Applications for Depletion MOSFET

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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?

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.

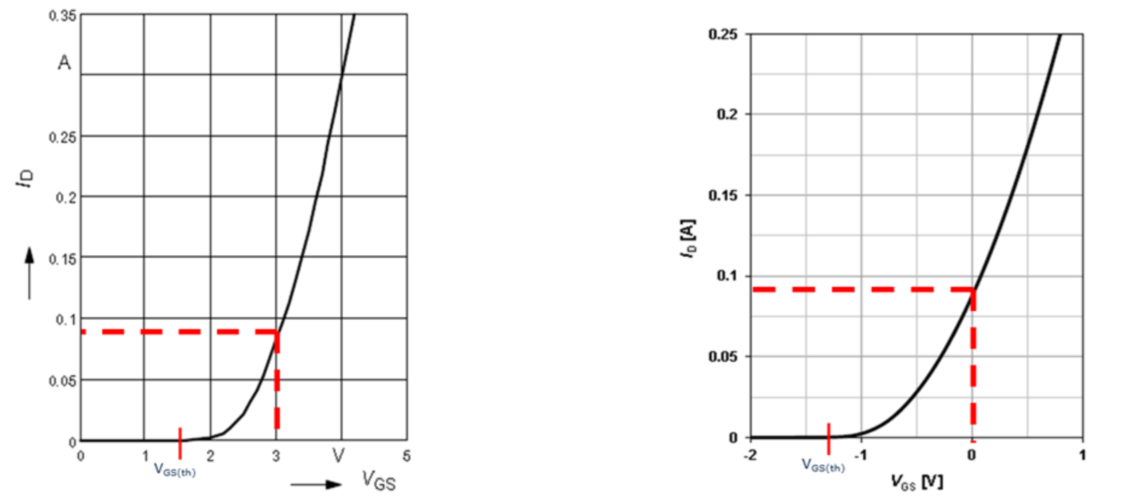

Figure 1 Transfer Charateristics of Enhancement and Depletion MOSFETs

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.

(a) Enhancemnet MOSFET (b) Depletion MOSFET

Figure 2 Schematic symbols

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.

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 Q_1 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 V_{IN} is applied there will be a current (I_D) 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 Q_1. The value is given by equation 1 below:

$$V_{\mathrm{GS}} = -I_{\mathrm{D}} * R1 \tag{1}$$

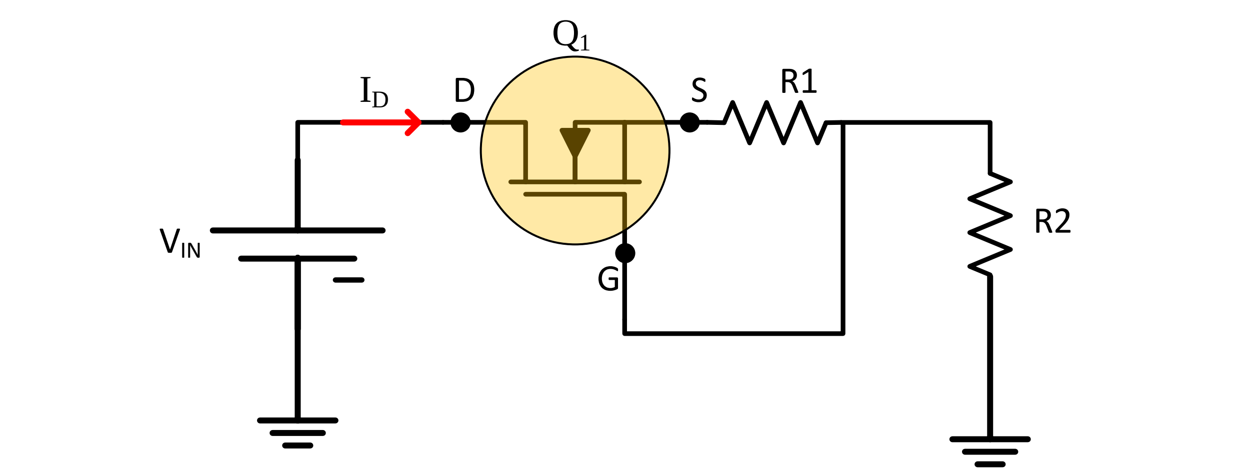

Figure 3 Simple circuit using a Depletion MOSFET and a resistor

As the gate to source voltage (V_{GS}) is reduced to a negative, the current through Q_1 decreases (from Figure 1). The current through Q_1 is given by equation 2 below:

$$I_{\mathrm{D}} = I_{\mathrm{DSS}}\left(1 - \frac{V_{\mathrm{GS}}}{V_{\mathrm{GS(th)}}}\right)^2 \tag{2}$$

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:

$$V_{DS} = VIN - (I_D * (R1 + R2)) \tag{3}$$

At lower V_{DS}, Q_1 will be in the resistive mode of operation so the drain current ID of Q_1 depends upon the $R_{DS(on)}$ and V_{DS} of Q_1. 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 $2*I_D*R_{DS(on)}$.

Therefore in the circuit (shown in Figure 3), when Q_1 is in linear mode the current I_D 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 Q_1 in the circuit is less than 0 V. For example, Figure 4 below shows the typical output charateristics 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 R1. Thus for a required current through Q_1, R1 can be calculated using the formula below.

$$R1 = \frac{V_{GS(th)}}{I_D}\left(\sqrt{\frac{I_D}{I_{DSS}}} - 1\right) \quad (4)$$

$V_{GS(th)}$ 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.

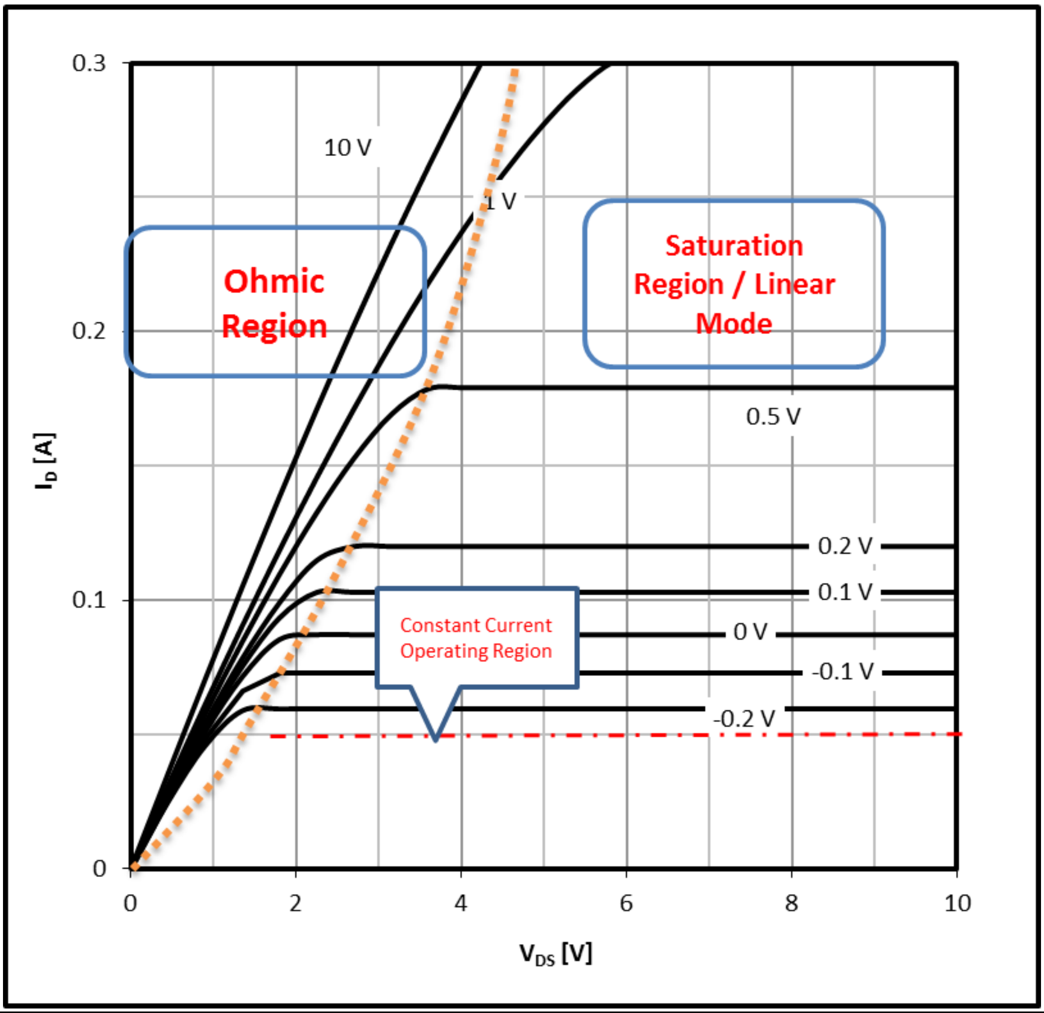

Figure 4 Output charateristics of a Depletion MOSFET

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).

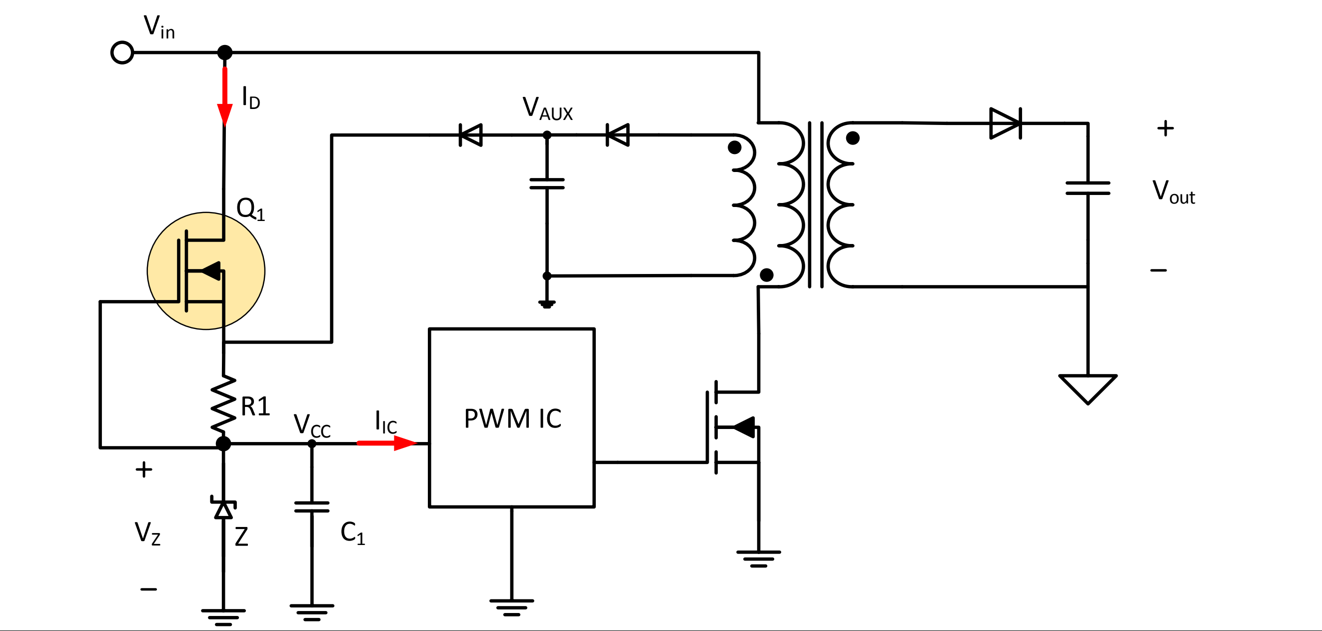

Figure 5 Start-up circuit for SMPS

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 V_{AC} or 230 V $_{AC}$ 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 Q_1 is configured as a source follower. Being a Depletion MOSFET, Q_1 is in the on-state when there is 0 V V_{GS}. When power is available at the input, Q_1 supplies current to charge up the capacitor C_1 through the external source resistor R1. Therefore, the voltage across the capacitor (V_{CC}) starts increasing.

