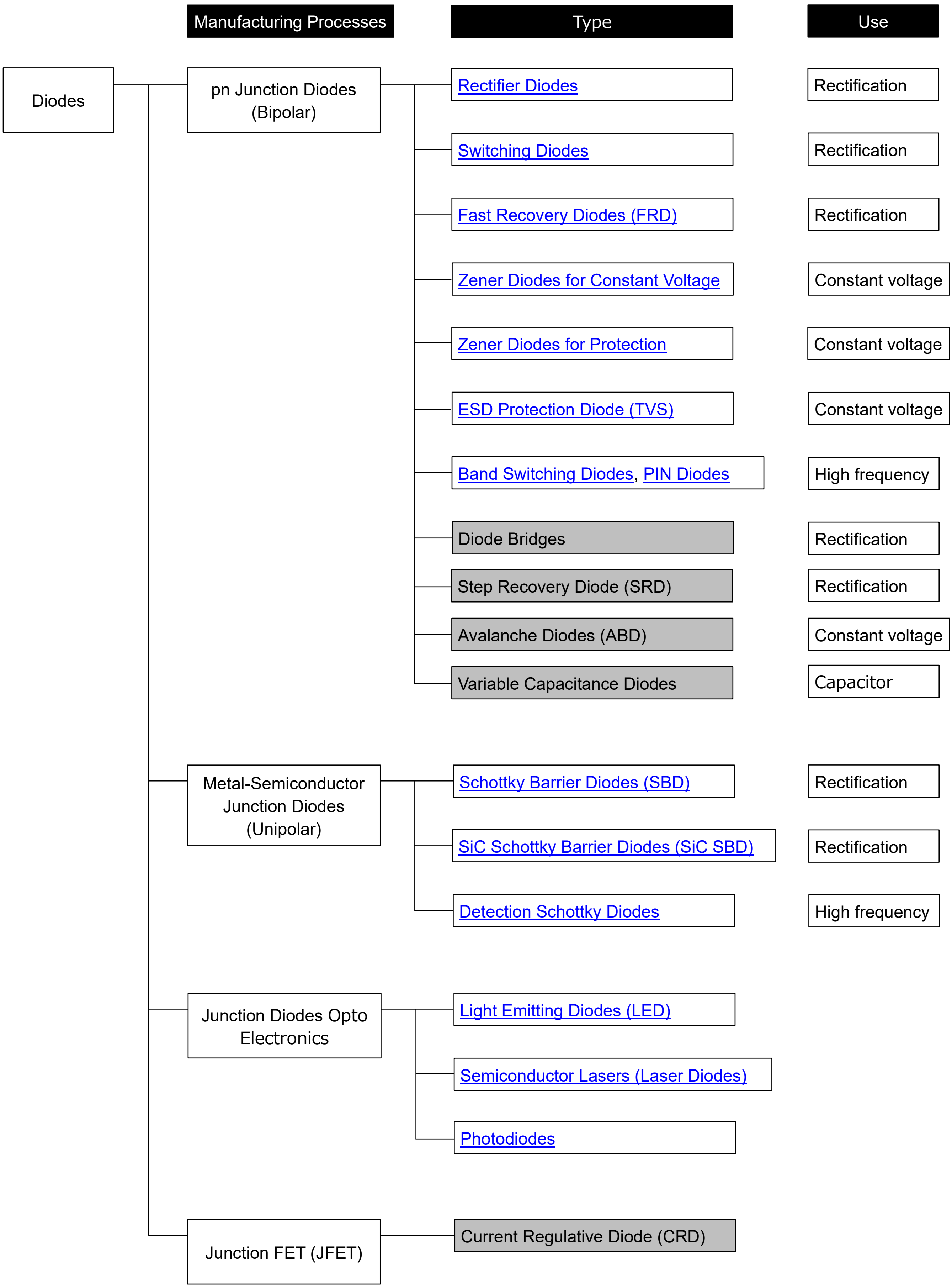

Figure 1. Main categories of diodes based on production processes and characteristics

The grayed out items in the type column indicate the diodes that have not been productized by ROHM.

