VI. Lab 6: Field Effect Transistors

A. Introduction.

In this lab you will explore some of the properties and uses of field effect transistors (FETs).

One thing to be aware of in this lab is that FETs can easily be damaged by discharge from static electricity. This is particularly true for MOSFETs. Sometimes FETs require special handling to prevent this problem, such as the use of ground straps on your wrist. However we've found in the past that we can get away without special handling, probably because of the significant humidity that we often have. If you do find that you've damaged more than one transistor let your instructor know. Also make sure that any damaged components are discarded.

B. Procedure

1. JFET Properties

In this part we'll study the properties of the J112 N-channel JFET. The spec sheet for this transistor is given at the end of this chapter.

Construct the circuit shown in Figure VI-1. We suggest that you adjust the output voltage of the DC supply on the breadboard to +10 V and use that for the +10 V supply, and use the EL302R for the adjustable supply voltage V_{adj}. The JFET pin-out is given in the specification sheet.

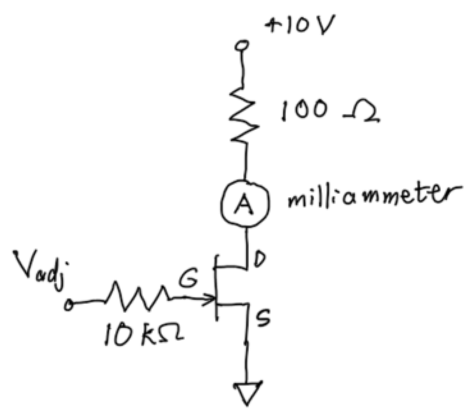

Figure VI-1. Circuit to measure the properties of the J112 n-channel JFET.

Measure the drain current I_D as a function of the gate-source voltage V_{GS}. Limit your voltage values to $|V_{GS}| < 5$ V. You will want to measure for both polarities of V_{GS}. (To do this, make sure that neither the + nor the – output terminal of the EL302R is connected to the ground terminal. If that is the case, you can reverse the connections on the EL302R to reverse the polarity since both outputs are floating, *i.e.* you don't have to worry about shorting the supply to ground.) Also, note that you normally don't apply significant positive voltages to the gate of an n-channel JFET, but you can get away with a few volts on your supply here because the $10\ \text{k}\Omega$ resistor limits the gate current.

For your report: Make a plot of I_D *vs.* V_{GS}. What value did you find for $V_{GS(off)}$? What increment in gate voltage $V_{GS} - V_{GS(off)}$ is needed to reach a drain current of 10 mA? What is the value of I_{DSS} for your transistor? Also, make a plot of the transistor's *transconductance* as a function of V_{GS}. This is the ratio $\frac{I_D}{V_{GS}}$, *i.e.* the output amps per input volt. How do your results compare with the data and graphs shown on the J112 data sheet? (Note: the units on the spec sheet graphs are improperly stated. They should be given as mS = milliSiemens. The graphs are correct as long as you substitute those units.)

2. N-channel MOSFET properties

In this part we'll study the properties of the 2N7000 N-channel MOSFET. The spec sheet for this transistor is given at the end of this chapter.

a) Drain current *vs.* Gate-Source voltage.

Build the circuit shown in Figure VI-2. The purpose of the 50 Ω resistor is to limit the drain current so you don't burn out the transistor. Use the one of the 1 Watt (green) 50 Ω resistors that we have. The pin-out for the 2N7000 is shown on the spec sheet. Please note that *the pin-out is not the same as the pin-out on the J112.* Also note that we can dispense with the current-limiting resistor on the gate since the gate input resistance is on the order of 1 GΩ.

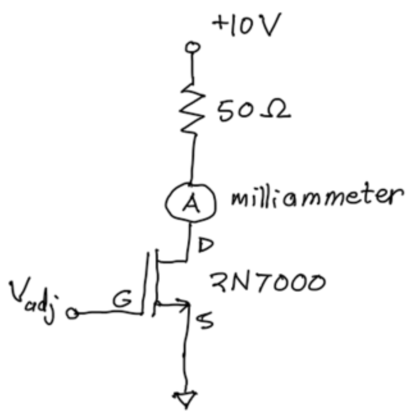

Figure VI-2. Circuit to measure the properties of the 2N7000 transistor.

Measure the drain current I_D as a function of the gate-source voltage V_{GS} for voltage range $0 < V_{GS} < 5$ V. *Limit the time that you allow the current to be more than 100 mA since this will make the 50 Ohm resistor hot.*

For your report: Make a plot of I_D *vs.* V_{GS}. What is the value of $V_{GS,th}$ for your transistor? What increment in gate voltage $V_{GS} - V_{GS,th}$ is needed to bring the drain current to 100 mA? With $V_{GS} = 5$ V (transistor fully "on") what is the voltage drop V_{DS}? What is the resistance of your transistor "switch"? Also, plot the transistor's transconductance as a function of V_{GS}. How do your results compare with the values shown on the 2N7000 data sheet? (Note that the large currents ~ 1 A shown in the graph can only be realized for short pulses.)

b) <u>Drain current *vs.* Drain-to-Source voltage</u>

Change your circuit so that you have a fixed gate-to-source voltage $V_{GS} = 5$ V, and can vary the Drain-to-Source voltage. Measure the drain current I_D as a function of V_{DS} over the voltage range $0 < V_{DS} <$ few V.

