Accurate and Efficient Characterization of Power Devices at 3000 V/20 A

Agilent B1505A Power Device Analyzer/Curve Tracer
Application Note B1505-1

Introduction

Driven by the twin requirements of improved energy efficiency and lower carbon emissions, the need for accurate power device characterization continues to take on increased importance. Device structures and fabrication processes are being improved, and new wide band gap (WBG) semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN), are being studied to support higher voltages and provide a lower turn-on resistance. Meeting these needs requires a measurement instrument with the ability to handle both high voltage and high current.

Curve tracers have traditionally been used for power device characterization, but they have poor voltage and current measurement accuracy and they lack low current measurement resolution. Parameter analyzers such as the Agilent B1500A have very good voltage and current measurement accuracy, but they do not have the wide voltage and current ranges necessary for power device evaluation. To solve these issues, Agilent has introduced the B1505A Power Device Analyzer/Curve Tracer. It provides an easy-to-use one-box solution that combines superb voltage and current measurement accuracy and low-current measurement resolution with high voltage and high current measurement capability. The B1505A’s new HVSMU (High Voltage Source Monitor Unit) can source voltages up to 3000 V, and the B1505A’s new HCSMU (High Current Source Monitor Unit) can supply currents of up to 20 A.

The B1505A also supports an MFCMU (Multi Frequency Capacitance Measurement Unit), which can measure capacitance at frequencies ranging from 1 kHz up to 5 MHz. In addition, the B1505A supports a bias-T that works with the HVSMU to enable capacitance measurements to be made at up to 3000 V of DC bias.

Agilent EasyEXPERT software, which is resident on both the B1500A and B1505A, provides convenient GUI-based control for all of these measurement resources. EasyEXPERT’s impressive auto analysis, graphical, and data manipulation capabilities create an all-in-one solution for power device characterization and analysis. EasyEXPERT eliminates the burdens of having to develop your own control software and having to configure multiple instruments in a custom rack and stack system.

This application note introduces the B1505A’s key benefits, and describes several practical measurement examples. Characterization of both power MOSFET and bipolar transistors will be covered, as well as devices using unique state-of-the-art materials.
All-in-one solution for multiple power device characterization needs

To increase energy efficiency in electric and electronic equipment, power devices such as power diodes and transistors have focused on three key areas: increasing high voltage tolerance, lowering the on-resistance, and decreasing the parasitic capacitance. These characteristics are important because they improve circuit switching speeds, and this is one of the key techniques used to reduce power consumption and improve energy efficiency in power circuit design. Unfortunately, from a power device development point of view these characteristics are at odds with one another. This often means that designing a device for a target application requires a lot of trial and error and repeated design cycles.

The following measurement capabilities are critical for effective and accurate power device evaluation:

- Accurate high-voltage sourcing and measurement capabilities to characterize device breakdown voltages
- Accurate high-current sourcing and measurement capabilities to measure small values of on-resistance
- Precise capacitance-voltage (CV) measurement capabilities at DC biases up to the maximum device voltage rating

Breakdown voltage measurements require that the measurement equipment at least be able to source voltages up to the device breakdown voltage. High-power silicon MOSFETs can have breakdown voltages of more than 1500 V, and new materials such as SiC can have breakdown voltages exceeding 2000 V. This means that measurement equipment must be able to source up to and beyond 2000 V. In addition, during the breakdown measurement the leakage current needs to be precisely monitored, since detailed current-voltage (IV) characteristics are necessary to determine important parameters such as defect density. Conventional curve tracers can supply high voltage, but their current measurement accuracy is in the tens of microamps (µA) level in AC or rectified AC mode and in the nanoamp (nA) level in leakage mode. This accuracy is insufficient for new materials (such as SiC, GaN, etc.) that require picoamp (pA) level leakage current measurements. The B1505A HVSMU easily meets these needs since it can force voltage up to 3000 V while measuring currents with sub-pA accuracy.

Narrow pulse widths and accurate measurement capabilities are crucial for evaluating the on-state characteristics of power devices at high current. When large currents flow through power devices a great deal of heat can be generated that can cause thermal drift. In the case of power MOSFETs, large drain currents can create channel self-heating that in-turn reduces carrier mobility and alters the transistor characteristics. Pulsed bias measurements can minimize this effect by reducing the duration of the power dissipation and thereby suppressing the self-heating.

Conventional curve tracers can measure voltages down to the millivolt (mV) level with 50 µV resolution; however this resolution level requires low on-resistance (milliohm range) devices to use currents of greater than 1 A. The HCSMU supports a 200 mV voltage measurement range, which is an order of magnitude better than the minimum voltage measurement range of the HPSMU (which is 2 V). This permits the HCSMU to measure voltage down into the microvolt range (~100 µV), thereby enabling accurate milliohm on-resistance measurements.