Figure 6 shows the start-up current (I_{st}) and voltage wave forms of a typical PWM IC. As V_{CC} reaches $V_{CC,ON}$, it allows the PWM IC to start PWM pulses to primary MOSFET Q_2. As a result the auxiliary voltage (V_{AUX}) from the auxiliary winding starts building up. During this time the power required by the IC is supplied by the capacitor C_1. Once V_{AUX} is up, it turns off Q_1 and the IC's power is delivered only by the auxiliary winding. The condition for V_{AUX} to turn off Q_1 is

$$V_{\mathrm{AUX}} \geq V_{GS(th),min} + V_{\mathrm{Z}} + 0.7\ V \tag{5}$$

The time taken to reach $V_{CC,ON}$ across the capacitor is given by equation (6) below.

$$t_{stc} = \mathrm{C1} * \frac{V_{CC,ON}}{I_D - I_{st}} \tag{6}$$

I_D is the required current though Q_1. From section 2 it is clear that when the Depletion MOSFET has high V_{DS} and the V_{GS} is ≤ 0V, the MOSFET operates in linear mode. Here current I_D does not depend on V_{DS} and remains constant, therefore t_{stc} and the start-up time for the SMPS are always constant.

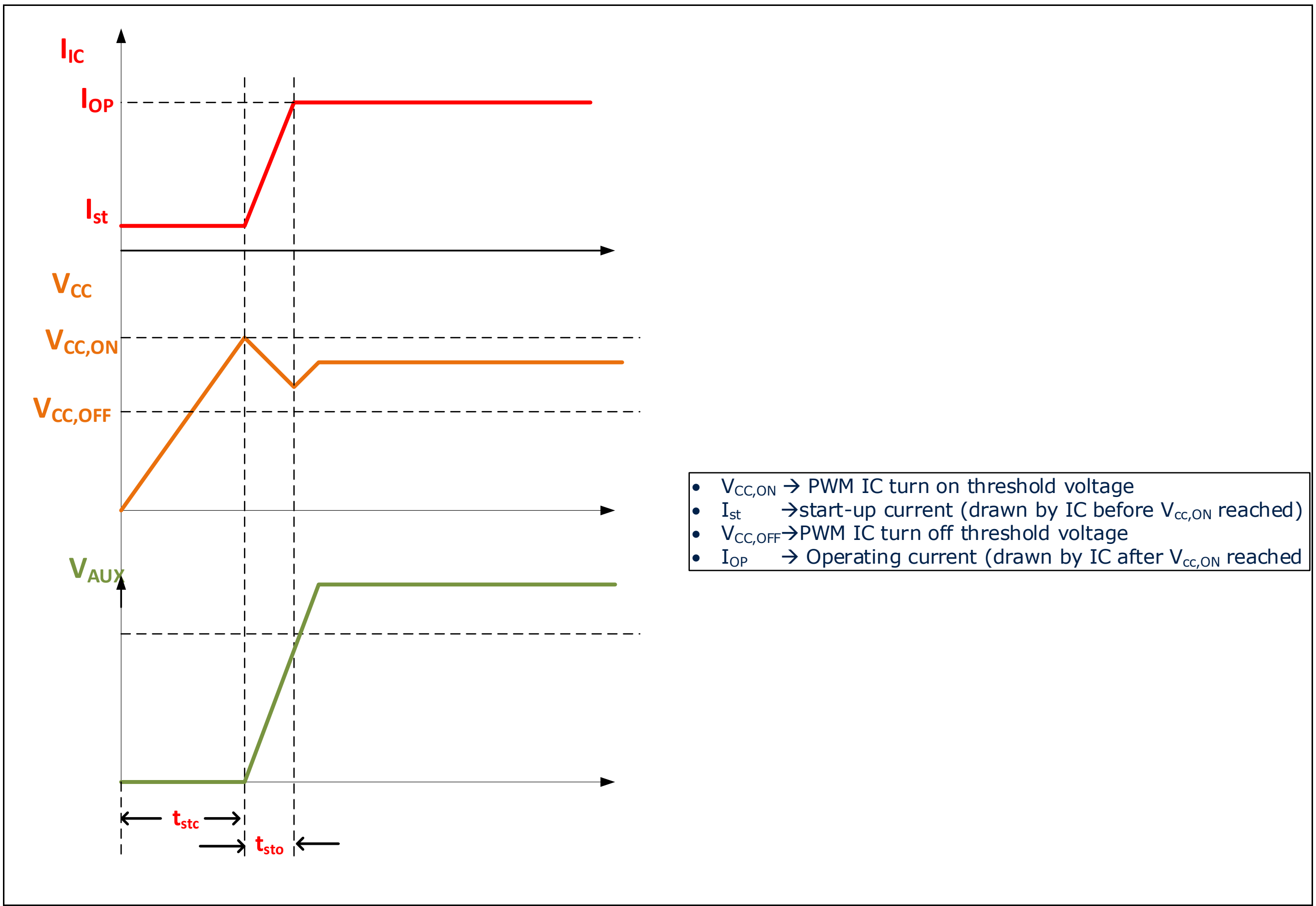

Figure 6 PWM IC start-up waveforms

For example, consider a PWM IC with electrical parameters as stated in Table 1 below:

Table 1 PWM IC electrical parameters

	I_{st} [µA]	I_{op} [µA]	$V_{IN,on}$ [V]	$V_{IN,off}$ [V]
PWM IC	300	7000	15	8

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

$$I_D = C1 * \frac{V_{CC,ON}}{t_{stc}} + I_{st} = 10\mu * \frac{15\ V}{500\ ms} + 300\ \mu A = 600\ \mu A \tag{7}$$

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 µA. So at 340 V of V_{IN} the start-up resistor value can be calculated.

$$R_{start-up} = \frac{V_{IN}}{I_D} = \frac{340\ V}{600\ \mu A} \approx 570\ k\Omega \tag{8}$$

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.

