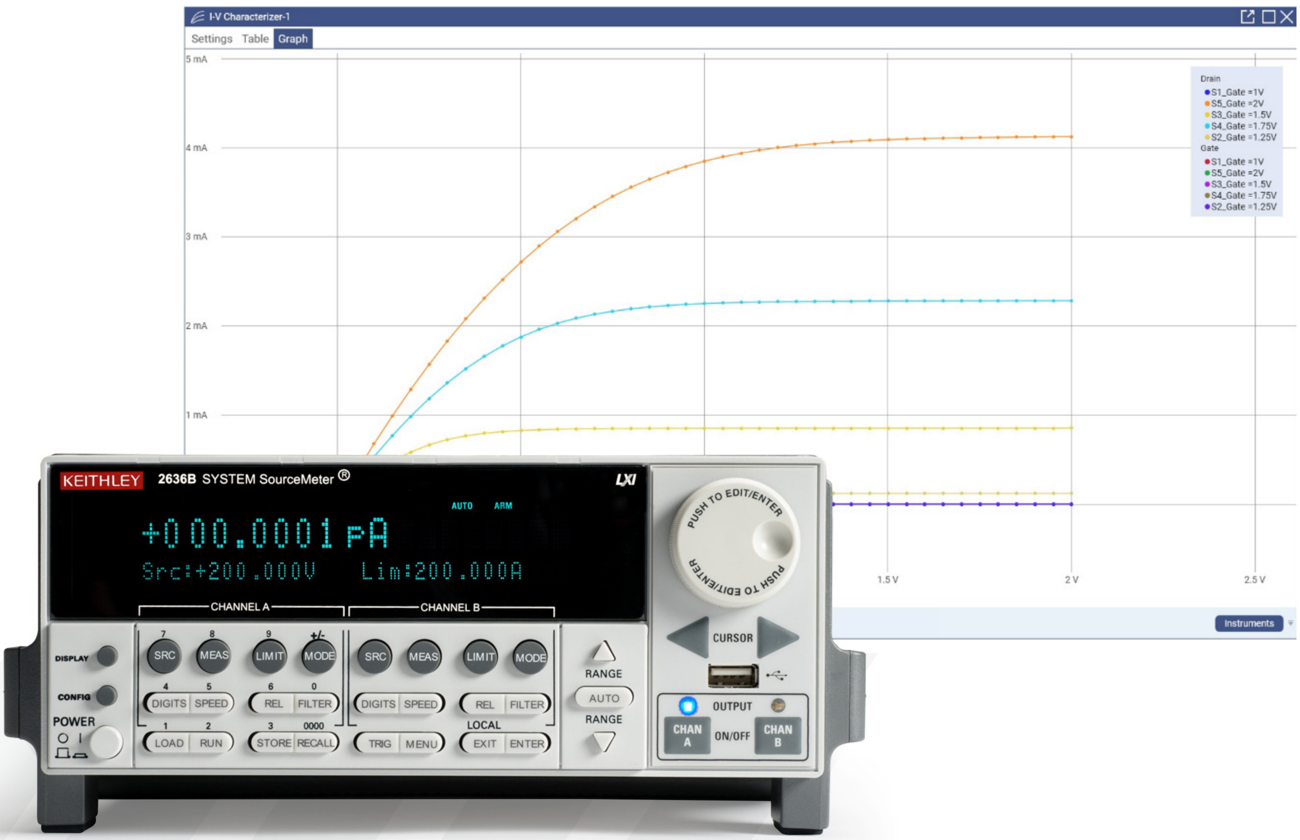
Tektronix®

DC I-V Characterization of MOSFET Devices Using KickStart Software

APPLICATION NOTE



Introduction

The MOSFET (Metal Oxide Semiconductor Field Effect Transistor) is one of the most common transistor devices in modern electronic circuit designs. There are a wide variety of materials and structures being introduced to specific applications, but the MOSFET structure and its working principle exhibit continuous widespread adaptation. They have been primarily used for switching and power amplifier applications. MOSFETs have excellent performance in electrical switching circuits because the devices have two opposing electrical characteristics which control very low current in the off-state and some amount of current in the on-state. MOSFETs can be worked as an amplifier itself with some other devices or used as a part of operational amplifiers which are common devices in analog circuits. Source measure units (SMUs) are the instruments best suited to conduct the DC I-V characterization of MOSFET devices because SMUs can cover a broad range of source and measurement needs. Keithley provides various SMU models and software to characterize the MOSFET devices. Specifically, the Series 2636B/35B/34B System SourceMeter® Instrument covers low current down to a 100 pA range and 0.1 fA resolution. The KickStart software features the I-V Characterizer app to be able to test the behaviors of different discrete components. This note is to focus on showing how the DC I-V characterization of the MOSFET can be accomplished using the 2636B System SourceMeter® Instrument and the KickStart Instrument Control Software.

MOSFET Device

