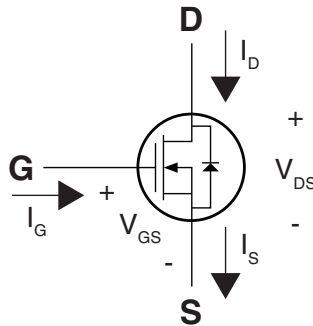# Depletion-Mode Power MOSFETs
and Applications

1   Introduction

Applications like constant current sources, solid state relays, and high voltage DC lines in power systems require N-channel depletion-mode power MOSFETs that operate as normally-on switches when the gate-to-source voltage is zero (V_{GS}=0V). This paper will describe IXYS IC Division's latest N-channel, depletion-mode, power MOSFETs and their application advantages to help designers to select these devices in many industrial applications.

Figure 1   N-Channel Depletion-Mode MOSFET

A circuit symbol for an N-channel depletion-mode power MOSFET is given in Figure 1. The terminals are labeled as G (gate), S (source) and D (drain). IXYS IC Division depletion-mode power MOSFETs are built with a structure called vertical double-diffused MOSFET, or DMOSFET, and have better performance characteristics when compared to other depletion-mode power MOSFETs on the market such as high VDSX, high current, and high forward biased safe operating area (FBSOA).

Figure 2 shows a typical drain current characteristic, I_D, versus the drain-to-source voltage, V_{DS}, which is called the output characteristic. It's a similar plot to that of an N-channel enhancement mode power MOSFET except that it has current lines at V_{GS} equal to -2V, -1.5V, -1V, and 0V.

Figure 2   CPC3710 - MOSFET Output Characteristics
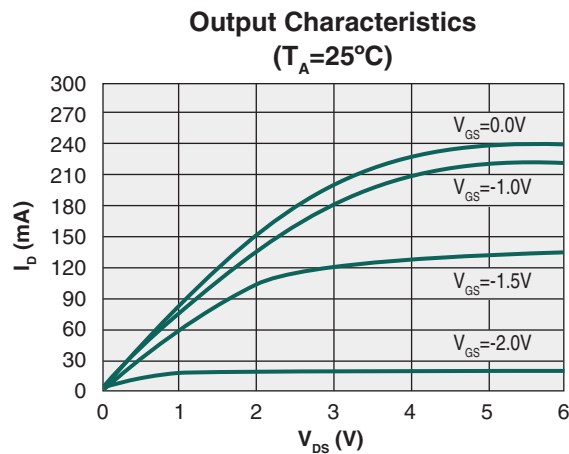
The on-state drain current, I_{DSS}, a parameter defined in the datasheet, is the current that flows between the drain and the source at a particular drain-to-source voltage (V_{DS}), when the gate-to-source voltage (V_{GS}) is zero (or short-circuited). By applying positive gate-to-source (V_{GS}) voltage, the device increases the current conduction level. On the other hand, negative gate-to-source (V_{GS}) voltage reduces the drain current. The CPC3710 stops conducting drain current at V_{GS}= -3.9V. This -3.9V is called the gate-to-source cutoff voltage or threshold voltage ($V_{GS(off)}$) of the device. In order to ensure proper turn-on, the applied gate-to-source (V_{GS}) voltage should be close

to 0V, and to properly turn off, a more negative V_{GS} voltage than the cutoff voltage ($V_{GS(off)}$) should be applied. Theoretically, the on-state drain current, $I_{D(on)}$, can be defined as:

$$I_D = I_{DSS} \bullet \left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$

Equation (1)

Note that Equation (1) is a theoretical formula that, in most cases, would not yield an accurate value of the drain current. $V_{GS(off)}$ has a range of -3.9V to -0.8V and $I_{D(on)}$ depends both on $V_{GS(off)}$ and the temperature.

A list of IXYS IC Division N-channel discrete depletion-mode power MOSFETs is given in Table 1. The table shows the device's four main parameters: the drain-to-source breakdown voltage (BV_{DSX}), the on-state resistance ($R_{DS(on)}$), the minimum and maximum gate-to-source cutoff voltage ($V_{GS(off)}$), and the on-state drain current (I_{DSS}) along with standard discrete package options such as SOT-89 and SOT-223.

