

DC Electrical Characterization of RF Power Transistors

Introduction

The communications industry has witnessed tremendous growth recently. The demands for greater bandwidth and mobility are the main drivers of innovation in this industry. The communications integrated circuit is key to this continuous innovation. For most wireless networks geared to transmitting and receiving data, the ability to amplify signals at high frequency is critical. This task is commonly achieved with a Radio Frequency (RF) power amplifier and low noise amplifier. This note will provide an overview of techniques that can be used to characterize RF power transistor DC characteristics.

In communications applications, most power amplifiers are operated at high frequency. For example, the RF power amplifiers used in mobile phones typically operate at a frequency of several gigahertz (GHz). For space-based communications, the amplifier may operate at frequencies of tens of gigahertz. This very high frequency range means that the traditional Complementary Metal Oxide Semiconductor (CMOS) process can not be used to manufacture the amplifier economically. Therefore, different high-mobility semiconductor materials are commonly used, such as GaAs, SiGe, or other III-V group semiconductor materials. The most commonly used building blocks of these amplifiers are not CMOS transistors; rather, types such as Metal Semiconductor Field Effect Transistors (MESFETs), Heterojunction Bipolar Transistors (HBTs), Pseudomorphic High Electron Mobility Transistors (PHEMTs), and Lateral-Diffused Metal Oxide Semiconductor Transistors (LDMOSs) are often used.

This note will not attempt to provide a comprehensive discussion of the electrical characterization of the different types of devices used to make these amplifiers. It will cover the most commonly used instruments, a typical measurement setup, and a few of the important DC parameters that can be extracted from

the measurements. An HBT will be used as an example in the discussion.

Instrumentation and Measurement Setup

There are several possible ways to characterize the electrical properties of an RF transistor. While various voltage or current sources and current or voltage meters could be used in combination to make the measurements, recent instrumentation advancements make this approach unnecessarily complicated. Instead, a Keithley SourceMeter® instrument or Source-Measure Unit (SMU) can be used to achieve greater flexibility in the measurement setup and greater confidence in the measurement results.

Instrumentation Options

Keithley Instruments has a growing family of SourceMeter® instruments and Source-Measure Units (SMUs) that can be used to characterize RF transistors electrically. A SourceMeter instrument is essentially four instruments in one. It can be used as voltage or current source as well as a voltage or current meter. The Model 2400 is the basic SourceMeter instrument that's suitable for most RF testing applications. For higher voltage applications, the Model 2410 provides up to 1100V. For higher power or higher current devices, the Model 2420 and Model 2430 can be used to provide up to 3A continuous or 10A pulse operation respectively. These various models can be used interchangeably in the same test setup. They're built using the same GPIB programming conventions and share most GPIB programming commands, which simplifies control and maintenance. To achieve better source and measurement capability, the Model 236 SMU can be used. The Model 237 SMU is designed for in high voltage applications (up to 1100V), while the Model 238 SMU measures currents up to 1A. The Model 6430 Sub-Femtoamp

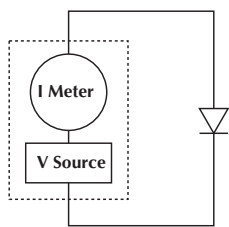


Figure 1a.