The MOSFET device is a silicon-based semiconductor and shown in **Figure 1**. There is an oxide layer grown on the silicon semiconductor layer and the metal layer is placed on the top of the oxide as the gate. From top to bottom, the structure should be metal, oxide, and semiconductor and, therefore, identifiable as a MOS structure. There are three electrodes in the MOSFET — gate , drain, and source — to operate the device. In the case of an n-type MOSFET, the semiconductor layer must be a p-type silicon substrate created by doping an impurity on the silicon to ensure the holes are the majority carriers. The hole in the atomic structure of the silicon is intended to lose an electron when the impurity material is added on the generic silicon so that the more holes can make more positive charges. The oxide is a very thin layer produced by combining oxygen with silicon (SiO_2). It works as an insulator to prevent any current flow from the gate to the semiconductor area. The impurity implanted semiconductor can act as a conductor or an insulator depending on the gate, drain, and source bias conditions. The MOS (Metal Oxide Semiconductor) portion of the term "MOSFET" is indicative of the structure of the device.

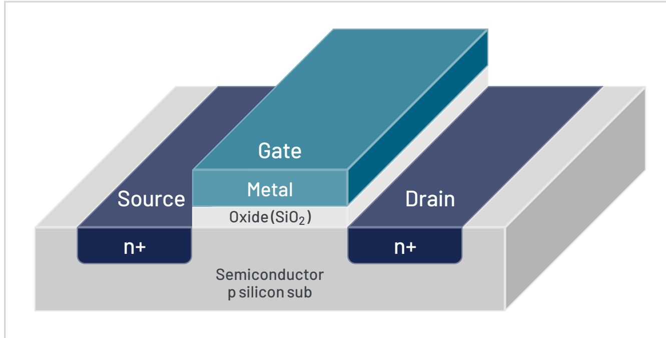


Figure 1. N type MOSFET structure.

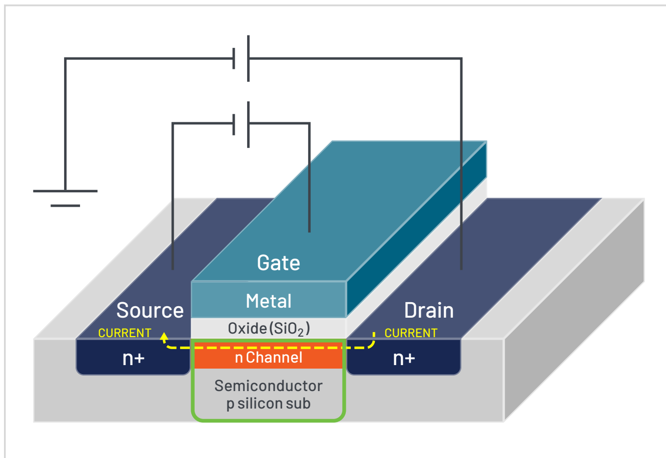


Figure 2. N type MOSFET operation.

The typical gate current flowing to the substrate and to the source may be less than 1 pA. When a positive voltage higher than the threshold voltage is applied on the gate, then the majority carriers move away from the oxide and the minority carriers which are free electrons move underneath the oxide in **Figure 2**. This electric field is called a channel and the current can flow through the channel from the drain to the source working as a conductor. When no gate voltage bias or any negative bias is applied then the device works as an insulator and no current can flow. The FET (Field Effect Transistor) implies the operation principle of the MOSFET device.

