Basic Knowledge of Discrete Semiconductor Device

Chapter II

Diodes

September 2018
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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

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

Functions of Rectifier Diodes

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

**Rating:**
\( I_{F(AV)} \)

- **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.

**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.
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 $t_{rr}$ value.

$t_{rr}$ of a general rectifier diode is several $\mu$s to several tens of $\mu$s. 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.

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 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.)

"Z" is added to the normal diode symbol.

Anode (A)  Cathode (K)

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

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

TVS diodes use this region.

Zener diodes use this region.
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
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

Both diodes have the function of clamping a certain voltage, but their usage is different.
**Difference between TVS Diodes and Zener Diodes (2)**

**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.

**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)

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

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
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.)
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. $\Phi_B$ 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 $\Phi_B$ makes leakage current small, but makes forward voltage $V_F$ big. For metals with small $\Phi_B$, the opposite tendency are obtained.

**Table:**

<table>
<thead>
<tr>
<th>Metal</th>
<th>$\Phi_B$</th>
<th>$V_F$</th>
<th>$I_{RRM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt</td>
<td>Big</td>
<td>Big</td>
<td>Small</td>
</tr>
<tr>
<td>Mo</td>
<td>Small</td>
<td>Small</td>
<td>Big</td>
</tr>
<tr>
<td>V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Graphs:**

- **OFF duration:** The current does not flow.
- **ON duration:** The current flows from anode to cathode.
### Characteristics Application of Various Diodes

<table>
<thead>
<tr>
<th>Types of diodes</th>
<th>Application or expected application fields</th>
</tr>
</thead>
</table>
| 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
- Temperature: 150°C to 175°C

**PN junction Di**
- Reverse voltage: 600 V
- Temperature: 125°C to 150°C

**Si SBD**
- Reverse voltage: 30 V to 60 V
- Temperature: 100°C to 125°C
- 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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