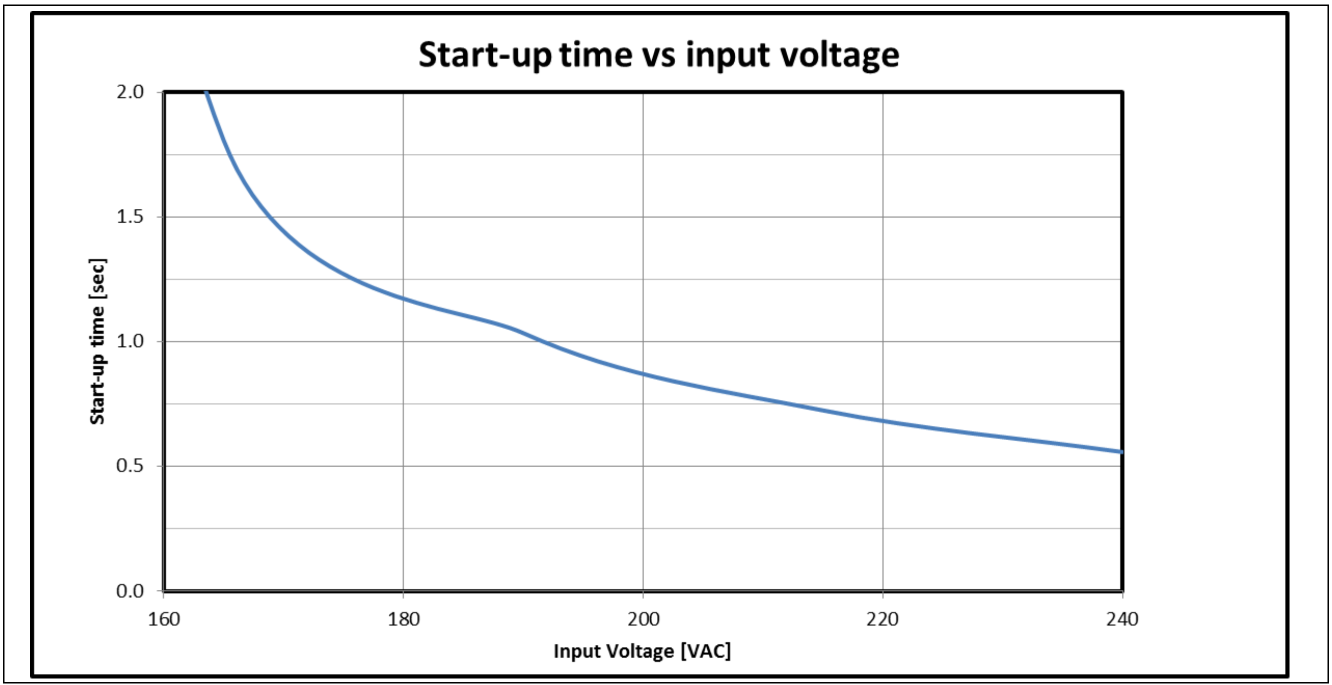

Figure 7 Start-up time vs input voltage in the resistor solution

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 Electical parameters

Part Number	BV_{DSS} [V]	$V_{GS(th),min}$ [V]	$V_{GS(th),typ}$ [V]	$V_{GS(th),max}$	$I_{DSS,min}$ @V_{GS} = 0 V [mA]
BSS126	600	-2.7	-2.0	-1.6	7

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 Q1 during start-up time is given by:

$$P_d = \left(V_{IN} - V_{CC,ON}\right) * (I_D) \tag{9}$$

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

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

Thus the chip temperature rise is given by:

$$\Delta Tj = Pd * Z_{thJA@Single\ pulse,@tstc} \tag{10}$$

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:

$$\Delta Tj = 0.195\ W * 130\frac{K}{W} \approx 25\ K$$

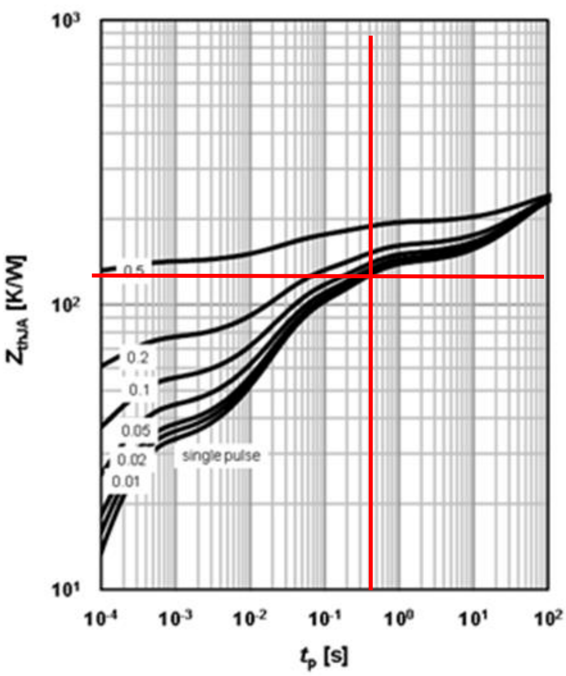

Figure 8 BSS126 max. transient thermal impedance

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, Q_1 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:

$$V_{cc} = V_Z + V_{GS} \tag{11}$$

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

$$V_{cc} = V_Z - \left(V_{GS(th)} \left(1 - \sqrt{\frac{I_D}{I_{DSS}}} \right) \right) \tag{12}$$