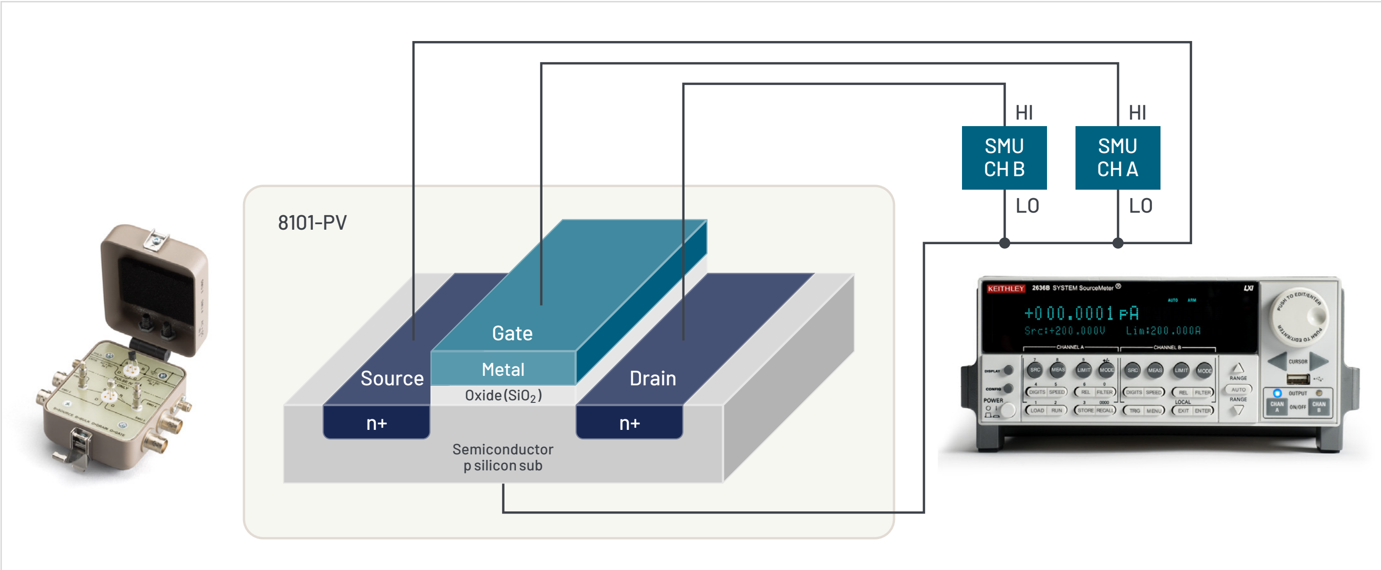


Figure 3. Test setup for MOSFET.

Instrument Connection for MOSFET Test

Two SMU channels are required for these tests and a dual-channel instrument from the Series 2600B System SourceMeter line is recommended. The 8101-PIV fixture is recommended for connections to the FET under test when the voltage does not exceed 42 VDC. If lethal voltages may be exposed when the test fixture lid is open, a safety interlock circuit must be connected before use to avoid a possible shock hazard. Triaxial cables are recommended to make connections to the fixture from instrument.

MOSFET Transfer Characteristic

The transfer characteristic of MOSFET devices is a measure of the drain current as output versus the gate voltage as input. This is referred to as a Vgs-Ids test because it shows the drain current characteristic with respect to changes in the gate voltage. Typically for this transfer test, a fixed voltage is applied to the drain while the voltage sweeps at the gate from slightly negative to some amount of positive bias for an n-type MOSFET. **Figure 4** shows settings for this test case, with the voltage for the gate sweeping from −0.5 V to 3 V with 101 points and the drain at a fixed bias of 0.05 V. Note that the measure settings for the drain use auto range so that the SMU channel can cover current measurement from the lowest level to the maximum level of the device. If the device may be capable of high power and high current, the 4-Wire Sense mode is recommended for the drain.