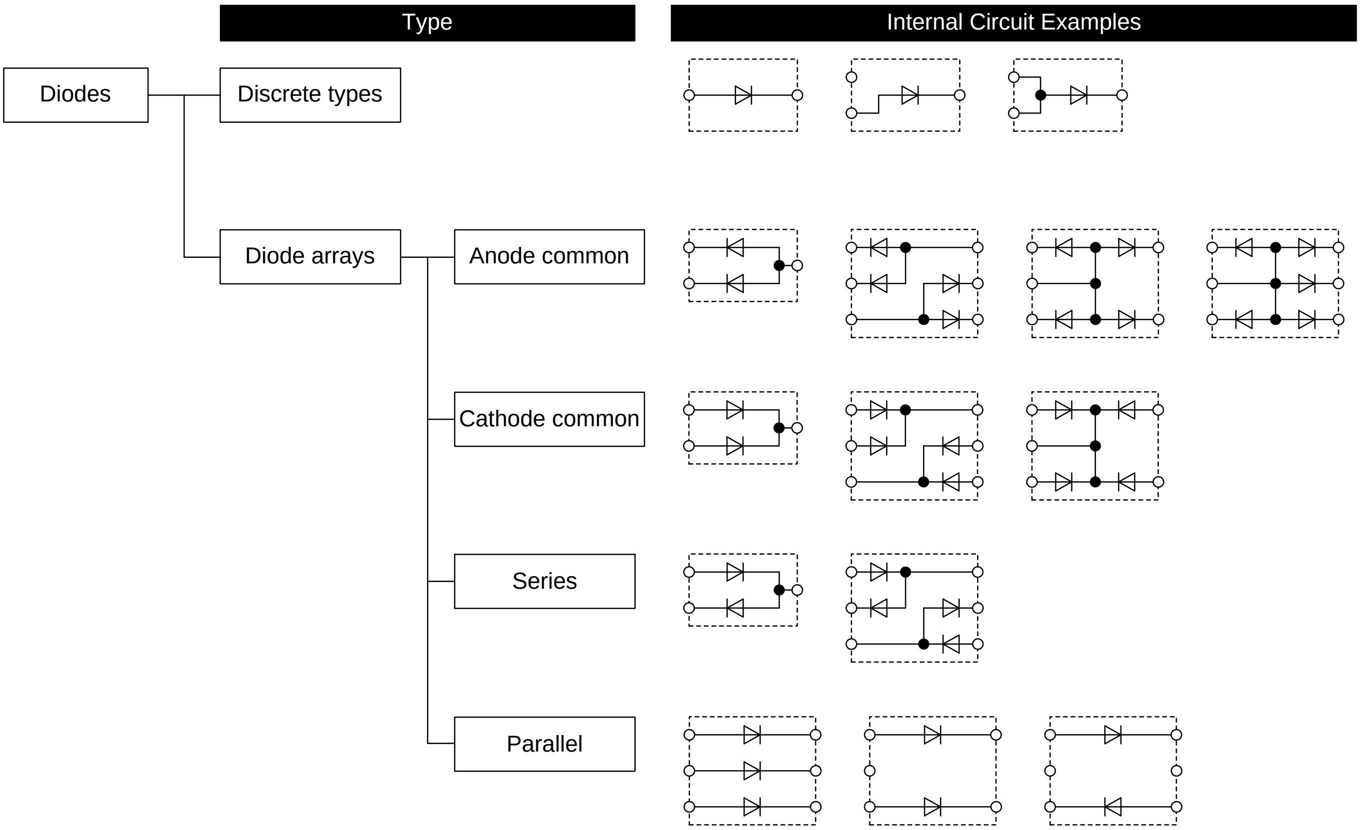

Figure 2. Categories based on internal circuits

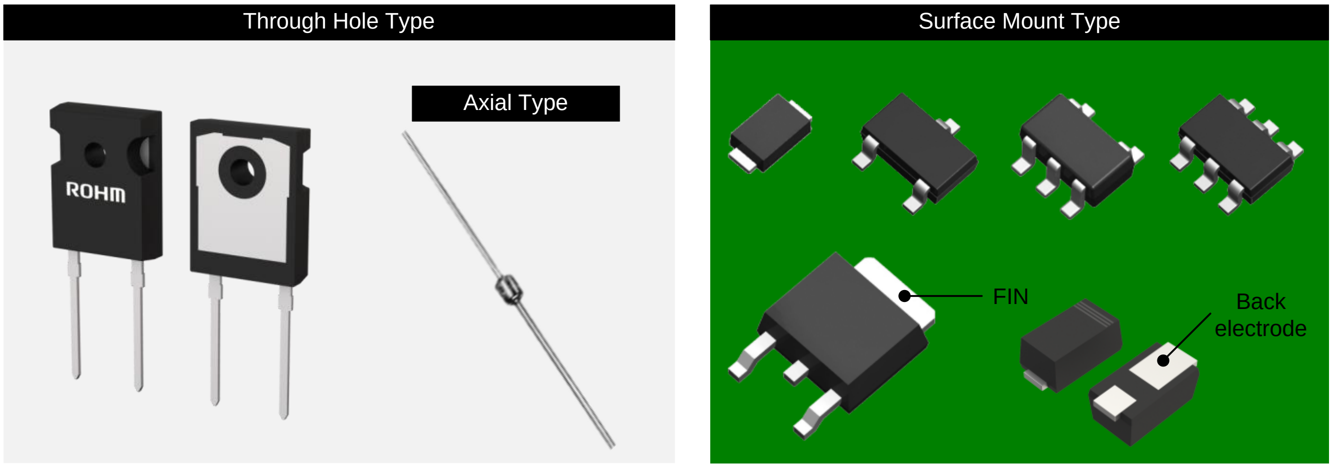

Figure 3. Categories based on shapes

From here, an overview of each diode type is provided.

General rectifier diode

As the name suggests, rectifier diodes are designed to rectify AC (50/60 Hz) from a commercial power supply and convert it into DC. Typically, this type of diode can easily realize characteristics such as a high breakdown voltage of 400 V or 600 V and a large current of 1 A or greater.

Figure 4 shows a circuit that performs full-wave rectification and conversion into DC from a commercial power supply and the related voltage waveforms. The diodes convert the input sine wave into a unidirectional voltage and the capacitor smooths it out to obtain DC.

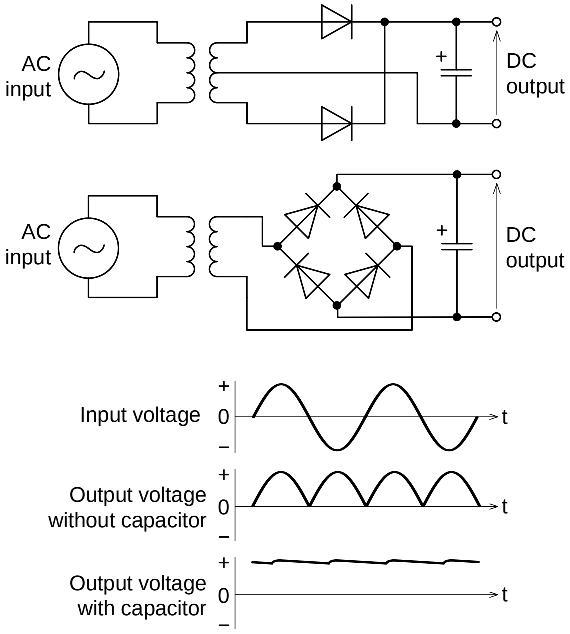

Figure 4. Full-wave rectification circuit for commercial power supply and voltage waveforms

The device structure is shown in Figure 5. The mesa type is employed for the rectifier diodes. “Mesa” is a geographical term, meaning “a flat-topped plateau with steep sides” (derived from Spanish). The mesa type is shaped exactly as described.

In the manufacturing process, an n-type semiconductor with a high impurity concentration is formed under an n-type silicon substrate and a p-type semiconductor is formed over the substrate to create a pn junction. The mesa shape is formed by etching slopes on both edges. A rectifier diode chip is completed by forming protective films on the slopes and the electrodes on the top and bottom.