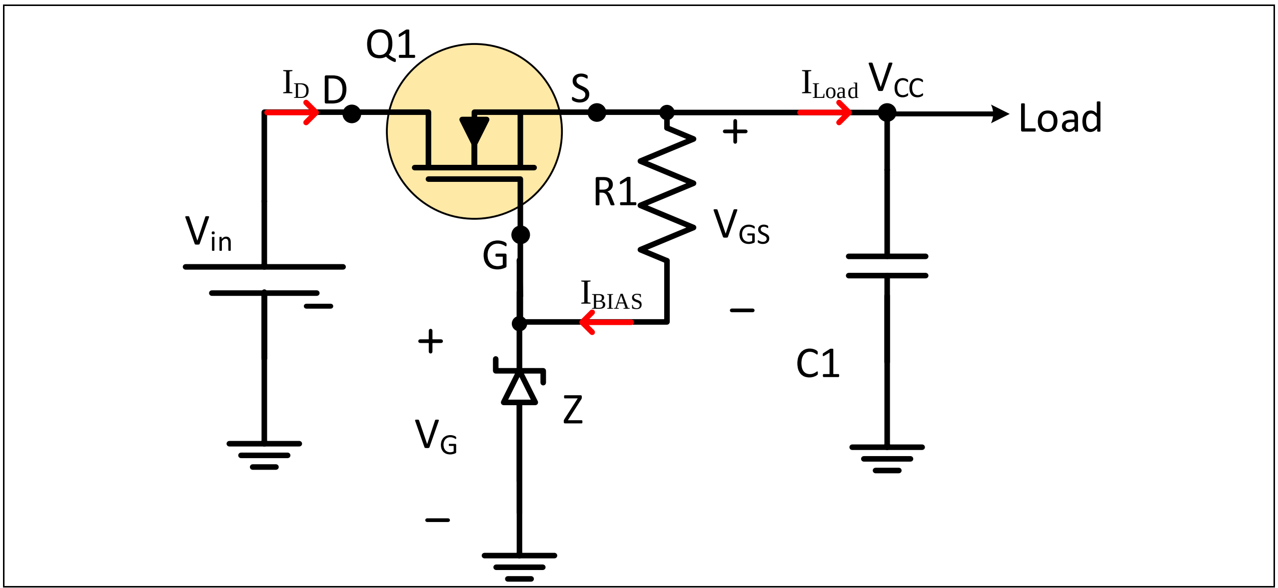

Figure 9 Using a Depletion MOSFET as a voltage regulator

The power dissipation for Q_1 can be calculated from the voltage drop across it times the current through it:

$$P_{Q_1} = (V_{DRAIN} - V_{SOURCE})(I_{LOAD} + I_{BIAS}) \tag{7}$$

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.

Static characteristics

Drain-source breakdown voltage	$V_{(BR)DSS}$	V_{GS}=-10 V, I_D=250 µA	100	-	-	V
Gate threshold voltage	$V_{GS(th)}$	V_{DS}=3 V, I_D=50 µA	-2.9	-2.2	-1.8	

Figure 10 Cutt-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 3 BSS169 Depletion MOSFET parameters

Part Number	BV_{DSS} [V]	$V_{GS(th),min}$ [V]	$V_{GS(th),typ}$ [V]	$V_{GS(th),max}$	$I_{DSS,min}$ @V_{GS} = 0 V [mA]
BSS169	100	-2.9	-2.2	-1.8	90

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).

$$Vz = Vcc{,}typ + \left(VGS(th){,}typ\left(1 - \sqrt{\frac{ID}{IDSS}}\right)\right) \tag{8}$$

$$V_Z = 5\,V + \left(-2.2\,V * \left(1 - \sqrt{\frac{5*10^{-3}\,A}{90*10^{-3}\,A}}\right)\right) \cong 3.3\,V$$

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).

$$P_{Q_1} = (V_{DRAIN} - V_{SOURCE})(I_{LOAD} + I_{BIAS}) \tag{95}$$

$$P_{Q_1} = (24 - 4.7) * (5 * 10^{-3} + 30 * 10^{-6}) \approx 0.1\,W$$

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.