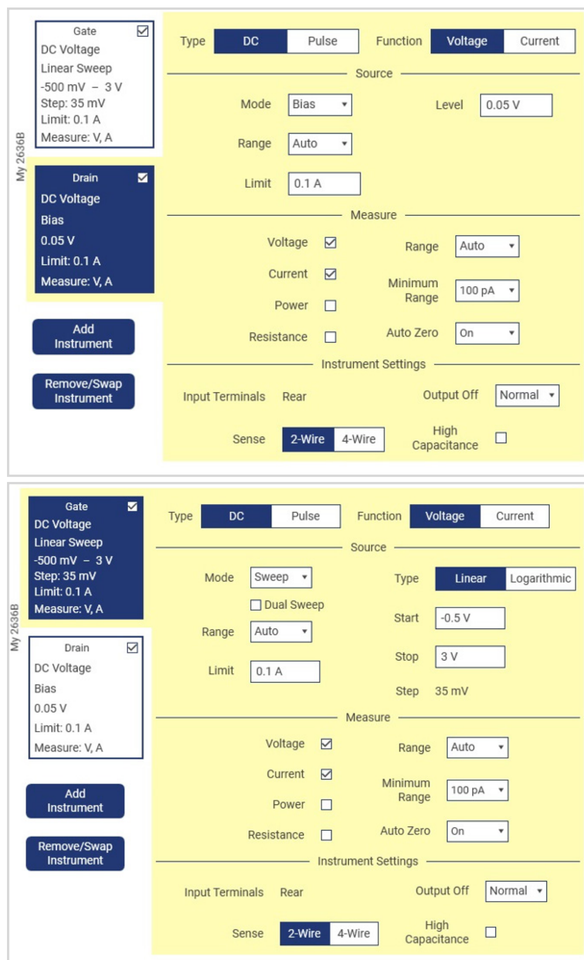


Figure 4. Drain (top) and gate (bottom) settings for transfer measurement in KickStart.

Figure 5 shows the transfer characteristic results for the demo device in linear scale. The x-axis is the gate voltage sweeping from –0.5 V to 3 V as the input source to the device and the y-axis is the current measurement at the drain. The drain current is shown to be about 0 A as the gate voltage approaches 1 V and steadily increases thereafter. The area beyond the 1 V point where some quantity of current flows is identified as the on-state of the device.