By employing the mesa type, the edge is formed with a sloping cut against the pn junction interface, reducing the field strength at the edge. As a result, the characteristics of high breakdown voltage can be obtained easily.

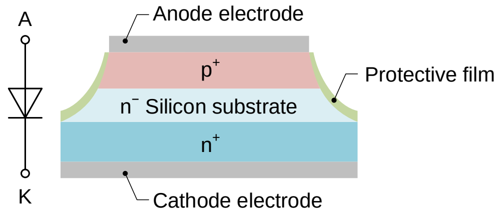

Figure 5. Device structure of rectifier diode

Fast recovery diode (FRD)

FRDs with a fast reverse recovery time (t_{rr}) are used for the power supply applications at a frequency higher than the commercial frequency, because using general rectifier diodes in such applications deteriorates the conversion efficiency.

With the general rectifier diodes, holes in the n region start returning to the p region when the bias is switched from forward to reverse. However, since the return speed is slow, the current flows backward and causes a loss while the holes are returning.

The FRDs are characterized by a fast t_{rr} as well as a high forward voltage (V_F) and breakdown voltage. Therefore, they are suitable for applications such as high-voltage switching power supplies.

Figure 6 shows an application example of the simplest PFC circuit configured with a boost converter. An FRD is used for rectification.

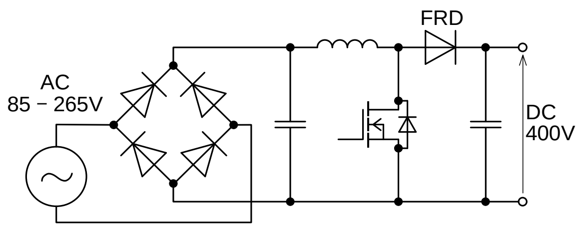

Figure 6. Boost PFC circuit

Figure 7 shows the circuit of a full-bridge LLC converter used with several kilowatts at 48 V or a higher voltage. FRDs are used for the diode bridge on the secondary side.

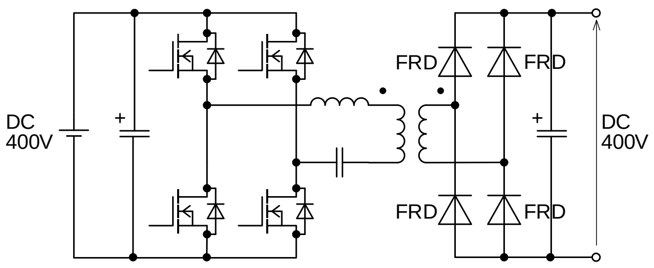

Figure 7. LLC converter circuit

Figure 8 shows a three-phase full-bridge inverter in which FRDs are used for the path to pass the reflux current from the inductive load.

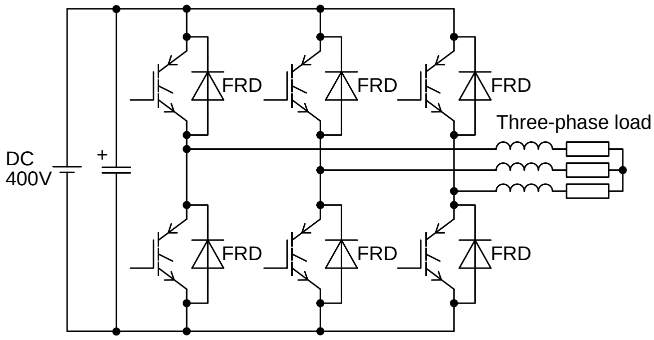

Figure 8. Three-phase full-bridge inverter circuit

Figure 9 shows an example of a non-discharge RCD snubber circuit mounted on a half-bridge circuit. FRDs are used in the snubber circuit.

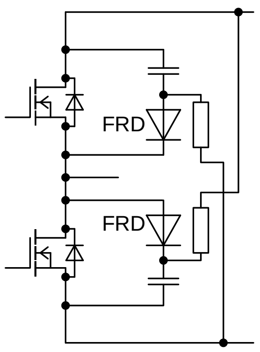

Figure 9. Non-discharge RCD snubber circuit

The device structure is shown in Figure 10. The planar (flat) type is employed for the diodes, except for the general rectifier diodes described above.

In the manufacturing process, an n^- type semiconductor with a low impurity concentration is formed on an n-type silicon substrate. By thickening this n^- layer, the slope of the field strength on the pn junction interface can be reduced, enabling a high breakdown voltage. Next, the pn junction is created by forming a p-type semiconductor on the n^- layer.

For the FRD, impurities of specific metals are diffused in the n layer to provide carrier traps and make t_{rr} faster. When the bias is switched from forward to reverse, the holes slowly returning from the n region to the p region are captured by the carrier traps, making t_{rr} faster. Although t_{rr} can be adjusted with the impurity concentration, forward voltage V_F is increased instead. There is a trade-off relationship between t_{rr} and V_F.

Finally, an FRD is completed by forming the protective film on the top and the electrodes on the top and bottom.

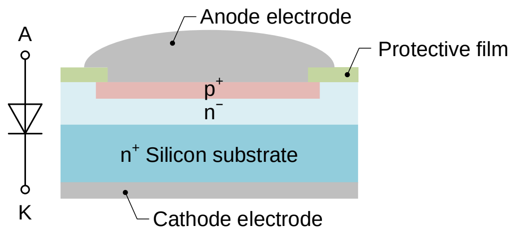

Figure 10. Device structure of fast recovery diode

Switching diode

Switching diodes are used for small signal circuits in a wide range of applications. There are currently many diodes that are specialized in specific characteristics, including Schottky barrier diodes with a low forward voltage, protection diodes, and high-frequency diodes. As a result, the switching diodes are used for simple switching (logic) operations, reverse current protection for control circuits, bias for transistor amplifiers, simple voltage control circuits, and so on.

Figure 11 shows an OR connection that is commonly used in a simple control circuit. This connection also functions as the reverse current protection.

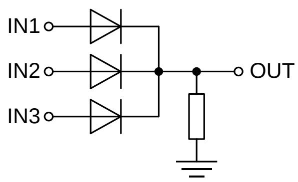

Figure 11. OR connection with diodes

Figure 12 shows a single ended push-pull (SEPP) amplifier, which operates as a Class AB amplifier when diodes are inserted to apply a bias to transistors. The switching diodes can be used for amplifiers with a small power output.

