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

Characteristic	Symbol	Unit	Description
Gate leakage current	I_{GSS}	μA	The leakage current that occurs when the specified voltage is applied across gate and source with drain and source short-circuited
Drain cut-off current	I_{DSS}	μA	The leakage current that occurs when a voltage is applied across drain and source with gate and source short-circuited
Drain-source breakdown voltage	$V_{(BR)DSS}$ $V_{(BR)DSX}$	V	The maximum voltage that the device is guaranteed to block between drain and source $V_{(BR)DSS}$: With gate and source short-circuited $V_{(BR)DSX}$: With gate and source reverse-biased
Gate threshold voltage	V_{th}	V	V_{th} stands for "threshold voltage." V_{th} is the gate voltage that appears when the specified current flows between source and drain.
Drain-source on-resistance	$R_{DS\ (ON)}$	Ω	The resistance across drain and source when the MOSFET is in the "on" state
Forward transfer admittance	$\lvert Y_{fs} \rvert$	S	Also called g_m, $\lvert Y_{fs} \rvert$ is the ratio of the drain current variation at the output to the gate voltage variation at the input and is defined as $\lvert Y_{fs} \rvert = \Delta I_D / \Delta V_{GS}$. $\lvert Y_{fs} \rvert$ indicates the sensitivity or amplification factor of the power MOSFET. $\lvert Y_{fs} \rvert$ can be read from the I_D-V_{GS} curve.

1.2. Dynamic Characteristics

Symbol	Unit	Unit	Description
Capacitances	C_{iss} C_{rss} C_{oss}	pF	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.
Effective output capacitance	$C_{o(er)}$	pF	Effective output capacitance calculated from E_{oss}, which is needed to charge C_{oss}
Gate resistance	r_g	Ω	The internal gate resistance of a MOSFET
Switching time	t_r t_{on} t_f t_{off}	ns	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.
MOSFET dv/dt capability	dv/dt	V/ns	The maximum drain-source voltage ramp allowed at the turn-off of a MOSFET

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.

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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 manly 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.