Agilent B1505A Key Benefits

The B1505A has many features that culminate in the following key benefits:

- All-in-one solution for multiple power device characterization needs
- Improved efficiency and automated measurement
- Easy data extraction and analysis (both numerical and graphical)
The HCSMU can also supply up to 20 A at 20 V in pulsed mode, with a minimum pulse width of 50 µs (an industry first). This pulsing capability represents a significant improvement over that of the 4142B’s HCU (High Current Unit), which had a minimum pulse width of 100 µs. In summary, the B1505A supports stable and accurate sub-milliohm level on-resistance measurements through its ability to force up to 20 A in pulsed mode (thereby avoiding self-heating effects), and these capabilities satisfy low on-resistance measurement requirements for both current and future semiconductor devices. Figure 1 shows a low resistance measurement example performed on a wire. The HCSMU sweeps the output current from -50 mA to +50 mA with a 1 mA step, and voltages of a few hundred microvolts are accurately measured. A regression analysis results in a line with a slope of 4.189614E–003 that is equal to the resistance of 4.19 mΩ.

Capacitance-voltage (CV) measurements are commonly used to measure transistor parasitic capacitance for device modeling or model parameter extraction purposes, and to derive other important semiconductor device parameters such as oxide thickness, doping concentration, interface state density and defect density. In the past, DC bias voltage ranges of ±40 V or ±100 V have been sufficient to characterize Si VLSI and low power devices. In contrast, power devices require that CV measurements with DC bias voltages at their maximum rated value be made in order to correlate the parasitic capacitance with switching performance. The B1505A supports an external high-voltage bias-T that allows the HVSMU and MFCMU (Multi-Frequency Capacitance Measurement Unit) to work together and make CV measurements with DC biases of ±3000 V at frequencies ranging from 10 kHz to 1 MHz.

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**Improved efficiency and automated measurement**

The B1505A has several automated test features that can improve efficiency. The B1505A supports the module selector unit, which is a unique piece of hardware that allows the user to switch between the HPSMU, HVSMU, and HCSMU modules automatically and easily, without having to change any cables. EasyEXPERT software also supports a quick test mode that permits test sequencing and automated testing without the need to write any code.

Power MOSFETs are one of the most commonly characterized power devices. Important device parameters include breakdown voltage, on-resistance and sub-threshold leakage current; these parameters require the HVSMU, HCSMU, and HPSMU (respectively). Unfortunately, since each of these tests requires a different measurement module you have to reconfigure or reconnect the SMU to the device under test (DUT) each time you change the test. The need to frequently change the device connections reduces efficiencies and creates the risk of device damage if the connections are made incorrectly. In particular, frequent changes to the device connections can become especially tiresome when working on a wafer prober. For these reasons, some means to automate the switching between the HVSMU, HCSMU and HPSMU modules is highly desirable.

The B1505A module selector unit supports automated switching between the HPSMU, HVSMU and HCSMU as shown in figure 2. You have only to select the desired SMU measurement resource and the module selector unit will automatically create the correct switch settings. In addition, a 100 kΩ protection resistor can be placed in series with the HVSMU to prevent the DUT from being inadvertently damaged. The end results are an elimination of improper connections and an improvement in overall operating efficiency.

The quick test function enables you to perform test sequencing without programming and transforms automated testing into a simple, single-click operation. The combination of the quick test mode and the module selector unit results in a much more error-free and efficient automated test environment. This is especially true when executing measurements in a semi-automatic wafer prober environment, where the B1505A and module selector unit can easily support fully automated wafer probing across an entire wafer.

*Figure 2. The module selector unit provides an easy means to automate the B1505A’s various resources*
Easy data extraction and analysis
(both numerical and graphical)

EasyEXPERT has powerful graphical
analysis capabilities that can improve
your data processing efficiency and
simplify high power device parameter
extraction. This section explains
these features and shows how they
can be used to reduce development
times.

Spreadsheet software programs
such as Microsoft® Excel® are
popular for data processing and
parameter extraction, but they are not
necessarily the best tools for power
device evaluation. Spreadsheets can
generate graphs in semi-log and
log-log formats to show exponential
relationships such as diode IV
characteristics, but they do not
support data search features such as
a marker function. Locating a
specific data value requires a visual
search, and this is not a particularly
efficient technique for data analysis.
In contrast, EasyEXPERT has a
graphical marker function that you
can move along a curve to locate a
target value using the rotary knob
or mouse wheel. The marker values
are displayed in the graph area as
shown in figure 3. If the interpolation
is turned on, then the marker function
will return an interpolated value for
a specified target value. This can be
effective for determining parameters
such as the threshold voltage at a
specified current on a diode IV curve.

Conventional curve tracers not
only lack the log scale plotting
features needed for semiconductor
characterization, but they also
do not possess the graphical
analysis functionality necessary for
semiconductor device evaluation.
For example, curve tracers can draw
tangent lines but they require the
user to adjust the line slope manually.
This function is problematic since
different people will adjust the
tangent line differently, resulting
in inconsistent measurement data.
Conversely, EasyEXPERT has built-
in functions to draw tangent and
regression lines, and these return
reliable results since no observer
bias is introduced. Figure 3 shows
an example of two regression lines
for a Si pn diode characteristic.
One line shows the thermal carrier
recombination-generation (R-G)
current and the other line represents
the current in the diffusion regions.

