METRIC
Designation: F 617M – 95

Standard Test Method for Measuring MOSFET Linear Threshold Voltage [Metric] [1]

This standard is issued under the fixed designation F 617M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the measurement of MOSFET (see Note 1) linear threshold voltage under very low sweep rate or d-c conditions. It is a d-c conductance method applicable in the linear region of MOSFET operation where a drain voltage V_D of approximately 0.1 V is typical.

NOTE 1—MOS is an acronym for metal-oxide semiconductor; FET is an acronym for field-effect transistor.

1.2 This test method is applicable to both enhancement-mode and depletion-mode MOSFETs, and for both silicon-on-insulator (SOI) and bulk-silicon MOSFETs. The test method specifies positive voltage and current conventions specifically applicable to *n*-channel MOSFETs. The substitution of negative voltage and negative current make the test method directly applicable to *p*-channel MOSFETs.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Terminology

2.1 *Definitions of Terms Specific to This Standard:*

2.1.1 *drain-leakage current—of a MOSFET,* the d-c current from the drain terminal when the gate voltage with respect to the threshold voltage is such that the MOSFET is in the OFF state.

2.1.2 *threshold voltage—of a MOSFET,* for operation in the linear region, the gate-to-source voltage at which the drain current is reduced to the leakage current.

3. Summary of Test Method

3.1 The drain-source current of the MOSFET under test is measured at several values of gate voltage for a fixed drain-source voltage. A linear plot is made of the drain current as a function of gate voltage. The maximum tangent to the resulting curve is extrapolated to the gate-voltage axis or to the voltage independent line representing the drain-leakage current. This intercept is the threshold voltage for the drain-source voltage and temperature conditions of the test.

3.2 Before this test method can be implemented, test conditions appropriate for the MOSFET to be measured must be selected and agreed upon by the parties to the test. Conditions will vary from one MOSFET type to another, and are determined in part by the intended application. The following items are not specified by this test method, and shall be agreed upon between the parties to the test:

3.2.1 Reference temperature to which the measured threshold voltages shall be normalized.

3.2.2 Permissible range of ambient temperature within which the measurement is to be conducted. The reference temperature shall be within this range.

NOTE 2—The temperature sensitivity of the threshold voltage may be as large as − 5 mV/°C, or more. The reproducibility of the measurements will be degraded accordingly, unless the values of the threshold voltage are normalized to a common reference temperature. To reduce the effect that uncertainties in the temperature sensitivity of the test devices will have on the reproducibility, no more than an appropriately small range of test temperatures should be allowed.

3.2.3 Drain voltage V_D at which the measurement is to be made.

3.2.4 Maximum drain current, I_{DM}, maximum gate voltage, V_{GM}, and gate voltage steps, ΔV_G, over which the measurement is to be made. Values for I_{DM}, V_{GM}, and ΔV_G shall be selected to permit taking enough data points to define adequately the drain-current, gate-voltage characteristic curve in the region of the inflection point, namely, where the tangent to the curve has the largest slope (maximum tangent). The value selected for ΔV_G shall be one of the following: 0.02, 0.05, 0.10, 0.20, or 0.50 V. The

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[1] This test method is under the jurisdiction of ASTM Committee F-1 on Electronics and is the direct responsibility of Subcommittee F01.11 on Quality and Hardness Assurance.

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recommended procedure for selecting values for I_{DM}, V_{GM}, and ΔV_G is provided in the Appendix.

4. Significance and Use

4.1 The threshold voltage is a basic MOSFET parameter that must be determined for the design and application of discrete MOSFETs and MOS (see Note 1) integrated circuits. Threshold voltage is utilized in circuit design to specify the turn-on voltage of MOSFETs, and thereby determine performance attributes such as speed, power, noise margin, etc., of digital and analog circuitry.

4.2 The radiation-induced change in threshold voltage is a measure of ionizing radiation damage which results from immobile charges trapped in the gate insulator and the insulator-semiconductor interface regions of the MOSFET.