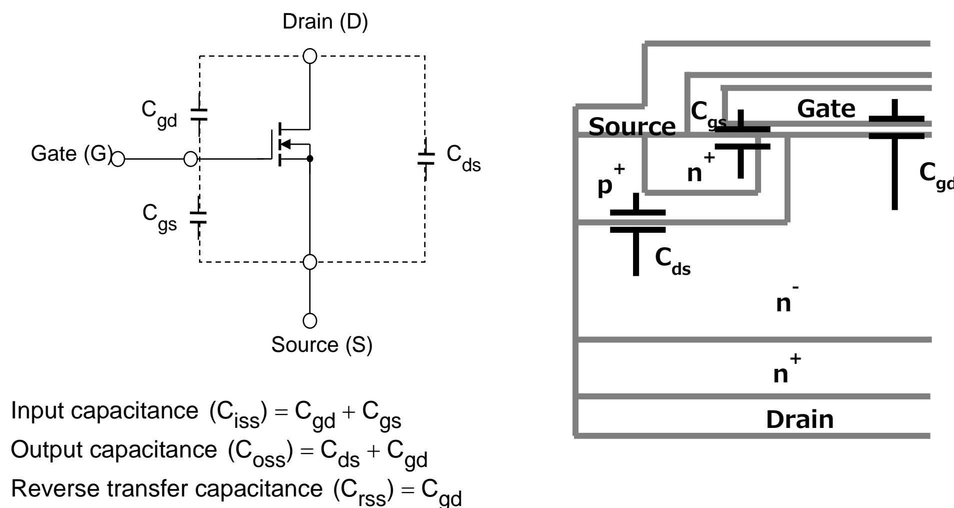

Figure 1.1 Capacitance Equivalent Circuit

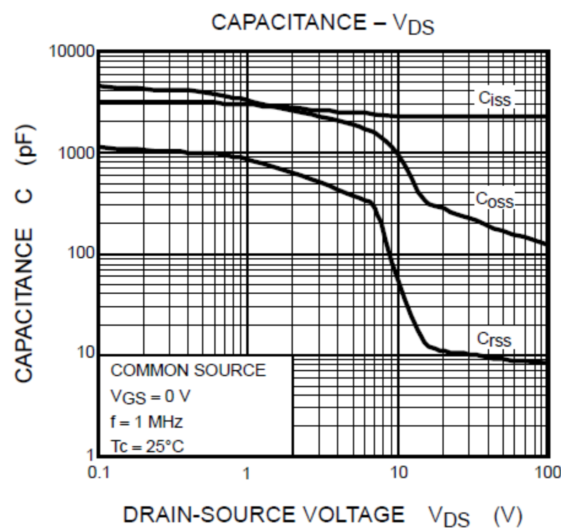

Figure 1.2 Capacitance vs V_{DS}

1.2.2. Effective output capacitance (energy-related)

$C_{o(er)}$ is the effective output capacitance (energy-related) dependent on the drain voltage and is calculated as follows. Superjunction MOSFETs have a large output capacitance because of their structure. Power loss occurs at the turn-on and turn-off of the MOSFET due to the charging and discharging of the output capacitance.

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

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

C(v) is a function of the V_{DS}-dependent output capacitance C_{OSS}.

1.2.3. 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.

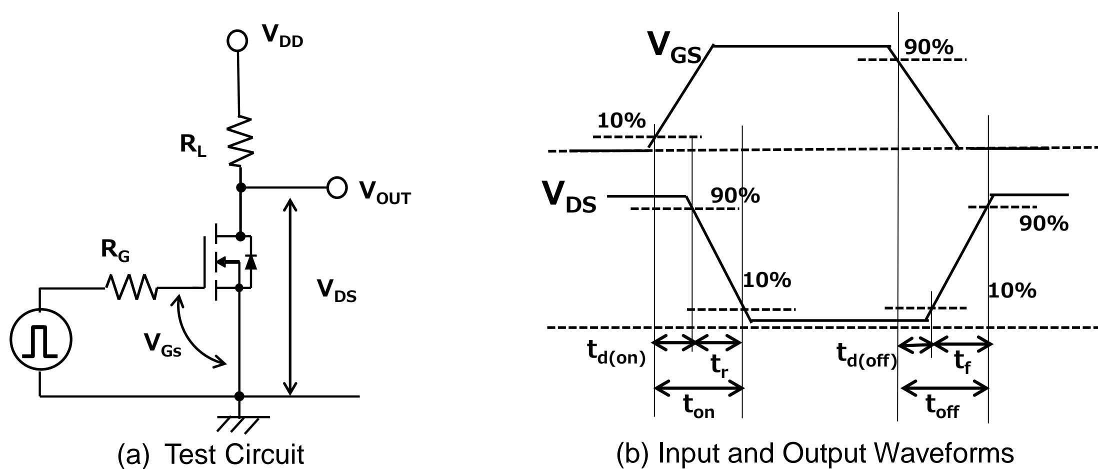

Figure 1.3 Switching Time Test Circuit and Input/Output Waveforms

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 $t_{d\ (off)} + t_f$.