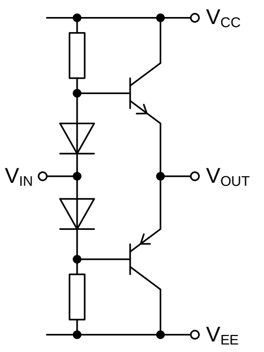

Figure 12. Class AB SEPP amplifier circuit

Figure 13 shows a simple voltage limiting circuit for protecting electronic devices such as ICs from static electricity. If the circuit cannot provide sufficient protection, the transient voltage suppressor (TVS) diodes are used.

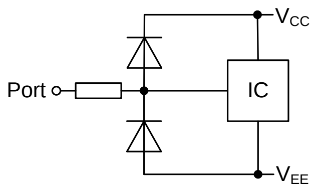

Figure 13. Simple protection circuit used against electrostatic breakdown

Figure 14 shows the device structure, which employs the general planar type. In the manufacturing process, an n⁻ type semiconductor with a low impurity concentration is formed on an n-type silicon substrate. Next, the pn junction is created by forming a p-type semiconductor on the n⁻ layer. Finally, a switching diode is completed by forming the protective film on the top and the electrodes on the top and bottom. The process is basically the same as that of FRD.

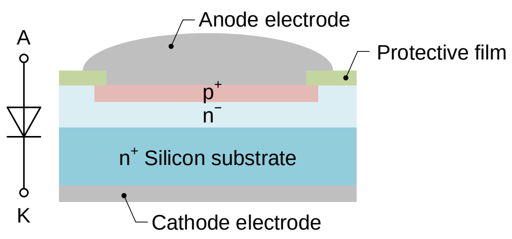

Figure 14. Device structure of switching diode

Zener diode

Zener diodes have a feature that keeps the voltage roughly constant even if the current changes. This enables applications in constant voltage circuits and protective elements that safeguard electronic devices from surge current and static electricity.

While general diodes use the forward characteristics, the Zener diodes use the reverse characteristics as shown in Figure 15.

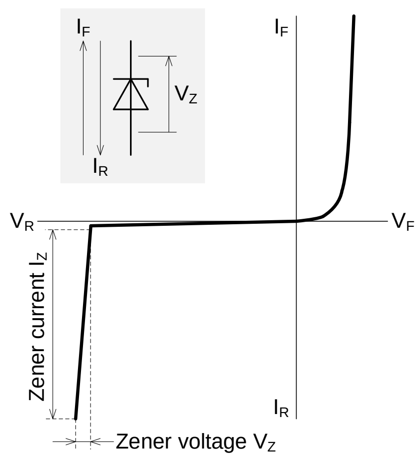

Figure 15. Voltage-current characteristics of Zener diodes

The Zener diodes use the reverse characteristics.

Figure 16 shows a reference-voltage generation circuit configured with an op-amp. A Zener diode is used for the reference voltage of non-inverting input of the op-amp. Since the Zener diodes produce a large amount of noise typically, they cannot be used for circuits sensitive to noise. In addition, a Zener voltage of approximately 5 V or higher enters the avalanche breakdown regions. Therefore, care must be taken since the produced noise is an order of magnitude larger compared with low-voltage devices. Furthermore, since the power supply impedance of the diode is decreased in this region, the noise cannot be improved by connecting capacitors in parallel.

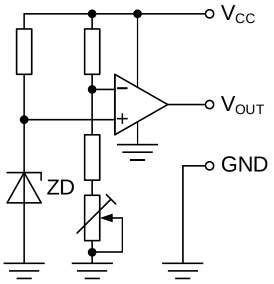

Figure 16. Reference voltage generation circuit

Figure 17 shows an example of using a Zener diode as a protective element that safeguards an electronic device from surges. The surge voltage is clamped by the Zener voltage. Since the Zener diodes cannot provide protection against waveforms with short surge pulses and high power surges, the TVS diodes are used for such protection.

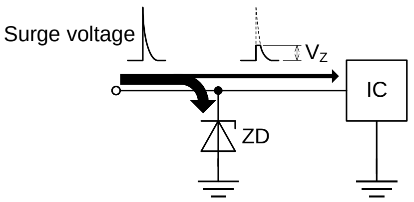

Figure 17. Surge protection for electronic device

Figure 18 shows the device structure, which is basically the same as the switching diodes. In the manufacturing process, an n^- type semiconductor with a low impurity concentration is formed on an n-type silicon substrate. Next, the pn junction is created by forming a p-type semiconductor on the n^- layer. A girdling layer is formed for the p layer to improve the surge breakdown voltage. Various Zener voltages can be produced by controlling the thicknesses of the n^- and p^+ layers and the impurity concentration. Finally, a Zener diode is completed by forming the protective film on the top and the electrodes on the top and bottom.

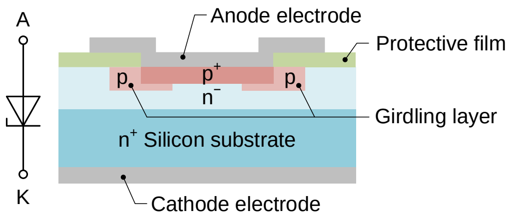

Figure 18. Device structure of Zener diode

TVS diode

Transient voltage suppressor (TVS) diodes are used to protect electronic devices from static electricity and unexpected surge voltage. The operation principle is the same as the Zener diodes described above. However, the TVS diodes have specialized characteristics for protection, including electrostatic discharge (ESD) rating guarantee, high current rating, and low terminal capacitance.

As shown in Figure 19, the TVS diode is placed in parallel with an electronic device to be protected. The diode is OFF when the circuit is operating normally. The diode is turned ON if overvoltage including surges is applied, which consumes the pulse current and clamps the overvoltage to protect the subsequent stage.

