Applications for Depletion MOSFET

Pradeep Kumar Tamma

Application Note

About this document

Scope and purpose
Depletion MOSFETs, unlike Enhancement MOSFETs, are in an On-state even at 0 V of gate to source voltage ($V_{GS}$). This feature makes them suitable for using as a constant current source as well as in other ways. This application note explains how Depletion MOSFETs can be used in different applications.

Intended audience
This document is intended for SMPS or LED driver designers, as an introduction to Depletion MOSFET and highlighting the advantages.

Table of Contents

1 What is a Depletion MOSFET? ........................................................................................................2
2 Linear mode operation of a Depletion MOSFET ...........................................................................3
3 Application Examples ....................................................................................................................5
  3.1 Start-up circuit for SMPS ........................................................................................................5
  3.2 Linear regulators ....................................................................................................................8
    3.2.1 Examples .........................................................................................................................9
  3.3 Other examples .....................................................................................................................10
4 Depletion MOSFETs from Infineon ..............................................................................................11
Applications for Depletion MOSFET

What is a Depletion MOSFET?

1 What is a Depletion MOSFET?

As Depletion MOSFETs are in the on-state, they operate as an ON switch even when the gate to source voltage ($V_{GS}$) is zero. This can be best shown by comparing the transfer characteristics of both Enhancement and Depletion MOSFETs.

![Figure 1: Transfer Characteristics of Enhancement and Depletion MOSFETs](image)

Figure 1 above illustrates an example of the transfer characteristics of both devices. For a MOSFET, the gate to source voltage ($V_{GS}$) should be greater than the gate to source threshold voltage ($V_{GS(th)}$) in order to conduct current through it. For an N-channel Enhancement MOSFET $V_{GS(th)}$ is greater than 0 V. Therefore, even at $V_{GS}$ of 0 V, a Depletion MOSFET conducts current. To turn off a Depletion MOSFET the $V_{GS}$ should be less than the $V_{GS(th)}$ which is a negative. This is clearly shown in schematic symbols of both. Figure 2 below shows the schematic symbols for Enhancement and Depletion MOSFETs respectively.

![Figure 2: Schematic symbols](image)

In the symbols there is a clear difference in the second vertical line from the left. For the Enhancement MOSFET this line is discontinuous which mean that the MOSFET is in an off state at zero gate voltage. With the Depletion MOSFET, as it is in an on-state at zero gate voltage, the second vertical line is a solid continuous one.
Applications for Depletion MOSFET

Linear mode operation of a Depletion MOSFET

2 Linear mode operation of a Depletion MOSFET

In the previous section, how a Depletion MOSFET conducts at zero gate to source voltage and how it can be turned off was described. Now it will be discussed how a Depletion MOSFET can be used in a circuit.

Figure 3 below illustrates a simple Depletion MOSFET circuit. Initially the voltage across the resistor R1 is 0 V, therefore, the gate to source voltage of Q₁ is 0 V. As stated in the previous section, at zero gate to source voltage there will be current flowing through the MOSFET. Thus, when Vᵢₙ is applied there will be a current (I₀) flowing in the circuit. Due to this current, there will be a voltage drop across the resistor R1 which in turn reduces the gate to source voltage of Q₁. The value is given by equation 1 below:

\[ V_{GS} = -I_D \times R1 \]  

Figure 3 Simple circuit using a Depletion MOSFET and a resistor

As the gate to source voltage (Vᵢₙ) is reduced to a negative, the current through Q₁ decreases (from Figure 1). The current through Q₁ is given by equation 2 below:

\[ I_D = I_{DSS} \left(1 - \frac{V_{GS}}{V_{GS(th)}} \right)^2 \]  

With:
- I_{DSS} = on-state drain current at V_{GS} = 0 V
- V_{GS(th)} = threshold voltage of the MOSFET

The drain to source voltage is:

\[ V_{DS} = V_{IN} - (I_D \times (R1 + R2)) \]  

At lower V_{DS}, Q₁ will be in the resistive mode of operation so the drain current ID of Q₁ depends upon the R_{DS(on)} and V_{DS} of Q₁. Thus the equation (2) will no longer be valid. But at higher V_{DS} the MOSFET will be in linear mode region. In this mode the drain current gets saturated and does not depend on V_{DS} which means equation (2) is valid here. For a MOSFET to be in linear mode V_{DS} should be greater than or equal to 2sqrt(I₀R_{DS(on)}).

Therefore in the circuit (shown in Figure 3), when Q₁ is in linear mode the current I₀ is independent of the V_{DS}. Thus, a Depletion MOSFET in series with a resistor can be used as a constant current source whose current value is independent of the drain to source voltage. As mentioned previously, the V_{GS} of Q₁ in the circuit is
Linear mode operation of a Depletion MOSFET

less than 0 V. For example, Figure 4 below shows the typical output characteristics of BSP179 and the red dotted line is the constant current operating region for a respective $V_{DS}$.

