AN-9010
MOSFET Basics

Summary
The Bipolar Power Transistor (BPT), as a switching device for power applications, had a few disadvantages. This led to the development of the power Metal Oxide Semiconductor Field Effect Transistor (MOSFET). The power MOSFET is used in applications such as Switched Mode Power Supplies (SMPS), computer peripherals, automotive, and motor control. Continuous research has improved its characteristics for replacing the BJT. This application note is a general description of power MOSFETs and a presentation of some of Fairchild’s product specifications.

History
The theory behind the Field Effect Transistor (FET) has been known since 1920–1930, which is 20 years before the bipolar junction transistor was invented. At that time, J.E. Lilienfeld of the USA suggested a transistor model having two metal contacts on each side with a metallic plate (aluminum) on top of the semiconductor. The electric field at the semiconductor surface, formed by the voltage supplied at the metallic plate, enables the control of the current flow between the metal contacts. This was the initial concept of the FET. Due to lack of appropriate semiconductor materials and immature technology, development was very slow. William Shockely introduced Junction Field Effect Transistors (JFETs) in 1952. Dacey and Ross improved on it in 1953. In JFETs, Lilienfeld’s metallic field is replaced by a P-N junction, the metal contacts are called source and drain, and the field effect electrode is called a gate. Research in small-signal MOSFETs continued without any significant improvements in power MOSFET design, until new products were introduced in the 1970s.

In March of 1986, Fairchild formed with nine people and began research on power MOSFETs. 1990’s, Fairchild has developed a QFET® devices using planar technology and low-voltage PowerTrench® products using trench technology.
1. FETS

1.1. Junction Field Effect Transistors (JFETs)

There are two types of JFETs: an N-channel type and a P-channel type. They both control the drain-to-source current by the voltage supplied to the gate. As shown in Figure 1 (a), if the bias is not supplied at the gate, the current flows from the drain to the source. When the bias is supplied at the gate, the depletion region begins to grow and reduces the current, as shown in Figure 1 (b). The reason for the wider depletion region of the drain, compared to the source depletion region, is that the reverse bias of the gate and the drain, $V_{DG} (= V_{GS} + V_{DS})$, is higher than the bias between the gate and the source, $V_{GS}$.

![Figure 1. Structure of a JFET and its Operation](image)

1.2. Metal Oxide Semiconductor Field Effect Transistors (MOSFETs)

The two types of MOSFETs are depletion type and enhancement type, and each has a N/P-channel type. The depletion type is normally on and operates as a JFET (refer to Figure 2). The enhancement type is normally off, which means that the drain-to-source current increases as the voltage at the gate increases. No current flows when no voltage is supplied at the gate (refer to Figure 3).

![Figure 2. Structure of a Depletion Type MOSFET and its Operation](image)

![Figure 3. Structure of an Enhancement Type MOSFET and its Operation](image)
2. Structure of a MOSFET

2.1. Lateral Channel Design

The drain, gate, and source terminals are placed on the surface of a silicon wafer. This is suitable for integration, but not for obtaining high power ratings because the distance between source and drain must be large to obtain better voltage blocking capability. The drain-to-source current is inversely proportional to the length.

2.2. Vertical Channel Design

The drain and source are placed on the opposite sides of a wafer. This is suitable for a power device, as more space can be used as source. As the length between the source and drain is reduced, it is possible to increase the drain-to-source current rating and increase the voltage blocking capability by growing the epitaxial layer (drain drift region).

1. The VMOSFET Design: the first to be commercialized, this design was has a V-groove at the gate region, as shown in Figure 4 (a). Due to stability problems in manufacturing and a high electric field at the tip of the V-groove, VMOSFETs were replaced by DMOSFETs.

2. The DMOSFET Design: has a double-diffusion structure with a P-base region and a N+ source region, as shown in Figure 4 (b). It is the most commercially successful design.

3. The UMOSFET Design: As shown in Figure 4 (c), this design has a U-groove at the gate region. Higher channel density reduces the on-resistance as compared to the VMOSFETs and the DMOSFETs. UMOSFET designs with the trench etching process were commercialized in the 90’s.

Figure 4. Vertical Channel Structure
3. Characteristics of a MOSFET

3.1. Advantages

3.1.1. High Input Impedance — Voltage-Controlled Device — Easy to Drive
To maintain the on-state, a base drive current 1/5th or 1/10th of collector current is required for the current-controlled device (BJT). A larger reverse base drive current is needed for the high-speed turn-off of the current-controlled BJT. Due to these characteristics, base drive circuit design becomes complicated and expensive. On the other hand, a voltage-controlled MOSFET is a switching device driven by a channel at the semiconductor’s surface due to the field effect produced by the voltage applied to the gate electrode, which is isolated from the semiconductor surface. Because the required gate current during switching transient, as well as the on and off states, is small; the drive circuit design is simpler and less expensive.

3.1.2. UniPolar Device — Majority Carrier Device — Fast Switching Speed
As there are no delays due to storage and recombination of the minority carrier, as in the BJT, the switching speed is faster than the BJT by orders of magnitude. Therefore, it has an advantage in a high-frequency operation circuit where switching power loss is prevalent.

3.1.3. Wide Safe Operating Area (SOA)
It has a wider SOA than the BJT because high voltage and current can be applied simultaneously for a short duration. This eliminates destructive device failure due to second breakdown.

3.1.1. Forward-Voltage Drop with Positive Temperature Coefficient — easy to use in Parallel
When the temperature increases, forward-voltage drop also increases. This causes the current to flow equally through each device when they are in parallel. Hence, the MOSFET is easier to use in parallel than the BJT, which has a forward-voltage drop with a negative temperature coefficient.

3.2. Disadvantage
In high breakdown voltage devices over 200 V, the conduction loss of a MOSFET is larger than that of a BJT, which has the same voltage and current rating due to the on-state voltage drop.