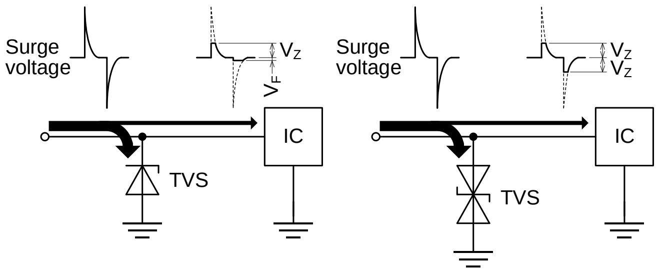

Figure 19. Electronic device protection with TVS diode

The TVS diodes are classified into the unidirectional and bidirectional types. It is necessary to select the type of TVS to be installed according to the signal polarity. If the line has positive (or negative) polarity only, such as with a DC power supply, or if the signal only has the positive polarity with the low and high levels, such as with digital signals, both the unidirectional and bidirectional types can be used. In addition, the bidirectional type is used if the signals have both positive and negative polarities, such as with unbiased analog signals or controller area network (CAN) communications.

Figure 20 shows an example of TVS placed on various communication lines. The TVS has capacitance between the terminals. Therefore, the communication quality may be deteriorated if this capacitance is large and affects waveforms. As a result, it is necessary to select elements with an adequate capacitance at the frequency of the communication line.

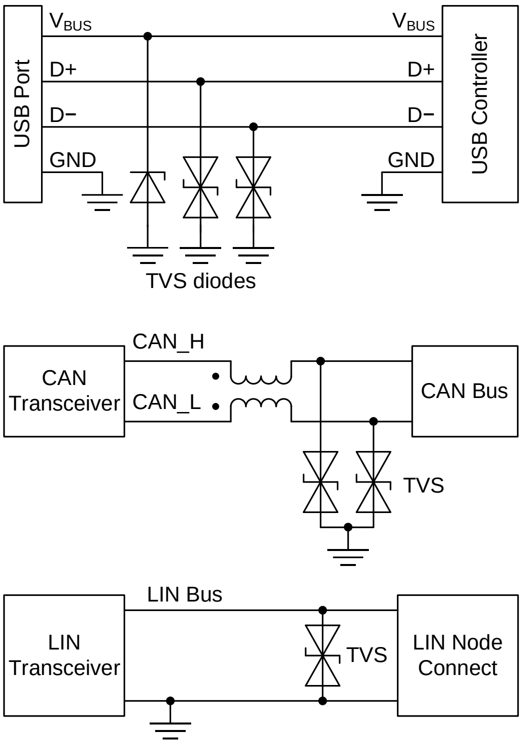

Figure 20. Protection of communication lines

PIN diode

PIN diodes have a low conductive resistance against the forward current. The resistor value works as a variable resistor with the current, and behaves as a capacitor with low capacitance against the backward current. These diodes are used for high-frequency circuits because of a small terminal capacitance.

Figure 21 shows a π-type attenuator circuit. The attenuation rate can be varied by changing the diode current to change the resistor value.

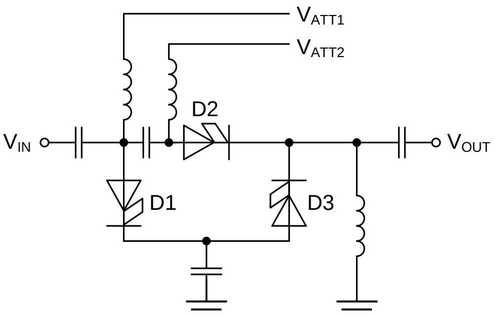

Figure 21. π-type attenuator circuit

Figure 22 shows a Colpitts oscillator circuit. A PIN diode is used for switching the oscillation frequencies.

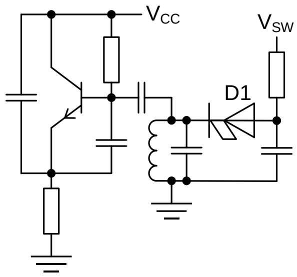

Figure 22. Colpitts oscillator circuit

Figure 23 shows the device structure. Although the structure is basically the same as the switching diode, it features a thick n^- layer. In the manufacturing process, an n^- type semiconductor with a low impurity concentration is formed on an n-type silicon substrate. The n^- layer is referred to as an “i layer” because the impurity concentration is close to the intrinsic semiconductor. Diodes with the “p-i-n” structure are referred to as “PIN” diodes.

Next, the pn junction is created by forming a p-type semiconductor on the n^- layer. Finally, a PIN diode is completed by forming the protective film on the top and the electrodes on the top and bottom.

As the forward current is increased, electrons (carriers) in the n^- layer are increased and the resistance of the n^- layer is decreased. The phenomenon causing these changes is referred to as conductivity modulation. This phenomenon enables the PIN diodes to work as a variable resistor with the current value.

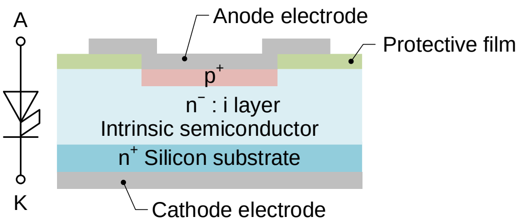

Figure 23. Device structure of PIN diode

Schottky barrier diode (SBD)

The diode characteristics are obtained with the pn junction in general diodes. In contrast, the SBD use the Schottky barrier generated by the junction of metal and semiconductor.

Compared with the pn junction diodes, the SBD generally have a lower forward voltage (V_F) and a faster reverse recovery time (t_{rr}). However, care must be taken since backward current I_R is large and thermal runaway may occur depending on the conditions.

Since the SBD have a low V_F, the typical applications are DC-DC and AC-DC converters that require high efficiency and IC terminal protection. However, they are mainly used on the secondary side because the breakdown voltage is lower than FRD.

The characteristics of SBD depend on the metal (barrier metal) types. Table 1 shows the features and suitable applications for each metal.

The SBD using metal A feature a very low V_F. However, I_R is larger than other metals. Therefore, they are not suitable for an environment with large heat generation and high ambient temperature, because they are prone to thermal runaway in such an environment. They are suitable for applications in battery power supply devices because their low V_F reduces the conduction loss and the drop in voltage.

Metal B enables devices with balanced V_F and I_R characteristics. They are commonly used for switching circuits including DC-DC converters.