The current through MOSFET $Q_1$ depends on the gate to source voltage and this in turn depends upon the series resistance $R_1$. Thus for a required current through $Q_1$, $R_1$ can be calculated using the formula below.

$$ R_1 = \frac{V_{GS(th)}}{I_D} \left( \sqrt{\frac{I_D}{I_{DSS}}} - 1 \right) $$  \hspace{1cm} (4)

$V_{GS(th)}$ is the gate threshold voltage of the MOSFET, $I_{DSS}$ is the on current at $V_{GS} = 0$ V and $I_D$ is the required current.

![Output characteristics of a Depletion MOSFET](image)

Figure 4  Output characteristics of a Depletion MOSFET
3 Application Examples

3.1 Start-up circuit for SMPS

A major application where a Depletion MOSFET can be used is the start-up circuit for switch mode power supplies (SMPS).

![Start-up circuit for SMPS](image)

Commonly used low voltage bipolar or CMOS PWM ICs usually operate from supply voltages of up to 18 V. When the input power for the converter is available at voltages higher than the maximum voltage rating of the IC, the voltage has to be reduced with a start-up circuit. A frequent requirement is for operation directly from a rectified 120 VAC or 230 VAC line without the use of tap changing switches for the selection of different voltages. Figure 5 shows a starting circuit using a Depletion MOSFET, a resistor and a zener diode.

Depletion MOSFET Q1 is configured as a source follower. Being a Depletion MOSFET, Q1 is in the on-state when there is 0 V VGS. When power is available at the input, Q1 supplies current to charge up the capacitor C1 through the external source resistor R1. Therefore, the voltage across the capacitor (VCC) starts increasing.

Figure 6 shows the start-up current (Ist) and voltage wave forms of a typical PWM IC. As VCC reaches VCC,ON, it allows the PWM IC to start PWM pulses to primary MOSFET Q2. As a result the auxiliary voltage (Vaux) from the auxiliary winding starts building up. During this time the power required by the IC is supplied by the capacitor C1. Once Vaux is up, it turns off Q1 and the IC’s power is delivered only by the auxiliary winding. The condition for Vaux to turn off Q1 is

\[ V_{\text{aux}} \geq V_{\text{gs(th)},\text{min}} + V_Z + 0.7V \]  

The time taken to reach VCC,ON across the capacitor is given by equation (6) below.

\[ t_{\text{stc}} = C1 \times \frac{V_{\text{cc,ON}}}{I_D - I_{st}} \]  

Ist is the required current though Q1. From section 2 it is clear that when the Depletion MOSFET has high VDS and the VGS is ≤ 0V, the MOSFET operates in linear mode. Here current Ist does not depend on VDS and remains constant, therefore tstc and the start-up time for the SMPS are always constant.
For example, consider a PWM IC with electrical parameters as stated in Table 1 below:

<table>
<thead>
<tr>
<th>Table 1</th>
<th>PWM IC electrical parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>PWM IC</td>
<td>300</td>
</tr>
</tbody>
</table>

Assume that \( C_1 \) is equal to 10 \( \mu F \), \( V_{IN} = 340 \text{ V} \). A reasonable start-up time \( t_{stc} \) is 500 ms, so by reconfiguring the equation (5) the drain current \( I_D \) is

\[
I_D = C_1 \cdot \frac{V_{CC,ON}}{t_{stc}} + I_{st} = 10 \mu \text{A} \cdot \frac{15 V}{500 \text{ ms}} + 300 \mu \text{A} = 600 \mu \text{A}
\]

(7)

This current is constant irrespective of \( V_{IN} \). Therefore, the start-up time \( t_{stc} \) is constant even for a wide range of input (90 to 240 \( V_{AC} \)). This is not the case with resistive solutions. For the above same example with a start-up time of 500 ms the current in the resistor will be the same as the drain current 600 \( \mu \text{A} \). So at 340 V of \( V_{IN} \) the start-up resistor value can be calculated.

\[
R_{\text{start-up}} = \frac{V_{IN}}{I_D} = \frac{340 V}{600 \mu \text{A}} \approx 570 \text{ k}\Omega
\]

(8)

But for a wide input range the start-up time will no longer be a constant in the resistor solution. Figure 7 shows the variations of start-up time with input voltage.
Therefore, using a Depletion MOSFET as a start-up circuit has the greater benefit of keeping the start-up time constant irrespective of the input voltage. Table 2 shows the basic electrical parameters of the Infineon Depletion MOSFET BSS126.