3.3. Basic Characteristic
- Vertically oriented four-layer structure (N⁺ P N⁻ N⁺)
- Parasitic BJT exists between the source and the drain. The P-type body region becomes base, the N⁺ source region becomes an emitter and the N⁻ type drain region becomes the collector (refer to Figure 5). The breakdown voltage decreases from BV_{CBO} to BV_{CEO}, which is 50 ~ 60% of BV_{CBO} when the parasitic BJT is turned on. In this state, if a drain voltage higher than BV_{CEO} is supplied, the device falls into an avalanche breakdown state. If the drain current is not limited externally, it is destroyed by the second breakdown.

The N⁺ source region and the P-type body region must be shorted by metallization to prevent the parasitic BJT from turning on.

If the V_{DS} rate of increase is large in the high speed turn-off state, there is a voltage drop between the base and the emitter, which causes the BJT to turn on. This is prevented by increasing the doping density of the P- body region, which is at the bottom of the N⁺ source region, and by lowering the MOSFETs switching speed, by designing the circuit so that the gate resistance is large. Due to the source region being short, another parasitic component, the diode, is formed. This is used in half- and full-bridge converters.

Table 1. Output Characteristic Regions

<table>
<thead>
<tr>
<th>Region</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohmic Region</td>
<td>A constant resistance region. If the drain-to-source voltage is zero, the drain current also becomes zero regardless of gate-to-source voltage. This region is at the left side of the V_{GS} = V_{GS(th)} = V_{DS} boundary line (V_{GS} = V_{GS(th)} &gt; V_{DS} &gt; 0). Even if the drain current is very large, in this region the power dissipation is maintained by minimizing V_{DS(on)}.</td>
</tr>
<tr>
<td>Saturation Region</td>
<td>A constant-current region. It is at the right side of the V_{GS} = V_{GS(th)} = V_{DS} boundary line. Here, the drain current differs by the gate-to-source voltage, and not by the drain-to-source voltage. Hence, the drain current is called saturated.</td>
</tr>
<tr>
<td>Cut-Off Region</td>
<td>Called the cut-off region because the gate-to-source voltage is lower than the V_{GS(th)} (threshold voltage).</td>
</tr>
</tbody>
</table>
3.4.1. Transfer Characteristics

$i_D$ characteristics due to $V_{GS}$ in the active region (refer to Figure 7).

$I_D$ equation due to $V_{GS}$:

$$i_D = K (V_{GS} - V_{GS(th)})^2$$

$$K = \mu_n C_{OX} \frac{W}{2L}$$

where:

$\mu_n$: majority-carrier mobility;

$C_{OX}$: gate oxide capacitance per unit area;

$C_{OX} = \varepsilon_{OX}/t_{OX}$;

$\varepsilon_{OX}$: dielectric constant of the silicon dioxide;

$t_{OX}$: thickness of the gate oxide;

$W$: channel width; and

$L$: channel length.

A parabolic transfer curve exists in a logic-level device according to Equation 1. In a power MOSFET, this is true only in the low $I_D$ of the transfer curve and the other areas show linearity. This is because the mobility of the carrier is not constant, but decreases due to the increase of the electric field along with the increase of $I_D$ at the inverse layer.
4. Characteristics of MOSFETs in ON and OFF STATE

4.1. OFF State

4.1.1. $BVDSS$
This is the maximum drain-to-source voltage the MOSFET can endure without the avalanche breakdown of the body-drain P-N junction in off state (where the gate and source are shorted). The measurement conditions are $V_{GS} = 0 \, \text{V}$, $I_D = 250 \, \mu\text{A}$, and the drift region’s (N’ epitaxy) length is determined by the $BVDSS$. Avalanche, reach-through, punch-through, Zener, and dielectric breakdowns are the factors that drive breakdown. Three of these factors are described below:

**Avalanche Breakdown:**
The mobile carriers’ sudden avalanche breakdown caused by the increasing electric field in the depletion region of the body-drain P-N junction up to a critical value. It is the main factor among others that drives breakdown.

**Reach-Through Breakdown:**
A special case of avalanche breakdown occurring when the depletion region of the N’ epitaxy contacts the N+ substrate.

**Punch-Through Breakdown:**
An avalanche breakdown occurring when the depletion region of the body-drain junction contacts the N+ source region.

4.1.2. $I_{DSS}$
The drain-to-source leakage current when it is an off state where the gate is being shorted with the source. The increase in $I_{DSS}$, which is sensitive to temperature, is large with the increase in temperature, while the increase in $BVDSS$ is very little.

4.2. Turn-On Transient

4.2.1. Process of Channel Formation

**Formation of the depletion region:**
When a small positive gate-to-source voltage is supplied to the gate electrode (*refer to Figure 8 (a))*.

A positive charge induced in the gate electrode induces the same amount of negative charge at the oxide – silicon interface (P-body region, which is underneath the gate oxide). The holes are pushed into the semiconductor bulk by an electric field and the depletion region is formed by the acceptors with a negative charge.

**Formation of the inversion layer:**
As the positive gate-to-source voltage increases (*refer to Figure 8 (b) and Figure 8 (c))*), the depletion region becomes wider towards the body and begins to drag the free electrons to the interface. These free electrons are created by thermal ionization. The free holes, created with free electrons, are pushed into the semiconductor bulk. The holes that have not been pushed into the bulk are neutralized by the electrons that have been dragged by the positive charge of the holes from the N’ source. If the supplied voltage keeps increasing, the density of the free holes of the body and the free electrons of the interface becomes equal. At this point, the free electron layer is called an inversion layer. The inversion layer enables the current flow by becoming the conductive pass (=channel) of the MOSFETs drain and source.

**Threshold Voltage:**
The gate-to-source voltage, which forms the inverse layer, is called $V_{GS(th)}$ (=threshold voltage).