5. Interferences

5.1 If the gate current is greater than 1 % of the drain current, the threshold voltage measurement results are not valid.

5.2 If the current through voltmeter V_2(see Fig. 1) is large enough to alter the threshold voltage, either a meter with a higher impedance must be used (see section 7.2.2) or the drain-current reading must be reduced by the amount of the meter current.

5.3 The high (positive) input of the ammeter, *A*, (see Fig. 1) must always be connected to the drain side of the MOSFET, regardless of the polarity of the device. Note that with such a connection, the ammeter will give negative current readings for *n*-channel MOSFETs. The reason for connecting the high input to the drain side of the MOSFET is to reduce errors in the measurement of drain current due to meter-leakage currents. Electronic ammeters are designed for low internal-leakage operation only when the high input is connected to the low-leakage, high-resistance side of the current path.

5.4 Care must be taken to prevent electrical voltage overstress damage to the gate dielectric as a result of device handling during the threshold voltage measurement. Under certain conditions, electrostatic discharge from the human body can result in permanent damage to the gate insulator.

5.5 Valid threshold voltage measurement data will be obtained only if the magnitude of the drain voltage applied during the threshold voltage measurement is less than the drain-substrate junction-breakdown voltage.

5.6 The reproducibility of the test method is degraded by the uncertainty and variation of the MOSFET temperature during the test and by the temperature sensitivity of the threshold voltage (see Note 2).

5.6.1 It is expected that the power dissipation of the MOSFET during the measurement of the linear threshold voltage will be so low that a negligible increase in device temperature will occur. This is the reason that the temperature of the package ambient is to be measured rather than the temperature of the MOSFET.

5.6.2 Before the measurement is begun it is important that the device will have reached its equilibrium temperature after transfer and handling, for example, and that the temperature indicator is adjacent to the MOSFET.

5.6.3 The range of the package-ambient temperature (see 8.18) is a measure of the uncertainty and variation of the MOSFET temperature during the test.

5.7 This test method is valid only if the MOSFET stability is sufficient to prevent changes in threshold voltage due to bias-temperature stress applied during the threshold voltage measurement.

5.8 MOSFET threshold voltage measurements should be made under dark conditions when the MOSFET package admits enough light to increase the apparent leakage current.

5.9 Care must be taken that the manufacturer's specification limits on the MOSFET are not exceeded, even for very brief periods, or the characteristics of the MOSFET may be changed.

6. Apparatus

6.1 *Transistor Test Fixture*, to connect the MOSFET under test to the test circuit. Electrical contacts shall be clean and of good quality.

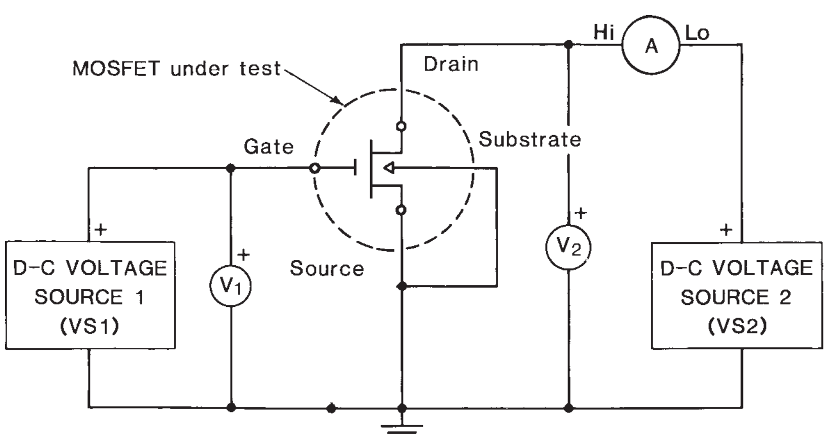


FIG. 1 Test Circuit for *n* -Channel Enhancement-Mode MOSFETs (see 1.2 and 5.3)

6.2 *Voltmeters*:

6.2.1 V_1, with an input impedance of approximately 10 MΩ or greater, and a capability of measuring a voltage as large as V_{GM} (see section 4.2.4) to within ±0.5 mV.

