Application Note 356

—HP 4142B Modular DC Source/Monitor Practical Applications—

High Speed DC Characterization of Semiconductor Devices from Sub pA to 1A

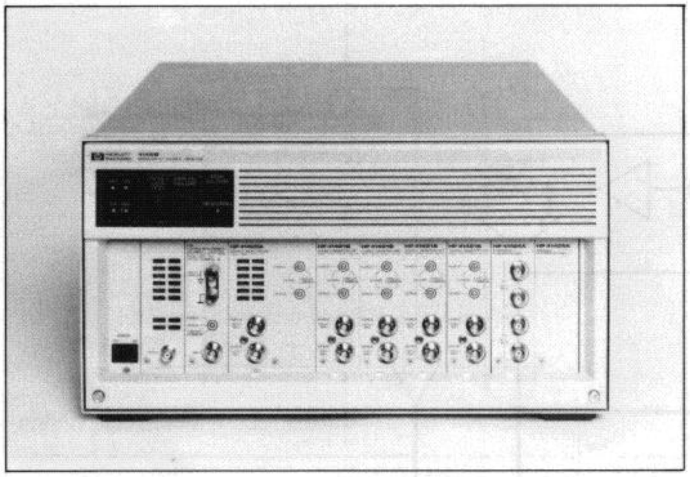
CONTENTS

INTRODUCTION

The HP 4142B Modular DC Source/Monitor is a high speed, highly accurate computer controlled DC parametric measurement instrument for characterizing not only today's semiconductor devices–MOSFETs, bipolar transistors, GaAs devices, etc.–but tomorrow's as well. Whether used for semiconductor process monitoring, device development, or process development, the HP 4142B's wide measurement range and high resolution affords quick and efficient DC parameter evaluations from ±20fA to ±1A, and ±4μV to ±200V.

To facilitate application-specific system requirements, the HP 4142B's plug-in module architecture allows you to choose from a variety of modules to enable you to tailor your HP 4142B to suit your measurement needs. Table 1 lists presently available plug-in modules. The HP 4142B's modular design also allows you to easily expand your hardware if required, and to quickly upgrade your testing capabilities as new modules become available.

This application note describes how to take advantage of the HP 4142B's superior performance to obtain optimum measurement results. Included are detailed measurement technique descriptions, and GaAs MESFET, power MOSFET, and bipolar power transistor device characterization examples.



1. HP 4142B FEATURES

(1) Wide measurement range and high resolution

There are two types of source monitor units (SMUs) available. You can program each SMU to function as a voltage source/current monitor (V source mode) or a current source/voltage monitor (I source mode).

The maximum output/measurement ranges are ±200V/±1A for the HP 41420A, and ±100V/±100mA for the HP 41421B. Output resolution is ±100μV/±50fA, and measurement resolution is ±40μV/±20fA. The HP 41424A Voltage Source/Voltage Monitor Unit (VS/VMU) is also available, and includes two voltage sources (VSs) and two voltage monitors (VMs). You can use the voltage monitors together to perform 4μV resolution differential measurements.

(2) High speed measurement

The HP 4142B can improve measurement throughput. Voltage or current can be forced in approximately 3.5ms, and voltage or current measurements can be made in approximately 4ms. And with the HP 41425A Analog Feedback Unit, you can extract V_{th} or h_{FE} in only 12ms.

(3) Pulsed output available

SMU and VS pulsed measurement modes provide voltage and current pulses (current pulses from SMUs only) to minimize thermal drift when characterizing devices. With pulse widths from 1ms to 50ms, you can accurately characterize high power devices such as power MOSFETs or GaAs devices.

(4) Furnished control software allows easy programming

The HP 4142B is controlled by HP-IB commands. In addition, the furnished control software provides a variety of useful, frequently used subprograms that can be called from your program, thus reducing program development time. This software is divided into the Test Instruction Set, Parameter Measurement Library, and Data Processing Library (Data file and characteristic graph generation).

Table 1. HP 4142B Plug-in Modules

Model number	Voltage range	Current range	Measurement resolution	Accuracy V	Accuracy I
HP 41420A SMU	±100 μV to ±200 V	±50 fA to ±1 A	40 μV, 20 fA	0.05%	0.2%
HP 41421B SMU	±100 μV to ±100 V	±50 fA to ±100 mA	40 μV, 20 fA	0.05%	0.2%
HP 41424A VS/VMU	±1 mV to ±40 V	±20 mA to ±100 mA	4 μV, 20 μA	0.05%	0.3%
HP 41425A AFU	Searches for a specified current or voltage on one SMU by controlling the voltage output of another SMU.				

2. USING THE HP 4142B

This section describes how to fully use HP 4142B features to efficiently perform measurements.

① **SMU Basic Usage Points**
Compliance function, filter, etc.
② **Operation Speed Concepts and Optimization**
Setup time, measurement time, range-changing time, averaging time, etc.
③ **Using Pulse Mode to Reduce Thermal Drift**
Pulse mode reduces temperature rise at a junction.
④ **Analog Feedback Unit (AFU) Usage**
Feedback integration time, ramp rate, and delay time.

2.1 SMU Basic Usage Points

Figure 1 (a) shows an SMU block diagram. Voltage and current are output from 16-bit digital-to-analog converters (VDAC and IDAC). The DACs can output 20,000 points, so the resolution for each range is 1/20,000 of the full range.

Measurements are made by a 17-bit analog-to-digital converter, and the resolution for each range is 1/50,000 of the full range. The error amplifiers A_1, A_2, and A_3 shown in the figure are used for setting voltage, source current (I_+), and sink current (I_-), respectively. When the SMU is set to V source mode, A_1 controls the SMU voltage output. In this mode, current is monitored by range resistor Rr, fed back to A_2 and A_3, and is limited to the value (±I compliance) set by IDAC (See Figure 1 (b)).

When the SMU is a current source, A_2 controls the SMU current output from the SMU. V compliance will be positive in this case, and voltage is limited by A_1.

When the SMU is a current sink, A_3 controls current input to the SMU. V compliance will be negative in this case, and voltage is limited by A_1.

If accuracy is more important than measurement speed, the filter at the DAC output should be set to ON to suppress spikes and overshoot caused by changing the output value or range. The filter should be used with devices that cannot handle voltage spikes, or with very high gain devices. The filter is set to ON at power ON. If measurement speed is more important than accuracy, turn the filter OFF. When the filter is OFF, the DAC output settling time is 1/40 of the filter ON value.