### Table 2  
**BSS126 Electrical parameters**

<table>
<thead>
<tr>
<th>Part Number</th>
<th>$BV_{DSS}$ [V]</th>
<th>$V_{GS(th),min}$ [V]</th>
<th>$V_{GS(th),typ}$ [V]</th>
<th>$V_{GS(th),max}$ [V]</th>
<th>$I_{DSS,min}$ @ $V_{GS}=0$ [mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSS126</td>
<td>600</td>
<td>-2.7</td>
<td>-2.0</td>
<td>-1.6</td>
<td>7</td>
</tr>
</tbody>
</table>

After the PWM IC is up and running, the only current drawn by $Q_1$ is a small amount of drain to source leakage current which is typically less than 100µA.

The power dissipation of $Q_1$ during start-up time is given by:

$$P_d = (V_{IN} - V_{CC,ON}) \times (I_D)$$

(9)

Since $Q_1$ conducts only for a short duration, the maximum chip temperature rise is minimal. The power dissipation in BSS126 is:

$$P_d = (V_{IN} - V_{CC,ON}) \times (I_D) = (340 V - 15 V) \times 600\mu = 0.195 W$$

Thus the chip temperature rise is given by:

$$\Delta T_J = P_d \times Z_{thJA} @ \text{Single pulse @ tstc}$$

(10)

$Z_{thJA}$ is the maximum transient thermal impedance of BSS126. Since the MOSFET conducts only at the start-up time of the SMPS, it is considered that the power dissipation is a single pulse event. 

Figure 8 shows $Z_{thJA}$ for a single pulse of 500ms duration as in our example is equal to 130 K/W on a standard PCB. Therefore, the maximum temperature rise of BSS126 in the application example is:
Applications for Depletion MOSFET

Application Examples

\[ \Delta T_j = 0.195 \, W \times 130 \frac{K}{W} \approx 25 \, K \]

Figure 8  BSS126 max. transient thermal impedance

3.2  Linear regulators

A Depletion MOSFET can also be used as a pass transistor for a linear regulator. Figure 9 shows a linear regulator circuit using a Depletion MOSFET and a zener diode.

In the circuit, Q1 acts as a source follower where the source voltage \( V_{cc} \) follows the gate voltage \( V_G \) minus the gate to source voltage. \( V_{GS} \) increases with increasing drain current. Thus, with a fixed gate voltage, the source voltage will drop with increasing load current. For design purposes, \( V_{GS} \) under saturation and cut-off conditions (0 V and \( V_{GS(th)} \), respectively) can be used. These values can be readily obtained from the data sheet, for example Figure 10 shows the cut-off and saturation conditions of the Infineon BSS169. Bias current for the zener diode is determined by \( V_{GS}/R1 \). The output capacitor \( C_1 \) is to compensate for the ripple at the input side. The zener diode \((Z)\) sets the gate voltage and should be selected to provide a source voltage within the range determined, taking into account the variances of \( V_{GS} \) with load. The source \( V_{cc} \) generated is approximately equal to:

\[ V_{cc} = V_Z + V_{GS} \]

Substituting \( V_{GS} \) value (from equation (2)) in the above equation we get:

\[ V_{cc} = V_Z - \left( V_{GS(th)} \left( 1 - \sqrt{\frac{I_D}{I_{DSS}}} \right) \right) \]
Applications for Depletion MOSFET

Application Examples

Figure 9  Using a Depletion MOSFET as a voltage regulator

The power dissipation for Q1 can be calculated from the voltage drop across it times the current through it:
\[ P_{Q1} = (V_{DRAIN} - V_{SOURCE})(I_{LOAD} + I_{BIAS}) \]  
(7)

The point to be noted here, is that the MOSFET’s saturation current \( I_{DSS} \) must be greater than the load and bias currents otherwise the device can be stressed due to over current which can destroy it.

Figure 10  Cut-off conditions of BSS169

3.2.1  Examples

The above application can be explained more clearly with an example. Consider a regulator with 5 V output at 5 mA of output current from 24 V input using Infineon’s Depletion MOSFET BSS169. The important features of BSS169 are shown in the table below:

<table>
<thead>
<tr>
<th>Static characteristics</th>
<th>BV_{DSS}</th>
<th>V_{GS(th),min}</th>
<th>V_{GS(th),typ}</th>
<th>V_{GS(th),max}</th>
<th>I_{DSS,min} @V_{GS} = 0 V [mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drain-source breakdown voltage</td>
<td></td>
<td>V_{GS(th),min}</td>
<td>V_{GS(th),typ}</td>
<td>V_{GS(th),max}</td>
<td>I_{DSS,min} @V_{GS} = 0 V [mA]</td>
</tr>
<tr>
<td>Gate threshold voltage</td>
<td>V_{GS(th),min}</td>
<td>V_{GS(th),typ}</td>
<td>V_{GS(th),max}</td>
<td>I_{DSS,min} @V_{GS} = 0 V [mA]</td>
<td></td>
</tr>
</tbody>
</table>