![Figure 8. Process of Channel Formation](image)
4.3. ON State

Drain current (\(I_D\)) changes due to the increase in drain-to-source voltage (\(V_{DS}\)) (\(V_{GS}\) is constant). \(I_D\) starts to flow when the channel has formed and \(V_{DS}\) is supplied. When the \(V_{GS}\) is a constant value and the \(V_{DS}\) is increased, the \(I_D\) also increases linearly. As shown in the MOSFET output characteristics graph, when the real \(V_{DS}\) goes over a certain level, the rate of increase in \(I_D\) decreases slowly. Eventually, it becomes a constant value independent of \(V_{DS}\) and becomes dependent on \(V_{GS}\).

To understand the characteristics, shown in Figure 9, note the voltage drop at \(V_{CS}(x)\) due to ohmic resistance when \(I_D\) is flowing at the inverse layer. \(V_{CS}(x)\) is the channel-to-source voltage from the source at a distance of \(x\). This voltage is equal to the \(V_{GS} - V_{ox(x)}\) at all \(x\) points. \(V_{ox(x)}\) is the gate-to-body voltage crossing the gate oxide from the source at a distance of \(x\) and it has the maximum value at \(V_{DS}\) at \(x=L\) (the drain end of the channel). As shown in Figure 9(a), when low voltage \(V_{DD}=V_{DD1}\) is supplied, low \(I_D(=I_{D1})\), which has almost no voltage drop of \(V_{CS}(x)\), flows. As \(V_{ox(0)}\)~\(V_{ox(L)}\) is constant, the thickness of the inversion layer remains uniform. As higher \(V_{DD}\) is supplied, \(I_D\) increases, the voltage drop of \(V_{CS}(x)\) occurs, and the value of \(V_{ox(x)}\) decreases. These reduce the thickness of the inversion layer starting from \(x=L\). Because of this, the resistance increases and the graph of \(I_D\) starts to become flat, as opposed to increasing with the increment of \(V_{DD}\). When \(V_{ox(L)}=V_{GS}-V_{DS}=V_{GS(th)}\) as \(I_D\) increases, the inversion layer at \(x=L\) doesn’t disappear due to the high electric field \((J=\sigma E)\) formed by the reduction in thickness, and maintains the minimum thickness. The high electric field not only maintains the minimum thickness of the inversion layer, it also saturates the velocity of the charge carrier at \(V_{ox(L)}=V_{GS}-V_{DS}=V_{GS(th)}\).

The velocity of the charge carrier increases with the increase in the electric field initially and, at a certain point, is saturated. Silicon starts saturating when the electric field reaches \(1.5x10^4[V/cm]\) and the drift velocity of the electron is \(8x10^6[cm/s]\). At this point, the device goes into the active region. When a higher \(V_{DD}\) is supplied, as shown in Figure 9(b), the electric field at \(x=L\) increases more and the channel region that maintained the minimum thickness expands towards the source. \(V_{DS}\) becomes \(V_{DS}>V_{GS}-V_{GS(th)}\) due to the increase of \(V_{DD}\), and \(I_D\) is kept constant.

4.4. Turn-off Transient

The reverse process of the turn-on transient described above is the turn-off transient.
5. User’s Manual

5.1. Characteristics of Capacitance

The three types of parasitic capacitance are:
- Input capacitance: \( C_{iss} = C_{gd} + C_{gs} \)
- Output capacitance: \( C_{oss} = C_{gd} + C_{ds} \)
- Reverse transfer capacitance: \( C_{rss} = C_{gd} \)

The following figures show the parasitic capacitance.

5.1.1. \( C_{gs}: \) Capacitance between Gate and Source

\[
C_{gs} = C_O + C_{N^+} + C_P
\]

\( C_O \) is the capacitance between the gate and source metal:

\[
C_O = \frac{\varepsilon_I A_O}{t_O}
\]

where:
- \( \varepsilon_I \) = the dielectric constant of the intervening insulator;
- \( t_O \) = the thickness of the intervening insulator; and
- \( A_O \) = the area of the overlap between the source and gate electrode.

\( C_{N^+} \) is the capacitance between the gate and the \( N^+ \) source diffusion region:

\[
C_{N^+} = \frac{\varepsilon_{ox} A_{N^+O}}{t_{ox}} = C_{OX} A_{N^+O}
\]

where:
- \( \varepsilon_{ox} \) = the dielectric constant of the gate oxide;
- \( t_{ox} \) = the gate oxide thickness;
- \( C_{OX} \) = gate-oxide capacitance per unit area; and
- \( A_{N^+O} \) = the area of overlap of the gate electrode over the \( N^+ \) emitter.

\( C_P \) is the capacitance between the gate and p-body. It is affected by the gate, the drain voltage, and the channel length. The \( C_P \) is the only component that is influenced by the change of the drain voltage (\( V_{DS} \)) among other \( C_{gs} \) components. When \( V_{DS} \) increases, the depletion region expands to the P-body and decreases the value of \( C_P \). Even if the \( V_{DS} \) increases up to breakdown voltage, there is almost no change in the value of \( C_P \), as the depletion region doesn’t exceed 10% of the P-body. Hence, the change of \( C_{gs} \) due to \( V_{DS} \) is very small.

5.1.2. \( C_{gd}: \) Capacitance between Gate and Drain

This is influenced by the voltage of the gate and the drain. When there are variations in \( V_{DS} \), the area under \( C_{gd} \) (n-drift region meeting with the gate oxide) is changed, and the value of the capacitance is affected. As shown in Equation (2), when \( V_{DS} \gg \phi_B \), the capacitance decreases as \( V_{DS} \) increases with the relation of \( C_{gd} \propto (1 - k\sqrt{V_{DS}}) \).

\[
C_{gd}( \text{per unit area}) = C_{OX} \left(1 - \frac{2 W_{d(\text{epi})}}{X} \right)
\]

where:
- \( X \) = the length between adjoining cells;
- \( C_{OX} \) = gate-oxide capacitance per unit area;
- \( W_{d(\text{epi})} \) = the width of the depletion region in the epitaxial layer (= N-drift region); and
- \( W_{d(\text{epi})} = \sqrt{\frac{2 k_{s} \varepsilon_{o} (V_{DS} + \phi_B)}{q C_B}} \).