6.2.2 V_2, with an input impedance of approximately 10 MΩ or greater (see 6.2) and a capability of measuring a voltage as large as V_D(see section 4.2.3) to within ±1 %.

6.3 *Ammeter, A*, capable of measuring I_{DM}(see section 4.2.4) with a minimum accuracy of ±0.5 %.

6.4 *Voltage Sources*, VS_1 and VS_2, meeting the following specifications after warmup:

6.4.1 Drift less than ±0.15 % of the set voltage over an 8-h period.

6.4.2 Periodic and random deviation (noise and ripple) less than 0.5% of the output voltage.

6.4.3 Voltage adjustable to at least the minimum accuracy requirements defined for meters V_1 and V_2, respectively, and

6.4.4 Capable of supplying voltages and currents required to make the measurements of the method.

6.5 *Temperature-Measuring Device*, capable of measuring the temperature of the package ambient with a precision of ±0.2°C.

7. Sampling

7.1 This test method determines the properties of a single specimen. If sampling procedures are used to select devices for test, the procedures shall be agreed upon by the parties to the test.

8. Procedure

8.1 Assemble the test circuit shown in Fig. 1.

8.2 If a substrate electrode is provided on the MOSFET, connect the substrate to the source electrode.

8.3 Turn on the apparatus and allow it to warm up at least for the period specified by the apparatus manufacturer before proceeding further.

8.4 Set voltage sources VS_1 and VS_2 to 0 V and insert the MOSFET to be tested into the test fixture. Wait until the MOSFET has reached its equilibrium temperature in the fixture before proceeding further.

NOTE 3—The time for the device to reach an equilibrium temperature after having been handled or transferred from a different temperature environment can be a minute or more, depending on the magnitude of the temperature change and the design of the package.

8.5 Measure and record the temperature of the package ambient and ensure that the temperature is within the range agreed upon between the parties to the test (see 3.2.2).

8.6 Adjust the voltage source VS_2 until voltmeter V_2 indicates the specified voltage value V_D (see 3.2.3 and 1.1).

8.7 Adjust voltage source VS_1 to change the gate voltage (indicated by voltmeter V_1) in the direction of increasing drain current, I_D, until a current is attained that is approximately 1 % of the specified value of I_{DM}(see 3.2.4).

8.8 Verify that voltmeter V_2 continues to read the specified value V_D and, if necessary, readjust voltage source VS_2 to obtain the specified value V_D.

8.9 Record the drain current, I_D, indicated by ammeter, *A* (see 6.3). Record the gate voltage, V_G, and call this voltage V_{GL}.

8.10 Adjust voltage source VS_1, to change the gate voltage an amount equal to $0.5\,|V_{GM} - V_{GL}|$ in the direction of decreasing drain current.

8.11 Verify that voltmeter V_2 continues to read the specified value V_D and, if necessary, readjust voltage source VS_2 to obtain the specified value V_D.

8.12 Record the current indicated by ammeter *A* and call it I_L. This is the drain leakage current to be used in this test method.

8.13 Adjust voltage source VS_1 until the gate voltage is at the nearest ΔV_G step below V_{GL}(see 3.2.4 and X1.4).

8.14 Adjust voltage source VS_1 to change the gate voltage by ΔV_G in the direction of increasing drain current.

8.15 Verify that voltmeter V_2 continues to read the specified value V_D and, if necessary, readjust voltage source VS_2 to obtain the specified value V_D.

8.16 Record the drain current, I_D, indicated by ammeter *A* and the gate voltage, V_G, indicated by voltmeter V_1.

8.17 Repeat 8.14, 8.15, and 8.16 until either I_{DM} or V_{GM}(see 3.2.4) is reached or until it is established that enough data points have been taken to determine the tangent with the largest slope.