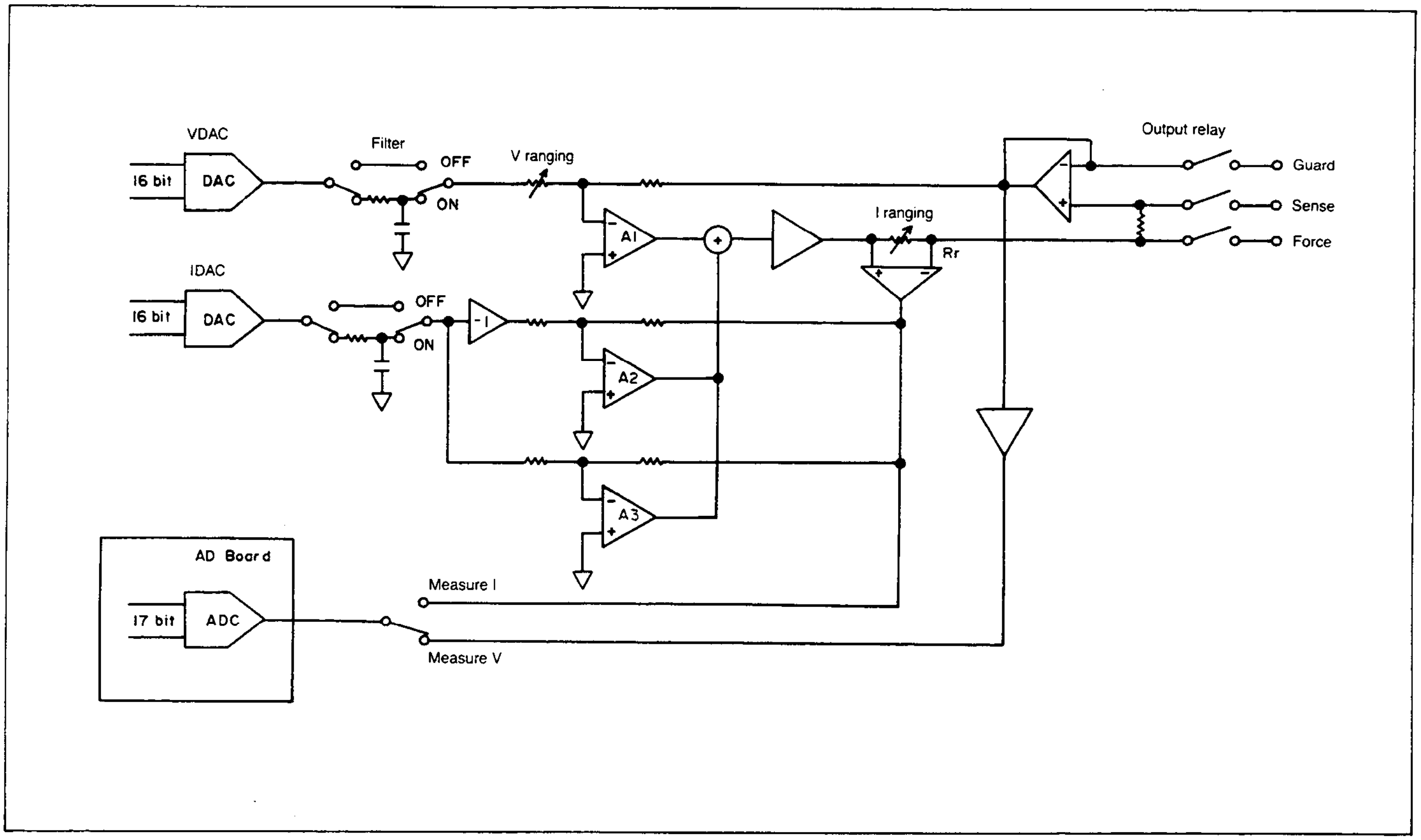


Figure 1 (a). SMU Block Diagram

The SMUs have separate Force and Sense terminals, allowing Force and Sense lines to be extended separately (Kelvin connections) up to the test device. This eliminates the effects of contact and cable residual resistance on measurement accuracy. Each Force and Sense terminal has a guard conductor to reduce leakage current, thus ensuring accurate low current measurements. Force and Sense terminals are connected internally by a resistor, allowing sensing and forcing via a single cable (non-Kelvin connection). SMU output is disabled by an output relay when the HP 4142B is turned ON, or by program commands to prevent damage to DUTs.

Table 2 lists SMU output voltage, current compliance, filter, and output relay settings, at POWER ON, and when the HP 4142B is set to the output enable state or the Zero Output state.

As Figure 2 (a) shows, you can set each SMU to function as a voltage source/current monitor by specifying V source mode, or as a current source/voltage monitor by specifying I source mode. In this equivalent circuit, the HP 4142B cannot measure current when in I source mode, and cannot measure voltage when in V source mode.

Figure 2 (b) shows an equivalent circuit that allows current to be measured when in I source mode, or voltage to be measured when in V source mode. This circuit is only available when you use the TV or TI commands, or when using the ASM command during Analog Feedback Unit (AFU) measurements. For example, when using the AFU to determine FET threshold voltage V_{th}, the AFU changes the FET gate voltage until a target drain current value is reached, and then measures the gate voltage to determine the threshold voltage.

You can specify the current measurement range when the SMU is in V source mode. If you do not specify the range, it is determined by the current compliance. Therefore, if the current compliance is large, the measurement resolution will be low.

Be aware of the following when making current measurements during a voltage sweep.

(1) For staircase voltage sweeps, AUTO ranging for current measurements is available, allowing a wide range of currents to be measured automatically. A maximum of eight channels can be measured at the same time.

(2) For pulsed voltage sweeps, only fixed range current measurements are available. The current measurement range for one sweep is limited to about 4 decades, so if a high fixed current measurement range is used, low current measurement resolution will suffer. Only one channel can be measured at a time.