The ideality factor (n), which is
an indication of the Si pn junction
quality, is calculated from the line
gradients via user functions; two
ideality factors (n1 and n2) are shown
in the “Parameters” section of the
window.

You can specify analysis operations
(such as drawing regression lines)
on the auto analysis setup page,
which permits you to get analysis
results immediately after completing
a measurement. These graphical
analysis capabilities eliminate the
onerous post-measurement task
of performing data processing and
parameter extraction on your PC,
thereby providing big boosts to
productivity and efficiency.

Figure 3. An example of diode IV graphical analysis using EasyEXPERT
The following sections cover typical power MOSFET characterization examples.

**Static characteristics: Id-Vds and output resistance**

Static or output characterization is one of the most important and prevalent power MOSFET measurements. It is usually performed by applying a sweep voltage that includes the threshold voltage to the gate terminal. Since power MOSFETs are high-current devices, the swept voltage is often pulsed to reduce self-heating effects. When Id is plotted versus Vds for fixed values of Vgs, Id reaches a constant (saturated) value once Vgs reaches a value sufficiently large enough to invert the channel.

The graphical analysis functions of EasyEXPERT can be used to analyze these types of plots. For example, EasyEXPERT can draw a regression line across a rectangular region specified by two cursors located on the curve. The slope or gradient of this line is the dynamic output conductance and its inverse is the dynamic output resistance.

Figure 4 shows typical power MOSFET Id-Vds and output resistance static characteristics. The primary sweep source is applied to the drain and Vds is swept from 0 V to 40 V in 0.4 V steps; the secondary sweep source is applied to the gate and Vgs is swept from 3.6 V to 4.4 V in 0.2 V steps. During this process the Id is measured at each point and a series of Id-Vds plots (one for each value of Vgs) are created. The graph analysis function draws a regression line at Id = 0.8 A and measuring the slope of this line yields a value for the dynamic resistance of 6777 Ω.

![Figure 4. Static characteristics Id-Vds and output resistance of a power MOSFET](image)

**Vds:** 0 V - 40 V, 0.4 V step  
**Vgs:** 3.6 V – 4.4 V, 0.2 V step  
**Pulse width:** 400 μs  

\[ R_{out} = \frac{1}{1.47515E-004} = 6777 \ \Omega \]
On-resistance, Rds(on), is another important parameter. Rds(on) is defined as the forced drain voltage (Vds) divided by the drain current Id in the region where the MOSFET is in the on state. EasyEXPERT can easily calculate Rds via the built-in user function capability as shown in figure 5.

Figure 5 shows a sample Rds-Vgs plot. A pulsed drain current (Id) of 6 A is forced while the gate voltage (Vgs) is swept from 0 V to 20 V and the drain voltage is measured. Rds vs. Vgs is plotted on the graph. When Vgs is lower than 4 V, Rds is relatively greater because the MOSFET is not fully on. You can easily read out Rds values using the marker function.

![Figure 5. On-resistance characteristics Rds(on)-Vgs of a power MOSFET](image-url)
Extracting threshold voltage (Vth) from the Id-Vgs characteristics

There are several alternative ways to extract the threshold voltage (Vth). The most basic way is to determine the voltage value corresponding to a specified drain current value on an Id-Vgs curve. There are two ways to do this. You can manually use the marker function to read values off of the Id-Vgs plot or you can define a marker condition on the Auto Analysis Setup page. When using the auto analysis feature, the marker automatically moves to drain current you have specified and this allows the Vth to be read from the x-axis.

Figure 6 shows a Vth extraction example. A marker condition of Id = 10 µA has been set in the Auto Analysis Setup page and the Vth value is retrieved using the read-out function @MX (which returns the x value of the marker position). The resulting graph shows an Id-Vgs plot with the marker at Id = 10 µA and a derived Vth of 2.245 V.

Figure 6. Vth extraction from an Id-Vgs curve for a power MOSFET using a specified drain current value
Another common Vth extraction technique involves analyzing the MOSFET Id-Vgs curve in its linear region. In this technique the gate voltage is swept to measure Id-Vgs while a small constant voltage bias is applied to the drain. The derivative of the drain current (Id) with respect to the gate voltage (Vgs) is known as the transconductance (gm), and this can be calculated numerically using the built-in differential function (diff). A plot of the transconductance can then be displayed on the Y2 axis as shown in figure 7. Using EasyEXPERT’s auto analysis features, a marker is positioned at the point where gm is a maximum and a tangent line to the Id curve is drawn at this position. The intercept of this tangent line with the X-axis can be automatically obtained by using the read out function @L1X. An estimate of Vth can then be obtained using the linear extrapolation method by subtracting half of the value of the drain-source voltage (Vds) from the X intercept of the tangent line. This example illustrates how not only measured parameters but extracted curves such as gm and extracted parameters such as Vth can be both automatically calculated and displayed using EasyEXPERT.