Metal C is suitable for usage under high temperature because I_R is very small and the heat generation is small.

The general rectifier diodes with the pn junction have a small I_R, which is negligible in most cases. In contrast, I_R of SBD cannot be ignored. This is an important point when using the SBD.

Figure 24 shows a boost DC-DC converter circuit with a battery as the power supply. An SBD is used for the non-synchronous freewheeling diode.

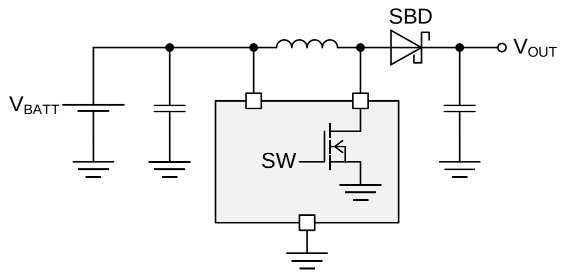

Figure 24. Boost DC-DC converter circuit with battery power supply

Figure 25 shows a non-synchronous buck DC-DC converter, using an SBD for the free wheeling diode.

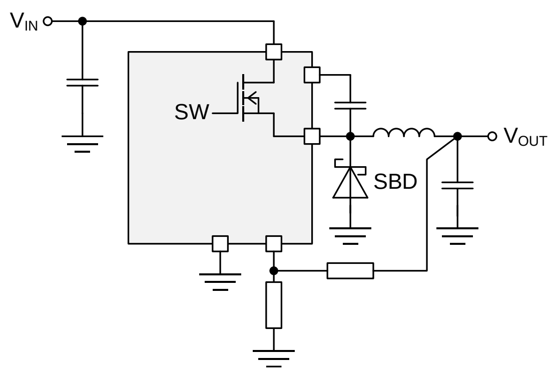

Figure 25. Non-synchronous buck DC-DC converter circuit

Table 1 Features and suitable applications for each metal (barrier metal) type.

Metal	Features	Characteristics				Suitable applications
		V_F	I_R	t_{rr}	High temperature	
A	Very low V_F	★★★★	★	★★★	★	Battery power supply devices
B	Low V_F, small I_R Balanced type	★★★	★★	★★★	★★	DC-DC converters AC-DC converters
C	Very small I_R	★★	★★★	★★★	★★★	High temperature environments
General rectifier diode		★	★★★★	★	★★★★	General purposes

V_F: Forward voltage, I_R: Reverse current, t_{rr}: Reverse recovery time

★ is an indicator of quality. The larger the number of stars, the better the characteristics.

Figure 26 shows a flyback AC-DC converter. An SBD is used for the rectifier diode on the secondary side.

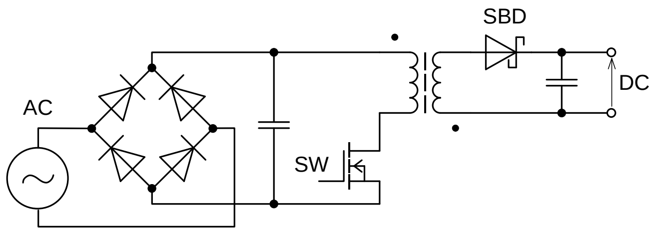

Figure 26. Flyback AC-DC converter circuit

Figure 27 shows the device structure of SBD. The n^- type semiconductor with a low impurity concentration is formed on the n-type silicon substrate. Next, barrier metal is deposited on the n^- layer, forming the Schottky junction between the n-type semiconductor and the metal. Finally, an SBD is completed by forming the protective film on the top and the electrodes on the top and bottom.

Depending on the types of metals used for this barrier metal, some products may have a large I_R as shown in Table 1. In the SBD with a large I_R, the power loss occurs due to multiplication of the reverse voltage and the reverse current, increasing the junction temperature. Since I_R has a positive temperature coefficient, I_R is increased as the junction temperature is increased. Therefore, positive feedback may occur, eventually causing thermal breakdown (increase in I_R → increase in the junction temperature → increase in I_R → increase in the junction temperature). This is referred to as thermal runaway. Since the thermal runaway is more likely to occur under a higher ambient temperature, it is necessary to pay attention to the thermal design when using a product with a large I_R.

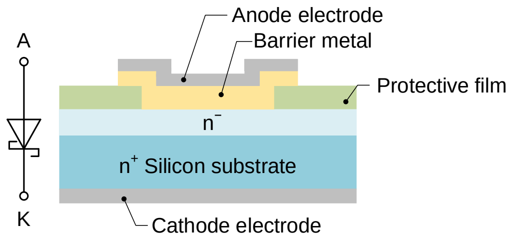

Figure 27. Device structure of Schottky barrier diode

Schottky barrier diode for detection

To detect weak signals at high frequency, it is necessary to reduce the terminal capacitance and forward voltage V_F. The die size needs to be decreased in order to reduce the terminal capacitance. On the other hand, the die size needs to be increased in order to reduce V_F. Therefore, there is a trade-off relationship between the terminal capacitance and the forward voltage. These conditions have been optimized to productize the SBD for detection.

While the terminal capacitance of general SBD is 10 pF or greater, that of SBD for detection is clearly specified to be 1 pF or less. Furthermore, since V_F is for detection, the forward current is specified as a small value, such as 1 mA, and the maximum current is also small, such as approximately 10 mA. In addition, reverse current I_R is typically large due to the trade-off with a low V_F.

Figure 28 shows a high-frequency detection circuit. The peak detection is performed with the SBD and RC in the subsequent stage.

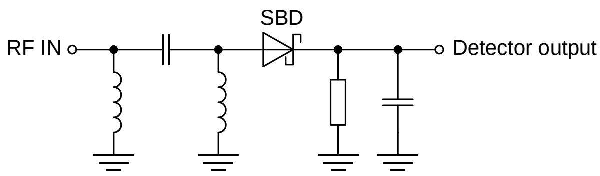

Figure 28. High-frequency detection circuit

SiC Schottky barrier diode (SiC SBD)

The high-speed device structure of SBD results in a breakdown voltage of approximately 200 V in conventional Si SBD. In contrast, a high breakdown voltage of 1,200 V can be achieved with SiC SBD. The fast recovery diodes (FRD) with the pn junction structure are currently mainstream of diodes with high speed and high breakdown voltage. However, the recovery loss during the switching operation can be significantly reduced by replacing the FRD with SiC SBD.