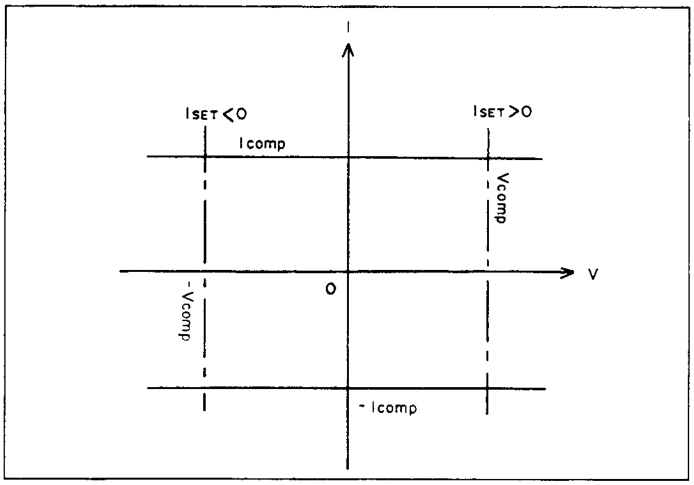


Figure 1 (b). Compliance

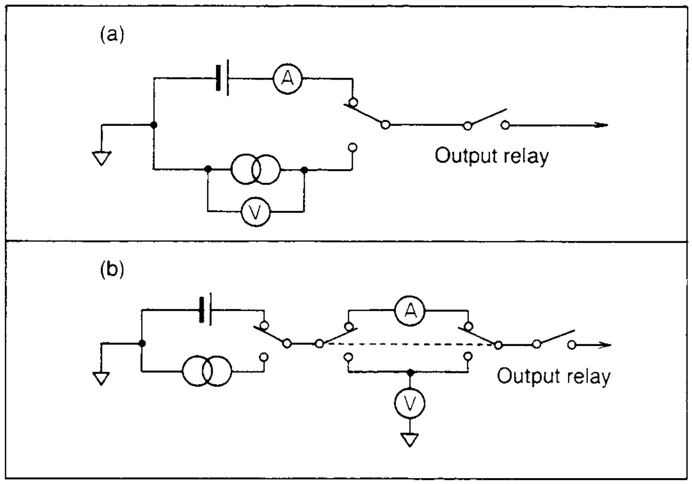


Figure 2. SMU Equivalent Circuit

Table 2. SMU States

	Output voltage	Current compliance	Filter	Output relay
Power ON (Reset)	0 V @20 V range	100 μA @100 μA range	ON	Open
Output enable state	0 V @20 V range	100 μA @100 μA range	ON	Closed
Zero output state	0 V (range does not change)	If I range is 1 mA~1 A: 100 μA @ 100 μA range. If I range is 1 nA~100 μA: Full-scale @ present I range.	Does not change	Closed

2.2 Operation Speed Concepts and Optimization

Figure 3 shows a breakdown of the execution time elements for setting HP 4142B output and making measurements. T_1 (about 2.5ms) is the time required to transmit the command from the controller to the HP 4142B, and convert the code into HP 4142B internal code. T_2 and T_3 are the actual setup times, and vary depending on the voltage or current range, output changes, and the filter ON or OFF status. Measurement time T_4 varies depending on the voltage or current range. T_5 is the time required for the measurement data to be transmitted from the HP 4142B to the controller, and is about 1.3ms for ASCII format.

T_2 is the time it takes to change from one range to another. Voltage range changes take about 3ms, independent of the range. Current range changes depend on the range as listed in Table 3. For example, to change from the 1A range to the 1nA range takes about 36ms, which is about 1/3 that of previous equipment (HP 4141B).

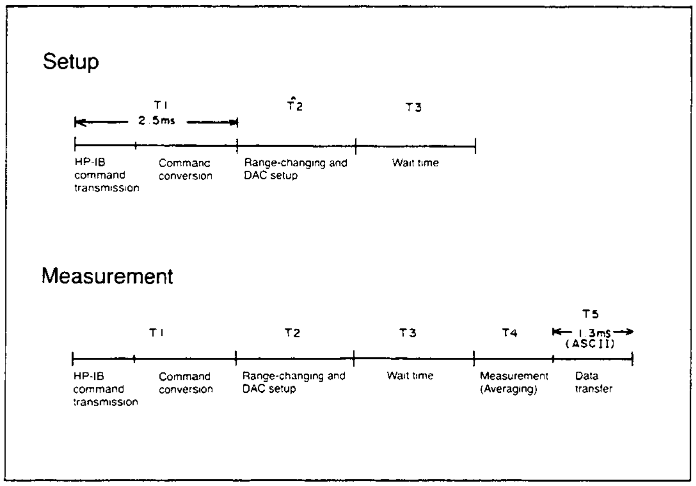


Figure 3. Execution Time Elements

Table 3. Current Range-changing Times *Unit: ms*

I Range before changing (A)	I Range after changing (A): 1	100 m	10 m	1 m	100 μ	10 μ	1 μ	100 n	10 n	1 n
1		13	15	17	19	21	25	29	32	36
100 m	13		10	12	14	16	20	23	27	31
10 m	15	10		10	12	14	18	21	25	29
1 m	17	12	10		10	12	15	19	23	26
100 μ	19	14	12	10		10	13	17	21	24
10 μ	21	16	14	12	10		11	15	18	22
1 μ	25	20	18	15	13	11		11	15	18
100 n	29	24	21	19	17	15	11		11	15
10 n	32	27	25	23	21	18	15	11		11
1 n	36	31	29	26	24	22	18	15	11	

Conditions: DI4, 0, 1, 10 (1 is Full scale) is executed, and a resistor is connected so the output voltage is 1V.

T_3 is the time it takes for a digital value input to the DAC to become a stable analog value at the SMU output. For current (IDAC), the wait time ranges from 0.1ms to 328ms (see Table 4), depending on the combination of the voltage and current ranges. For voltage (VDAC), the wait time ranges from 5ms to 500ms when the SMU filter is ON.

To decrease noise effects, use the averaging function (T_4). Three averaging modes are available – AUTO, MANUAL, and POWER LINE CYCLE. To assure accurate HP 4142B measurements, a minimum number of samples is required. For voltage measurements, required minimum samples is 1. For current measurements, required minimum samples depends on the voltage output range and the current measurement range. In AUTO mode, the HP 4142B automatically guarantees that the minimum required samples are taken by multiplying the number of samples you specify by the required minimum samples.

actual number of samples taken
= (required minimum samples) (specified number of samples)

In MANUAL mode, the number of samples you specify is the actual number of samples taken, so you must be sure that the required minimum samples are taken.

In POWER LINE CYCLE mode, 32 samples are taken and averaged for each line frequency period that you specify. For further details about averaging, refer to the HP 4142B Operation Manual, Chapter 3.

To increase output and measurement speed, observe the following points.

① Do not use a high voltage or low current range unless necessary: A 2V to 40V range or a 100μA to 1A range is recommended.
② If the voltage and current output values are changed simultaneously, extra waiting time is needed. Compliance changes should be minimized.
③ If commands are stored in HP 4142B program memory, T_1 (2.5ms) can be reduced to about 1ms.