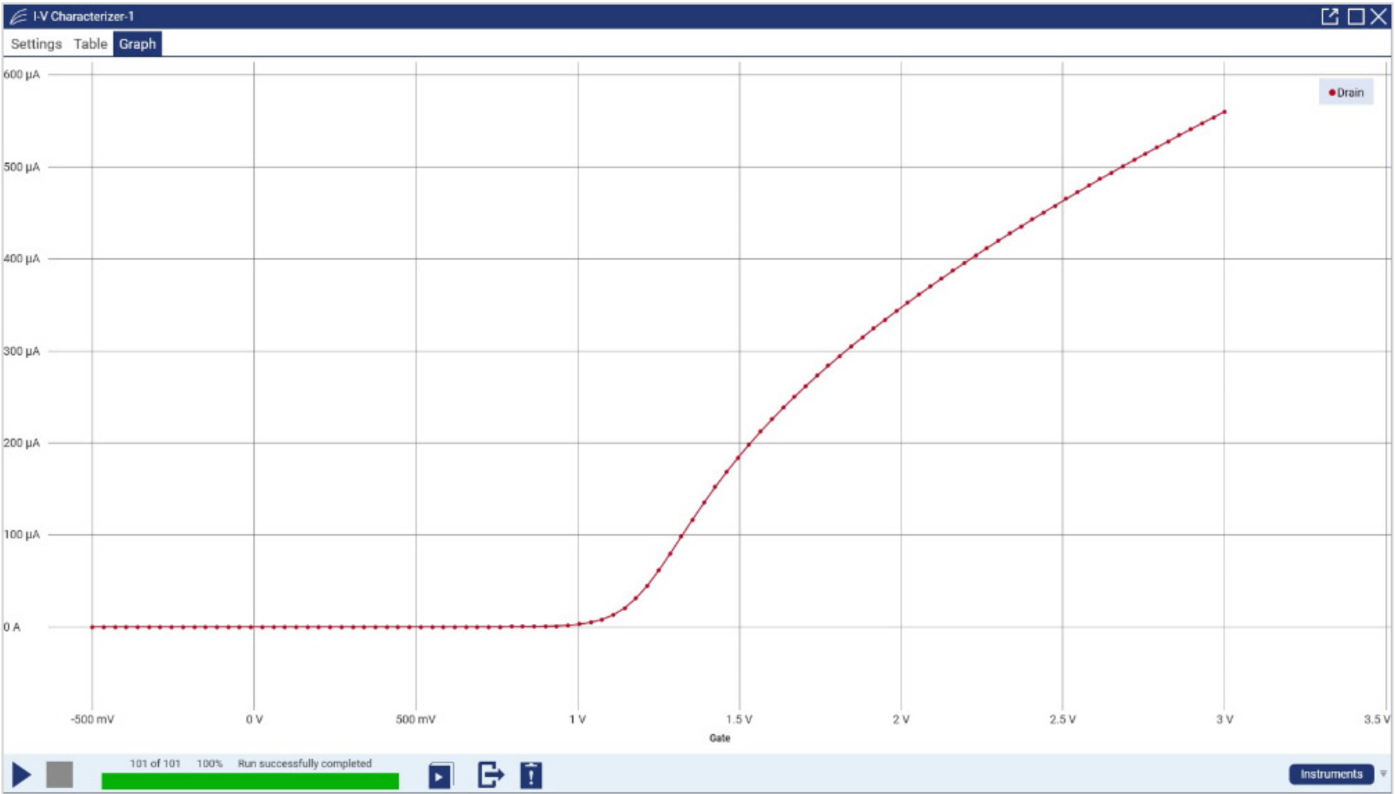


Figure 5. Transfer curve in linear scale shown in the KickStart I-V Characterizer App.

For detailed analysis, the transfer curve is usually displayed using a logarithmic scale as shown in **Figure 6** to better help visually identify low level activity in the drain current prior to and through the point at which it starts to substantially conduct over each individual gate bias sweep point. From the gate voltage 0 V to 1 V, there is still some current flowing. While the gate voltage remains below 0 V no drain current flows and the device is completely shut off. This is referred to as the device off-state. The leakage current of the off-state device is an item of serious concern because a higher leakage can contribute to unprecedented power loss in the application circuits. In this case, the leakage current is less than 60 fA when the gate bias is below 0 V. A Keithley Series 2636B/35B/34B SMU will support below 1 pA leakage current measurement.