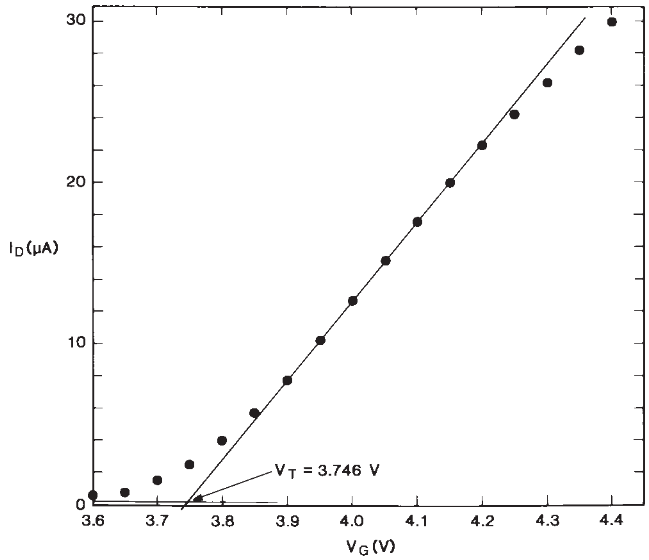
8.18 Measure and record the temperature of the package ambient. Record the average and the difference of the temperature measured here and in step 8.5; call these values the mean and the range of the package ambient temperatures, respectively.

9. Calculations and Interpretation

9.1 *Option I—Determination of Threshold Voltage by Graph Analysis*:

9.1.1 Data shall be graphed so that the gate voltage, V_G, is plotted on the abscissa and the drain current, I_D, is plotted on the ordinate (Fig. 2).

9.1.1.1 Select the voltage scale, V_S(voltage/cm), in accordance with the value of ΔV_G specified (see X1.4), as shown below:



NOTE 1—The size of the data points in this graph is grossly exaggerated for the purpose of clarity.

FIG. 2 Illustrative Data for an *n* -Channel Enhancement Device with a Reading of 3.746 V for the Threshold Voltage

ΔV_G(V)	V_S(v/cm)
0.02	≤ 0.02
0.05	≤ 0.05
0.10	≤ 0.05
0.20	≤ 0.10
0.50	≤ 0.20

9.1.1.2 Select the current scale, I_S(current/cm), so that

$$I_S \sim \frac{I_{DM} \cdot V_S}{10\, \Delta\, V_G}$$

using the value for V_S obtained in 10.1.1.1 and the values specified for $\Delta\ V_G$ and I_{DM}(see X1.2).

9.1.1.3 In each case, convenient scales for reading and graphing shall be used where the major unit (centimetre) is divided decimally and equals 1, 2, or 5×10^{r} units of voltage or current, where *r* is a positive or negative integer.

NOTE 4—The selection of the voltage scale is designed to maximize the accuracy with which V_T may be read from the graph while also allowing for the use of normal 18 by 25-cm graph paper. It is expected that no more than 8 to 10 data points will need to be plotted to determine the maximum tangent. The selection of the current scale is intended to have the angle that the maximum tangent line makes with the horizontal be approximately 45°. The selection of this limit is to reduce the effect of inherent errors in drawing the tangent on the V_T determination.

9.1.2 Graph data scales selected in 9.1.1. Only enough data points need be graphed to determine the maximum-slope tangent to the curve formed by connecting the data points (see 9.1.3 and 9.1.4). Generally, data points at both ends of the data series will not need to be graphed.

9.1.3 Define the best straight-line fit to any three consecutive data points as a tangent to the curve of 9.1.2.

9.1.4 As determined by eye, find the tangent with the largest slope (maximum tangent) as follows: Beginning with the three consecutive data points graphed in 9.1.2 having the lowest drain currents and advancing one data point at a time, compare the slopes of consecutive tangents until a tangent is found that is followed directly by two tangents which have slopes that are equal to or are less than the slope of the said tangent. This tangent is called the maximum tangent. If there are insufficient data points available to find the maximum tangent, the values for I_{DM} and V_{GM} selected in X1.2 may be too small or the value for $\Delta\ V_G$ selected in X1.4 may be too large. If this is the case, one or more of the selected values must be altered appropriately and the method repeated.