Figure 7. Vth extraction from an Id-Vgs curve for a power MOSFET by constructing a tangent line to Id at the point of maximum transconductance.
Determining the subthreshold swing (S) from the Id-Vgs characteristics

Understanding the subthreshold leakage characteristics of power MOSFETs is important to be able to predict their switching characteristics. In addition, the subthreshold leakage current can also yield insights into process irregularities and defects.

The procedure to determine the subthreshold leakage is straightforward. Since in the weak inversion (or subthreshold regime) the drain current depends exponentially on the gate-source voltage, with the Id-Vgs curve plotted on a semi-log scale, a regression line is drawn in the linear region.

The slope of this regression line is called the subthreshold slope, and the inverse of this slope is referred to as the subthreshold swing (S) and it has units of volts/decade. Of course, this entire process can be automated using the auto analysis and function setup pages as shown in the figure 8.

Figure 8. Determining the subthreshold swing (S) from the Id-Vgs characteristics of a power MOSFET
The drain-source breakdown voltage (BVdss) and the drain cut-off current (Idss) can be obtained from drain current leakage measurements. With the gate and source shorted to common, the drain voltage is swept from zero to a very high voltage using the HVSMU. The resulting drain current is then measured and plotted on a semi-log scale. You can easily use the marker function to obtain values for BVdss and Idss.

Using the marker condition on the Auto Analysis Setup page, the marker will automatically move to the specified condition immediately after measurement completion. In addition, by defining the parameters BVdss or Idss using read out functions on the Function Setup and Display Setup pages, these parameters will be displayed on the final graph.

An application test as shown in figure 9 can be used to retrieve BVdss and Idss from a sweep measurement. In the application test, an Id-Vds measurement made using the classic test mode is performed and then the marker is moved to the point where \( \text{Id} = 1 \ \mu\text{A} \) (which is the value of Id that has been selected to define the breakdown voltage). The Vds value at the marker position is then set to the variable BVdss. An additional auto analysis is performed to move the marker to the point at which \( \text{Vds} = 1500 \ \text{V} \), which is the value of Vds that has been selected to define the cut-off current. The Id value at the marker position is then set to the variable Idss. The extracted parameters are displayed on the result graph.

Conventional analog curve tracers are not good at making accurate low current measurements (lower than 1 \( \mu\text{A} \)), which makes them useful only for making breakdown measurements. In contrast, the B1505A can measure low currents down to the sub-pico ampere level, enabling it to make both breakdown voltage and leakage current measurements.

**Figure 9.** Application tests can automatically determine both the drain-source breakdown voltage (BVdss) and drain cut-off current (Idss) of power MOSFETs.
Stray capacitances Cds, Cgd, and Cgs characteristics

The stray capacitances (Cds, Cgd, and Cgs) of power MOSFETs depend on the applied drain voltage, and these stray capacitances influence the MOSFET switching characteristics. For this reason the stray capacitances are important power MOSFET parameters. In general, power MOSFET data sheets list input capacitance Ciss, output capacitance Coss, and reverse transfer capacitance Crss. Usually, these are calculated by measuring the stray capacitances. The B1505A high voltage bias-T facilitates these measurements by allowing the multi-frequency capacitance measurement unit (MFCMU) to be used with the HVSMU to make capacitance measurements at up to 3000 V of DC bias.

Drain-source capacitance (Cds) is measured by using the technique shown in figure 10. The CMH and CML terminals from the high-voltage bias-T are connected to the drain and source terminals, respectively. The AC guard terminal is connected to the gate terminal to maintain it at the same potential as the source terminal. The drain bias voltage is swept from 0 V to the desired DC bias voltage, and a Cds-Vds plot is obtained. Note that Cgs and Cgd do not affect the Cds measurement when the AC guard is connected to the gate terminal.

Figure 10. Measuring the Cds vs. Vds characteristics with Vgs = 0 V
Gate-drain capacitance (Cgd) is measured using the technique shown in figure 11. The CMH and CML terminals from the high-voltage bias-T are connected to the drain and gate terminals, respectively. The AC guard terminal is connected to the source terminal to maintain it at the same potential as the gate terminal. The drain bias voltage is swept from 0 V to the desired DC bias voltage, and a Cgd-Vds plot is obtained. Note that Cgs and Cds do not affect the Cgd measurement when the AC guard is connected to the gate terminal.

Figure 11. Measuring the Cgd vs. Vds characteristics with Vs = 0 V
Gate-source capacitance (Cgs) is measured using the technique shown in figure 12. In this case the drain terminal must be tied to the AC guard, and the HVSMU is not directly connected to the high voltage bias-T. To make the drain terminal have a low AC impedance, the drain terminal is connected to the HVSMU through the 100 kΩ R-box while the AC guard is connected through a large bypass capacitor. For the example shown in figure 12, a capacitance of at least 500 nF is necessary to achieve a 1% error. Note that the voltage rating on the capacitor must be larger than maximum drain voltage used in the Cgs measurements.