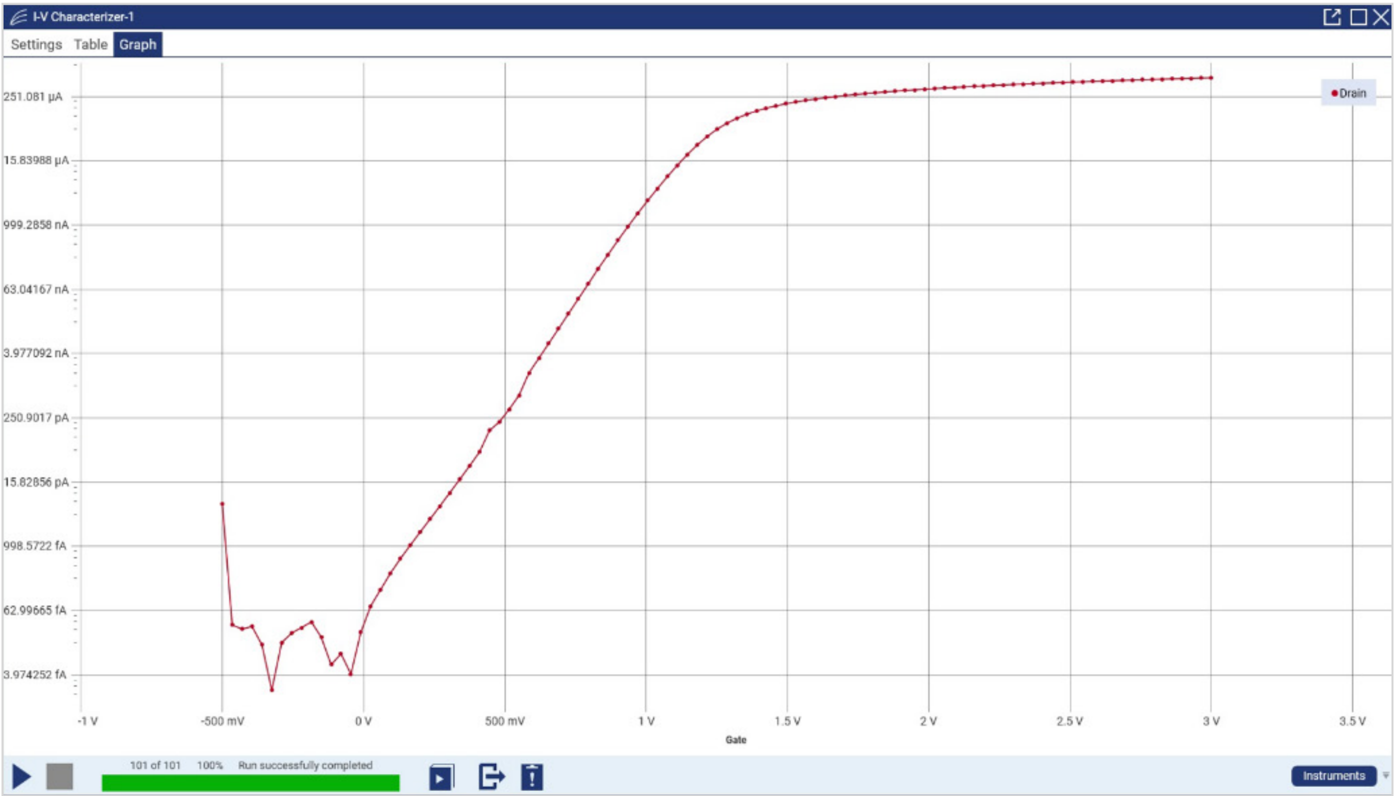


Figure 6. Transfer curve in logarithmic scale shown in the KickStart I-V Characterizer App.

Another benefit of the transfer characteristic is to be able to figure out the transconductance curve and the threshold voltage of the device. The KickStart software provides all the raw data inclusive of test settings and measurements. This data can be exported to a spreadsheet program such as Microsoft Excel. The transconductance (Gm) can be plotted and the Vth can be calculated as shown in **Figure 7**.

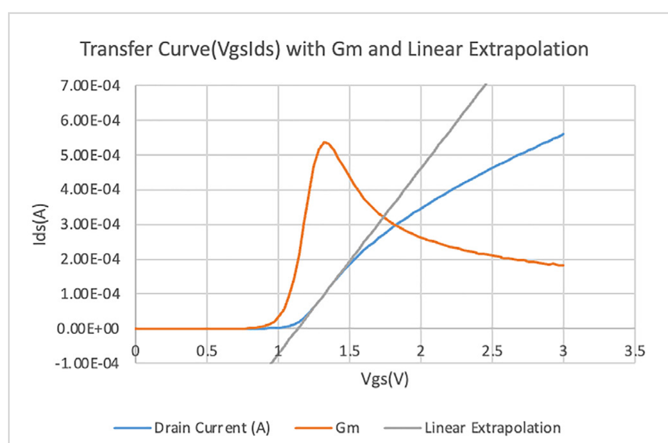


Figure 7. Transfer curve with transconductance and tangent.

The transconductance is the derivative of the transfer curve which is the slope of each measurement point, and it is described as:

$$Gm = \frac{\Delta Ids}{\Delta Vgs}$$

Many methods have been introduced to calculate the threshold voltage. The linear extrapolation method is the most widely used to extract the threshold voltage. It must first be determined that the gate voltage axis intercepts at the 0 A drain current of the linear extrapolation where the transfer curve is at the maximum transconductance point. Then the threshold voltage is calculated by adding half the drain voltage. The Vth calculation in this case is 1.16 V using the linear extrapolation method.