As \( C_{gd} \) increases \((1 + g_{ds} R_L \text{(load resistance)})\) times due to the Miller effect, it prominently decreases the frequency characteristics.

**Frequency Response of Power MOSFET**

The frequency response of the power MOSFET is limited by the charging and discharging of the input capacitance. If the \( C_{gs} \) and \( C_{gd} \), which determine the input capacitance, become smaller; it is possible to work in high frequency. As the input capacitance is unrelated to the temperature, the MOSFET’s switching speed is unrelated to the temperature.
5.1.3. C_{ds}: Capacitance between Drain and Source
The capacitance varies due to the variation of the C_{ds} thickness, which is the junction thickness of the P-body and the N' drift region, with the change of V_{DS}:

\[ C_{ds(\text{per unit area})} = \frac{q k_s \varepsilon_\text{o} C_B}{2 (V_{DS} + \phi_B)} \]

where:
- q = elementary electronic charge;
- \( (= 1.9 \times 10^{-19} \text{ [C]}) \) \( k_s \) = silicon dielectric constant;
- \( \varepsilon_\text{o} \) = the permeability of free space
  \( (8.86 \times 10^{-14} \text{ [F/cm]} \),
- \( C_B \) = epitaxial layer background concentration \( [\text{atoms/cm}^3] \);
- \( V_{DS} \) = drain-to-source voltage; and
- \( \phi_B \) = diode potential.

As shown in the equation above, \( V_{DS} >> \phi_B \) C_{ds} decreases as \( V_{DS} \) increases with the relationship of \( C_{ds} \propto \frac{1}{\sqrt{V_{DS}}} \).

5.2. Characteristics of the Gate Charge
It is the amount of charge required during MOSFET turn-on or turn-off transient.

The types of charges are:
- Total Gate Charge: \( Q_g \) (The amount of charge during \( t_0 \sim t_4 \))
- Gate-Source Charge: \( Q_{gs} \) (The amount of charge during \( t_0 \sim t_2 \))
- Gate-Drain (Miller) Charge: \( Q_{gd} \) (The amount of charge during \( t_2 \sim t_3 \))

Figure 12 shows the gate-source voltage, gate-source current, drain-source voltage, and drain-source current during turn-on. They are divided into four sections to show the equivalent circuits at the diode-clamped inductive load circuit.

![Figure 12. V_{GS}(t), I_{G}(t), V_{DS}(t), I_{D}(t) When Turned On](image)

Figure 13. Equivalent Circuits of the MOSFET with Turn-on Divided into 4 Periods at the Diode-clamped Inductive Load Circuit

5.3. Characteristics of the Gate Charge
As \( I_G \) charges \( C_{gs} \) and \( C_{gd} \), \( V_{GS} \) increases from 0 V up to \( V_{GS(th)} \). The graph of increasing \( V_{GS}(t) \) seems to be increasing linearly, but it is, in fact, an exponential curve having a time constant of \( \tau_1 = R_G(C_{gs} + C_{gd}) \). As shown in
Figure 13(a), $V_{DS}$ is still equal to $V_{DD}$ and $I_D$ is zero. The MOSFET is still in the turn-off state.

$t_1 \sim t_2$

$V_{GS}$ increases exponentially, passing $V_{GS(th)}$, and, as $V_{GS}$ continues to increase, $I_D$ begins to increase and reaches full load current ($I_O$). So $V_a$ varies to $I_O$ condition in $t_2$. When $I_D$ is smaller than $I_O$ and when it is in a state where the $D_F$ is being conducted, $V_{DS}$ maintains the $V_{DD}$. Figure 14 shows the voltage a little less than $V_{DD}$. This is caused by the voltage drop due to the existing inductance in the line.

Figure 14 shows the $V_{GS}(t)$ measuring the $V_a$ variation in accordance with $I_O$ conditions in turn-on state.

$t_2 \sim t_3$

$V_{GS}$ is a constant value in accordance with the transfer characteristics as it is in an active region where $I_O$ is the full load current ($I_O$). So, $I_O$ can only flow through $C_{gd}$ and is obtained by Equation (3).

$$i_G = \frac{V_{GG} - V_a}{R_G}$$

(3)

$V_{DS}$ can be configured as the following ratios:

$$\frac{dv_{DG}}{dt} = \frac{dv_{DS}}{dt} = \frac{i_G}{C_{gd}} = \frac{V_{GG} - V_a}{R_G C_{gd}}$$

(4)

This is the region where the MOSFET is still operating in the active region and, as the $V_{DS}$ decreases, it gets closer to the ohmic region. When $V_{DD}$ increases, $t_2 \sim t_3$ (flat region of $V_{GS}$) also increase.

Figure 15 graphs $V_{GS}(t)$ and shows the variation of $t_2 \sim t_3$ (flat region of $V_{GS}$) in accordance with the $V_{DD}$ condition.

At $t_3$, $V_{DS}$ becomes $V_{DS(on)}=I_O R_{DS(on)}$ and the transient is completed. The MOSFET is placed at the boundary of entering the ohmic region from the active region.

$t_3 \sim t_4$

$t_3 \sim t_4$ is the period where it operates in an ohmic region. The $V_{GS}$ increases up to $V_{GG}$ with a time constant of $\tau_2 = \frac{R_G C_{gd} + C_{gd}}{R_G}$.

5.3. Drain-Source On Resistance ($R_{DS(on)}$)

In a MOSFET, $R_{DS(on)}$ is the total resistance between the source and the drain during the on state. It is an important parameter, determining maximum current rating and loss. To reduce $R_{DS(on)}$, the integrity of the chip and trench technique are used. This can be stated as in Equation (5):

$$R_{DS(on)} = R_N + R_{CH} + R_A + R_J + R_D + R_S$$

(5)

where:

$R_N$ The resistance of the source region with $N^+$ diffusion. It only uses a small portion of resistance compared to other components that form $R_{DS(on)}$. It can be ignored in high-voltage power MOSFETs.