9.1.5 With the use of a straightedge and a fine-pointed pencil, or equivalent, draw the maximum tangent of 9.1.4 so that it extends downward to zero current.

9.1.6 Identify on the graph the three data points used to define the maximum slope.

9.1.7 Draw a horizontal line parallel to the abscissa at a level corresponding to the leakage current determined in 8.12.

9.1.8 Determine and record the voltage corresponding to the intersection of the two lines drawn in 9.1.5 and 9.1.7. Determine the intersection by reading the graph.

9.1.9 Count the number of data points between the voltage recorded in 9.1.8 and the voltage of the second data point defining the maximum tangent.

9.1.10 If the number determined in 9.1.9 is larger than two or if $V_G = 0.02$, then the voltage recorded in 9.1.8 is the threshold voltage, V_T, for the drain voltage and temperature conditions of the test. Record the value of V_T on the graph of 9.1.1.

9.1.11 If the conditions stated in 9.1.10 do not hold, the value for ΔV_G selected in X1.4 is too large and the method must be repeated using an appropriately reduced value for ΔV_G.

NOTE 5—To ensure that the threshold voltage measurement was made in the linear region of operation, examine the plot. If the lowest value of the gate voltage that lies on the line of maximum slope (drawn in 9.1.5) is greater than the sum of the drain voltage and the threshold voltage, the threshold voltage was determined for the linear region of operation.

9.1.12 If a value for the temperature coefficient of the threshold voltage (α) is available for the devices under test, proceed to 9.1.14. Otherwise, repeat the procedure up to and including 9.1.10 with a representative sample of the MOSFETs being tested at two temperatures, T_1 and T_2. Make sure that T_1 is within the permissible range of ambient temperatures (see 3.2.2), and make sure that $T_2 - T_1$ is greater than about 15°C.

9.1.13 Determine the average for the values of α from the representative sample of MOSFETs and use this average value in 9.1.14. The values of α shall be obtained by using the equation:

$$\alpha = \frac{V_T(2) - V_T(1)}{V_T(1)\,(T_2 - T_1)} \tag{1}$$

where V_T (1) and V_T (2) are the threshold voltages at temperatures T_1 and T_2, respectively.

9.1.14 Normalize V_T, the threshold voltage obtained in 9.1.10, to the threshold voltage, V_{Tr}, at the reference temperature T_r(see 3.2.1), using the following equation:

$$V_{Tr} = V_T\,[1 + \alpha(T_r - T)] \tag{2}$$

where V_T is the threshold voltage measured at the test temperature of T and α is the value for the threshold voltage temperature coefficient of the devices under test. Record the value of V_{Tr} on the graph of 9.1.1.

9.2 *Option II—Determination of Threshold Voltage by Calculation*:

9.2.1 Graph data either by machine or manually so that the gate voltage, V_G, is plotted on the abscissa and the drain current, I_D, is plotted on the ordinate as shown in Fig. 2. Only enough data points required in 9.2.3 need be graphed.

9.2.2 Define the best straight-line fit to any three consecutive data points as a tangent to the curve of 9.2.1.

9.2.3 As determined by linear regression, find the tangent with the largest slope (maximum tangent) as follows: Beginning with the three consecutive data points graphed having the lowest drain currents and advancing one data point at a time, compare the slopes calculated of consecutive tangents until a tangent is found which is followed directly by two tangents which have slopes that are equal to or are less than the slope of the said tangent. This tangent is called the maximum tangent. If there are insufficient data points available to find the maximum tangent, the values for I_{DM} and V_{GM} selected in X1.2 may be too small or the value for ΔV_G selected in X1.4 may be too large. If this is the case, one or more of the selected values must be altered appropriately and the method repeated.

9.2.4 Identify the three data points defining this tangent on the graph of 9.2.1.

9.2.5 Determine by calculation and record the gate voltage at which the tangent line of 9.2.3 would intersect a horizontal line (parallel to the abscissa) at the level corresponding to the leakage current determined in 8.12.