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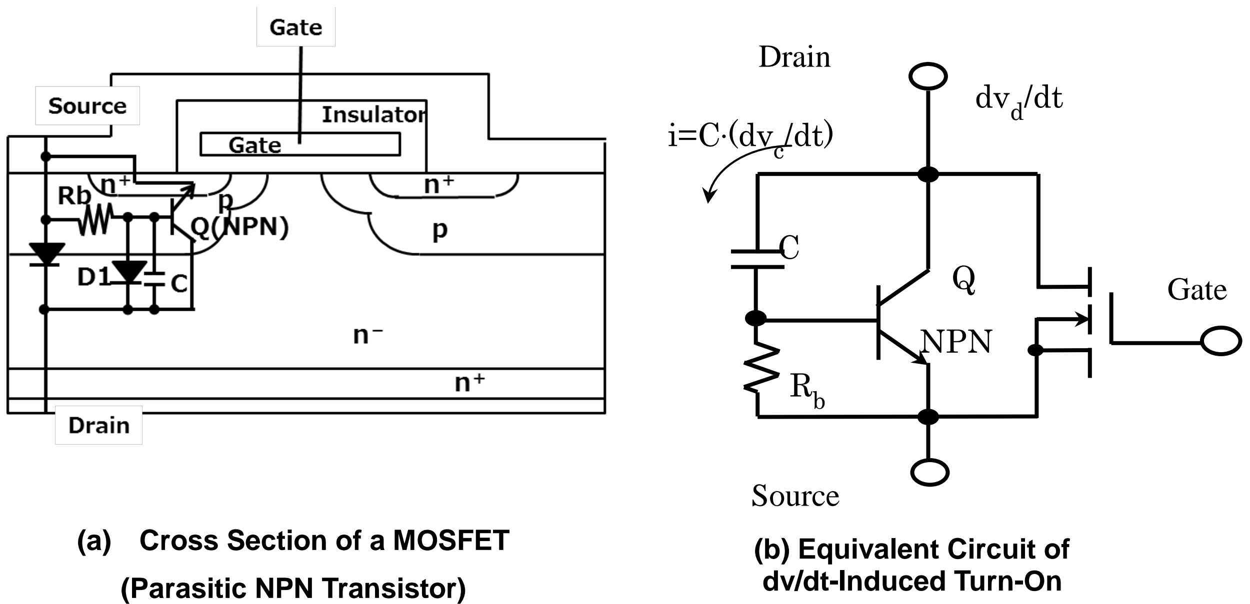
1.2.4. dv/dt capability

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 $i=C\cdot(dv_C/dt)$. 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.



(a) Cross Section of a MOSFET (Parasitic NPN Transistor)

(b) Equivalent Circuit of dv/dt-Induced Turn-On

Figure 1.4 Cross Section and Equivalent Circuit of a MOSFET

1.3. Charge Characteristics

Characteristic	Symbol	Unit	Description
Total gate charge	Q_g	nC	The amount of charge to apply voltage (from zero to designated voltage) to gate
Gate-source charge 1	Q_{gs1}		The amount of charge required for a MOSFET to begin to turn on (before dropping drain-source voltage)
Gate-drain charge	Q_{gd}		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.
Gate switch charge	Q_{sw}		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
Output charge	Q_{oss}		Drain-source charge

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.

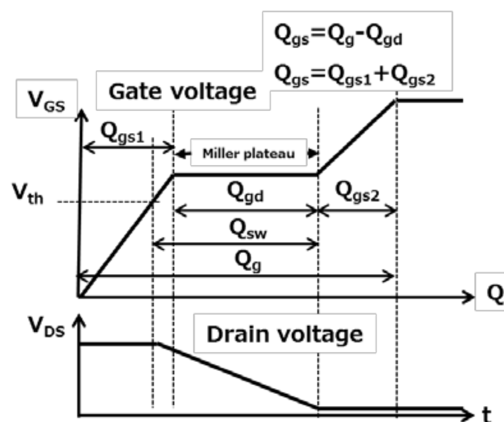


Figure 1.5 Definition of Total Gate Charge, Q_g

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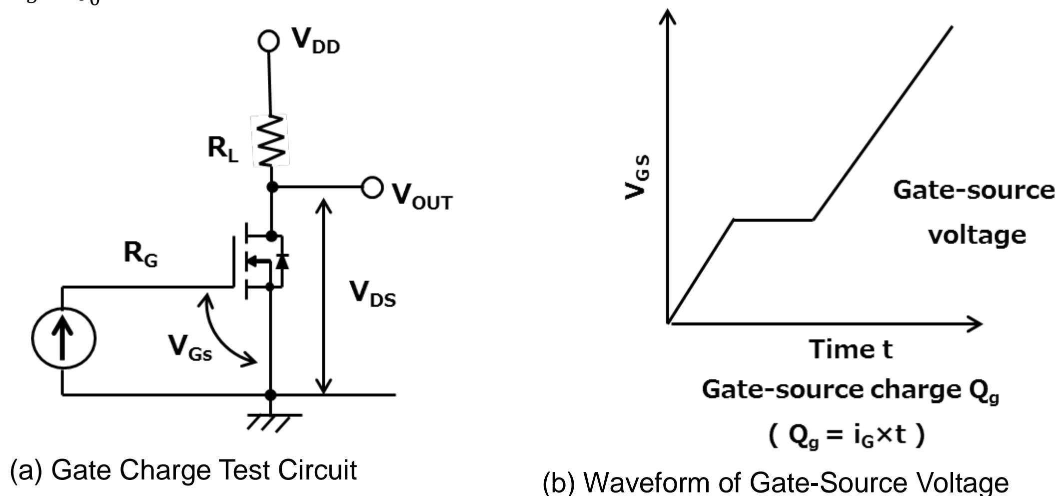
1.3.2. Calculation of Total Gate Charge