Forward voltage V_F of SiC SBD is a little less than 1 V, similar to Si FRD. V_F is determined by the height of the Schottky barrier and can usually be reduced by designing a lower barrier height. However, there is a trade-off relationship between V_F and the leakage current in a reverse bias condition, which increases as the barrier height decreases. In the second generation of ROHM's SiC SBD, innovations in processes successfully reduced V_F by approximately 0.15 V while maintaining the leakage current and the recovery performance at the same level as conventional products. Furthermore, in the third generation SiC SBD, V_F and the leakage current are further reduced by combining the junction barrier Schottky (JBS) structure and the low V_F process for the second generation. In particular, V_F is significantly reduced at high temperature. The temperature dependence differs from that of Si FRD, showing an increase in V_F due to an increase in the operating resistance as temperature increases. As a result, thermal runaway is less likely to occur.

Figure 29 shows the simplest PFC circuit configured with a boost converter. An SiC SBD is used for rectification.

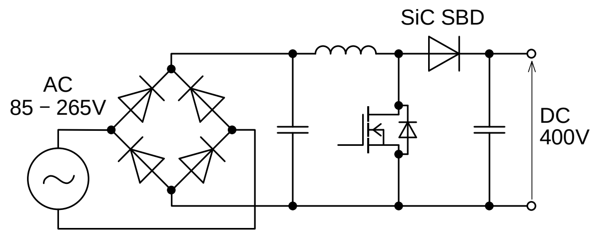

Figure 29. Boost PFC circuit

Figure 30 shows a three-phase Vienna PFC circuit showing a low total harmonic distortion (THD). SiC SBD are used for rectification.

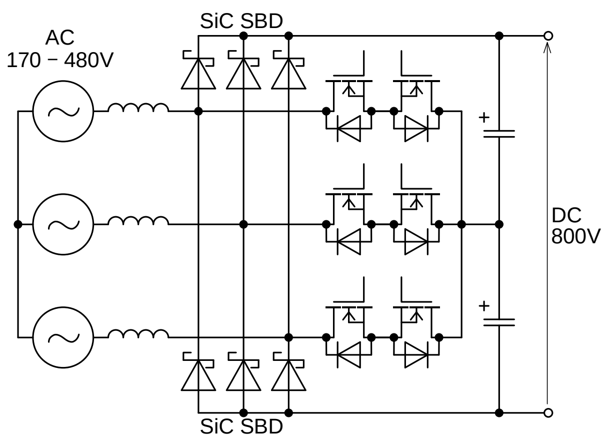

Figure 30. Three-phase Vienna PFC circuit

Figure 31 shows the device structure of the third generation SiC SBD. The n^- type SiC with a low impurity concentration is formed on the n-type SiC substrate. Next, p^+ are embedded into parts of the n^- layer and the barrier metal is deposited. This is referred to as the JBS structure. Since micro pn junction diodes are fabricated on the Schottky interface in the JBS structure, holes are injected via the pn junctions when a large current flows, reducing the increase in the resistance of the drift layer (the layer to pass the current). As a result, a high tolerance against the inrush current can be obtained.

Furthermore, although the leakage current is increased when a strong field is applied to a Schottky interface with many defects, including crystal defects, the leakage current can be reduced by embedding the p^+ layer and moving the strong field directly under the p^+ layer to reduce the field strength at the Schottky interface.

Finally, an SiC SBD is completed by forming the protective film on the top and the electrodes on the top and bottom.

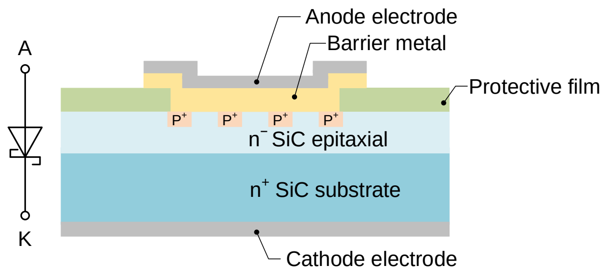

Figure 31. Device structure of third generation SiC SBD JBS (junction barrier Schottky) structure

Light emitting diode (LED)

LEDs (light emitting diodes) are optical semiconductors that emit light by passing a current. The light can typically be obtained efficiently because the electric energy is directly converted into light energy. LEDs are used in many applications because light emissions in various colors can be generated with combinations of compound semiconductors.

Figure 32 shows an LED driving circuit. The simplest circuit to determine the current with a resistor is shown on the left, while the constant current driving circuit is shown on the right.

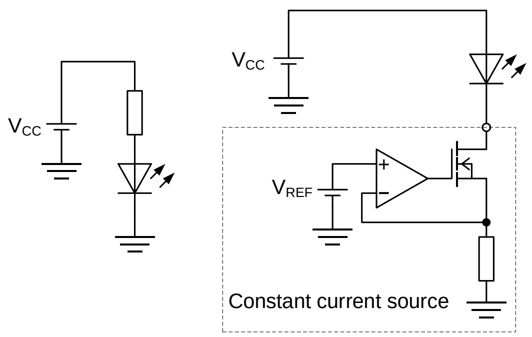

Figure 32. LED driving circuit

Figure 33 shows the LED dimming systems. The dimming systems include analog dimming (also known as DC or linear dimming) and PWM dimming.

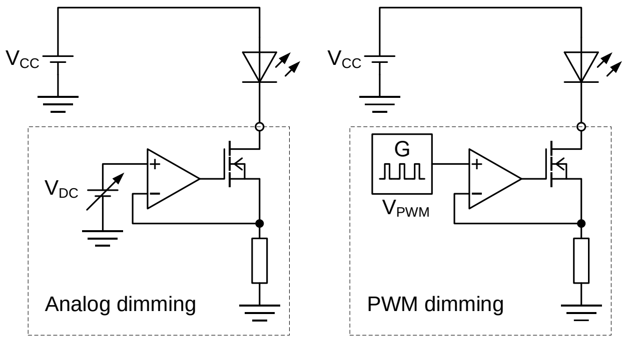

Figure 33. LED dimming systems

Figure 34 shows the device structure of the standard-brightness type of general red LED. The structure is different in other high-brightness type, blue, or green LEDs.

