Power MOSFET Electrical Characteristics

Description

This document explains electrical characteristic of power MOSFETs.
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1. Electrical Characteristics

(The specified characteristics differ from product to product. Ta=25°C unless otherwise specified.)

1.1. Static Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate leakage current</td>
<td>$I_{GSS}$</td>
<td>μA</td>
<td>The leakage current that occurs when the specified voltage is applied across gate and source with drain and source short-circuited</td>
</tr>
<tr>
<td>Drain cut-off current</td>
<td>$I_{DSS}$</td>
<td>μA</td>
<td>The leakage current that occurs when a voltage is applied across drain and source with gate and source short-circuited</td>
</tr>
<tr>
<td>Drain-source breakdown voltage</td>
<td>$V_{(BR)DSS}$</td>
<td>V</td>
<td>The maximum voltage that the device is guaranteed to block between drain and source</td>
</tr>
<tr>
<td></td>
<td>$V_{(BR)DSX}$</td>
<td>V</td>
<td>$V_{(BR)DSS}$: With gate and source short-circuited</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$V_{(BR)DSX}$: With gate and source reverse-biased</td>
</tr>
<tr>
<td>Gate threshold voltage</td>
<td>$V_{th}$</td>
<td>V</td>
<td>$V_{th}$ stands for &quot;threshold voltage.&quot; $V_{th}$ is the gate voltage that appears when the specified current flows between source and drain.</td>
</tr>
<tr>
<td>Drain-source on-resistance</td>
<td>$R_{DS (ON)}$</td>
<td>Ω</td>
<td>The resistance across drain and source when the MOSFET is in the &quot;on&quot; state</td>
</tr>
<tr>
<td>Forward transfer admittance</td>
<td>$</td>
<td>Y_{fs}</td>
<td>$</td>
</tr>
</tbody>
</table>

1.2. Dynamic Characteristics

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitances</td>
<td>$C_{iss}$</td>
<td>pF</td>
<td>$C_{iss}$ is the input capacitance, $C_{rss}$ is the reverse transfer capacitance, and $C_{oss}$ is the output capacitance. Capacitances affect the switching performance of a power MOSFET.</td>
</tr>
<tr>
<td></td>
<td>$C_{rss}$</td>
<td>pF</td>
<td>$C_{rss}$ is the reverse transfer capacitance.</td>
</tr>
<tr>
<td></td>
<td>$C_{oss}$</td>
<td>pF</td>
<td>$C_{oss}$ is the output capacitance.</td>
</tr>
<tr>
<td>Effective output capacitance</td>
<td>$C_{o(er)}$</td>
<td>pF</td>
<td>$C_{o(er)}$ is a fixed capacitance that gives the same stored energy as $C_{iss}$ while $V_{DS}$ is rising from 0 V to specified voltage.</td>
</tr>
<tr>
<td>(energy related)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective output capacitance</td>
<td>$C_{o(tr)}$</td>
<td>pF</td>
<td>$C_{o(tr)}$ is a fixed capacitance that gives the same charging time as $C_{oss}$ while $V_{DS}$ is rising from 0 V to specified voltage.</td>
</tr>
<tr>
<td>(time related)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gate resistance</td>
<td>$r_g$</td>
<td>Ω</td>
<td>The internal gate resistance of a MOSFET</td>
</tr>
<tr>
<td>Switching time</td>
<td>$t_r$</td>
<td>ns</td>
<td>$t_r$ is the rise time, $t_{on}$ is the turn-on time, $t_f$ is the fall time, and $t_{off}$ is the turn-off time.</td>
</tr>
<tr>
<td></td>
<td>$t_{on}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$t_f$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$t_{off}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOSFET dv/dt capability</td>
<td>$dv/dt$</td>
<td>V/ns</td>
<td>The maximum drain-source voltage ramp allowed at the turn-off of a MOSFET</td>
</tr>
</tbody>
</table>

1.2.1. Capacitance characteristics

In a power MOSFET, the gate is insulated by a thin silicon oxide. Therefore, a power MOSFET has capacitances between the gate-drain, gate-source and drain-source terminals as shown in Figure 1.1.