Table 4. Wait Time after Changing IDAC *Unit: ms*

I range \ V range	2 V	20 V	40 V	100 V	200 V
1 mA~ 1 A	0.1 (2.5)	0.5 (2.8)	0.8 (3.1)	1.9 (4.2)	2.7 (5.1)
100 μA	0.2 (2.5)	0.6 (3)	1.1 (3.5)	2.7 (5)	4.4 (6.7)
10 μA	0.4 (2.7)	2.6 (4.9)	5 (7.3)	5 (14)	5 (26)
1 μA	0.8 (3)	2.3 (5)	4 (6)	5 (11)	5 (19)
100 nA	3 (5)	5 (9)	5 (14)	5 (29)	5 (53)
10 nA	5 (12)	5 (10)	5 (22)	5 (38)	5 (63)
1 nA	5 (29)	5 (56)	5 (87)	5 (178)	5 (328)

Conditions: IDAC changes from 0 to Full scale.
( ) means Filter ON.

2.3 Using Pulse Mode to Reduce Thermal Drift

This section describes the relationship between pulse mode input and the temperature rise at a junction.

Let's assume that power pulse P_0 (Figure 5 – pulse width t and period T) is applied to a device. The device model is cubic (Figure 4), and the section that generates heat due to power application is S in cross-sectional area and x in thickness. If all heat is assumed to be dissipated in the longitudinal direction, then the transient thermal resistance R_{th} and the thermal capacity C_{th} can be expressed by the following equations.

$$R_{th}(t) = \frac{1}{\varkappa} \cdot \frac{x}{S}$$

$$C_{th}(t) = c \cdot \varrho \cdot S \cdot x$$

where, $\varkappa$: Thermal conductivity
c: Specific heat
ϱ: Density

If power P_o is applied for t seconds, the temperature rise ΔT_j at the junction is expressed by the following equation.

$$\Delta T_j \propto R_{th} \cdot P_0 = \frac{P_0 \cdot x}{\varkappa \cdot S}$$

$$\propto \frac{P_0 \cdot t}{C_{th}} = \frac{P_0 \cdot t}{c \cdot \varrho \cdot S \cdot x}$$

$$\therefore x^2 \propto t$$

Therefore, the relation between the transient thermal resistance R_{th} and the pulse width t is as follows:

$$R_{th}(t) \propto x \propto \sqrt{t}$$

The temperature rise ΔT_j at the junction when one power pulse is applied is the product of R_{th} and the power. Accordingly, the above equation shows that ΔT_j is proportional to the square root of the pulse width.

The temperature rise at the junction when n pulses are applied is expressed by the following equation.

$$\Delta T_j \fallingdotseq P_0 \left\{ \frac{t}{T} R_{th}(nT) + R_{th}(t) \right\}$$

Table 5 lists ΔT_j values as calculated by using various values in the above equation. For this calculation, the relation between the pulse width and R_{th} need to be known. Figure 6 shows a graph of pulse width vs. R_{th} when the device is a power transistor (in TO-126 package). Using the HP 4142B, you can set the duty ratio to a minimum of 0.2% (pulse width = 1ms and period = 500ms). As listed in Table 5, ΔT_j is less than 10°C when the duty ratio is less than 1%. Therefore, use pulse mode when it is necessary to reduce thermal drift.

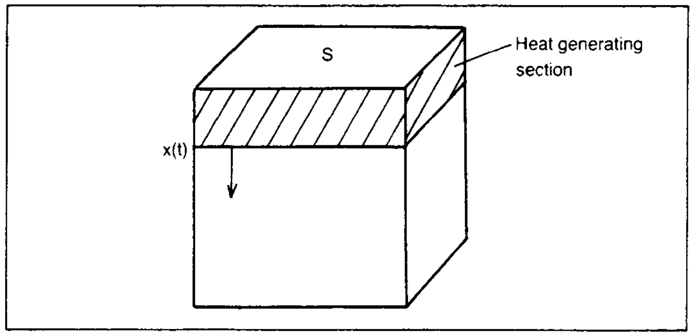


Figure 4. Device Model

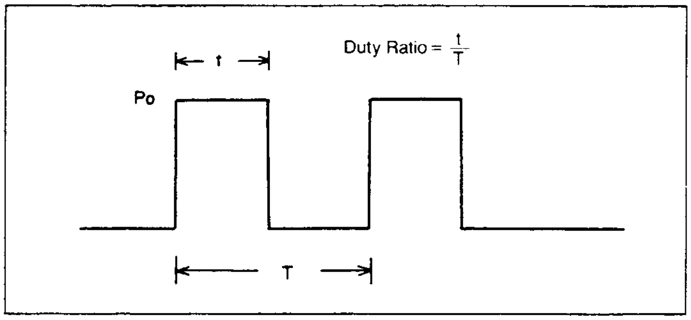


Figure 5. Power Pulse

Table 5. ΔT_j at, P_0=10W, n=100, t=1ms

Duty ratio (%)	R_{th} (nT) (°C/W)	R_{th} (t)	ΔT_j (°C)
100	120	—	1200
10	10	0.6	16
1	30	0.6	9
0.2	100	0.6	7

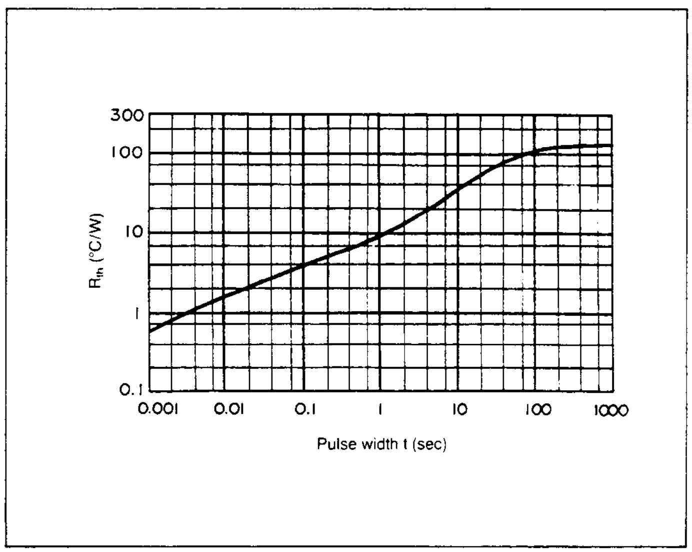


Figure 6. R_{th}–t Pulse Width Curve

2.4 Analog Feedback Unit (AFU) Usage

(1) Hardware configuration and description

Analog search measurements are performed by using an AFU and two SMUs. The AFU provides precision control via a feedback loop to obtain a previously specified target value at the DUT output.

Figure 7 shows a block diagram of the measurement circuit. Unless specified otherwise, the DUT is a bipolar transistor. Operations of each module are as follows:

① **Search SMU**
The search SMU forces a voltage modulated by AFU output to the base ⓐ.