$R_{CH}$ The resistance of the channel region, which is the dominant $R_{DS(on)}$ factor in low-voltage MOSFETs. This resistance can be varied by the ratio of the channel’s width to the length, the thickness of the gate oxide, and the gate drive voltage.

$R_A$ As the gate drive voltage is supplied, charges start to accumulate in $N^+$ epi surface (the plate under $C_{gd}$) and forms a current path between the channel and the JFET region. The resistance of this accumulation region is $R_A$. The resistance varies by the change in the accumulation layer and the mobility of the free carriers at the surface. If the gate electrode is reduced, its effect is the same as reducing the length of the accumulation layer, so the value of $R_A$ is reduced while $R_J$ increases.

$R_J$ The $N^+$ epi region between the P-bodies is called the JFET region because the P-body region acts like the gate region of a JFET. The resistance of this region is $R_J$.

$R_D$ The resistance occurring from right below the P-body to the top of the substrate is $R_D$ and is the most important factor in high-voltage MOSFETs.
The resistance of the substrate region. It can be ignored in high-voltage MOSFETs. In low-voltage MOSFETs, where the breakdown voltage is below 50 V, it can have a large effect on \( R_{DS(on)} \).

Additional resistances can arise from non-ideal contact between the source/drain metal and the N+ semiconductor regions, as well as from the leads used to connect the device to the package.

\( R_{DS(on)} \) increases with the temperature (positive temperature coefficient) because the mobility of the hole and electron decreases as the temperature rises. The \( R_{DS(on)} \), at a given temperature of a P/N-channel power MOSFET can be estimated with the following equation.

\[
R_{DS(on)}(T) = R_{DS(on)}(25°C) \left( \frac{T}{300°C} \right)^{2.3}
\]

where \( T \) = absolute temperature.

This is an important characteristic of device stability and paralleling. It doesn’t need any external circuit assistance to have good current sharing when \( R_{DS(on)} \) increases with the temperature and is connected in parallel.

### 5.4. Threshold Voltage (\( V_{GS(th)} \))

This is the minimum gate bias that enables the formation of the channel between the source and the drain. The drain current increases in proportion to \( (V_{GS} - V_{GS(th)})^2 \) in the saturation region.

**High \( V_{GS(th)} \)**

It is difficult to design gate drive circuitry for the power MOSFET because a high gate bias voltage is needed to turn it on.

**Low \( V_{GS(th)} \)**

When the \( V_{GS(th)} \) of the N-channel power MOSFET becomes negative due to the existence of charges in the gate oxide, it shows the characteristics of a normally on state, where the conductive channel exists even in a zero-gate bias voltage. Even if \( V_{GS(th)} \) is positive and the value is very small, there could be a turn-on either by the noise signal of the gate terminal or by the increasing gate voltage during high-speed switching.

\( V_{GS(th)} \) can be controlled by the gate oxide thickness. Normally, gate oxide is kept thick in a high-voltage device so the \( V_{GS(th)} \) is set at 2–4 V. Gate oxide is kept thin in a low-voltage device (logic level) so \( V_{GS(th)} \) is 1–2 V. Additionally, \( V_{GS(th)} \) can be controlled by background doping (the density of P-body for the N-channel power MOSFET). It increases in proportion to the square root of the background doping.

#### 5.4.1. Temperature Characteristic

\( V_{GS(th)} \) decreases as the temperature increases. The rate of decrease can be varied by the gate oxide thickness and background doping level. In other words, the decrease rate increases when the gate oxide becomes thicker and the background doping level increases.

#### 5.5. Transconductance (\( g_{fs} \))

Transconductance is the gain in the MOSFET, expressed in Equation (7). It represents the change in drain current by the change in the gate-source bias voltage:

\[
g_{fs} = \frac{\Delta I_{DS}}{\Delta V_{GS}}
\]

\( V_{DS} \) should be set so that the device can be activated in the saturation region. \( V_{GS} \) should be supplied so that the \( I_{DS} \) becomes half of the maximum current rating. \( g_{fs} \) varies depending on the channel width/length and the gate oxide thickness. As shown in Figure 17, after \( V_{GS(th)} \) is applied, \( g_{fs} \) increases dramatically with the increase in the drain current and becomes a constant after drain current reaches a certain point (at higher values of drain current). If \( g_{fs} \) is high enough, high current handling capability can be gained from the low gate drive voltage. High-frequency response is also possible.

#### 5.5.1. Temperature Characteristic

\( g_{fs} \) decreases as the temperature increases due to the reduction of mobility. Equation (8) is similar to the \( R_{DS(on)} \) and temperature relationship; it is possible to know the \( g_{fs} \) changes by the changes in temperature:

\[
g_{fs}(T) = g_{fs}(25°C) \left( \frac{T}{300°C} \right)^{2.3}
\]

where \( T \) is absolute temperature.

#### 5.6. Drain-Source Breakdown Voltage (\( BVDSS \) Breakdown Voltage Temperature Coefficient (\( \Delta BVDSS/\Delta T \)))

\( BVDSS \) is the maximum drain-to-source voltage where the MOSFET can endure without the avalanche breakdown of the body-drain pn junction in off state (where the gate and source are shorted). The measurement conditions are \( V_{GS}=0 \) V, \( I_{DS}=250 \) \( \mu \)A, and the length of the drift region (N epitaxy) is determined by the \( BVDSS \). Avalanche, reach-through, punch-through, Zener, and dielectric breakdowns are the factors that drive breakdown.