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:

$$Q_g = \int_0^t i_G(t)dt$$



(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.

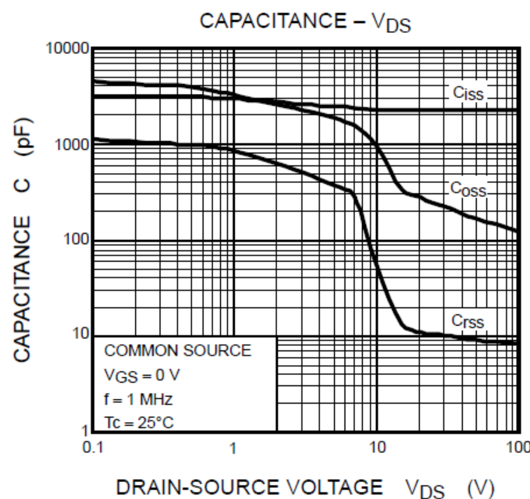


Figure 1.7 Capacitance vs V_{DS}

1.4. Source-Drain Characteristics

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

Characteristic	Symbol	Unit	Description
Reverse drain current (DC) Reverse drain current (pulsed)	I_{DR} I_{DRP}	A	The maximum current that can flow to the body diode of a MOSFET in the forward direction
Diode forward voltage	V_{DSF}	V	Drain-source voltage that appears when a current is applied to the body diode of a MOSFET in the forward direction
Reverse recovery time	t_{rr}	ns	The time t_{rr} and the amount of charge Q_{rr} 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 I_{rr}.
Diode reverse recovery charge	Q_{rr}	μC	
Diode peak reverse recovery current	I_{rr}	A	
Diode dv/dt capability	dv/dt	V/ns	The maximum voltage ramp allowed during the reverse recovery time of the diode

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 I_{DR} and I_{DRP} are defined on individual product datasheet. Figure 1.9 shows current characteristics of body diode. Reverse breakdown voltage is same as drain-source voltage V_{DSS}.