**Figure 12. Measuring the Cgs vs. Vds characteristics with Vgs= 0 V**

Power MOSFET data sheets list the capacitance parameters under the electrical characteristics. The typical parameters shown are output capacitance Coss, input capacitance Ciss, and reverse transfer capacitance Crss; they can be calculated from Cds, Cgs, and Cgd using the equations shown in the figure 13. Some data sheets also show Coss, Ciss, Crss versus Vds plots as sample data. As shown in figure 12, Cgs has a weak dependency on drain voltage (Vds) so that Cgs at Vds =0 can be used to estimate its value.

**Figure 13. Power MOSFET capacitance parameters Coss, Ciss, and Crss**
Power BJT Characterization

The following sections discuss power BJT (bipolar junction transistor) characterization.

Static characteristics $I_c$-$V_{ce}$ and Early voltage

An $I_c$-$V_{ce}$ plot is one of most important power BJT characteristics. In this plot, a base current ($I_b$) is supplied to the base terminal in the common emitter configuration while the collector voltage ($V_{ce}$) is swept from zero to a specified voltage. The collector current ($I_c$) is measured and an $I_c$-$V_{ce}$ plot is generated. Typically, the base current ($I_b$) is changed several times and this process is repeated each time so as to create a family of curves. For power BJT devices, this process can cause the device to heat up considerably due to the power being dissipated. The B1505A’s HCSMU can output current pulses down to 50 µs, which permits accurate $I-V$ measurements while avoiding the self-heating effect. Figure 14 shows a sample $I_c$-$V_{ce}$ measurement using the pulse mode.

The Early voltage ($V_{early}$), which is a BJT SPICE parameter, can be determined from the $I_c$-$V_{ce}$ characteristic using EasyEXPERT’s graphical analysis capabilities. EasyEXPERT allows you to specify a point on the $I_c$-$V_{ce}$ plot and to draw a tangent line as shown in figure 14. The display shows the X and Y intercept values of the tangent line as well as the tangent line’s slope. The X-intercept is the Early voltage.

Figure 14. Determining the Early voltage of a power BJT from its $I_c$-$V_{ce}$ characteristics using EasyEXPERT’s auto-analysis capabilities
Gummel plot and common emitter current gain (beta)

A Gummel plot, which shows the BJT gain or beta, is one of the more important BJT measurements. It requires instrumentation with accurate low current measurement capability, since the base current (I_b) is typically over one hundred times smaller than the collector current (I_c). In a Gummel plot both the base and collector currents (I_b and I_c) are measured as the base-emitter voltage (V_{be}) is swept. The base-collector voltage is kept at a constant value (usually zero volts), and I_b and I_c are plotted versus V_{be} using a semi-log scale. Figure 15 shows a typical Gummel plot measurement example for a BJT.

![Gummel plot measurement circuit](image)

**Figure 15. Typical Gummel plot measurement technique and results for a BJT**

A Gummel plot of a power BJHT using both DC and pulsed measurement techniques and the associated measurement circuit

![Gummel plot circuit](image)

**Figure 16. Gummel plot of a power BJHT using both DC and pulsed measurement techniques and the associated measurement circuit**

- I_c: Gradient = 16.69 → ideality factor n = 1.005
- I_b: Gradient = 12.78 → ideality factor n = 1.312
- Gradient = 15.45 → ideality factor n = 1.085
The B1505A can perform accurate power BJT Gummel plot measurements using both DC and pulsed measurement techniques. While a base-emitter voltage of 1 V may not seem like a lot, the power dissipation through the base-collector junction can be more than 1 W when the collector current is over 1 A. To prevent self-heating effects from distorting the measurement results, pulsed measurements with controlled duty cycles must be made to limit increases in the junction temperature.

Figure 16 shows a sample power BJT Gummel plot along with a diagram of the measurement circuit diagram and sample data. Two HPSMUs are used to make picoamp level low current measurements while an HPSMU and HCSMU are used to make high current measurements (more than 1 A) in pulsed mode. The module selector unit is used to switch between the HPSMU and HCSMU. An application test that combines the two types of measurements (DC and pulsed measurements) plots the results on a graph. Graphical analysis capabilities permit the extraction of device parameters such as the ideality factor n. The collector current (Ic) is linear at low and intermediate Vce voltages and exhibits an ideality factor of n=1.005 (gradient = 16.69 at Vce = 0.3 V); however, the base current Ib shows an ideality factor of n=1.085 when Vce is 0.55 V, and an ideality factor of n=1.312 when Vbe is between 0 to 0.3 V.