For your report: Make a plot of your measured I_D *vs.* V_{DS}. There should be a range of small V_{DS} for which the drain current changes linearly with V_{DS}. Do you see this? If so, over about what range in voltage V_{DS} does this linear dependence exist? In this range the MOSFET behaves like a resistor whose value can be tuned with the gate-source voltage V_{GS}. What is the value of the resistance that your transistor has for $V_{GS} = 5$ V?

Compare your result to what is shown on the data sheet for the 2N7000. (You won't be able to cover the full range shown in the data sheet, since continuous currents are limited to 0.2 A for this transistor.)

3. Power MOSFET switching of a load

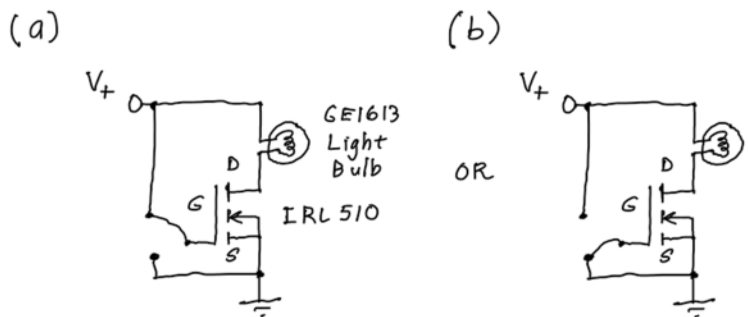

Figure VI-3. Circuit to switch a light bulb on and off with an N-channel MOSFET. (a) Switch on, (b) Switch off.

MOSFETs make excellent switches for high current loads due to their very low Drain-Source on resistance. In this part, we'll study this application. Our load will be a GE1613 light bulb, which is specified for operation at 6.4 Volts and 9 Watts. We'll use an IRL510 N-channel enhancement mode MOSFET as a switch. This is a power MOSFET rated for switching a maximum current of 4.0 A. Specifications for the IRL510 are reproduced at the end of this chapter. The IRL510 has a screw hole in a metal plate on one side. This is provided so that you can anchor the transistor to a heat sink so that it doesn't get too hot. Today, we'll be using this transistor at considerably less current than it is rated for, so we'll be able to get away without using a heat sink.

To explore this application of a MOSFET, build the circuit shown in Figure VI-3(a). The transistor pin-outs are shown on the spec sheet. Use one of the EL302R power supplies to provide the power at voltage V_+. Before you turn it on, make sure the "on" pushbutton in the lower right is in its out position. When you turn the power on, make sure the supply is not providing power ("on" light not lit), and change the setpoints to a voltage of 6.0 Volts and a current of 1.4 Amps. This will limit the voltage and current delivered to the light bulb so that you don't burn it out.

Please build your circuit on one of the small single breadboards as shown in Figure VI-4. The reason for this is that we're pushing a little past the 1 A maximum current specification for a breadboard. It is unlikely that this will damage the breadboard, but if it does we'd rather it damage the cheap single breadboards than the expensive Global Specialties protoboards. One other thing to be aware of in this circuit is that the outer shell of the lamp socket may have a voltage near V_+ on it. This is not hazardous, but you should be careful not to accidentally connect that socket to some other point in the circuit.

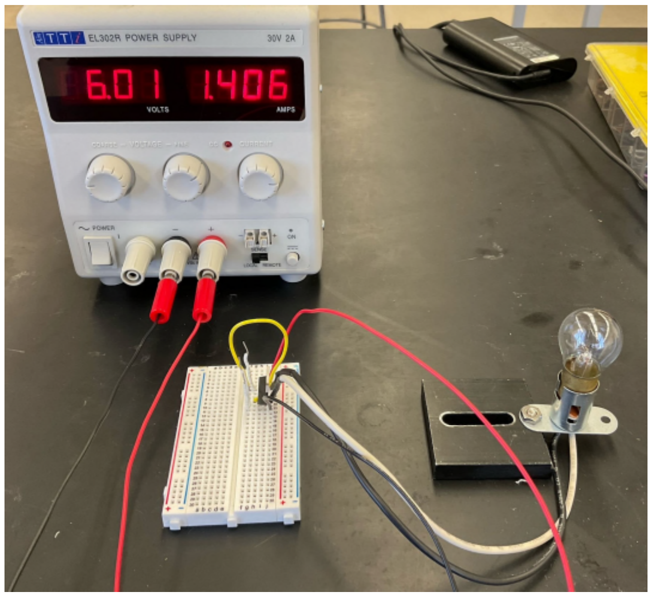

Figure VI-4. Power MOSFET circuit set-up.