Table 1:   IXYS IC Division N-Channel Depletion-Mode MOSFETs

Part No.	BV_{DSX} (V)	$R_{DS(on)}$ (Ω)	$V_{GS(off)}$ Min V	$V_{GS(off)}$ Max V	I_{DSS} Min mA	Package
CPC3701	60	1	-0.8	-2.9	600	SOT-89
CPC3703	250	4	-1.6	-3.9	300	SOT-89
CPC3708	350	14	-2	-3.6	130	SOT-89, SOT-223
CPC3710	250	10	-1.6	-3.9	220	SOT-89
CPC3714	350	14	-1.6	-3.9	240	SOT-89
CPC3720	350	22	-1.6	-3.9	130	SOT-89
CPC3730	350	30	-1.6	-3.9	140	SOT-89
CPC3902	250	2.5	-1.4	-3.1	400	SOT-223
CPC3909	400	6	-1.4	-3.1	300	SOT-223
CPC3960	600	44	-1.4	-3.1	100	SOT-223
CPC3980	800	45	-1.4	-3.1	100	SOT-223
CPC3982	800	380	-1.4	-3.1	20	SOT-23
CPC5602	350	14	-2	-3.6	130	SOT-223
CPC5603	415	14	-2	-3.6	130	SOT-223

2   Selecting a Depletion-Mode MOSFET

Depletion-mode power MOSFETs will function in those applications requiring a normally-on switch. The main selection criteria for a depletion-mode MOSFET, based on the application, are as follows:

1.   Select the breakdown voltage meeting the margin for reliable operation ~ BV_{DSX}, the drain-to-source breakdown voltage.

The application voltage must be lower than the drain-to-source breakdown voltage of the device. BV_{DSX} needs to be selected to accommodate the voltage swing between the positive bus and the negative bus as well as any voltage peaks caused by voltage ringing due to transients.

2.   Identify the current requirement, and pick a package capable of handling that current ~ I_{DSS}, the on-state drain current.

The application current must be lower than the on-state drain current (I_{DSS})of the device. It is the maximum current that can flow between the drain and source, which occurs at a particular drain-to-source voltage (V_{DS}) and when the gate-to-source voltage (V_{GS}) is zero.

3. $V_{GS(off)}$, the gate-to-source cutoff voltage

N-channel depletion-mode MOSFETs have a negative channel cutoff voltage, which is designated as $V_{GS(off)}$. A designer has to know the magnitude of the negative cutoff voltage (or threshold voltage). A negative gate-to-source voltage (V_{GS}) will reduce the drain current until the device's cutoff voltage level is reached and conduction ceases.

3 Applications

3.1 Current Source #1

Figure 3 shows a very precise current source to the load, RL1. TL431 is a programmable voltage reference IC. The feedback voltage from the sense resistor RS is controlled to be 2.5V. The circuit will operate as a current source at any current level below the CPC3710's rated current rating, I_{DSS}. Note that at 200V power dissipation will be 1W.

Figure 3   Depletion-Mode MOSFET Current Source and the Current Waveform
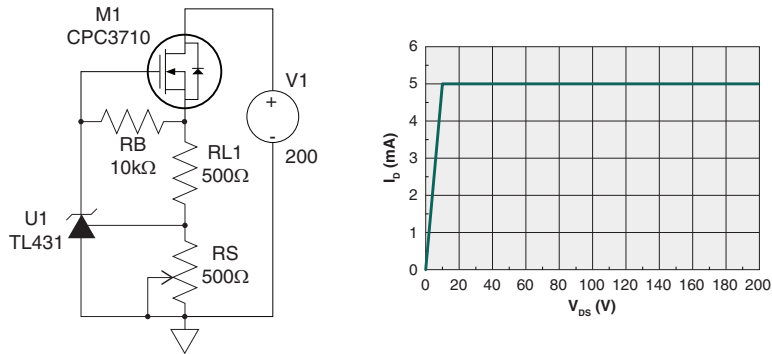
The theoretical sense resistor value is given by:

$$RS \cong \frac{V_{REF}}{I_D}$$

Equation (2)

Where:

- V_{REF} = 2.5V (TL431)
- I_D = 5mA (Desired Current)

Note that Equation (2) is a theoretical formula that would probably not estimate the practical values of RS. In most cases, it's convenient to use a potentiometer to set the desired current level.