9.2.6 Determine the number of data points between the voltage recorded in 9.2.5 and the voltage of the second data point defining the maximum tangent.

9.2.7 If the number determined in 9.2.6 is larger than two or if $V_G = 0.02$, then the gate voltage recorded in 9.2.5 is the threshold voltage, V_T, for the drain voltage and temperature conditions of the test. Record the value of V_T on the graph of 9.2.1 (see Note 5).

9.2.8 If the conditions stated in 9.2.7 do not hold, the value for ΔV_G selected in X1.4 is too large and the method must be repeated using an appropriately reduced value for ΔV_G.

9.2.9 If a value for the temperature coefficient of the threshold voltage (α) is available for the devices under test, proceed to 9.2.11. Otherwise, repeat the procedure up to and including 9.2.7 with a representative sample of the MOSFETs. Each MOSFET shall be tested at two temperatures, T_1 and T_2. Make sure that T_1 is within the permissible range of ambient temperatures (see 3.2.2), and make sure that $T_2 - T_1$ is greater than about 15°C.

9.2.10 Determine the average for the values of α from the representative sample of MOSFETs and use this average value in 9.2.11. The values of α shall be obtained by using the following equation:

$$\alpha = \frac{V_T(2) - V_T(1)}{V_T(1)\,(T_2 - T_1)} \tag{3}$$

where V_T (1) and V_T (2) are the threshold voltages at temperatures T_1 and T_2, respectively.

9.2.11 Normalize V_T, the threshold voltage obtained in 9.2.7, to the threshold voltage V_{Tr} at the reference temperature, T_r(see 3.2.1), using the following equation:

$$V_{Tr} = V_T[1 + \alpha\,(T_r - T)], \tag{4}$$

where V_T is the threshold voltage measured at the test temperature of T and α is the value used for the threshold voltage temperature coefficient of the devices under test. Record the value of V_{Tr} on the graph of 9.2.1.

10. Report

10.1 Report, as a minimum, the following information:

10.1.1 Identification of operator,

10.1.2 Date of test,

10.1.3 Device type and identification of MOSFET tested,

10.1.4 The mean and range of the package ambient temperature,° C,

10.1.5 Upper-limit values of gate voltage, V_{GM}, and drain current, I_{DM},

10.1.6 Drain voltage, V_D,

10.1.7 Measured value of drain-leakage current, I_L, the drain voltage, V_D, and gate voltage, V_G, at which it was measured,

10.1.8 The curve drawn in 10.1.1 or 10.2.1,

10.1.9 The value of the temperature coefficient used to determine V_{Tr},

10.1.10 The threshold voltages V_T and V_{Tr}, and

10.1.11 Identification of the option used to determine V_T.

11. Precision and Bias

11.1 A parallel-mode interlaboratory experiment, involving three MOSFET device types, was conducted with a reference laboratory and seven participating laboratories. Each participating laboratory measured four test devices from each of the three device types. The test devices of each type were selected to have similar drain-current, gate-voltage characteristics. This was done to permit the devices of a given type to be considered as equivalent for the purposes of the experiment.

11.2 The measure used in the analysis of the interlaboratory experiment for precision is D_{ij}, which is the threshold voltage for the *j*-th device as measured by the *i*-th laboratory minus the threshold voltage for that device as determined earlier by the reference laboratory. The analysis for bias between the reference laboratory and each of the participating laboratories used *t*-values defined as the ratio of the difference value mean,

$$D_i = \sum_{j=1}^{4} = D_{ij} / 4. \tag{5}$$

to the standard deviation of the mean.

11.3 The results of the interlaboratory experiment indicate that the reproducibility of the threshold voltage measurements, when normalized to a reference temperature, was within 15 mV for either of the two options. No bias, at a 95 % confidence, was observed for either of the two options.

11.4 The three MOSFET device types selected for the experiment were the M116, SD213DE, and CD4007UBE. The first two are discrete *n*-channel enhancement devices in TO-72 packages. The third is an integrated circuit in a 14-lead DIP package from which two *p*-channel enhancement devices were accessed. The mean values for the linear threshold voltage for these devices were about 1.8, 1.2, and −1.4 V, respectively. The temperature coefficient of the threshold voltage for the three types of devices were measured with a sample of four devices from each type. The mean values obtained were used to normalize the threshold voltage data to 24°C before being analyzed.