#### 5.6.1. Temperature Characteristic

As junction temperature increases, it does so linearly. Whenever it goes up 100°C, 10% of \( BVDSS \) at 25°C increases (refer to the breakdown voltage temperature coefficient (\( \Delta BVDSS/\Delta T \)) and Figure 18 breakdown voltage vs. temperature).
5.7. Drain-to-Source Leakage Current ($I_{DSS}$)

$I_{DSS}$ can be measured by providing the maximum drain-to-source voltage and 80% of the voltage ($T_C=125^\circ \text{C}$) in the off state, where the gate is shorted to the source. $I_{DSS}$ is more sensitive to the temperature than $BVDSS$ and it has a positive temperature coefficient.

5.8. Gate-to-Source Voltage ($V_{GS}$)

$V_{GS}$ represents the maximum operating gate-to-source voltage. The negative voltage handling capability enables the enhancement of the turn-off speed by providing reverse bias to the gate and the source.

5.9. Gate-Source Leakage, Forward / Reverse ($I_{GSS}$)

$I_{GSS}$ is measured by providing the maximum operating gate-to-source voltage ($V_{GS}$) between the gate and the source. Forward or reverse direction is determined by the polarity of the $V_{GS}$. $I_{GSS}$ is dependent on the quality of the gate oxide and device size.

5.10. Switching Characteristics ($t_{d(on)}$, $t_{r}$, $t_{d(off)}$, $t_{f}$)

Power MOSFETs have good switching characteristics as there is no storage delay caused by the minority carrier and no variation caused by the temperature. Figure 19 shows the switching sequence divided into sections.

Table 2. Switching Characteristics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn-On Delay ($t_{d(on)}$):</td>
<td>This is the time for the gate voltage, $V_{GS}$, to reach the threshold voltage $V_{GS(th)}$. The input capacitance during this period is $C_{gs}+C_{gd}$. This means that this period is the charging period to bring up the capacitance to the threshold voltage.</td>
</tr>
<tr>
<td>Rise Time ($t_{r}$):</td>
<td>It is the period after the $V_{GS}$ reaches $V_{GS(th)}$ to complete the transient. It can be divided into two regions. One is the period where the drain current starts from zero (increasing with the gate voltage in accordance with the transfer characteristics) and reaching the load current. The other region is when the drain voltage starts to drop and reaches the on-state voltage drop. As shown in the gate charge characteristics graph, the $V_{GS}$ maintains a constant value as the drain current is constant in this region where the voltage decreases. During the rise time, as both the high voltage and the high current exist in the device, high power dissipation occurs. The rise time should be reduced by reducing the gate series resistance and the drain-gate capacitance ($C_{gd}$). After this, the gate voltage continues to increase up to the supplied voltage level; but, as the drain voltage and the current are already in steady state, they are not affected during this region.</td>
</tr>
<tr>
<td>Turn-Off Delay ($t_{d(off)}$):</td>
<td>The gate voltage operates in the supplied voltage level during On state and, when the turn-off transient starts, it starts to decrease. The $t_{d(off)}$ is the time for the gate voltage to reach the point where it is required to make the drain current become saturated at the value of load current. During this time, there are no changes to the drain voltage and the current.</td>
</tr>
<tr>
<td>Fall Time ($t_{f}$):</td>
<td>Fall time is the time where the gate voltage reaches the threshold voltage after $t_{d(off)}$. It is divided into the region where the drain voltage reaches the supply voltage from On-state voltage and the region where the drain current reaches zero from the load current. As there is a lot of power dissipation in the $t_{f}$ region during turn-on state, the power dissipation occurs in the $t_{f}$ region during turn-off state. Hence, $t_{f}$ must be reduced as much as possible. After this, the gate voltage continues to decrease until it reaches zero. As the drain voltage and the current are already in steady state, they are not affected during this region.</td>
</tr>
</tbody>
</table>
5.11. Single–Pulsed Avalanche Energy
Unclamped Inductive Switching (EAS)

5.11.1. MOSFET Turn-Off (Inductive Load Circuit)
While in on state (supplying positive voltage exceeding the threshold voltage in N-channel device), the electrons flow into the drain from the source through the inversion layer (=channel) of the body surface and form a current flow from the drain to the source. If it is an inductive load, this current increases linearly. To turn off the MOSFET, the gate voltage must be removed or a reverse voltage applied so that it eliminates the inversion layer of the body surface. Once the charge at the inversion layer begins to dissipate and the channel current (drain current) begins to reduce, the inductive load increases the drain voltage so that it maintains the drain current. When the drain voltage increases, the drain current is divided into the channel current and the displacement current. Displacement current is the current generated as the depletion region is developed at the drain-body diode and it is proportional to dV_DS/dt (the ratio of drain voltage rise by the time). The dV_DS/dt is limited by how fast the gate is discharged and by how fast the drain-body depletion region is charged. The charge of the drain-body depletion region is determined by C_ds and the magnitude of the drain current. When the drain voltage increases and cannot be clamped by an external circuit UIS (Unclamped Inductive Switching), the drain-body diode starts to build the current carriers through avalanche multiplication and the device falls into a Sustaining Mode. While in Sustaining Mode, all the drain current (avalanche current) goes through the drain-body diode and is controlled by the (channel current equals to zero) inductor load. If the current (leakage current, displacement current (dV_DS/dt current), and avalanche current) flowing at the body region underneath the source is large enough; the parasitic bipolar transistor becomes active and can result in device failure.