3.2 Current Source #2

Figure 4 shows a current source example with a voltage reference IC and a depletion-mode MOSFET, Q1, which compensates for supply voltage fluctuations. The current source provides a total current to the load comprising the set current through the resistor, RS, and the IC quiescent current, I_Q. This circuit provides precision current and ultra-high output impedance.

Figure 4   N-Channel Depletion-Mode MOSFET with a Voltage Reference to provide a Precise Current Source

$$I_{SET} = \frac{V_{OUT}}{R_{SET}}$$

$$I_{OUT} = I_{SET} + I_Q$$

Output Impedance > 100MΩ

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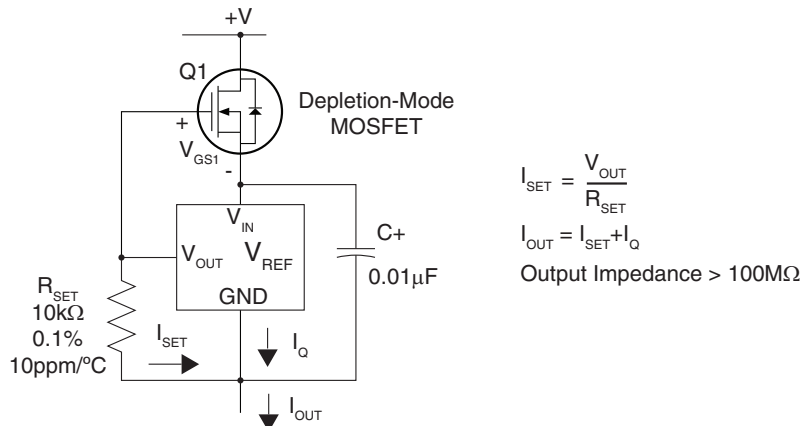
3.3   NMOS Inverter Circuit

Figure 5 shows an NMOS inverter circuit that uses a depletion-mode MOSFET as a load. The depletion-mode MOSFET, Q1, acts as a load for the enhancement-mode MOSFET, Q2, which acts as a switch.

Figure 5   NMOS Inverter with Depletion-Mode Device used as a Load
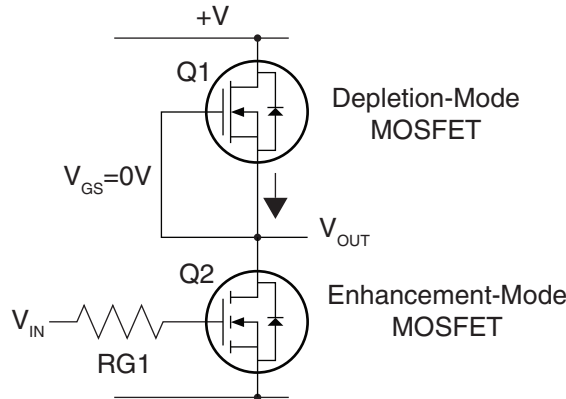
3.4   Off-Line Switch-Mode Power Supply

Many applications in industrial and consumer electronics require off-line switch-mode power supplies that operate from wide voltage variations of 110VAC to 260VAC. Figure 6 shows such a power supply that uses a depletion-mode MOSFET, Q1, to kick-start the off-line operation by providing initial power to the IC (U1) through the source of Q1.