② **Sense SMU**
The sense SMU forces the specified voltage to the collector, and measures collector current. The sense SMU transmits monitored output to the AFU ⓑ.

③ **AFU**
The AFU consists of a reference DAC (target value), an error amplifier that compares reference DAC output to the monitor output from the sense SMU, and an integrator. The integrator operates in one of two modes – ramp-wave voltage generation mode or analog feedback mode. Figure 8 shows how these two modes are inter-related. Analog feedback mode is switched to either positive or negative by the error amplifier.

Immediately after the measurement starts, the AFU integrator outputs a ramp wave to increase DUT base voltage from the search start voltage at the specified ramp rate. When the collector current approaches the specified target value, the integrator is switched to analog feedback mode. At this point, overshoot occurs at the DUT input and output due to delayed target value detection and the switching time of an internal switching circuit (about 20μs). Negative feedback is used to settle the collector current to the target value (time constant τ_{AF} determined by AFU integrator and DUT gain).

During negative feedback, oscillation may occur due to the DUT frequency characteristics. To prevent this, the feedback integration time should be set to τ_{AF} as described later. Parameter setting procedures are as follows.

(2) Parameter value calculations

When the AFU is used, the important parameters are the feedback integration time, ramp rate, and delay time.

These three parameters all have default values, so if you do not specify them, the default values are automatically set. If an error, such as oscillation occurs, input the optimum values, as determined by one of the following methods.

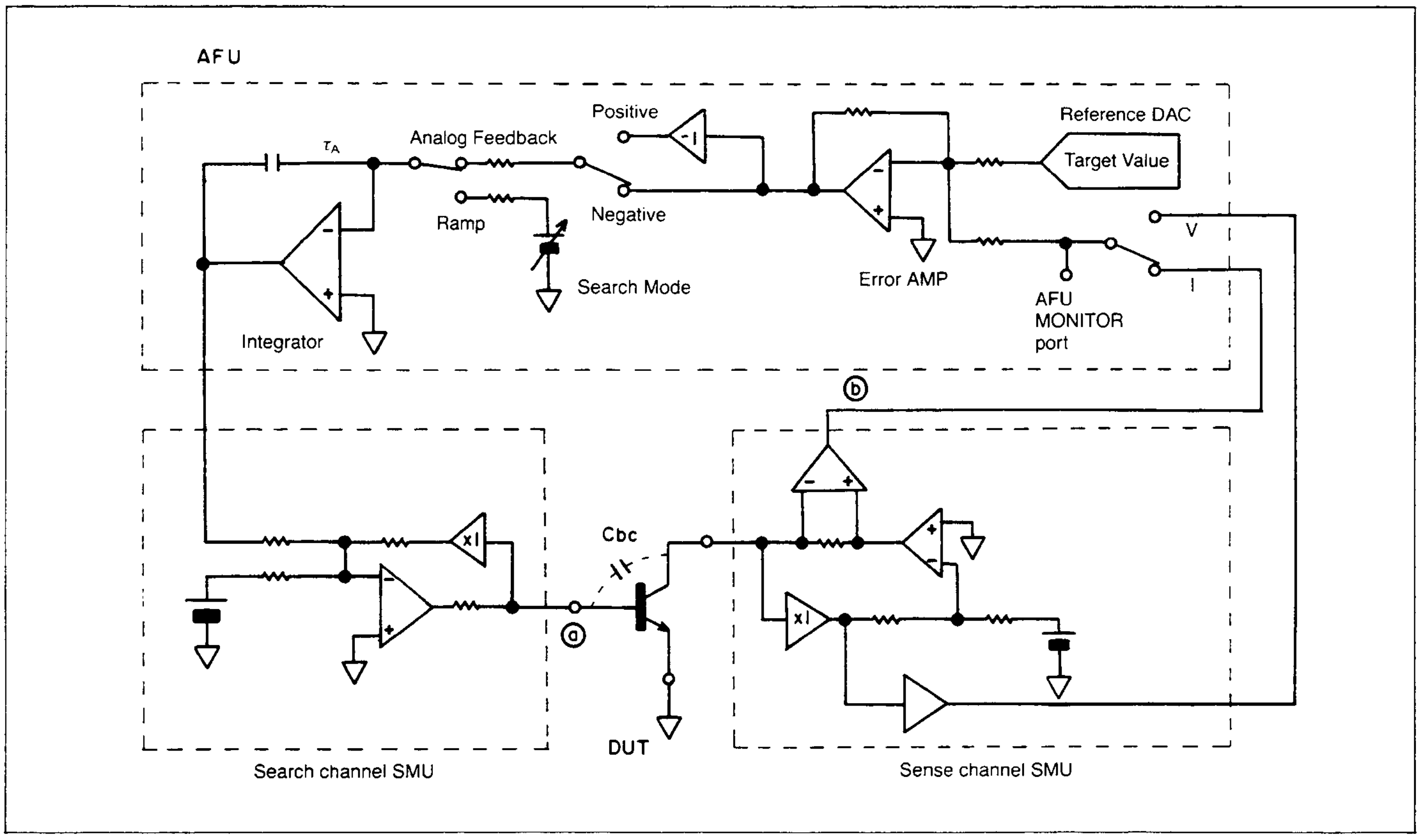
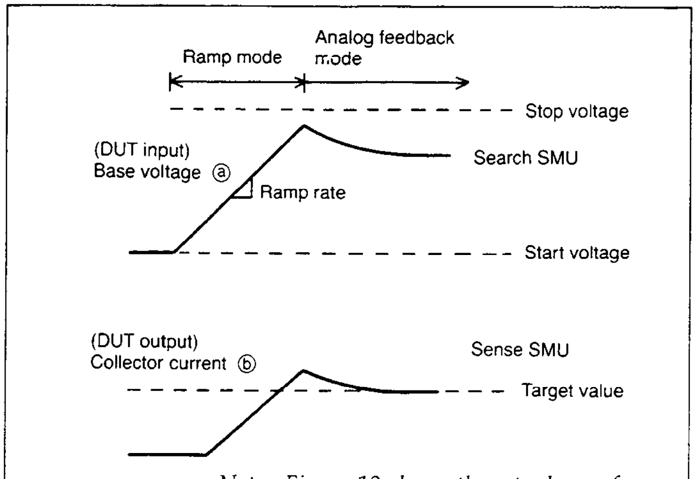


Figure 7. AFU Block Diagram



Note: Figure 12 shows the actual waveforms.

Figure 8. AFU-Related Waveforms

① Use the Control Software parameter calculation subprograms (Para_vth, Para_hfe) to calculate the optimum parameter values for V_{th} and h_{FE} measurements, respectively.
② Understand the basic principles, and calculate the optimum parameter values.