11.5 The reproducibility for device type M116 was about 15 mV while for the other types it was about 8 mV. The difference is conjectured to be due to the difference in the temperature coefficient of the threshold voltage. This temperature sensitivity was −4.6 mV/°C for the M116 type devices which is approximately double that of the other types. This difference would accordingly accentuate the effect of uncertainties or variations in the device temperature during the test.

11.6 The experiment also indicated that Option II requires care in its application in that outlier points and even some small scatter of points can introduce significant variability. These problems are more apt to be detected and corrected for in Option I than in Option II.

12. Keywords

12.1 drain leakage current; linear threshold voltage; MOSFET; *n*-channel; *p*-channel; threshold voltage

APPENDIX

(Nonmandatory Information)

X1. RECOMMENDED PROCEDURE FOR SELECTING MAXIMUM DRAIN CURRENT, MAXIMUM GATE VOLTAGE, AND GATE-VOLTAGE STEP

X1.1 To select appropriate values for the maximum drain current, I_{DM}, the maximum gate voltage, V_{GM}, and the gate-voltage step, ΔV_G, will require some knowledge of the drain-current, gate-voltage ($I_D – V_G$) characteristic curves for the devices to be measured. Adequate estimates will be needed of the range over which the inflection-point coordinates and the threshold voltages will vary. In particular, estimates of the following will be required:

V_T(typ) typical threshold voltage,
V_T(lo) lowest threshold voltage,
V_{GI}(typ) typical gate voltage at an inflection point,
I_{DI} (hi) highest drain current at an inflection point, and
V_{GI} (hi) highest gate voltage at an inflection point.

Estimates which result in values for I_{DM} and V_{GM} that are too low or a value of ΔV_G that is too high will require that the method be repeated with revised values (see 10.1.4 and 10.1.11 or 10.2.3 and 10.2.8).

X1.2 Select values for I_{DM} and V_{GM} as follows:

$$I_{DM} \gtrsim 2\, I_{DI}(\text{hi})$$
$$|V_{GM} - V_{GI}(\text{hi})| \gtrsim |V_{GI}(\text{hi}) - V_T(\text{lo})| \quad (X1.1)$$

The relationship of these estimates and I_{DM} and V_{GM} is illustrated in Fig. X1.1.

X1.3 The value of ΔV_G to be used in the method is determined from

$$\Delta V = \frac{|V_{GI}(\text{typ}) - V_T(\text{typ})|}{5}$$

X1.4 To select the value for ΔV_G, choose the value from the following list which is closest to the ΔV calculated in X1.3: 0.02, 0.05, 0.10, 0.20, 0.50 V. Linking ΔV_G to ΔV is intended to result in approximately four data points being taken between the threshold voltage and the inflection point, thereby allowing an adequate number of points to establish the maximum tangent.

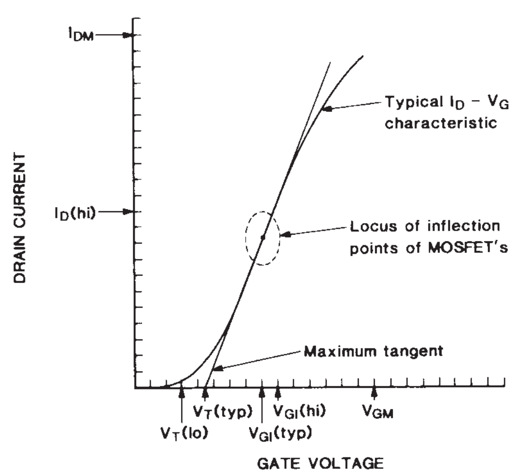


FIG. X1.1 Illustration of Parameters Defined in Appendix on Graph of Typical $I_D – V_G$ Characteristic of a Lot of MOSFETs