Figure 6   Power Supply Start-Up Circuit with Depletion-Mode MOSFET
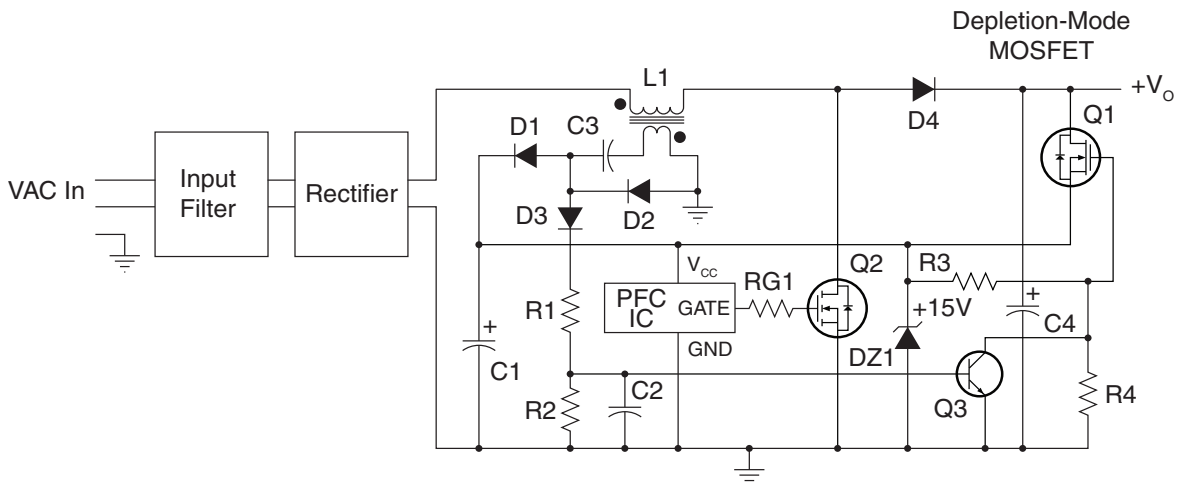

Q1 provides initial power from the output, $+V_O$. R3 and R4 set up a working point to obtain the minimum required current from Q1. The Zener diode, DZ1, limits the voltage across the IC (U1) to +15V. After the start-up, the secondary winding of boost inductor L1 generates the supply voltage for the IC through D1, D2 and C3, and enough current through D3 and R1 for the base of Q3 that turns on and clamps the gate of Q1 to ground.

3.5 Voltage Ramp Generator

Applications such as high voltage sweep circuits and automatic test equipment require high voltage ramps with a linear relationship between output voltage and time. The circuit shown in Figure 7 utilizes one depletion-mode MOSFET to design a voltage-ramp generator circuit.

Figure 7   High Voltage Ramp Generator with Depletion-Mode and Enhancement-Mode N-Channel MOSFETs
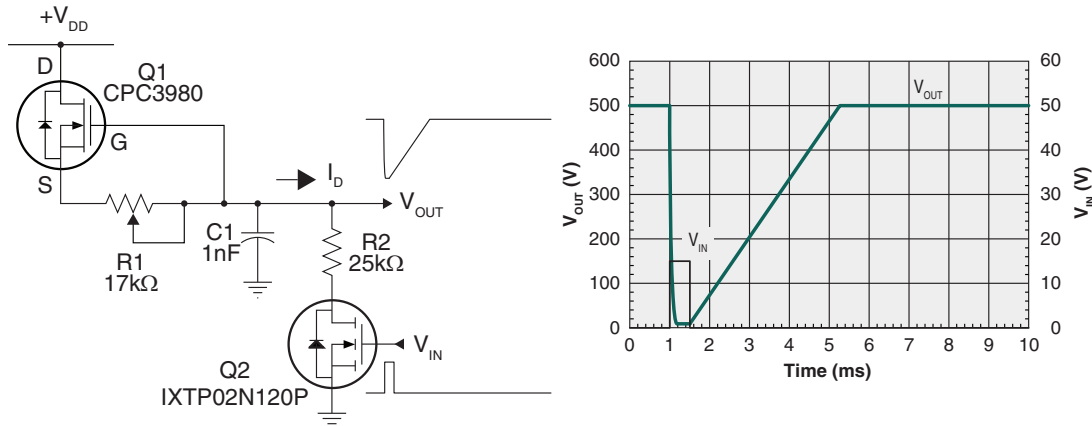
Q1 is configured as a constant current source charging a capacitor, C1; R1 provides negative feedback to regulate and set the desired current value. The constant current source charges the capacitor C1, and generates a voltage ramp, V_{OUT}, across the capacitor. Q2 can be turned on with a TTL or a CMOS control signal to reset the ramp voltage by discharging the capacitor to ground through R2. Resistor R2 is used to limit the discharge current for Q2 to operate within its SOA rating.