Once you have your circuit built as shown in Figure VI-3(a) and have your power supply set-points properly adjusted, go ahead and output power to your circuit (*i.e.* push the "on" button in). The lamp should light. At this point, go ahead and measure (i) the current through the lamp (read from the power supply), (ii) the voltage across the lamp, and (iii) the voltage across the transistor Drain to Source.

Next, with the bulb on, disconnect the Gate from V_+, but don't connect the Gate to anything else yet. Watch what happens. Does the light bulb go out or stay on? If it stays on, watch it for a minute or two. Is the current changing? Finally, connect the Gate to the circuit ground (connection as shown in Figure VI-3(b)). What happens now?

For your report: Report the value of the current through the bulb, the voltage across the bulb, and the voltage across the Drain to Source of the transistor when the MOFSET switch is on. What Drain-Source on resistance does your transistor have, and how does that compare to the value given on the specification sheet? What is the power dissipated in the bulb? What is the power dissipated in the transistor? What fraction of the total power is dissipated in the transistor? Also, explain the behavior you observed when you disconnected the gate from V_+. If the bulb stayed on, explain why that happened. Also give an explanation for the rate of change of bulb current with time that you observed, if any.

C. Transistor specifications

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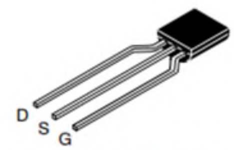
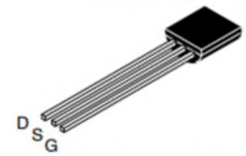
DATA SHEET
www.onsemi.com

N-Channel Switch

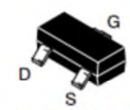
J111, J112, J113, MMBFJ111, MMBFJ112, MMBFJ113



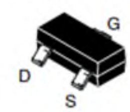
TO−92 3 4.83x4.76 LEADFORMED
CASE 135AR



TO−92 3 4.825x4.76
CASE 135AN



SOT−23 (TO−236)
CASE 318−08



SOT−23
CASE 318BM

Features

- This Device is Designed for Low Level Analog Switching, Sample and Hold Circuits and Chopper Stabilized Amplifiers
- Sourced from Process 51
- Source & Drain are Interchangeable
- These are Pb−Free Devices

ABSOLUTE MAXIMUM RATINGS (T_A = 25°C unless otherwise noted) (Note 1, 2)

Symbol	Parameter	Value	Unit
V_{DG}	Drain−Gate Voltage	35	V
V_{GS}	Gate−Source Voltage	−35	V
I_{GF}	Forward Gate Current	50	mA
T_J, T_{STG}	Operating and Storage Junction Temperature Range	−55 to 150	°C

Stresses exceeding those listed in the Maximum Ratings table may damage the device. If any of these limits are exceeded, device functionality should not be assumed, damage may occur and reliability may be affected.

1. These ratings are based on a maximum junction temperature of 150°C.
2. These are steady−state limits. ON Semiconductor should be consulted on applications involving pulsed or low−duty−cycle operations.

MARKING DIAGRAMS

J111, J112, J113, MMBFJ111, MMBFJ112, MMBFJ113

ELECTRICAL CHARACTERISTICS (T_J = 25°C unless otherwise noted)

Symbol	Parameter	Test Condition		Min	Max	Unit
OFF CHARACTERISTICS						
$V_{(BR)GSS}$	Gate−Source Breakdown Voltage	I_G = −1.0 μA, V_{DS} = 0		−35	−	V
I_{GSS}	Gate Reverse Current	V_{GS} = −15 V, V_{DS} = 0		−	−1.0	nA
$V_{GS}(off)$	Gate−Source Cut−Off Voltage	V_{DS} = 5 V, I_D = 1.0 μA	111	−3.0	−10.0	V
			112	−1.0	−5.0	
			113	−0.5	−3.0	
$I_D(off)$	Drain Cutoff Leakage Current	V_{DS} = 5.0 V, V_{GS} = −10 V		−	1.0	nA
ON CHARACTERISTICS						
I_{DSS}	Zero−Gate Voltage Drain Current (Note 5)	V_{DS} = 15 V, V_{GS} = 0	111	20	−	mA
			112	5.0	−	
			113	2.0	−	
$r_{DS}(on)$	Drain−Source On Resistance	$V_{DS} \leq$ 0.1 V, V_{GS} = 0	111	−	30	Ω
			112	−	50	
			113	−	100	