Figure 20 shows the drain voltage and the current when a single pulse (width: t_p) is supplied at the unclamped inductive load circuit.

$$E_{AS} = \frac{1}{2} L_I I_{AS}^2 \frac{BV_{DSS}}{BV_{DSS} - V_{DD}}$$

$$t_{AV} = \frac{L_I I_{AS}}{BV_{DSS}}$$

5.11.2. Power MOSFET Failure Characteristics during Inductive Turn-Off
It has the same electrical characteristics as the second breakdown of the bipolar transistor. It is independent from dV_DS/dt. By maintaining the gate turn-off voltage constantly and changing the magnitude of the external gate resistance, the magnitude of the gate turn-off current changes. This changes the dV_DS/dt. If dV_DS/dt current causes a device failure, the voltage that can lead to a second breakdown should be decreased with an increase in dV_DS/dt. When measuring the second breakdown voltage while changing the external gate resistance (changing dV_DS/dt), the highest voltage should be measured at the highest dV_DS/dt (according to “Turn-Off Failure of Power MOSFETs,” by David L. Blackburn). The voltage at which failure occurs increases with temperature. Critical current reduces as temperature increases. Critical current represents the maximum value of the drain current that can safely turn off the device in an unclamped mode. At currents exceeding this, a second breakdown occurs. It is not related to the magnitude of the load inductance. The avalanche current from the drain-body diode activates the parasitic bipolar transistor. This causes the MOSFET to fail.

5.12. Repetitive Avalanche Rating (E_{AR}, I_{AR})
E_{AR}
It represents avalanche energy for each pulse under repetitive conditions.
I_{AR}
It represents the maximum avalanche current and is the same as the I_D rating of the device.
5.13. Drain-to-Source dv/dt Ratings

When high dv/dt is supplied at the drain, there is a possibility of current conduction in the power MOSFET. In some cases, this can destroy the device. Below are some instances of device turn-on due to dv/dt.

5.13.1. Static dv/dt

Figure 21. Equivalent Circuit of a N-Channel MOSFET

False Turn-on

In off state, a sudden increase in drain voltage changes the voltage across the parasitic capacitance between the drain and the gate and develops displacement current (a) of Cdv/dt. If voltage exceeding V GS(th) develops between the gate and source due to the displacement current and the gate-to-source impedance (Zgs), it triggers a false turn-on of the MOSFET. The parasitic capacitance between the drain and gate can be Cgd or larger than Cgd, depending on the circuit layout. Zgs is the impedance of the drive circuit and can be presented as a series of R, L battery components. Due to the false turn-on, the device falls into a current-conduction state and, in severe cases, high power dissipation develops in the device and results in destructive failure. Equation (10) shows the voltage drop V GS across Zgs, and dv/dt capability in this mode:

\[
V_{GS} = Z_{gs} \cdot C_{gd} \cdot \frac{dv}{dt}
\]

Equation (10) reveals that the dv/dt capability is determined by the internal device structure. For high-dv/dt capability, the Zgs value must be small. This is achieved by increasing the doping level of the P-body region and reducing the length of the N+ emitter as much as possible. Zgs is also affected by the drain voltage. As the drain voltage increases, the depletion layer expands and enlarges the Zgs value. When the temperature rises, Zgs is increased by the reduction of mobility. As the Vbe decreases, the possibility of turn-on of the parasitic transistor increases. As the base and the emitter are shorted by the source contact, the Zgs value is very small. This occurs only if the dv/dt is enormously large.

In a false turn-on, the dv/dt can be controlled externally. In a parasitic transistor’s turn-on, the dv/dt is determined by device design. This is the difference between these modes.

5.13.2. Dynamic dv/dt

If there is a sudden current interruption, such as a clamped inductive turn-off in high-speed switching, the device is destroyed by concurrent stresses caused by high drain current, high drain-source voltage, and displacement current at the parasitic capacitance.

5.13.3. Diode Recovery dv/dt

This is the main cause of dv/dt failure in specific applications, such as circuits using a body drain diode. The datasheet gives the maximum value for dv/dt. Exceeding this value causes device failure due to excessive diode recovery dv/dt. Figure 22 shows a motor control circuit application with a diode recovery dv/dt problem.
the motor, the current flows through the parasitic diode (freewheeling diode) of Q3 as I2. The parasitic diode of Q3 falls into a forward bias state and, due to the characteristic of the diode, the minority charge begins to accumulate. When Q3 is turned on, the current again becomes I1 and the minority charge accumulated in the parasitic diode, Q3, is removed by the diode reverse-recovery current (Figure 23 section b of I3). Once the minority charge is removed to a certain level, the depletion region of the body drain diode expands and makes more reverse-recovery current (Figure 23 section b of IS). If this turns on the parasitic bipolar transistor, Q3 is destroyed. Figure 23 and Figure 24 show the diode recovery dv/dt test circuit and waveforms. From this test; dv/dt, V_DS (diode forward voltage), t_{rr} (reverse-recovery time), and Q_{rr} (reverse-recovery charge) data can be obtained. In the test, the V_DD value must be less or equal to the BV_DSS. Typically, the V_DD is set at 80% of BV_DSS and the pulse period of the driver V_{GS} must be controlled so that the I_S can become the continuous drain current I_D.

The value of di/dt and dv/dt becomes larger as R_{G} is reduced. t_{rr} can be obtained by measuring the part shown in the wave of I_S where the di/dt (measured from the point where it is 50% of I_{RM} above the ground to the point where it is 75% of I_{RM} below the ground) is 100 A/μs. Q_{rr} can be calculated as (I_{RM} x t_{rr})/2. dv/dt can be measured from the point where it is between 10–90% of V_DD with the di/dt condition (measured from the point where it is 50% of I_{RM} above the ground to the point where it is 75% of I_{RM} below the ground). I_{C} (continuous source current) and I_{SM} (pulsed – source current) represent the current rating of the source-drain diode. I_S = I_D (continuous drain current), and I_{SM} = I_{DM} (drain current – pulsed).

5.14. Thermal Characteristics (T_J, R_{\Theta_JC}, R_{\Theta-SA}, Z_{\Theta_JC}(t))

The power loss of the device turns into heat and increases the junction temperature. This degrades device characteristics and reduces its life span. It is very important to lower the junction temperature by discharging heat from the chip junction. The thermal impedance (Z_{\Theta_JC}(t)) is used to monitor the above.