The Gummel plot is also used to extract another important BJT parameter known as the common emitter current gain or beta (β) that is calculated from the ratio of the collector and base currents (Ic/Ib). The Gummel plot is frequently used to find the collector current range with maximum beta as this is an important parameter for BJT circuit design. Figure 17 shows sample Gummel plot data, and this plot shows that the β is maximum in the region where the collector current is approximately 400 mA.
Emitter resistance Re extraction using the flyback method

The flyback method is the most common means used to extract BJT emitter resistance (Re). In this technique an SMU is connected to the collector terminal and the SMU is set to current force mode with a very small output current (approximately zero amps) so that it functions essentially as a high-input impedance voltmeter. The SMU connected to the base terminal forces a relatively large current (more than 10 mA).

The collector-emitter voltage (Vce) is measured and plotted versus the base current (Ib) as shown in figure 18. As can be seen, when the base current is between 40 mA to 100 mA the plot is almost a straight line with a slope equal to the inverse of the emitter resistance (Re). Therefore, regression analysis can be performed on the graph to calculate the slope of the line and the inverse of it yields the emitter resistance (Re).

Once the regression line region has been defined, the conditions can be set up on the Auto Analysis Setup page and the equation for Re can be set up on the Function Setup page as shown in figure 18. This allows the emitter resistance (Re) to be determined automatically.

Figure 18. Emitter resistance Re extraction using the flyback method
Collector resistance $R_c$ and emitter resistance $R_e$ in the saturation region are described by the following equations:

$$V_{ce} = I_c \times R_c + (I_b + I_c) \times R_e$$
$$R_{out} = \frac{V_{ce}}{I_c} = R_c + (1 + \frac{I_b}{I_c}) \times R_e$$

As the above equations show, $R_{out}$ is the inverse of the slope of the BJT output characteristics in the saturation region. The base current ($I_b$) and collector current ($I_c$) are applied at a constant ratio using the primary sweep (VAR1) and synchronous primary sweep (VAR1') functions. The collector voltage is then measured to create an $I_c$ versus $V_{ce}$ plot. Figure 19 shows an example of an $I_c$ vs. $V_{ce}$ plot at when $I_c = 10xI_b$. The collector current $I_c$ is almost linear in the 400 mA to 1 A region, and the regression line slope in this region is equal to the inverse of output resistance ($R_{out}$). Using the fact that $I_c = 10xI_b$ enables us to simplify the above equation as follows:

$$R_{out} = R_c + 1.1 \times R_e$$
$$R_c = R_{out} - 1.1 \times R_e$$

The emitter resistance ($R_e$) is determined using the flyback method as described in the previous section. You can specify the regression line conditions and analysis functions in Auto Analysis Setup and Function Setup pages as shown in figure 19, which enables you to automatically calculate the collector resistance ($R_c$).
Breakdown voltage BVcbo, BVceo, and BVebo and leakage current

When specifying breakdown voltages the first two lower-case letters following “BV” indicate the two terminals to which the voltage is applied. The third lower-case letter indicates the status of the other device terminal (assuming a three terminal device). That is, “o” represents “open” and “s” represents “shorted” (indicating that it is shorted to the second terminal). Therefore, the junction breakdown voltages of power BJT are defined as follows:

- **BVcbo**: collector-base breakdown voltage with the emitter open
- **BVceo**: collector-emitter breakdown voltage with the base open
- **BVebo**: emitter-base breakdown voltage with the collector open

Since the B1505A covers a wide range of voltages, you can measure breakdown voltages for most power BJTs. Figure 20 shows some sample breakdown measurement results.

These plots not only show the breakdown voltages but also provide stable leakage current plots with picoamp current resolution. The doping concentration in collector region is the lowest relative to the other regions, so BVcbo has the highest breakdown voltage. Conversely, the doping concentration in emitter region is the highest relative to the other regions, so BVebo has the lowest breakdown voltage. The B1505A’s graphical capabilities easily allow you to superimpose these plots on a single graph and to add comments to the graph for use in reports and presentations.

**Figure 20. Breakdown voltage and leakage current measurements on a power BJT**

Junction capacitance: Cjc and Cje characteristics

A BJT has two pn junctions: one is between the emitter and base (Cje), and the other is between the collector and base (Cjc). For low-levels of DC bias (< 20 V) you can use the MFCMU’s built-in bias source. For higher levels of DC bias (up to 3000 V) you can use the MFCMU, HVSMU, and high-voltage bias-T. Figure 21 shows some sample junction capacitance measurement results. The emitter-base junction capacitance DC bias voltage is low enough to be measured with just the MFCMU. The collector-base junction capacitance DC bias voltage requires the use of the HVSMU and high-voltage bias-T along with the MFCMU.

**Figure 21. Junction capacitance Cjc and Cje characteristics of a power BJT**
Evaluation of New Semiconductor Materials

New wide bandgap (WBG) materials such as SiC and GaN show great promise for emerging high-power applications because of their ability to withstand large voltages and their fast switching speeds. While these types of materials can be analyzed using electrical, optical or physical characterization methodologies, electrical methods are generally preferred due to their ease of use. The following sections cover the electrical characterization of both diamond and SiC based materials.