Table 3  BSS169 Depletion MOSFET parameters

In the circuit, output current is equal to the current through the MOSFET denoted here by \( I_D \). The equation to calculate the zener voltage can be calculated from equation (12).
Due to $V_{GS(th)}$ spreading, the output voltage of the regulator varies from 4.7 V to 5.5 V. The power dissipation in BSS169 can be calculated from equation (12).

$$P_{Q1} = (V_{DRAIN} - V_{SOURCE})(I_{LOAD} + I_{BIAS})$$

$$P_{Q1} = (24 - 4.7) * (5 \times 10^{-3} + 30 \times 10^{-6}) \approx 0.1 \text{ W}$$

This is well below the specified maximum power dissipation of BSS169.

### 3.3 Other examples

A constant current source can be used in many different applications. A few examples are listed below:

- A constant current source is useful to generate a bias current that is independent of the voltage across it. It can be used to charge a capacitor at a constant rate, generating a linear ramp for timing purposes.
- A constant current source can be used as a trickle charger to maintain battery charge state.
- A constant current source can be used as a current limiter when the current is below the limit.
- A constant current source can also be used as a linear LED driver for driving LED strings typically up to 20mA. Figure 12 below shows a linear LED driver circuit using a Depletion MOSFET and a series resistor.
Depletion MOSFETs from Infineon

4 Depletion MOSFETs from Infineon

Infineon offers Depletion MOSFETs in SOT-223 and SOT-23 packages with breakdown voltages ranging from 60 V to 600 V. Table 4 shows Infineon’s Depletion MOSFET portfolio:

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Package</th>
<th>BVoss [V]</th>
<th>RDS(on) [Ω]</th>
<th>VGS(th),max [V]</th>
<th>VGS(th),min [V]</th>
<th>Ioss,min @VGS = 0V [mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSP149</td>
<td>SOT-223</td>
<td>200</td>
<td>1.8</td>
<td>-1</td>
<td>-2.1</td>
<td>140</td>
</tr>
<tr>
<td>BSP129</td>
<td>SOT-223</td>
<td>240</td>
<td>6</td>
<td>-1</td>
<td>-2.1</td>
<td>55</td>
</tr>
<tr>
<td>BSP179</td>
<td>SOT-223</td>
<td>400</td>
<td>24</td>
<td>-1</td>
<td>-2.1</td>
<td>20</td>
</tr>
<tr>
<td>BSP135</td>
<td>SOT-223</td>
<td>600</td>
<td>45</td>
<td>-1</td>
<td>-2.1</td>
<td>20</td>
</tr>
<tr>
<td>BSS159N</td>
<td>SOT-23</td>
<td>60</td>
<td>3.5</td>
<td>-2.4</td>
<td>-3.5</td>
<td>130</td>
</tr>
<tr>
<td>BSS169</td>
<td>SOT-23</td>
<td>100</td>
<td>6</td>
<td>-1.8</td>
<td>-2.9</td>
<td>90</td>
</tr>
<tr>
<td>BSS139</td>
<td>SOT-23</td>
<td>250</td>
<td>14</td>
<td>-1</td>
<td>-2.1</td>
<td>30</td>
</tr>
<tr>
<td>BSS126</td>
<td>SOT-23</td>
<td>600</td>
<td>7</td>
<td>-1.6</td>
<td>-2.7</td>
<td>7</td>
</tr>
</tbody>
</table>

For Infineon’s Depletion MOSFETs VGS(th) is spread across 5 bands. Each band has a distribution of 0.2 V and is assigned with an identification letter. Limits for each device vary from VGS(th),min to VGS(th),max. Figure 12 shows an example of VGS(th) bands of BSP149.

<table>
<thead>
<tr>
<th>Threshold voltage VGS(th) sorted in bands2</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
</tr>
<tr>
<td>K</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>M</td>
</tr>
<tr>
<td>N</td>
</tr>
</tbody>
</table>

Figure 12 Threshold voltage bands

Please note - a single specific band cannot be ordered separately. However, it can be requested that each reel contains only one band of VGS(th).
Applications for Depletion MOSFET

Depletion MOSFETs from Infineon

Revision History

Major changes since the last revision

<table>
<thead>
<tr>
<th>Page or Reference</th>
<th>Description of change</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>First Release</td>
</tr>
</tbody>
</table>