MOSFET Output Characteristic

The output characteristic is obtained by sweeping the gate voltage across the desired range of values in specific increments. A voltage is applied at the device gate, the drain voltage is then swept through the required range, once again at the desired increments, with the drain current measured at each of the corresponding drain voltage points. Plots can then be made from this data to show Vds-Ids with curves corresponding to each of the specified gate voltage levels. **Figure 8** shows a specific example of the output characteristic test setup for the demo DUT. The drain is swept from 0 V to 2 V in 50 mV increments. The gate is incremented from 1 V to 2 V using 0.25 V steps and should be enabled as a stepper in the common settings. This will generate five drain family curves.

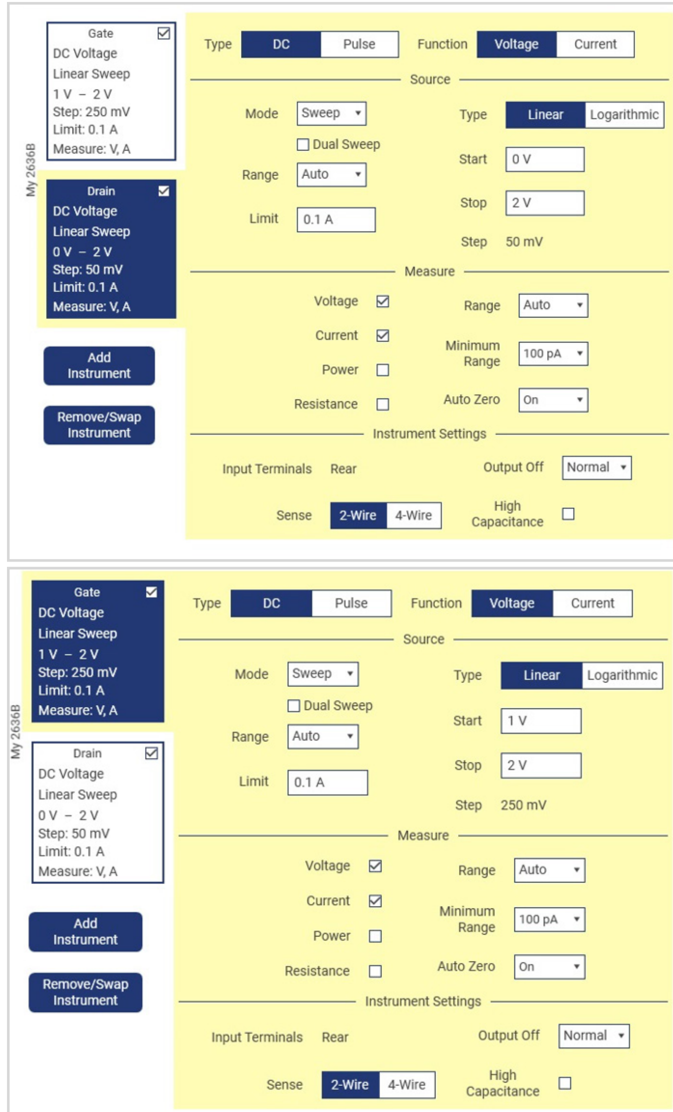


Figure 8. Drain (top) and gate (bottom) settings for output measurement in KickStart.

Figure 9 shows the result of the output characteristic test using a linear scale. As the drain voltage increases, the drain current grows and saturates with some level of current. Note how the current ceases to increase beyond some level of drain voltage. This area where the current plateaus is called the saturation region. The interval over which the current increases is called the linear or ohmic region. The drain voltage point that identifies the transition between these two regions is the pinch-off voltage. After the pinch-off voltage has been reached, the drain current levels of the saturation are importantly considered in the device characterization for the power amplifier circuit applications. Gate voltage settings less than the threshold voltage are not necessary for determining the output characteristics because the drain output current would be too low and not clearly shown. Note, in this case, that the output drain current (when the applied gate voltage is 1 V) is almost 0 A all the way to the maximum drain voltage.