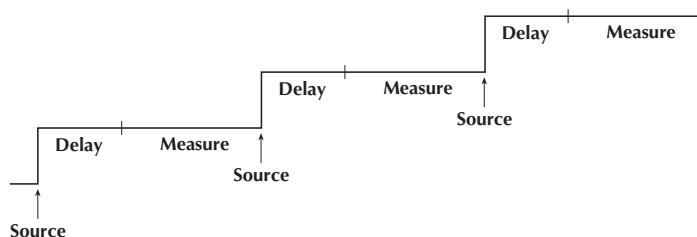


Figure 1b. SDM cycle

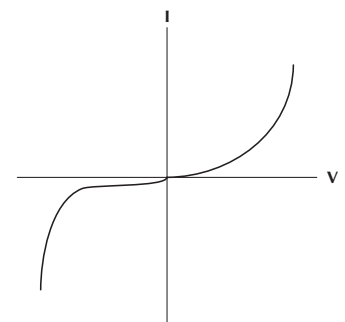


Figure 1c. Diode I-V sweep

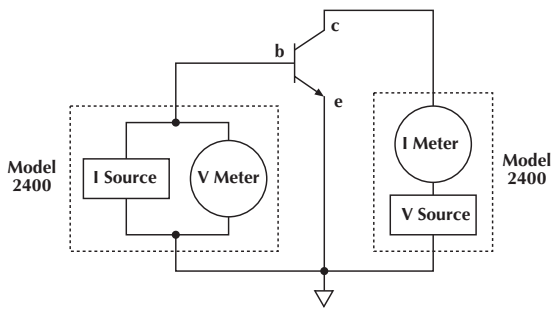


Figure 2a. Instrument setup to measure HBT collector family I-V curves

Remote SourceMeter instrument is suitable for applications that require exceptional measurement sensitivity. Keithley has also recently introduced another solution for DC characterization, the Model 4200-SCS. This fully integrated semiconductor characterization system includes a built-in PC, measurement instrumentation, and software.

Measurement Principle

As illustrated in *Figure 1b*, Keithley's SourceMeter instruments and SMUs are based on the *Source, Delay, Measure* (SDM) principle. The SourceMeter instrument is connected to the diode. It can be programmed to source voltage and measure the resulting current or to source current and measure the resulting voltage. Note that the SourceMeter instrument allows four-quadrant operation. For example, it can source voltage and sink current. To make a simple current-voltage (I-V) sweep, the SourceMeter instrument outputs a series of voltages while making corresponding current measurements (*Figure 1c*).

At each voltage step, the SourceMeter instrument will first source a voltage. The voltage change in the circuit will induce a transient current. The SourceMeter instrument will pause for a pre-determined time delay, then make a current measurement. The instrument will repeat this Source, Delay, Measure cycle for each output voltage. This SDM cycle is transparent to the user. The most important part to remember is how to use the delay time properly.

The voltage or current change due to the sourcing portion of the cycle will induce a transient current or voltage, so using an appropriate amount of delay time between sourcing and measurement is critical to overall measurement integrity. At different ranges, the instrument will adjust the delay time automatically to produce the optimal results. However, adding extra elements to the test circuit, such as long cables, a switch matrix, etc. will change the circuit's transient characteristics. In these cases, additional delay time will be needed to maintain the measurement integrity. This additional delay time is provided as user defined delay time. For additional information on how to characterize the measurement system and select appropriate delay times, refer to Keithley Application Note #2241, "Making Ultra-Low Current Measurements with the Low-Noise Model 4200-SCS Semiconductor Characterization System."

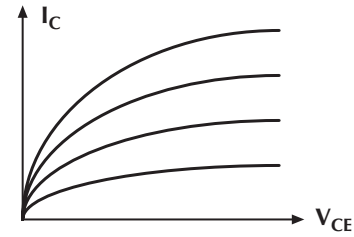


Figure 2b. HBT collector family curves

Typical Measurement Setup

In the following example, an HBT will be used to illustrate how to use a SourceMeter instrument to characterize a device's electrical DC parameters. *Figure 2* shows two SourceMeter instruments connected to the device. The first SourceMeter instrument is connected between the HBT base and the emitter. The second SourceMeter instrument is connected between the collector and the emitter. An external Trigger Control Unit (Model 2361) is often used as well, because the two SourceMeter instruments must be synchronized during measurement.