TYPICAL PERFORMANCE CHARACTERISTICS

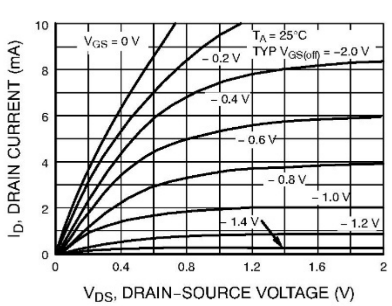


Figure 1. Common Drain−Source

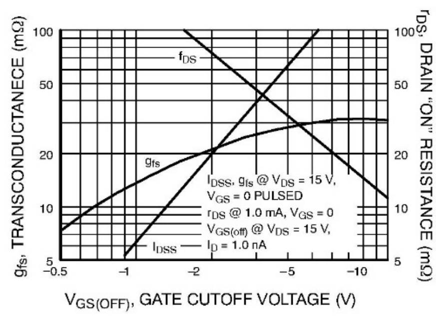


Figure 2. Parameter Interactions

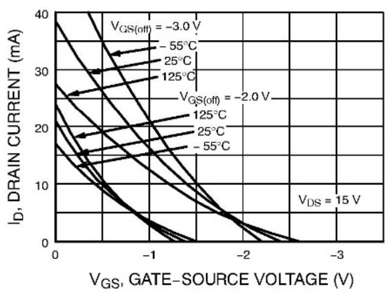


Figure 3. Transfer Characteristics

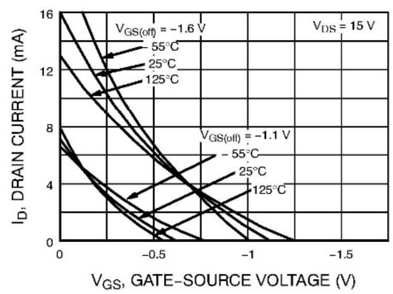


Figure 4. Transfer Characteristics

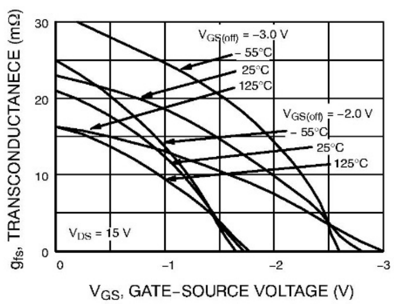


Figure 5. Transfer Characteristics

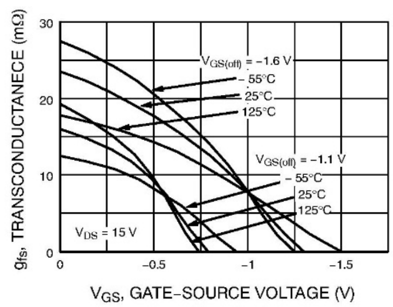


Figure 6. Transfer Characteristics

TYPICAL PERFORMANCE CHARACTERISTICS (CONTINUED)