Thermal characteristics terminology:
- Junction Temperature (T_J)
- Case Temperature (T_C): Temperature at a point of the package that has the semiconductor chip inside
- Heat Sink Temperature (T_S)
- Ambient Temperature (T_A): Temperature of the surrounding environment of the operating device.
- Junction-to-Case Thermal Resistance (R_{\Theta_JC})
- Case-to-Sink Thermal Resistance (R_{\Theta-CS})
- Sink-to-Ambient Thermal Resistance (R_{\Theta-SA})
As shown in Figure 25, the heat produced at the chip junction normally discharges over 80% in the direction of \( \textcircled{1} \) and about 20% in the direction of \( \textcircled{2}\textcircled{3}\textcircled{4} \). The path of the thermal discharge is the same as the movement of the current and is represented in Figure 26 after considering thermal resistance. This is true only for DC operation. Most MOSFETs are used in switching operations with a fixed duty factor. Thermal capacitance should be taken into consideration, along with thermal resistance. The thermal resistance from the chip junction to the ambient is \( R_{\theta JA} \) (junction-to-ambient thermal resistance) and the equivalent circuit can be expressed as Equation (12).

\[
R_{\theta JA} = R_{\theta JC} + R_{\theta CS} + R_{\theta SA} \quad (12)
\]

**Junction-to-Case Thermal Resistance (R\(_{\theta JC}\))**

\( R_{\theta JC} \) is the internal thermal resistance from the chip junction to the package case. Once the size of the die is decided, this thermal resistance of pure package is only determined by the package design and lead frame material. \( R_{\theta JC} \) can be measured under the condition of \( T_C = 25^\circ C \) and can be written as Equation (13):

\[
R_{\theta JC} = \frac{T_J - T_C}{P_D} \quad [^\circ C/W] \quad (13)
\]

Condition \( T_C = 25^\circ C \) means the infinite heat sink is mounted.

Infinite heat sink means the case temperature of the package is equal to the environment temperature. It is the heat sink, which can realize \( T_C = T_A \).

**Case-to-Sink Thermal Resistance (R\(_{\theta CS}\))**

This is the thermal resistance from the package case to the heat sink. It can vary due to the package and the mounting method to the heat sink.

**Sink-to-Ambient Thermal Resistance (R\(_{\theta SA}\))**

This is the thermal resistance from the heat sink to the ambient and it is determined by heatsink design.

### 5.14.1. Thermal Response Characteristics

Figure 27 shows the thermal response curve. As shown in Figure 27, the graph of the thermal response, shows the change of junction-to-case thermal impedance \( Z_{\theta JC(t)} \) due to the change of the square-wave pulse duration with a few duty factor conditions. \( Z_{\theta JC(t)} \) determines the junction temperature rise with the equation (14). (considering power dissipation to be a constant value \( (P_D) \) during the conduction period, it becomes saturated to the maximum value of \( R_{\theta JC} \) as it reaches low frequency or DC operation where the duty factor \( D=1 \). Figure 28 shows the junction temperature rise with the increasing duty factor.

\[
T_{J_{\text{max}}} - T_C = R_{dJC} \cdot P_{DM} \quad (14)
\]

A single-pulse curve determines the thermal resistance for repetitive power pulses having a constant duty factor \( D \), as shown in equation (15).

\[
Z_{\theta JC}(t) = R_{\theta JC} \cdot D + (1-D) \cdot S_{\theta JC}(t) \quad (15)
\]

where:

\( Z_{\theta JC}(t) \) is the thermal impedance for repetitive power pulses with a duty factor of \( D \);

\( S_{\theta JC}(t) \) is the thermal impedance for a single pulse;

\( I_D \) is continuous drain current; and

\( I_{DM} \) is drain current, pulsed.

As shown in Equation (16), the \( I_D \) rating is determined by the heat removal ability of the device. Figure 10 in the datasheet, maximum drain current vs. case temperature, shows increasing permissible \( I_D \) as \( T_C \) decreases.

\[
I_D(T_C) = \frac{T_{J_{\text{max}}} - T_C}{R_{DS(on)}(T_{J_{\text{max}}}) \cdot R_{\theta JC}} \quad (16)
\]

where:

\( R_{DS(on)}(T_{J_{\text{max}}}) \) is the maximum value of on-resistance in an appropriate drain current condition (\( \frac{1}{2} \cdot I_D \) in datasheet) at \( T_{J_{\text{max}}} \), as maximum \( R_{DS(on)} \) specified is at \( T_C = 25^\circ C \).
R\textsubscript{DS(on)} (T\textsubscript{J\textsubscript{max}}) could be analogized by the graph of on-resistance vs. temperature;

R\textsubscript{\Theta JC} is maximum junction-to-case thermal resistance; and

T\textsubscript{C} is case temperature.

In real device applications where it is not feasible to maintain the temperature at T\textsubscript{C}=25°C, the I\textsubscript{D} (60~70% of I\textsubscript{D} at T\textsubscript{C}=25°C) at T\textsubscript{C}=100°C is a more usable specification.

5.14.2. Drain Current - Pulsed (I\textsubscript{DM})

The drain current over continuous drain current rating should not go over the maximum junction temperature. The maximum upper limit is I\textsubscript{DM}. I\textsubscript{DM} is about four times the value of I\textsubscript{D}, as shown in equation (17).

\[ I_{DM} = I_D (T_C = 25^\circ C) \times 4 \]  

(17)

Repetitive rating: Pulse width limited by maximum junction temperature

5.15. Total Power Dissipation (P\textsubscript{D}), Linear Derating Factor

\[ P_D(T_C) = I_D^2 (T_C) \cdot R_{DS(on)}(T_J max) = \frac{T_{J max} - T_C}{R_{\Theta JC}} \]  

(18)

Linear derating factor is calculated by:

\[ \frac{I}{R_{\Theta JC}} \]  

(19)

5.16. Safe Operating Areas (SOA)

5.16.1. SOA (FBSOA)

It defines the maximum value of the drain-source voltage and drain current that guarantees safe operation when the device is at the forward bias.

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