To acquire collector family curves from the HBT, the base SourceMeter instrument is set to output current and measure voltage. The collector SourceMeter instrument is set to sweep voltage and measure current. After the first base current is set, the collector voltage is swept while the collector current is measured. Then, the base current is stepped up and the collector voltage is swept again while collector current is measured. This process is repeated until all the collector I-V curves at the different base current levels are acquired.

Measurement and Parameter Extraction

In high frequency RF amplifier design, the RF transistor is the basic building block. The RF transistors can be MESFET, HBT, LDMOS, etc. Due to the high frequency and linearity requirements, the integration level is not as high as that in CMOS design. Therefore, the RF amplifier often can be viewed as a "super-transistor" that exhibits electrical characteristics superior to a single transistor.

Generally speaking, RF transistor parameters can be grouped into two parts: DC and RF (functional). In design or process engineering, the DC parameters that are commonly important are the various junction breakdown voltages, junction leakage current, DC beta (hfe), junction resistance, etc. Important RF parameters include RF gain, noise figure, input/output impedance, S parameters, distortions, etc. This note focuses on the DC aspect of the RF amplifier; the RF parameter measurement will be discussed in another application note.

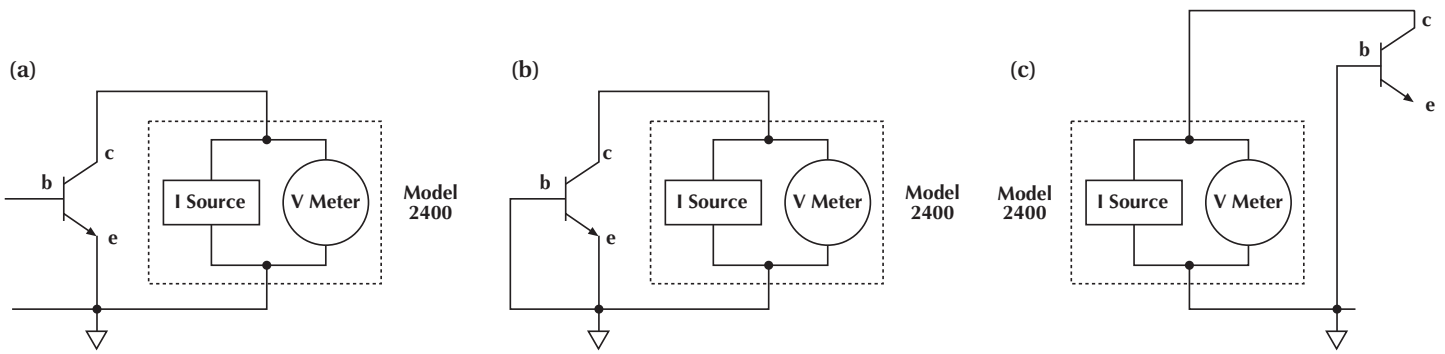


Figure 3a. Collector-emitter breakdown with base open; 3b. Collector-emitter breakdown with base shorted; 3c. Collector-base breakdown with collector open

Collector Family I-Curve

The collector family I-curve is one of the most commonly measured HBT parameters because it reflects the base control on the collector output current. From the collector family curve, it's possible to estimate the DC gain, the threshold voltage, the linear and saturation region of HBT operation, etc. Refer to the section on "Typical Measurement Setup" for a discussion on how to acquire the collector family curves.

Breakdown Voltage

A critical part of evaluating an RF amplifier is determining if it has a breakdown voltage compatible with the amplifier supply voltage. The design engineer must select an RF amplifier with DC and RF voltages that do not exceed the rated breakdown voltage for the amplifier. The breakdown voltage of an RF amplifier is largely determined by the device's design, the quality of the process, the materials used, and the operating condition. It is closely related to the RF function of the RF amplifier.