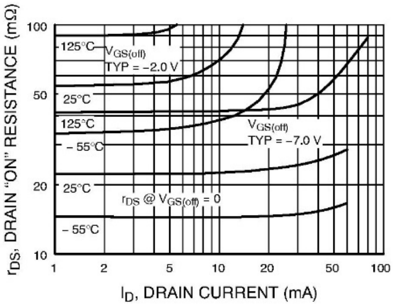


Figure 7. On Resistance vs. Drain Current

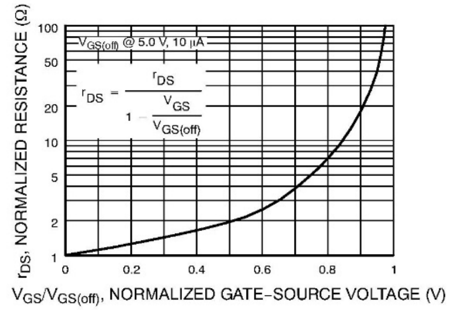


Figure 8. Normalized Drain Resistance vs. Bias Voltage

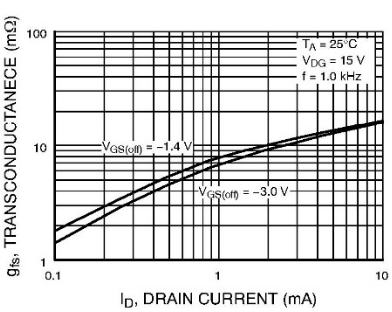


Figure 9. Transconductance vs. Drain Current

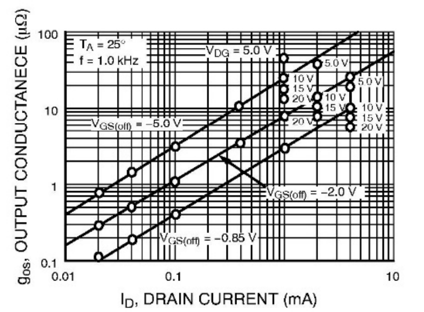


Figure 10. Output Conductance vs. Drain Current

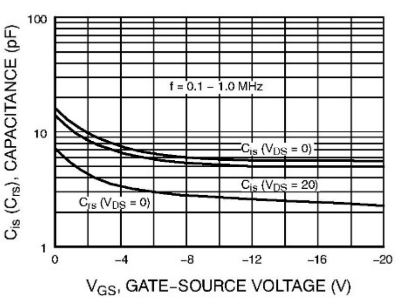


Figure 11. Capacitance vs. Voltage

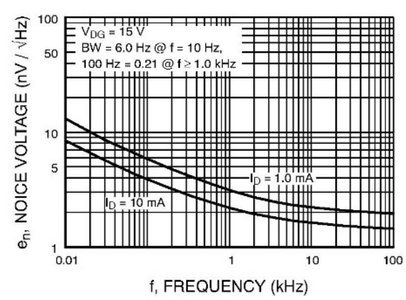


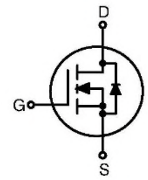
Figure 12. Noise Voltage vs. Frequency

onsemi

DATA SHEET
www.onsemi.com

N-Channel Enhancement Mode Field Effect Transistor

2N7000, 2N7002, NDS7002A

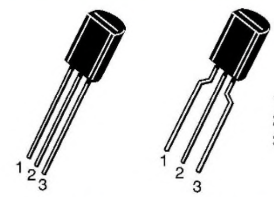


Description

These N−channel enhancement mode field effect transistors are produced using **onsemi**'s proprietary, high cell density, DMOS technology. These products have been designed to minimize on−state resistance while providing rugged, reliable, and fast switching performance. These products are particularly suited for low−voltage, low−current applications, such as small servo motor control, power MOSFET gate drivers, and other switching applications.

Features

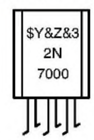
- High Density Cell Design for Low $R_{DS(on)}$
- Voltage Controlled Small Signal Switch
- Rugged and Reliable
- High Saturation Current Capability
- ESD Protection Level: HBM > 100 V, CDM > 2 kV
- This Device is Pb−Free and Halogen Free



TO−92 CASE 135AN **TO−92 CASE 135AR**

1 − Source
2 − Gate
3 − Drain

MARKING DIAGRAM



$Y = **onsemi** Logo
&Z = Assembly Plant Code
&3 = Date Code
2N7000 = Specific Device Code

2N7000, 2N7002, NDS7002A

ABSOLUTE MAXIMUM RATINGS Values are at T_C = 25°C unless otherwise noted.

Symbol	Parameter	Value 2N7000	Value 2N7002	Value NDS7002A	Unit
V_{DSS}	Drain−to−Source Voltage	60			V
V_{DGR}	Drain−Gate Voltage ($R_{GS} \leq$ 1 MW)	60			V
V_{GSS}	Gate−Source Voltage − Continuous	±20			V
	Gate−Source Voltage − Non Repetitive (tp < 50 ms)	±40			
I_D	Maximum Drain Current − Continuous	200	115	280	mA
	Maximum Drain Current − Pulsed	500	800	1500	
P_D	Maximum Power Dissipation Derated above 25°C	400	200	300	mW
		3.2	1.6	2.4	mW/°C
T_J, T_{STG}	Operating and Storage Temperature Range	−55 to 150		−65 to 150	°C
T_L	Maximum Lead Temperature for Soldering Purposes, 1/16−inch from Case for 10 s	300			°C

Stresses exceeding those listed in the Maximum Ratings table may damage the device. If any of these limits are exceeded, device functionality should not be assumed, damage may occur and reliability may be affected.

THERMAL CHARACTERISTICS Values are at T_C = 25°C unless otherwise noted.

Symbol	Parameter	Value 2N7000	Value 2N7002	Value NDS7002A	Unit
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	312.5	625	417	°C/W

ELECTRICAL CHARACTERISTICS
Values are at T_C = 25°C unless otherwise noted.

Symbol	Parameter	Conditions	Type	Min	Typ	Max	Unit
OFF CHARACTERISTICS							
BV_{DSS}	Drain−Source Breakdown Voltage	V_{GS} = 0 V, I_D = 10 μA	All	60	−	−	V
I_{DSS}	Zero Gate Voltage Drain Current	V_{DS} = 48 V, V_{GS} = 0 V	2N7000	−	−	1	μA
		V_{DS} = 48 V, V_{GS} = 0 V, T_C = 125°C		−	−	1	mA
		V_{DS} = 60 V, V_{GS} = 0 V	2N7002 NDS7002A	−	−	1	μA
		V_{DS} = 60 V, V_{GS} = 0 V, T_C = 125°C		−	−	0.5	mA
I_{GSSF}	Gate − Body Leakage, Forward	V_{GS} = 15 V, V_{DS} = 0 V	2N7000	−	−	10	nA
		V_{GS} = 20 V, V_{DS} = 0 V	2N7002 NDS7002A	−	−	100	
I_{GSSR}	Gate − Body Leakage, Reverse	V_{GS} = −15 V, V_{DS} = 0 V	2N7000	−	−	−10	nA
		V_{GS} = −20 V, V_{DS} = 0 V	2N7002 NDS7002A	−	−	−100	
ON CHARACTERISTICS							
$V_{GS(th)}$	Gate Threshold Voltage	V_{DS} = V_{GS}, I_D = 1 mA	2N7000	0.8	2.1	3	V
		V_{DS} = V_{GS}, I_D = 250 μA	2N7002 NDS7002A	1	2.1	2.5	

2N7000, 2N7002, NDS7002A

ELECTRICAL CHARACTERISTICS (continued)
Values are at T_C = 25°C unless otherwise noted.