Reverse current-voltage characteristics of diamond Schottky barrier diode

Diamond, which is well-known for its uses in jewelry, is made from carbon (atomic symbol C) and is well-known as the hardest material in the world. However, because carbon resides in column IV of the periodic table like silicon (Si) and germanium (Ge), it also exhibits semiconductor characteristics. Recent research has shown that the diamond has a band gap of 5.5 eV, which is much higher than the 1.11 eV and 1.43 eV bandgaps of Si and GaAs (respectively). This enables diamond to be used for high-power and high-temperature device applications and its excellent breakdown characteristics illustrate some of the advantages of WBG materials.

A diamond Schottky barrier diode (SBD) consists of four parts: a diamond substrate, a p-type epitaxial layer, an electrode for the metal-semiconductor (MS) Schottky contact, and an electrode for the Ohmic contact. Figure 22 shows an SBD measurement where the two test sample electrodes are connected to the HVSMU and GNDU. A reverse bias voltage is applied to the diode and swept from zero to 2000 V. The leakage current is measured using the HVSMU and plotted on a semi-log scale. Breakdown occurs at 1,826 V with a leakage current of 10 nA. The plot also shows that the leakage current is 252 pA at 1,000 V, which is two orders of magnitude lower than that of an equivalent Si diode.
Forward current-voltage characteristics of 4H-SiC Schottky barrier diode

SiC is a widely-studied IV-IV compound semiconductor WBG material with properties that make it ideal for high-power and high-temperature applications. There are three types of SiC crystal structures with the designations 3C, 6H and 4H and with the respective band gaps of 2.20 eV, 2.86 eV and 3.02 eV. In the following section the forward current-voltage (IV) characteristics of a 4H-SiC Schottky barrier diode (SBD) are measured and a typical parameter extraction process is explained.

The 4H-SiC SBD used in this example was fabricated on a commercial SiC wafer with a SiC epitaxial layer and a metal electrode. The GNDU and HPSMU are connected to the prober chuck and a positioner (respectively) as shown in figure 23. The forward voltage is swept from zero to 2 V and the forward current is measured using the HPSMU and plotted on a semi–log scale. The diode is operating in its linear region when the forward current is 100 µA, which is typical diode behavior. This can be used to determine two important parameters: the diode ideality factor (n) and the junction barrier height (Φ_B).
Diode IV characteristics are generally modeled by the following equation:

\[
I = I_s \left( e^{\frac{qV_n}{kT_s}} - 1 \right)
\]

\[
I_s = A \cdot A^* \cdot T^2 \cdot e^{\frac{\phi_B}{kT}}
\]

Where,
- \(I_s\): saturation current
- \(n\): diode ideality factor
- \(q\): electronic charge (1.60x10^{-19} \text{ C})
- \(k\): Boltzmann constant (8.617x10^{-5} \text{ eV/K})
- \(T\): absolute temperature
- \(V_n\): applied DC voltage
- \(A\): SBD area
- \(A^*\): modified Richardson constant (120x(m^*/\mu_b) \text{ amps/cm}^2\text{-K}^2)
- \(\Phi_B\): junction barrier height

In the intermediate region the diode plot is approximately linear, making it possible to create a regression line using the built-in analysis functions. Since the slope of this regression line is derived for the common logarithm case (base 10), to convert it to a natural logarithm you need to multiply it by \(\ln(10)\). In this example the slope for the natural logarithm case is 38.27 (which is 16.62 x \(\ln(10)\)). Since this slope is equal to \(q/nkT\), you can calculate the ideality factor \(n\) as follows:

\[
n = \frac{1}{8.617 \times 10^{-5} \times (273 + 25) \times 38.27} = 1.018
\]

As you can see, the characteristics of this SBD are close to the ideal case (\(n=1\)).

From the X-intercept and slope of the regression line, you can calculate Y-intercept as follows:

\[
(Y\text{-intercept}) = 10^{(\text{slope}) \times (X\text{-intercept})}
\]

\[
= 10^{(16.62) \times (1.407)}
\]

\[
= 4.127 \times 10^{24}
\]

In other words, the saturation current \((I_s)\) is 4.127x10^{24} \text{ A}.

This then enables us to calculate the junction barrier height \((\Phi_B)\) as follows:

\[
\Phi_B = -kT \ln\left( \frac{I_s}{AA^*T^2} \right)
\]

\[
= -8.617 \times 10^{-5} \times (273 + 25) \times \ln \left( \frac{4.127 \times 10^{24}}{0.05^2 \times \pi \times 34.80 \times (273 + 25)^2} \right)
\]

\[
= 1.64(\text{eV})
\]
Capacitance-voltage characteristics of 4H-SiC Schottky barrier diode