Two important breakdown voltages are commonly measured for an HBT. The first one is the collector-emitter breakdown voltage, which is typically measured with either base open or base shorted. The second breakdown voltage is the collector-base breakdown voltage, which is commonly measured with emitter open. **Figure 3a** illustrates the setup to measure the collector and emitter breakdown voltages with base open. **Figure 3b** shows the collector-emitter breakdown measurement with base shorted. **Figure 3c** shows the collector-base breakdown measurement

with emitter open. In these measurements, the SourceMeter instrument sources current through the HBT. The voltage is measured at the same time. The current will increase until the breakdown occurs. The corresponding voltage is recorded as the breakdown voltage.

Junction Leakage Current

Characterizing the off leakage current of the HBT is also very important, because this leakage current will waste power while the device is not operating. If this leakage is not properly controlled, it will shorten the operating time of a portable, battery-powered device. The most often measured leakage current parameter is the collector cutoff current, which is measured with the base shorted to ground. The base reverse bias leakage is another important leakage current measurement. It demonstrates the base leakage when the device is turned off. **Figure 4** illustrates the measurement setup.

DC Current Gain and Gummel Plot

The DC gain of an RF power amplifier is very closely linked to its RF gain. Most low power portable devices are operated in linear mode and the RF power amplifier requires a bias voltage supply. Therefore, the amplifier's DC gain is important. The DC gain can be measured directly and quickly by sourcing a base current and measuring the corresponding collector current. Another technique that is often used is to sweep the base and collector voltage while simultaneously measuring the base and collector current. After the measurements are complete, the base

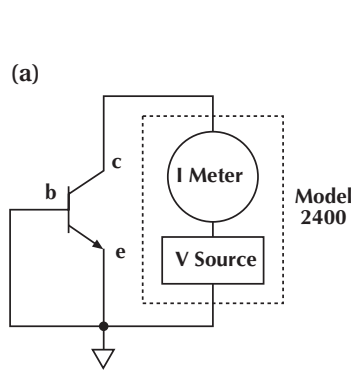


Figure 4a. Collector cutoff current with base shorted to ground

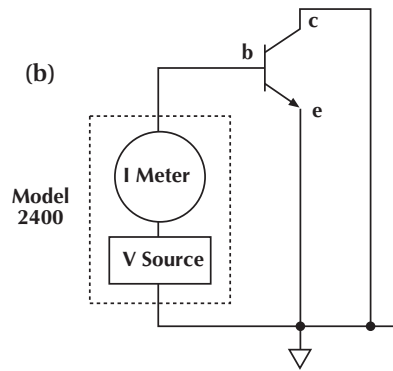


Figure 4b. Base leakage current

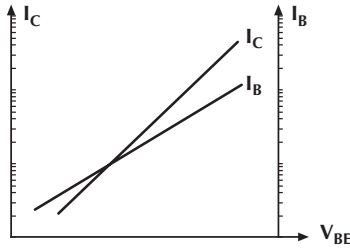


Figure 5a. Gummel plot

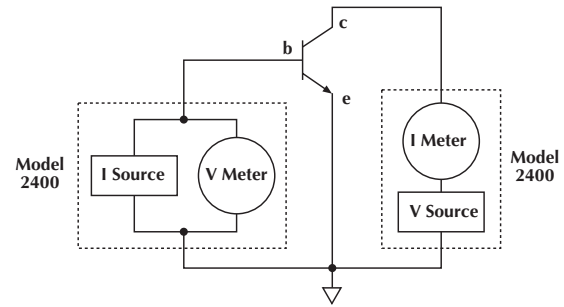


Figure 5b. DC gain measurement setup

and collector currents are plotted against the base voltage to produce a so-called Gummel plot (Figure 5a). The measurement setup is illustrated in Figure 5b.

Conclusion

This note has provided an overview on DC characterization of the RF transistors most commonly used in the communications industry. Despite the rapid development of new amplifier designs and materials, it is interesting to note that the instrumentation used to test them has not changed dramatically, even though the devices' characteristics have. Keithley offers a variety of instrumentation options that can help communications products manufacturers test their products quickly and cost-effectively.

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