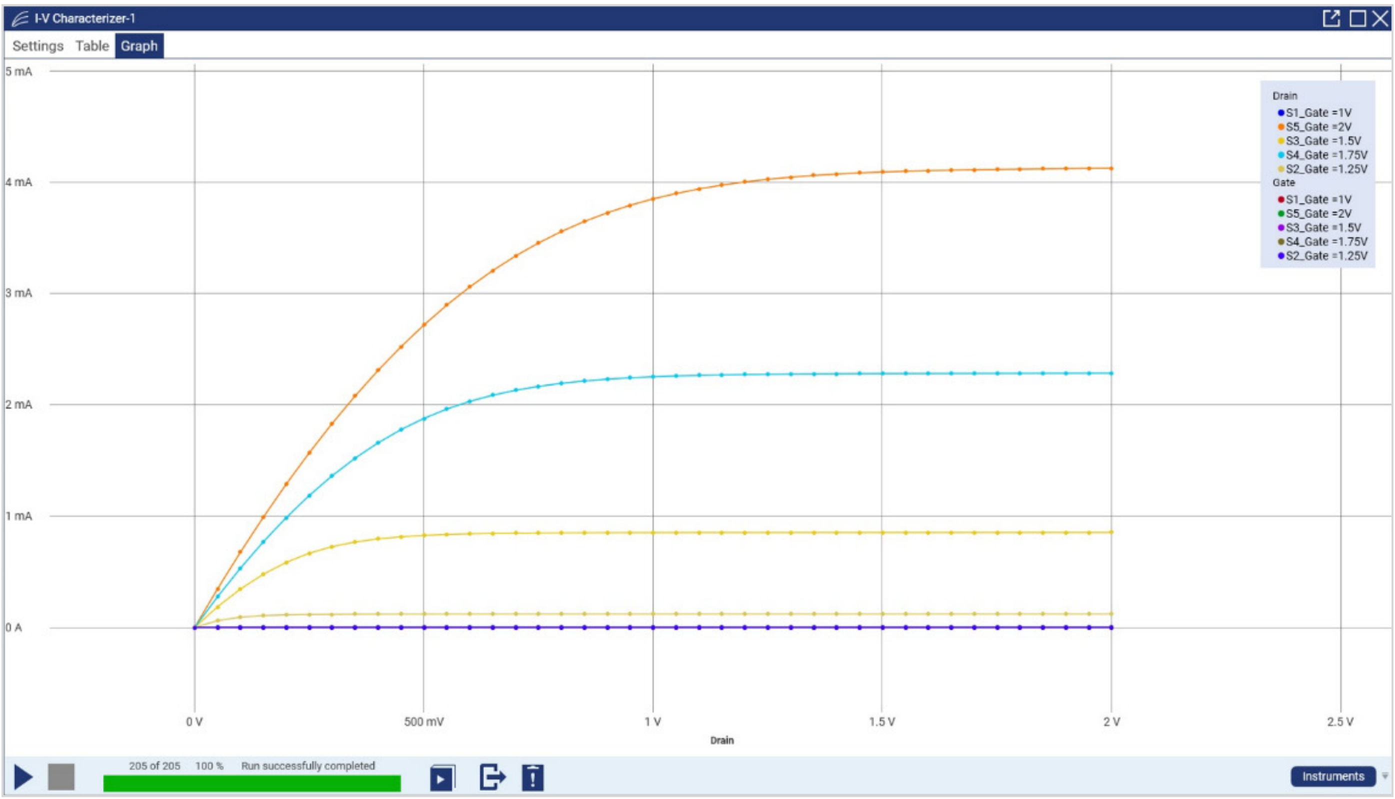


Figure 9. Output curve shown in the KickStart I-V Characterizer App.

There are other possible DC I-V characterizations of MOSFET devices with SMU instruments using the KickStart software. The breakdown voltage test is one of the important off-state characteristics. Using the same device connections, the gate and source voltages are biased at 0 V while the drain voltage is swept. At the extreme end of the drain sweep, the device will no longer be able to impede the flow of current and will start to conduct, and the current level at this transition point is defined as a breakdown current. The voltage read at this same point is deemed to be the breakdown voltage for the device. The leakage current of the drain at the off-state and the drain current at the specific condition can be easily tested using the KickStart software.

Conclusion

MOSFET devices continue to be used in switching circuits and power amplifier circuit applications, and DC I-V is still common and necessary for basic characterization of a MOSFET device. Keithley's KickStart software and Series 2636B/35B/34B SMUs make for a great solution that allows users to achieve the transfer, output, and other device characteristics.

Please visit the KickStart Software product page to learn more.

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