The gate-drain capacitance $C_{gd}$ and the gate-source capacitance $C_{gs}$ are mainly determined by the structure of the gate electrode, while the drain-source capacitance $C_{ds}$ is determined by the capacitance of the vertical p-n junction.
For the power MOSFET, the input capacitance \( C_{iss} = C_{gd} + C_{gs} \), the output capacitance \( C_{oss} = C_{ds} + C_{gd} \) and the reverse transfer capacitance \( C_{rss} = C_{gd} \) are important characteristics.

Figure 1.2 shows the dependency of \( C_{iss} \), \( C_{rss} \) and \( C_{oss} \) on drain-source voltage \( V_{DS} \).

Switching characteristics of a MOSFET mainly vary with the input capacitance \( C_{iss} \) and the output impedance of the drive circuit.

Gate current flows from gate to source instantaneously to charge the input capacitance. Therefore, the lower the output impedance of the drive circuit, the faster the switching speed. Large input capacitance of a MOSFET causes a large power loss at light load. \( C_{iss} \), \( C_{rss} \) and \( C_{oss} \) hardly vary with temperature.

**Figure 1.1 Capacitance Equivalent Circuit**

**Figure 1.2 Capacitance vs \( V_{DS} \)**
1.2.2. Effective output capacitance (energy related)

Effective output capacitance (energy related) $C_{o(er)}$ is the fixed capacitance calculated to give the same stored energy as $C_{oss}$ while the drain-source voltage rises from 0V to the specified voltage.

Expressing $E_{oss}$ in $C_{o(er)}$ is as follows.

$$E_{oss} = \frac{C_{o(er)} \times V_{DS}^2}{2}$$

In addition, $E_{oss}$ is equal to the value obtained by integrating the amount of charge $Q=C(v) \times v$ in the capacitance characteristic curve from the drain-source voltage of 0 V to the specified $V_{DS}$, so the following formula holds.

$$\frac{C_{o(er)} \times V_{DS}^2}{2} = \int_0^{V_{DS}} v \times C(v) \, dv$$

Therefore, $C_{o(er)}$ is expressed as follows.

$$C_{o(er)} = \frac{2}{V_{DS}^2} \int_0^{V_{DS}} v \times C(v) \, dv$$

$C(v)$: function of output capacitance $C_{oss}$ dependent on $V_{DS}$

$C_{o(er)}$ is used when it is necessary to calculate as capacitive energy in the design of power supplies, etc.

1.2.3. Effective output capacitance (time related)

Effective capacitance (time related) $C_{o(tr)}$ is the fixed effective capacitance calculated to give the same charging time as $C_{oss}$ while the drain-source voltage rises from 0V to the specified voltage.

Expressing the charge amount $Q_{oss}$ in $C_{o(tr)}$ is as follows.

$$Q_{oss} = C_{o(tr)} \times V_{DS}$$

In addition, $Q_{oss}$ is equal to the value obtained by integrating the $C(v)$ in the capacitance characteristic curve from the drain-source voltage of 0 V to the specified $V_{DS}$, so the following formula holds.

If the charging (discharging) current is the same on the left and right in the following formula, the charging (discharging) time is also same.

$$C_{o(tr)} \times V_{DS} = \int_0^{V_{DS}} C(v) \, dv$$

Therefore, $C_{o(tr)}$ is expressed as follows.

$$C_{o(tr)} = \frac{1}{V_{DS}} \int_0^{V_{DS}} C(v) \, dv$$

$C(v)$: function of output capacitance $C_{oss}$ dependent on $V_{DS}$

$C_{o(tr)}$ is used for time calculation purposes in the design of power supplies, etc.
1.2.4. Switching characteristics

Since power MOSFETs are majority-carrier devices, they are faster and capable of switching at higher frequencies than bipolar transistors.

Figure 1.3 shows a switching time test circuit, and Figure 1.3 gives the input and output waveforms.