Assume the ramp voltage:

$$\frac{dV}{dt} = 0.1\,V/\mu s$$

The value of capacitor C1 should be small enough to reduce excessive charging and discharging of energy, but large enough that output loads and stray capacitances will not introduce significant errors. C1 is chosen to be 1nF.

The charging current is defined as:

$$I = C1 \bullet \frac{dV}{dt}$$
$$I = 1nF \bullet 0.1\,V/\mu s = 100\mu A$$

Equation (3)

The value of R1 for a 100μA current source can be approximated:

$$R1 \cong \frac{V_{GS}}{I_D} \bullet \left(\sqrt{\frac{I_D}{I_{DSS}}} - 1 \right)$$

Where:

- V_{GS} = Pinch-off voltage = -1.75V @ desired $I_{DS(on)}$
- I_{DSS} = Saturation current = 100mA, typical
- I_D = 100μA

$$R1 = \frac{-1.75\,V}{100\,\mu A} \bullet \left(\sqrt{\frac{100\,\mu A}{100\,mA}} - 1 \right) = \frac{-1.75\,V}{100\,\mu A} \bullet (0.03162 - 1) = \frac{1.695\,V}{100\,\mu A} = 16.9\,k\Omega$$

Assume the switching frequency for Q2 is swf=200 Hz and the discharge time is:

$$t_{Dischg} = 100\,\mu s$$

Power loss in the output capacitor, C1:

$$P = \frac{1}{2} \bullet C1 \bullet V^2 \bullet f_{sw}$$ **Equation (4)**

Using equation (4),

$$P = \frac{1}{2} \bullet 1nF \bullet 500^2 \bullet 200Hz = 125\,\mu J \bullet 200Hz = 25\,\text{mJ/s} = 25\,mW$$

Discharging time:

$$t_{Dischg} = 4 \bullet R2C1$$ **Equation (5)**

Using equation (5):

$$R2 = \frac{100\,\mu s}{4 \bullet 1nF} = 25\,k\Omega$$

3.6 Linear Voltage Regulator

Many applications require a linear voltage regulator that operates from high input voltage that is sourced from a wide voltage range of 120 VAC to 240 VAC with a maximum peak voltage of +/- 340V. Applications like CMOS ICs and small analog circuits require a 5V to 15V DC power supply that provides protection from very fast high voltage transients, and that has low quiescent current requirements. Figure 8 shows a high voltage off-line linear voltage regulator using a Depletion-mode MOSFET that can meet the above requirement of low transient voltage and low quiescent current.

Figure 8   High Voltage Off-line Linear Voltage Regulator
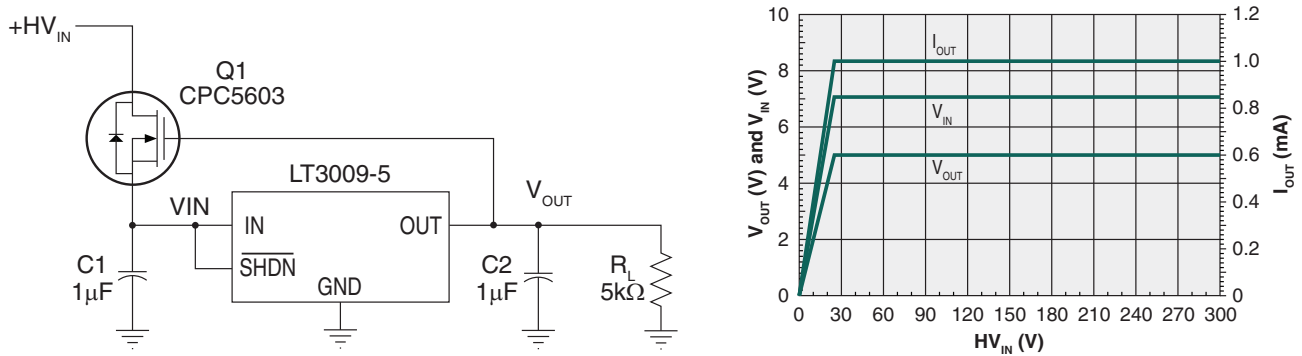
High voltage transients are generated in telecommunication circuits because of lightning and spurious radiation, and in automotive and avionics circuits because of inductive loads. Low quiescent current is required to minimize power dissipation in these linear regulators.