The pn junction is formed in a similar way to general diodes. Since general diodes use semiconductors made from a single element of group 14 in the long-form periodic table (group IV in the short-form), including Si, the recombination of electrons and holes hardly produces any light energy. In contrast, since the LEDs use compound semiconductors made from multiple elements of groups 13 and 15 in the long-form periodic table (groups III and V in the short-form), light energy is produced when the recombination occurs. The combinations of materials include GaAsP, AlGaAs, GaP, InGaP, and InGaAlP. The function as a light emitting element can be obtained by the epitaxial growth of these materials on a substrate.

A transparent electrode is employed as the front electrode in order to improve the light emitting efficiency.

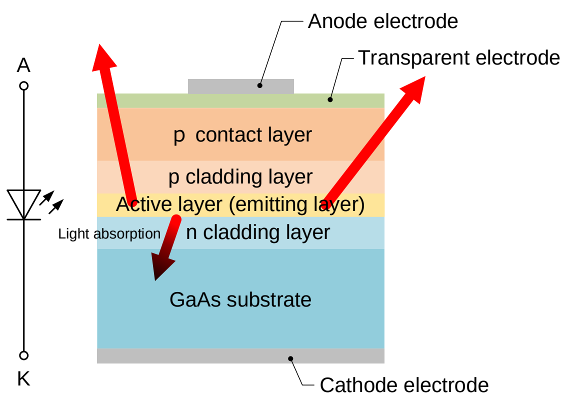

Figure 34. Device structure of LED
Red LED of standard-brightness type

Semiconductor laser (laser diode)

Semiconductor lasers, also referred to as laser diodes, are optical semiconductors. The acronym "LASER" stands for "light amplification by stimulated emission of radiation". Laser diodes are devices in which the principle of stimulated emission enables the light emitted by passing a current to generate strong coherent light. Compared with LEDs, the same light emitting element, laser diodes feature a narrow width in wavelength spectra and coherent light with very high directionality.

They are used for applications in various fields, including light detection and ranging (LiDAR) systems installed in self-driving vehicles and robot cleaners, laser printers, motion sensors, 3D scanners, CD/DVD players, barcode readers, and PM2.5 detection sensors.

Figure 35 shows the current oscillation type of driving circuit. With this circuit, a higher power in short pulses can be readily obtained for LiDAR.

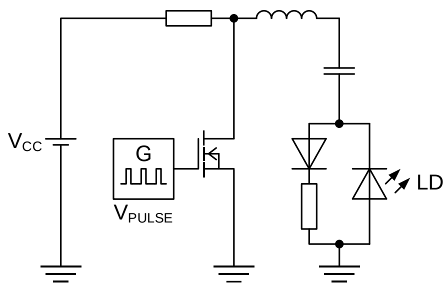

Figure 35. Current oscillation type of laser diode driving circuit

Figure 36 shows the automatic current control (ACC) type of driving circuit that keeps the current constant.

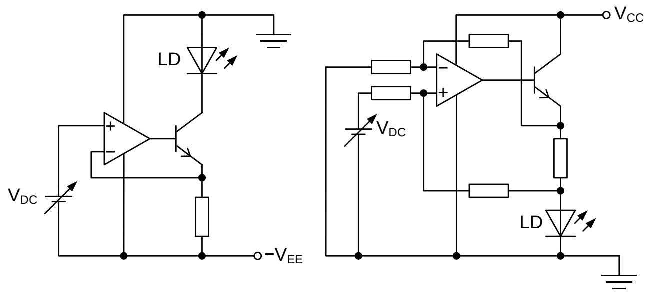

Figure 36. ACC type of laser diode driving circuit

Figure 37 shows the automatic power control (APC) type of driving circuit, which keeps the light output constant.

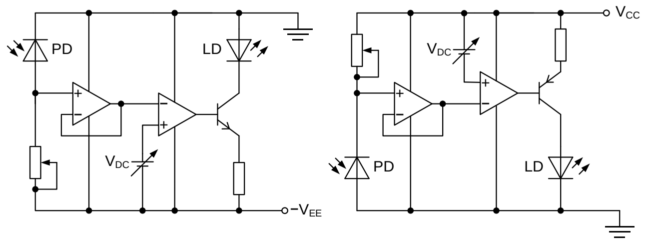

Figure 37. APC type of laser diode driving circuit

Figure 38 shows the device structure of a laser diode. This is the Fabry-Perot type, which is the simplest structure of laser diode. The structure on the n-type substrate has an active layer (light emitting layer) between the n-type and p-type cladding layers. When the current is passed, the recombination of electrons and holes in the active layer produces the light energy to emit light. The light is confined in the active layer because the cladding layers are made from materials with refractive indices lower than that of the active layer. Since the edges of the active layer are structured to reflect light, the light is amplified while traveling back and forth within the active layer, resulting in the stimulated emission. The laser beam is emitted through the semitransparent mirror structures on parts of the edge of the active layer.

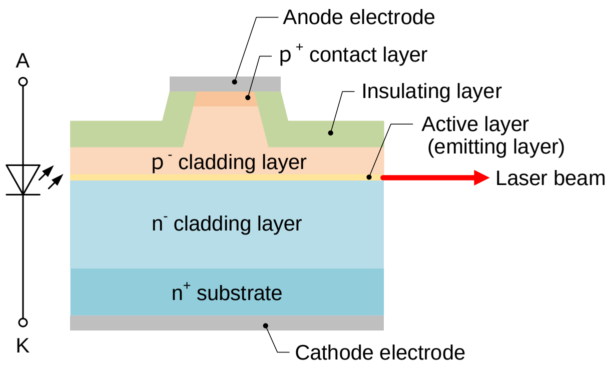

Figure 38. Device structure of laser diode

The features and typical applications of each diode are explained above. Understand the features of each diode before selecting the devices most suitable for any applications.

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