Figure 1.3 Switching Time Test Circuit and Input/Output Waveforms

The symbols used in the above input and output waveforms are briefly explained below:

1. \( t_{d\,(on)} \): Turn-on delay time
   The time from when the gate-source voltage rises over 10% of \( V_{GS} \) until the drain-source voltage reaches 90% of \( V_{DS} \)
2. \( t_r \): Rise time
   The time taken for the drain-source voltage to fall from 90% to 10% of \( V_{DS} \)
3. \( t_{on} \): Turn-on time
   The turn-on time is equal to \( t_{d\,(on)} + t_r \).
4. \( t_{d\,(off)} \): Turn-off delay time
   The time from when the gate-source voltage drops below 90% of \( V_{GS} \) until the drain-source voltage reaches 10% of \( V_{DS} \)
5. \( t_f \): Fall time
   The time taken for the drain-source voltage to rise from 10% to 90% of \( V_{DS} \)
6. \( t_{off} \): Turn-off time
   The turn-off time is equal to \( t_{d\,(off)} + t_f \).

1.2.5. \( dv/dt \) capability

When the drain-source voltage is raised sharply at the turn-on of a MOSFET, a displacement current flows to the PN junction capacitance (C) between drain and source, as shown in Figure 1.4, due to the rate of voltage change \( dv/dt \). The displacement current is calculated as \( i = C \cdot (dv/dt) \).

Current \( i \) causes a voltage drop of \( i \cdot R_b \) due to the resistance \( R_b \) of this layer. If the voltage drop exceeds the base-emitter forward voltage (\( V_{BE} \)) of the parasitic NPN transistor, it is forced into
conduction.

If the drain-source voltage, $V_{DS}$, is high at this time, the parasitic NPN transistor might enter secondary breakdown, causing a catastrophic failure.

![Cross Section and Equivalent Circuit of a MOSFET](image)

**Figure 1.4 Cross Section and Equivalent Circuit of a MOSFET**
1.3. Charge Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total gate charge</td>
<td>$Q_g$</td>
<td>nC</td>
<td>The amount of charge to apply voltage (from zero to designated voltage) to gate</td>
</tr>
<tr>
<td>Gate-source charge 1</td>
<td>$Q_{gs1}$</td>
<td>nC</td>
<td>The amount of charge required for a MOSFET to begin to turn on (before dropping drain-source voltage)</td>
</tr>
<tr>
<td>Gate-drain charge</td>
<td>$Q_{gd}$</td>
<td>nC</td>
<td>As the MOSFET begins to turn on, the drain-source voltage begins to fall, charging the gate-drain capacitance. The gate-source voltage stops increasing and reaches the Miller plateau. From this point to the ending point of Miller plateau is known as the gate-drain charge period.</td>
</tr>
<tr>
<td>Gate switch charge</td>
<td>$Q_{sw}$</td>
<td>nC</td>
<td>The amount of charge stored in the gate capacitance from when the gate-source voltage has reached $V_{th}$ until the end of the Miller plateau</td>
</tr>
<tr>
<td>Output charge</td>
<td>$Q_{oss}$</td>
<td>nC</td>
<td>Drain-source charge</td>
</tr>
</tbody>
</table>

1.3.1. Gate charge

Because the Gate (G) input terminal of a MOSFET is insulated, the amounts of charge $Q$ seen from the Gate, are important characteristics. Figure 1.5 illustrates the definitions of gate charge characteristics.

![Figure 1.5 Definition of Total Gate Charge, $Q_g$](image-url)
1.3.2. Calculation of Total Gate Charge

During the turn-on of a power MOSFET, a current flows to the gate, charging the gate-source and gate-drain capacitances. The amount of gate charge is measured using a test circuit shown in Figure 1.6 (a). A constant current is applied to the gate to obtain a graph like the one shown in Figure 1.6 (b) showing a change in gate-source voltage \( V_{GS} \) over time. The time axis can be expressed in terms of gate capacitance \( Q_g \) by multiplying time by constant gate current \( i_G \). Gate charge is calculated as follows:

\[
Q_g = \int_0^t i_G(t)dt
\]

![Gate Charge Test Circuit](image_url)

(a) Gate Charge Test Circuit

(b) Waveform of Gate-Source Voltage

Figure 1.6 Gate Charge

1.3.3. Output charge (\( Q_{oss} \))

\( Q_{oss} \) is the amount of charge for charging drain-source capacity.