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

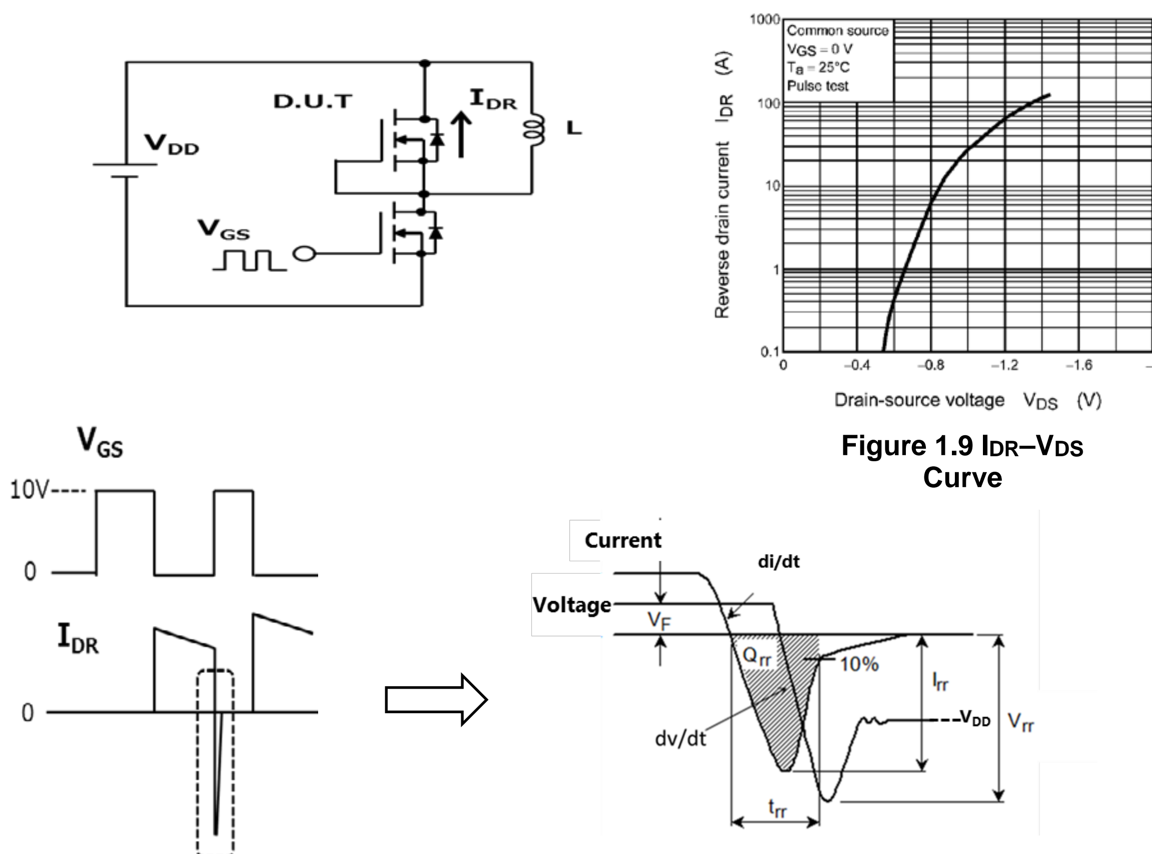
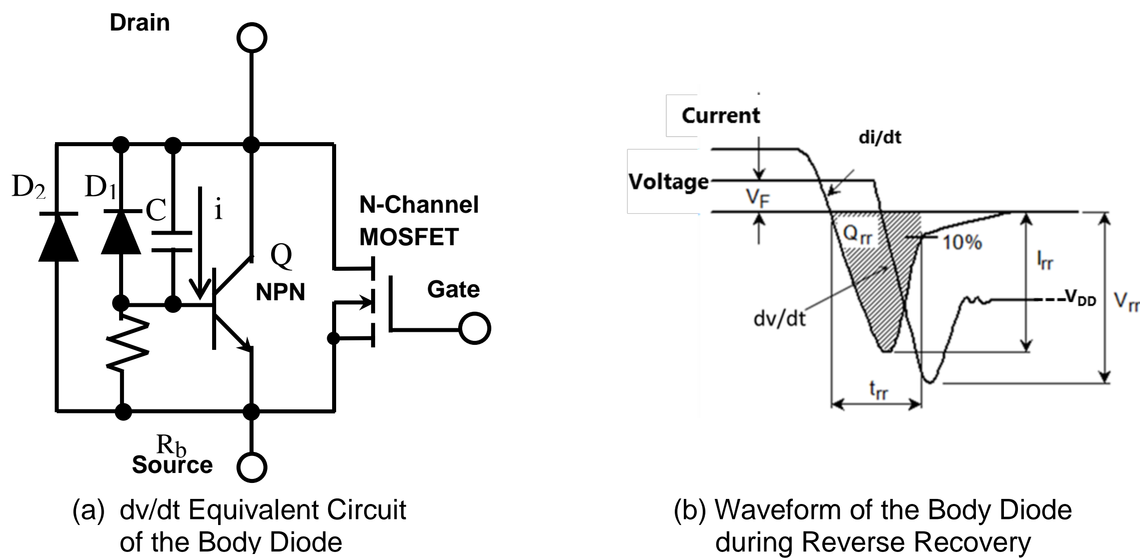


Figure 1.9 I_{DR}–V_{DS} Curve

Figure 1.8 Reverse Recovery Time of the Body Diode in a Power MOSFET

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·(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.



(a) dv/dt Equivalent Circuit of the Body Diode

(b) Waveform of the Body Diode during Reverse Recovery

Figure 1.10 Equivalent Circuit and Reverse Recovery Waveform of the Body Diode

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