Method ① is recommended. For these subprograms, refer to the HP 4142B Control Software Manual. Method ② is described next.

Figure 9 (a) shows a model of the measurement circuit in analog feedback mode. Note that time constant τ_{AF} shown in Figure 9 (a) differs from time constant τ_A in Figure 7. The τ_{AF} time constant includes the effects of the SMU and error amplifier gain.

Figure 9 (b) shows the frequency characteristics of this circuit. G_{II} (curve II) is the gain from ⓒ to ⓑ in Figure 9 (a), and is equal to the product of the integrator gain G_I and the DUT gain. The feedback gain β (gain from ⓑ to ⓒ in Figure 9 (a)) is 1, therefore the closed loop gain (G_{III}) can be expressed by the following equation.

$$G_{III} = \frac{V_I}{V_{set}} = \frac{G_{II}}{1+G_{II}\beta} = \frac{G_{II}}{1+G_{II}}$$

This loop will be stable if the phase shift is 180° or less when $G_{II}\cdot\beta$ is 1. Therefore, the feedback integration time τ_{AF} should be set so that the phase shift is 180° or less when $G_{II} = 1$ (0dB). In Figure 9 (b), f_1 is the frequency when the integrator gain is 0dB, and f_2 is the frequency when G_{II} is 0dB. The solid lines in Figure 9 (b) are asymptotes for the actual frequency characteristic curve $G_{III} = G_{II}/(1 + G_{II})$, and f_2 is the frequency at which $G_{III} = -3$dB. If the DUT frequency characteristic curve extends past f_2 without attenuation, then the phase shift at f_2 is 90°, so the loop will be stable.

The feedback integration time is an AFU parameter, and should be set to the time constant τ_{AF}. Feedback integration time determination is described in Table 6.

The ramp rate determines the slope of the ramp wave that is input to the DUT. If the ramp rate is set too high, the overshoot will be large and current compliance may be reached, or the measurement time will be increased because it will take longer for the value to settle to the target value. If the ramp rate is too low, it will take longer to reach the target value, thus increasing the measurement time. Set the ramp rate to the optimum value as described in Table 7.

After feedback starts, the HP 4142B waits 100μs or the feedback integration time, whichever is longer. This allows time for the DUT output value to settle within target value tolerance, and also takes into account the delay due to an internal switching circuit (about 20μs). After this, the HP 4142B waits the specified or default delay time before making a measurement. The delay time should be set long enough to handle a long DUT output settling time.

Tables 6 to 8 describe how to determine the feedback integration time, ramp rate, and delay time, respectively.

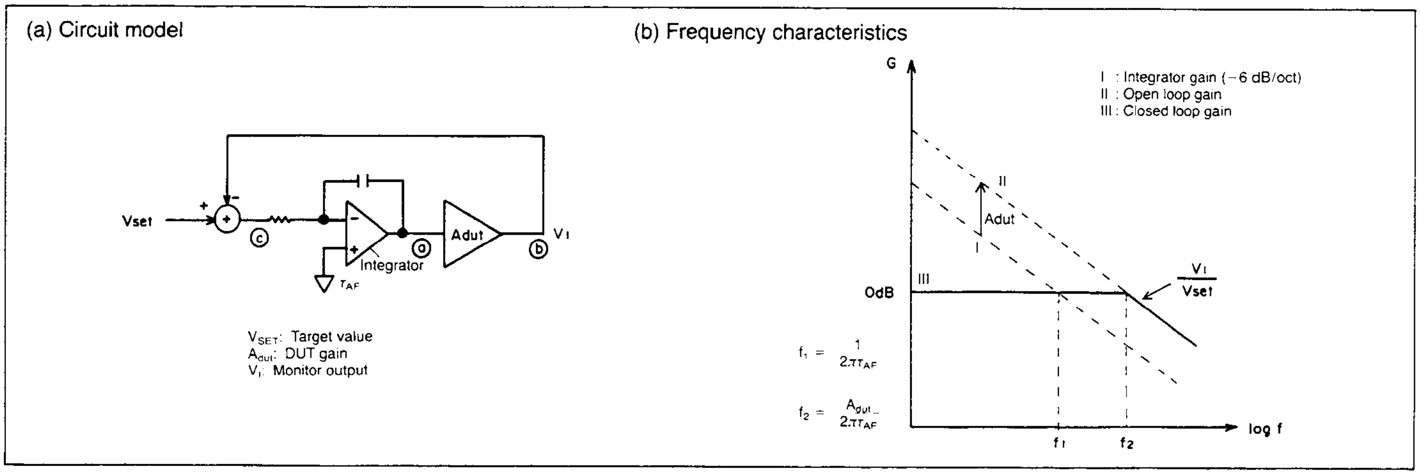


Figure 9. Analog Feedback Mode Circuit Model and Frequency Characteristics

Table 6. Feedback Integration Time Determination Method

If the feedback integration time is set to approximately τ_{AF}, the loop will be stable. To determine τ_{AF}, you must first calculate the time constants as determined by various parts of the system, and then choose the maximum value as shown by the following equations.

$$\tau_{AF} = 2A_{dut}\ \tau_{max} \fallingdotseq 80\tau_{max}$$

where $\tau_{max} = \mathrm{Max}\{\tau_1, \tau_2, \tau_3, \tau_4, \tau_5\}$

Calculations of the 5 time constants and Adut are shown below. DUT and SMU characteristics are necessary for the calculations.

Search channel SMU time constant calculation

(i) Determined by DUT input resistance — τ_1

This time constant is determined by the SMU frequency bandwidth, and the ratio of the current range resistance and the DUT input resistance.

$$\tau_1 = \frac{1}{2\pi f_v} \cdot \frac{R_{rs}}{R_{IN}} = \frac{32 I_{bmax}}{I_{rs}}\ (\mu s)$$

where f_v: SMU frequency bandwidth (200 kHz)
R_{rs}: Search channel SMU current range resistance ($=1/I_{rs}$)
I_{rs}: Full scale of the search channel SMU current range
I_{bmax}: Maximum base current ($= I_c/h_{FEmin}$)
R_{IN}: DUT input resistance

(ii) Determined by the current range and DUT input capacitance C_{IN} — τ_2

Select the proper τ_2 value from Table 6-1.