Since the value of \( C_{oss} \) of a MOSFET varies with \( V_{DS} \) when \( Q = CV \), \( Q_{oss} \) is calculated as follows:

\[
Q_{oss} = \int_0^{V_{DS}} C(v)dv
\]

where \( C(v) \) is a function of the output capacitance \( C_{oss} \) that is dependent on \( V_{DS} \).

\( Q_{oss} \) is equal to the integral of the \( C_{oss} \) (output capacitance) along \( V_{DS} \) shown in Figure 1.7, "Capacitance vs \( V_{DS} \)."

\( Q_{oss} \) affects efficiency in the application such as switching power supplies especially driving in light load.

![Capacitance vs \( V_{DS} \)](image_url)

Figure 1.7 Capacitance vs \( V_{DS} \)
1.4. Source-Drain Characteristics

(The specified characteristics differ from product to product. Ta=25°C unless otherwise specified.)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverse drain current</td>
<td>IDR</td>
<td>A</td>
<td>The maximum current that can flow to the body diode of a MOSFET in the forward direction</td>
</tr>
<tr>
<td>(DC)</td>
<td>IDR</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Reverse drain current</td>
<td>IDR</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>(pulsed)</td>
<td>IDR</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Diode forward voltage</td>
<td>VDSF</td>
<td>V</td>
<td>Drain-source voltage that appears when a current is applied to the body diode of a MOSFET in the forward direction</td>
</tr>
<tr>
<td>Reverse recovery time</td>
<td>tr</td>
<td>ns</td>
<td>The time tr and the amount of charge Qrr required for the reverse recovery current to reach zero during the reverse recovery operation of the body diode under the specified test conditions. The peak current during this period is Irr.</td>
</tr>
<tr>
<td>Diode reverse recovery</td>
<td>Qrr</td>
<td>μC</td>
<td></td>
</tr>
<tr>
<td>charge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diode peak reverse</td>
<td>Itr</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>recovery current</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diode dv/dt capability</td>
<td>dv/dt</td>
<td>V/ns</td>
<td>The maximum voltage ramp allowed during the reverse recovery time of the diode</td>
</tr>
</tbody>
</table>

1.4.1. Body Diode Characteristics

A power MOSFET has a circuit structure between source and drain equivalent to a diode. The forward current of the body diode IDR and IDR are defined on individual product datasheet. Figure 1.9 shows current characteristics of body diode. Reverse breakdown voltage is same as drain-source voltage VDSS.

Regarding the reverse recovery time tr of the body diode, Figure 1.8 shows an example of a test circuit and waveform.

![Figure 1.8 Reverse Recovery Time of the Body Diode in a Power MOSFET](image)
1.4.2. \(dv/dt\) Capability of the Body Diode

When the body diode in a power MOSFET is switched from forward voltage to reverse voltage while a current is flowing, it enters the reverse recovery state. This causes the drain-source voltage to increase sharply. As shown in Figure 1.10, due to a voltage change \(dv/dt\) a displacement current, \(i = C \cdot (dv/dt)\), flows to the capacitance \(C\) of the PN junction between drain and gate, thereby causing a voltage drop by the current \(i\) and resistance \(R_b\). This voltage drop, in turn, causes the parasitic NPN transistor to turn on. At this time, if the drain-source voltage \(V_{DS}\) is high, the parasitic NPN transistor might enter secondary breakdown. As is the case with the MOSFET \(dv/dt\), the diode might suffer a catastrophic failure, although the failure processes are different.

![Figure 1.10 Equivalent Circuit and Reverse Recovery Waveform of the Body Diode](image)
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