HV_{IN} Calculation:

$$I_D = I_{DSS} \bullet \left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$

Solving for V_{GS}:

$$V_{GS} = V_{GS(off)} \bullet \left(1 - \sqrt{\frac{I_D}{I_{DSS}}}\right)$$

Where:

- $V_{GS} = V_{OUT} - V_{IN}$

$$V_{IN} = V_{OUT} - V_{GS(off)} \bullet \left(1 - \sqrt{\frac{I_D}{I_{DSS}}}\right)$$

$$V_{IN} = 5 + 2 \bullet \left(1 - \sqrt{\frac{1mA}{10mA}}\right) = 5 + 2 \bullet (1 - 0.3162) = 6.38V$$

3.7   Current-Monitor Circuit

A simple current monitor circuit using an op-amp and a depletion-mode MOSFET is shown in Figure 9. R_1 monitors the current to the load and the MOSFET, Q1, provides an output voltage proportional to the current being monitored.

$$V_{OUT} = I_{LOAD} \bullet \left(\frac{R_S \bullet R_2}{R_1} \right)$$

Equation (7)

Resistor, R_1, should have a tolerance of 0.1% with an appropriate wattage rating.

Figure 9   Current Monitor using Depletion-Mode MOSFET and a Single-Supply Op-Amp
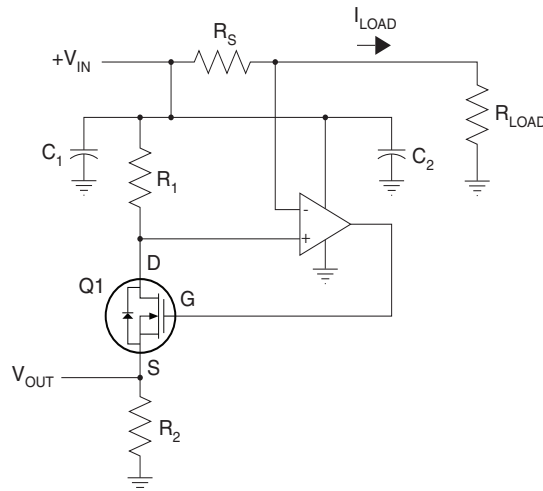
For example:

- R_S=0.1Ω
- R_1=100Ω
- R_2=1kΩ

Using equation (7):

$$\frac{V_{OUT}}{I_{LOAD}} = \frac{R_S \bullet R_2}{R_1} = \frac{0.1 \bullet 1000}{100} = 1\text{V/A}$$

3.8   Normally Closed Solid State Relay

Depletion-mode FETs can be used to create normally closed solid state relays using IXYS IC Division's optical driver, FDA217. Figure 10 shows a typical connection of two external CPC3980 depletion FETs arranged in back-to-back configuration to make an AC/DC switch. FDA217 has internal turn-off circuitry so that no external bleed resistors are required.

Figure 10   FDA217 used with CPC3980 FETs to create Normally Closed Solid State Relay
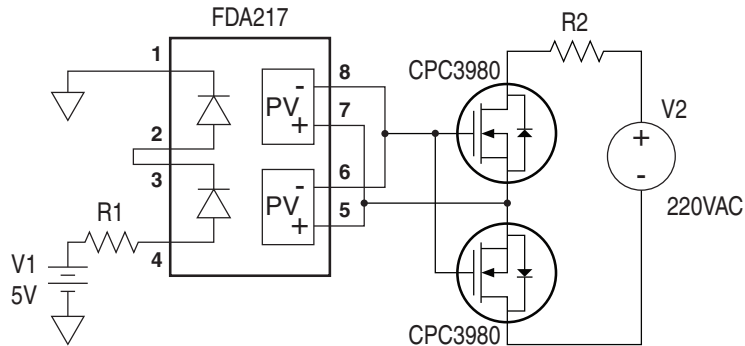
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