Symbol	Parameter	Conditions	Type	Min	Typ	Max	Unit
ON CHARACTERISTICS							
$R_{DS(on)}$	Static Drain−Source On−Resistance	V_{GS} = 10 V, I_D = 500 mA	2N7000	−	1.2	5	Ω
		V_{GS} = 10 V, I_D = 500 mA, T_C = 125°C		−	1.9	9	
		V_{GS} = 4.5 V, I_D = 75 mA		−	1.8	5.3	
		V_{GS} = 10 V, I_D = 500 mA	2N7002	−	1.2	7.5	
		V_{GS} = 10 V, I_D = 500 mA, T_C = 100°C		−	1.7	13.5	
		V_{GS} = 5 V, I_D = 50 mA		−	1.7	7.5	
		V_{GS} = 5 V, I_D = 50 mA, T_C = 100°C		−	2.4	13.5	
		V_{GS} = 10 V, I_D = 500 mA	NDS7002A	−	1.2	2	
		V_{GS} = 10 V, I_D = 500 mA, T_C = 125°C		−	2	3.5	
		V_{GS} = 5 V, I_D = 50 mA		−	1.7	3	
		V_{GS} = 5 V, I_D = 50 mA, T_C = 125°C		−	2.8	5	
$V_{DS(on)}$	Drain−Source On−Voltage	V_{GS} = 10 V, I_D = 500 mA	2N7000	−	0.6	2.5	V
		V_{GS} = 4.5 V, I_D = 75 mA		−	0.14	0.4	
		V_{GS} = 10 V, I_D = 500 mA	2N7002	−	0.6	3.75	
		V_{GS} = 5.0 V, I_D = 50 mA		−	0.09	1.5	
		V_{GS} = 10 V, I_D = 500 mA	NDS7002A	−	0.6	1	
		V_{GS} = 5.0 V, I_D = 50 mA		−	0.09	0.15	
g_{FS}	Forward Transconductance	V_{DS} = 10 V, I_D = 200 mA	2N7000	100	320	−	mS
		V_{DS} ≥ 2 $V_{DS(on)}$, I_D = 200 mA	2N7002	80	320	−	
		V_{DS} ≥ 2 $V_{DS(on)}$, I_D = 200 mA	NDS7002A	80	320	−	

DRAIN−SOURCE DIODE CHARACTERISTICS AND MAXIMUM RATINGS

Symbol	Parameter	Type	Min	Typ	Max	Unit
I_S	Maximum Continuous Drain−Source Diode Forward Current	2N7002	−	−	115	mA
		NDS7002A	−	−	280	

TYPICAL PERFORMANCE CHARACTERISTICS

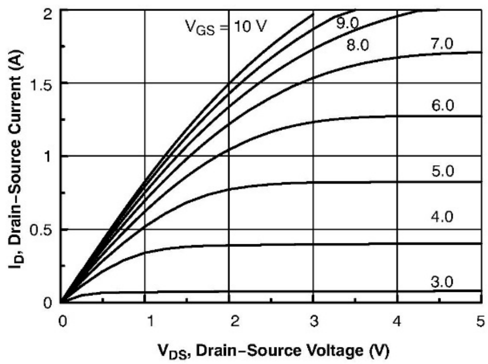


Figure 1. On-Region Characteristics

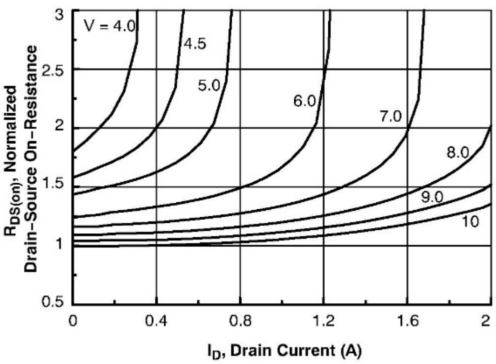


Figure 2. On-Resistance Variation with Gate Voltage and Drain Current

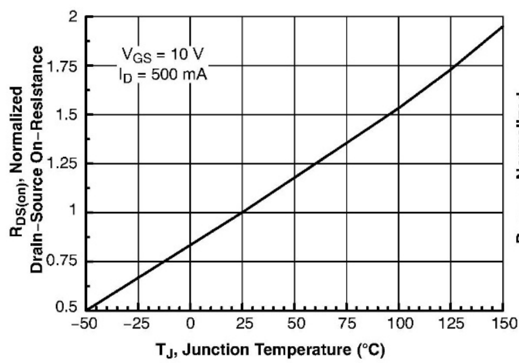


Figure 3. On-Resistance Variation with Temperature

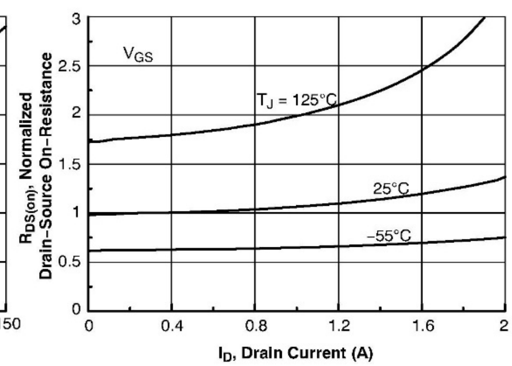


Figure 4. On-Resistance Variation with Drain Current and Temperature

2N7000, 2N7002, NDS7002A

TYPICAL PERFORMANCE CHARACTERISTICS (CONTINUED)