Table 6–1. τ_2 Determination Table Unit: μs

C_{IN} \ Range	1nA	10nA	100nA	1μA	10μA	100μA	1mA	10mA	100mA	1A
100pF	20	18	13	12	20	5.3	1.7	0.9	0.8	0.8
1000pF	200	80	45	32	23	7	2	1	0.8	0.8

Sense channel SMU time constant calculation

This time constant τ_3 is determined by the current range.
Select the proper τ_3 from Table 6-2. — τ_3

Table 6–2. τ_3 Determination Table Unit: μs

Range	1nA	10nA	100nA	1μA	10μA	100μA	1mA	10mA	100mA	1A
τ_3	60	25	25	16	11	3	3	3	3	3

DUT time constant calculation

(i) Determined by the h_{FE} frequency characteristic — τ_4

$$\tau_4 = \frac{h_{FEmax}}{2\pi f_T}$$

where f_T: Frequency when $h_{FE} = 1$

(ii) Determined by the base-collector capacitance C_{bc} — τ_5

$$\tau_5 = 2\,R_{rm} \cdot C_{bc} = \frac{2\,C_{bc}}{I_{rm}}$$

where R_{rm}: Current range resistance of the sense channel SMU ($=1/I_{rm}$)
I_{rm} : Full scale of the sense channel SMU current range

(iii) DUT gain (See Figure 9.) — A_{dut}

$$A_{dut} = g_m \cdot R_{rm} = 40 I_c \cdot R_{rm} \fallingdotseq 40$$

Table 7. Ramp Rate Determination Method

Calculate the four ramp rates indicated below, and select the minimum value.

$$RS = \text{Min}\{RS_1, RS_2, RS_3, RS_4\}$$

For preventing current compliance from being reached

(i) Determined by search channel SMU

When a ramp voltage is applied, current will flow into the DUT base and from the search SMU output to COMMON via capacitance C_{IN}. This combined current should not reach current compliance. As listed in Table 7-1, the appropriate ramp rate value RS_1 is determined by the DUT input capacitance C_{IN} and the current range.

Table 7–1. RS_1 Determination Table Unit: V/ms

C_{IN} \ Range	1nA	10nA	100nA	1μA	10μA	100μA	1mA	10mA	100mA
10pF	8 m	83 m	0.13	0.43	0.28	2.8	28	280	2800
100pF	1 m	10 m	59 m	0.31	0.28	2.8	28	280	2800

RS_1

(ii) Determined by the sense channel SMU

If ramp rate is determined by the following equation, current compliance will not be reached when overshoot occurs.

$$I_c + g_m \cdot RS_2 \cdot D = I_c\,(1 + 40 \cdot RS_2 \cdot D) \leqq I_{comp}$$

The above equation yields the following equation.

$$RS_2 = (I_{comp}/I_c - 1)/(40 \cdot D)$$

where D: Time required for switching from ramp-wave voltage generation mode to analog feedback mode (τ_1, τ_2, or 20ms, whichever is larger in Table 6).
I_c: Collector current target value
I_{comp}: Sense SMU current compliance

RS_2

For suppressing overshoot

(i) Determined by DUT collector-base capacitance C_{bc}

Calculate a ramp rate that keeps the current flowing in C_{bc} much smaller than I_c, as follows.

$$RS_3 = \frac{I_c}{100 \cdot C_{bc}}$$

where I_c: Collector current target value
100: This factor makes the current flowing in C_{bc} less than 1% of I_c.

RS_3

(ii) Determined to minimize the settling time

If RS_4 is determined by the following equation, the combined ramp-wave generation period and analog feedback period is minimized.

$$RS_4 = \sqrt{\frac{8\,|\,V_{stop} - V_{start}\,|}{\tau_{AF} \cdot D}}$$

where V_{start}: Ramp wave start voltage
V_{stop}: Ramp wave stop voltage
D is the switching time described in RS_2 (above).

RS_4

Table 8. Delay Time Determination Method

<table>
<tr>
<td rowspan="2">After feedback starts, the HP 4142B waits 100μs or the feedback integration time τ_{AF}, whichever is longer: this time is referred to as T_{do}. This allows time for the DUT output value to settle within target value tolerance, and also takes into account the delay due to an internal switching circuit.

$$T_{do} = \text{Max}\,(100\ \mu s,\ \tau_{AF})$$

To determine the delay time T_d, there are two factors to be considered: one is the overshoot recovery time T_1, and the other is the settling time T_2 in the analog feedback mode.

$$T_d = T_1 + T_2$$

T_1 and T_2 calculations are shown on the right.

If:

$$T_d > T_{do}$$

specify T_d as the delay time.

If:

$$T_d \leqq T_{do}$$

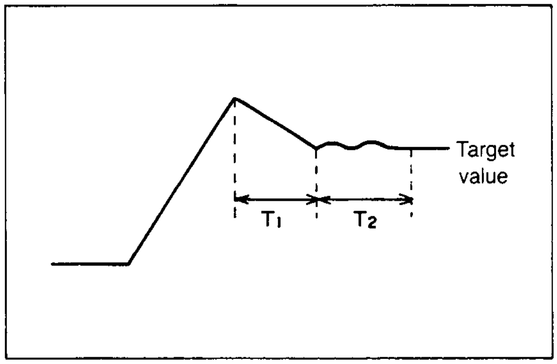
set the delay time to 0 (default value).</td>
<td>(i) Overshoot recovery time
The slew rate during this time is $8/\tau_{AF}$.

$$T_1 = \frac{V_1}{8/\tau_{AF}} = \frac{RS \cdot D \cdot \tau_{AF}}{8}$$</td>
<td>T_1</td>
</tr>
<tr>
<td>(ii) Settling time
As shown in Figure 9 (a), the closed loop bandwidth is $f_2 = A_{dut}/2\pi\tau_{AF}$. The transient response time constant is $\tau = 1/2\pi f_2$. The time required to come within 0.1% of the target value is 6 τ.
Therefore,

$$T_2 = 6\frac{\tau_{AF}}{A_{dut}}$$

Figure 10 shows sense SMU monitor output T_1 and T_2.

Figure 10. Sense SMU Monitor Output T_1 and T_2


</td>
<td>T_2</td>
</tr>
</table>

(3) Parameter calculation example

(a) Bipolar transistor

Here, we'll use the AFU to measure the h_{FE} of a bipolar transistor with the characteristics shown in Table 9.

Table 9. Bipolar Transistor Characteristics

V_c	I_c	$h_{FE\ min}$	$h_{FE\ max}$	C_{IN}	C_{bc}	f_T
5 V	1 mA	100	300	8 pF	4 pF	200 MHz

① **Current range determination**

To increase the measurement speed, the specified ramp rate should be as high as possible, and for analog feedback $T_2 = 6\,\tau_{AF}/A_{dut}$ should be as small as possible. To make T_2 smaller, decrease $\tau_{AF} = A_{dut}/2\pi f_2$ by making the frequency bandwidth f_2 as large as possible. Table 6 shows that τ_{AF} decreases if the current range increases. Therefore, make the current range as high as practically possible.