As is the case for all semiconductor devices, the junction capacitance of a Schottky barrier diode depends on the applied voltage since sweeping the voltage modulates the space charge and depletion regions. Note that the applied voltage must be limited to the region where the junction is in reverse bias. The procedure for measuring capacitance is to sweep the DC bias voltage while measuring capacitance. The capacitance versus voltage (CV) data is then plotted on a graph. The relationship between capacitance and applied voltage is given by the following equation:

\[
C = \left( \frac{K_s \varepsilon_0 A}{2K_s \varepsilon_0 \left( V_{bi} - V_A \right)} \right)^{1/2}
\]

\[
\frac{1}{C^2} = \frac{2}{qN_dK_s \varepsilon_0 A^2} (V_{bi} - V_A)
\]

Where,
- \( V_{bi} \): built-in junction voltage
- \( K_s \): semiconductor dielectric constant
- \( \varepsilon_0 \): permittivity of free space (8.85X10^-14 farad/cm)
- \( N_d \): total number of donor atoms/cm³

Figure 24 shows sample CV measurement data for the same 4H-SiC SBD that was analyzed in the previous subsection. Since this is an n-type SBD, the CMH and CML terminals of the high-voltage bias-T are connected to the prober chuck and probe tip, respectively. The bias voltage is swept from zero to 1 V with 10 mV steps, and the measured capacitance \( C \) (Cp-G mode) is plotted on the Y1 (left) axis. A user function (CC) is created to calculate \( 1/C^2 \) on the Function Setup page, and this is plotted on the Y2 (right) axis. As can be seen, the \( 1/C^2 \) plot is linear versus applied voltage, and you can calculate the built-in potential \( V_{bi} \) by using the following equation:

\[
V_{bi} = (X - \text{intercept}) + \frac{kT}{q}
\]

\[
= -1.481 + 0.026
\]

\[
= 1.455(V)
\]

Where, \( kT/q \) is for the thermal voltage compensation.

Figure 24. Low-voltage reverse-bias capacitance-voltage (CV) characteristic of 4H-SiC SBD
By taking the differential of the previous equation for $1/C^2$ you can determine the doping concentration ($N_D$), which is almost equal to carrier density, as follows:

$$N_D = \frac{2}{qK_e q A^2 \frac{d1/C^2}{dV}}$$

$$= \frac{2}{1.60 \times 10^{-19} \times 9.7 \times 8.85 \times 10^{-14} \times 0.05^2 \times \pi \times 3.005 \times 10^{27}}$$

$$= 7.84 \times 10^{13} \text{ (cm}^{-3}\text{)}$$

This allows you to calculate $(E_c - E_F)_{FB}$, the energy difference between the conduction band level ($E_c$) and the Fermi level ($E_F$) as follows:

$$(E_c - E_F)_{FB} = \frac{E_c}{2} - kT \ln \frac{N_D}{n_i}$$

$$= \frac{3.22}{2} - 8.67 \times 10^{-5} \times (273 + 25) \ln \frac{7.84 \times 10^{13}}{1.11 \times 10^{-8}}$$

$$= 0.318 \text{ (eV)}$$

The junction barrier height ($\Phi_B$) is calculated as follows:

$$\Phi_B = qV_{bi} + (E_c - E_F)_{FB}$$

$$= 1.455 + 0.318$$

$$= 1.773 \text{ (eV)}$$

Figure 25 shows CV measurement results for higher reverse bias voltage (300 V). The $1/C^2$ is linear at lower voltages, but approaches a constant value at higher voltages (> 200 V). This means that the depletion region width stops increasing at higher reverse biases.
Equation (4) suggests that the doping concentration can be calculated from the measured CV characteristics. When the SBD structure is acting as a parallel plate capacitor the width of the depletion region (which shows the depth $x$ from the surface of Schottky junction) is calculated as follows.

$$x = \frac{K \cdot \varepsilon \cdot A}{C}$$

Equations (4) and (7) can be defined as user functions as shown in figure 26 to obtain the doping profile (doping concentration versus position) automatically. Figure 27 shows an example of a SiC SBD doping profile extracted from a CV measurement. This result shows both that the doping density is roughly uniform with a value of $10^{14}$ cm$^{-3}$ and that the epitaxial layer depth is approximately 33 µm. It also shows that when the depletion region reaches the substrate the doping density is as high as $10^{17}$ cm$^{-3}$.

![Figure 26: User function definitions to calculate the doping profile from a CV characteristic](image)

![Figure 27: Doping profile example of 4H-SiC SBD retrieved from CV measurement](image)
Conclusion

The Agilent B1505A single box instrument solution builds upon the measurement capabilities (such as accuracy and resolution) furnished with traditional semiconductor parameter analyzers while expanding the voltage and current coverage to 3000 V and 20 A. The effectiveness of the B1505A has been demonstrated using actual power MOSFET and BJT measurement and characterization examples. In addition to traditional silicon-based devices, the B1505A can also be used to characterize new wide band gap materials that show great promise for future high-power and high-temperature device applications, and measurement examples of both SiC and diamond substrate devices have been shown in this application note. The B1505A is capable of providing accurate and stable parametric characterization of both current and future power devices, and it will continue to improve the efficiencies of power devices for many years to come.

References


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