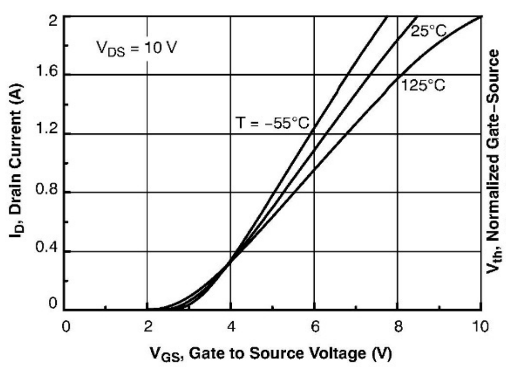


Figure 5. Transfer Characteristics

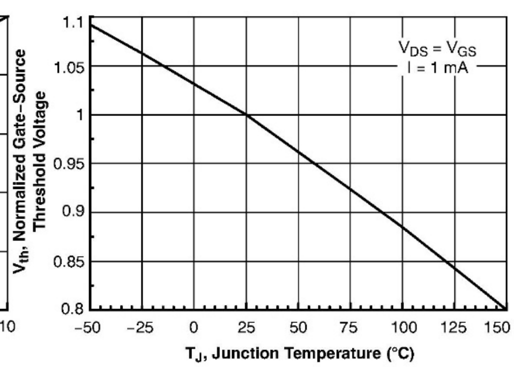
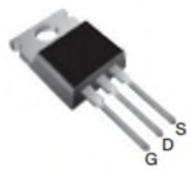
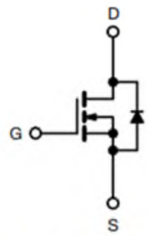


Figure 6. Gate Threshold Variation with Temperature

Power MOSFET

TO-220AB





N-Channel MOSFET

PRODUCT SUMMARY		
V_{DS} (V)	100	
$R_{DS(on)}$ (Ω)	V_{GS} = 5.0 V	0.54
Q_g (Max.) (nC)	6.1	
Q_{gs} (nC)	2.6	
Q_{gd} (nC)	3.3	
Configuration	Single	

FEATURES

- Dynamic dV/dt rating
- Repetitive avalanche rated
- Logic-level gate drive
- $R_{DS(on)}$ specified at V_{GS} = 4 V and 5 V
- 175 °C operating temperature
- Fast switching
- Ease of paralleling
- Material categorization: for definitions of compliance please see www.vishay.com/doc?99912

Available
RoHS*
Available

Note

* This datasheet provides information about parts that are RoHS-compliant and / or parts that are non RoHS-compliant. For example, parts with lead (Pb) terminations are not RoHS-compliant. Please see the information / tables in this datasheet for details

DESCRIPTION

Third generation power MOSFETs from Vishay provide the designer with the best combination of fast switching, ruggedized device design, low on-resistance and cost-effectiveness.

The TO-220AB package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 W. The low thermal resistance and low package cost of the TO-220AB contribute to its wide acceptance throughout the industry.

ABSOLUTE MAXIMUM RATINGS (T_C = 25 °C, unless otherwise noted)

PARAMETER			SYMBOL	LIMIT	UNIT
Drain-source voltage			V_{DS}	100	V
Gate-source voltage			V_{GS}	± 10	
Continuous drain current	V_{GS} at 5 V	T_C = 25 °C	I_D	5.6	A
		T_C = 100 °C		4.0	
Pulsed drain current [a]			I_{DM}	18	
Linear derating factor				0.29	W/°C
Single pulse avalanche energy [b]			E_{AS}	100	mJ
Repetitive avalanche current [a]			I_{AR}	5.6	A
Repetitive avalanche energy [a]			E_{AR}	4.3	mJ
Maximum power dissipation	T_C = 25 °C		P_D	43	W
Peak diode recovery dV/dt [c]			dV/dt	5.5	V/ns
Operating junction and storage temperature range			T_J, T_{stg}	-55 to +175	°C
Soldering recommendations (peak temperature) [d]	For 10 s			300 [d]	
Mounting torque	6-32 or M3 screw			10	lbf · in
				1.1	N · m