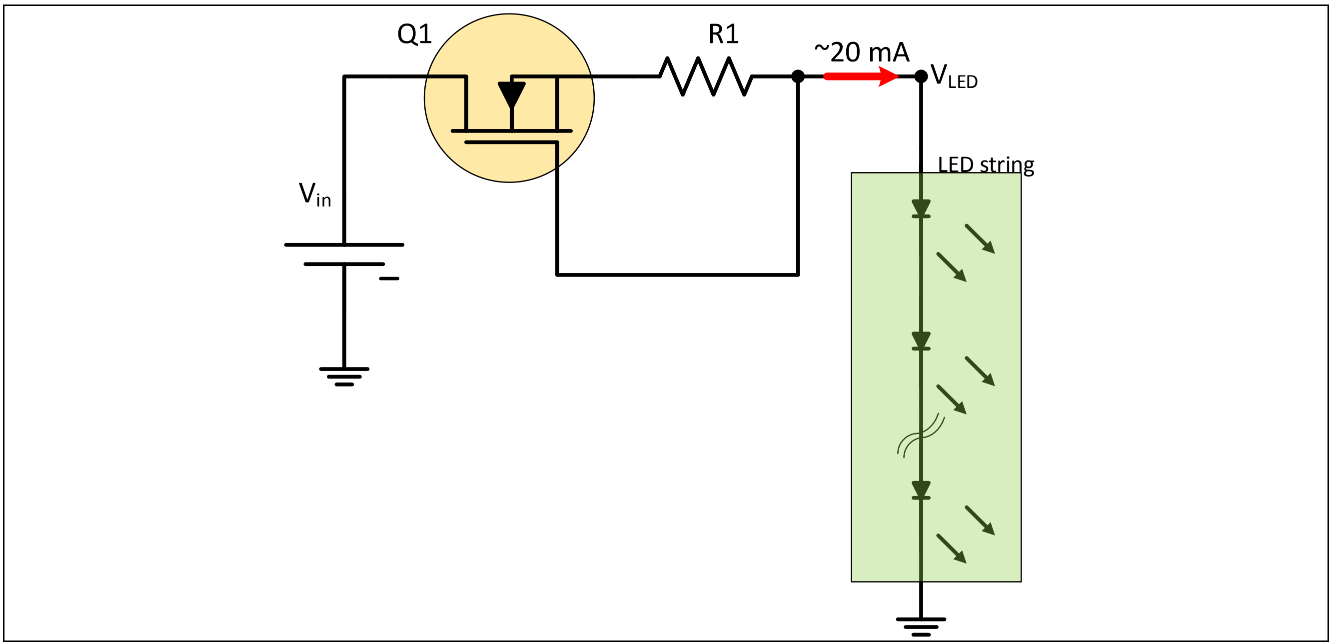

Figure 11 Linear LED driver

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 4 Depletion MOSFET portfolio

Part Number	Package	BV_{DSS} [V]	$R_{DS(on)}$ [Ω]	$V_{GS(th),max}$ [V]	$V_{GS(th),min}$ [V]	$I_{DSS,min}$ @V_{GS} = 0V [mA]
BSP149	SOT-223	200	1.8	-1	-2.1	140
BSP129	SOT-223	240	6	-1	-2.1	55
BSP179	SOT-223	400	24	-1	-2.1	20
BSP135	SOT-223	600	45	-1	-2.1	20
BSS159N	SOT-23	60	3.5	-2.4	-3.5	130
BSS169	SOT-23	100	6	-1.8	-2.9	90
BSS139	SOT-23	250	14	-1	-2.1	30
BSS126	SOT-23	600	7	-1.6	-2.7	7

For Infineon’s Depletion MOSFETs $V_{GS(th)}$ 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 $V_{GSth,min}$ to $V_{GSth,max}$. Figure 12 shows an example of $V_{GS(th)}$ bands of BSP149.

Threshold voltage $V_{GS(th)}$ sorted in bands[2]						
J	$V_{GS(th)}$	V_{DS}=3 V, I_D=8 µA	-1.8	-	-1.6	V
K			-1.95	-	-1.75	
L			-2.1	-	-1.9	
M			-2.25	-	-2.05	
N			-2.4	-	-2.2	

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 $V_{GS(th)}$.

Revision History

Major changes since the last revision

Page or Reference	Description of change
--	First Release

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