Notes

a. Repetitive rating; pulse width limited by maximum junction temperature (see fig. 11)

b. V_{DD} = 25 V, starting T_J = 25 °C, L = 4.8 mH, R_g = 25 Ω, I_{AS} = 5.6 A (see fig. 12)

c. $I_{SD} \leq$ 5.6 A, dI/dt $\leq$ 75 A/μs, $V_{DD} \leq V_{DS}$, $T_J \leq$ 175 °C

d. 1.6 mm from case

SPECIFICATIONS (T_J = 25 °C, unless otherwise noted)						
PARAMETER	**SYMBOL**	**TEST CONDITIONS**	**MIN.**	**TYP.**	**MAX.**	**UNIT**
Static						
Drain-source breakdown voltage	V_{DS}	V_{GS} = 0 V, I_D = 250 μA	100	-	-	V
V_{DS} temperature coefficient	$\Delta V_{DS}/T_J$	Reference to 25 °C, I_D = 1 mA	-	0.12	-	V/°C
Gate-source threshold voltage	$V_{GS(th)}$	$V_{DS} = V_{GS}$, I_D = 250 μA	1.0	-	2.0	V
Gate-source leakage	I_{GSS}	V_{GS} = ± 10 V	-	-	± 100	nA
Zero gate voltage drain current	I_{DSS}	V_{DS} = 100 V, V_{GS} = 0 V	-	-	25	μA
		V_{DS} = 80 V, V_{GS} = 0 V, T_J = 150 °C	-	-	250	
Drain-source on-state resistance	$R_{DS(on)}$	V_{GS} = 5.0 V, I_D = 3.4 A[b]	-	-	0.54	Ω
		V_{GS} = 4.0 V, I_D = 2.8 A[b]	-	-	0.76	
Forward transconductance	g_{fs}	V_{DS} = 50 V, I_D = 3.4 A[b]	1.9	-	-	S

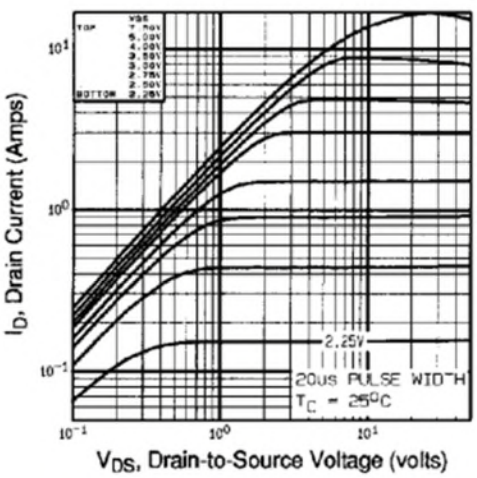


Fig. 1 - Typical Output Characteristics, T_C = 25 °C

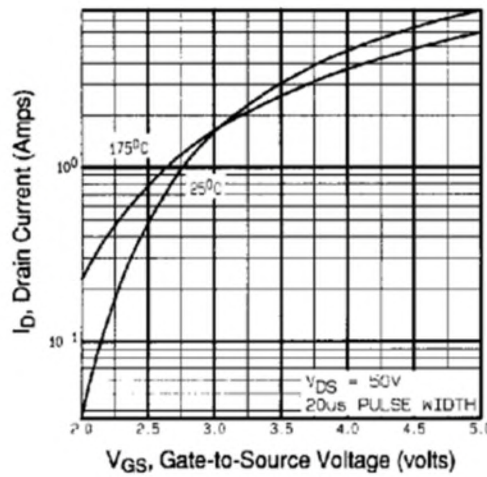


Fig. 3 - Typical Transfer Characteristics

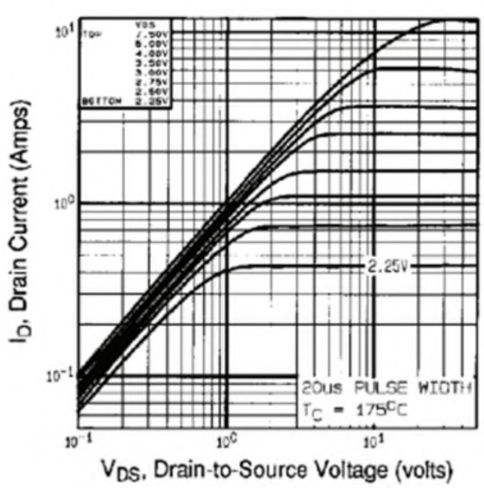


Fig. 2 - Typical Output Characteristics, T_C = 175 °C

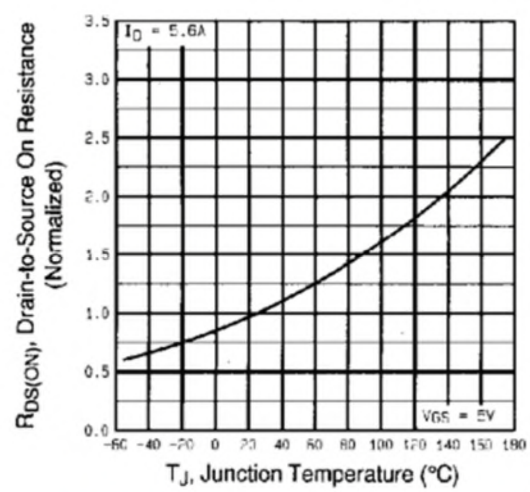


Fig. 4 - Normalized On-Resistance vs. Temperature