To allow an increased ramp rate, make the sense SMU current compliance/target value ratio as high as possible. Don't make the ratio too high, however, or the target value setting accuracy will be too low.

Considering the previous paragraphs, the sense SMU current range full scale (FS) value should be 1.15 to 10 times the target value.

The current range is determined by the current compliance value I_{comp}. Therefore, current compliance should be set as determined by the following equation.

$$FS \cdot 0.115 < I_{comp} \leqq FS \cdot 1.15$$

To specify a current range, use a current compliance value that is 1.15 times the full scale value of the range. In our example, the target value is 1mA, so 1.15mA should be specified for the sense SMU current compliance.

For the search SMU, the current range should be set according to the I_{bmax} value, which is determined by the following equation.

$$I_{bmax} = I_c/h_{FEmin} = 1\ mA/100 = 10\ \mu A$$

To set the search SMU current range, set the current compliance in the same way as you did for the sense SMU. For example, to specify the 10μA range, set current compliance to 11.5μA.

② **Search start and stop voltage determination**

The forward bias voltage of a bipolar transistor ranges from 0 to 1V. Therefore, set the start voltage and the stop voltage as follows:

Start voltage: 0 V
Stop voltage: 1 V

③ **Feedback integration time determination**

Calculate τ_1 to τ_5 using Table 6.

$\tau_1 = 32 \cdot I_{bmax}/I_{rs} = 32 \cdot 10\ \mu A/10\ \mu A = 32\ \mu s$

$\tau_2 = 20\ \mu s$ (C_{IN} = 8pF, which is less than 100pF, so use the 100pF row and 10 μA column in Table 6-1 to determine τ_2.)

$\tau_3 = 3\ \mu s$

$\tau_4 = h_{FEmax}/(2\pi \cdot f_T) = 300/2\pi \cdot 200 \cdot 10^6 = 0.24\ \mu s$

$\tau_5 = 2 \cdot C_{bc}/I_{rm} = 2 \cdot 4pF/1mA = 8\ ns$

Therefore,

$$\tau_{AF} = 80 \cdot \tau_{max} = 80 \cdot 32\ \mu s = 2.6ms$$

④ **Ramp rate determination**

Calculate RS_1 to RS_4 using Table 7.

RS_1 = 280 V/s (C_{IN} = 8pF, so use the 10pF row. Current range is 10 μA).

$$RS_2 = (I_{comp}/I_c - 1)/(40 \cdot \tau_1)$$
$$= (1.15/1-1)/(40 \cdot 32\ \mu s)$$
$$= 117\ V/s$$

$$RS_3 = I_c/(100 \cdot C_{bc}) = 1mA/(100 \cdot 4pF)$$
$$= 2.5 \times 10^6 V/s$$

$$RS_4 = \sqrt{8 \cdot |V_{stop} - V_{start}| / \tau_{AF} \cdot D}$$
$$= \sqrt{8 \cdot |1.0 - 0| / 2.6ms \cdot 32\ \mu s}$$
$$= 9.8 \times 10^6\ V/s$$

From the above values, pick the minimum value as the ramp rate.

$$RS = \min\{RS_1 \sim RS_4\} = RS_2 = 117V/s$$

⑤ **Delay time determination**

Determine T_1 and T_2 from Table 8.

$$T_1 = (RS \cdot D \cdot \tau_{AF})/8$$
$$= 117V/s \cdot 32\ \mu s \cdot 2.6ms/8 = 1.2\ \mu s$$
$$T_2 = 6 \cdot \tau_{AF}/A_{dut} = 6 \cdot 2.6ms/40 = 390\ \mu s$$

As described in Table 8, $T_{do} = \tau_{AF}$ = 2.6ms,

$$T_d = T_1 + T_2 = 391.2\ \mu s < T_{do} = 2.6ms$$

Therefore, the delay time should be the default value (0s).

⑥ **Programming example**

(i) Using HP-IB commands to specify parameters

Figure 11 shows an example program for measuring the base current I_b (for calculating h_{FE}) of a bipolar transistor using the AFU and two SMUs. This program sets the parameters that were calculated previously. Figure 12 shows waveforms related to Figure 11 program execution.

In Figure 11, Channel 3 is the source SMU (line 80–ASV3), and Channel 2 is the sense SMU (line 90–AVI2). Line 80 sets the source SMU parameters – source start voltage, source stop voltage, ramp rate, and current compliance. Line 90 sets the sense SMU parameters – collector voltage, target current, and current compliance. Line 100 sets the search operation mode, search measurement mode, and feedback integration time.

If the DUT input and output are directly related, set the search operation mode to negative feedback search; if the DUT input and output are inversely related, set the search operation mode to positive feedback search. The default setting is negative feedback search. Our DUT is a transistor, so DUT input (base voltage) and the target (collector current) are directly related. Therefore, line 100 sets the search operation mode to negative feedback search.

You can specify one of four search measurement modes depending on the combination of search and sense SMU measurements that are necessary. For h_{FE} calculation, we need to measure the base current I_b, so line 100 sets search measurement mode 2, which measures search SMU current I_b. For further details, refer to the HP 4142B Operation Manual.

Line 110 specifies that this is an analog search measurement. Line 120 triggers the measurement. Line 131 transfers the measurement data from the HP 4142B measurement data buffer into the controller as an ASCII string. Line 132 converts the ASCII string (removes header) so it can be displayed as the measurement value. Line 134 displays the measurement value I_b.

(ii) Using the library subprograms to specify parameters.

The furnished software contains subprogram Para_hfe for calculating AFU setting parameters (feedback integration time, ramp rate, and delay time) for h_{FE} measurements. Figure 13 shows an example program that uses this subprogram. Lines 64 through 72 assign the current compliance value, search start and stop voltages, maximum and minimum h_{FE} values, input capacitance C_{IN}, and feedback capacitance C_{bc}. Line 80 calls the subprogram that uses these values to calculate the feedback integration time, ramp rate, and delay time (Tau, Rs, Dt).

```
62    !
63    !
70    !
80    OUTPUT @Hp4142;"ASV3,0,1,117,11.5E-6"
90    OUTPUT @Hp4142;"AVI2,5,1E-3,1.15E-3"
100   OUTPUT @Hp4142;"ASM1,2,2.6E-3"
110   OUTPUT @Hp4142;"MM6"
120   OUTPUT @Hp4142;"XE"
130   !
131   ENTER @Hp4142;A$
132   Ib=VAL(A$[4,15])
134   PRINT Ib
135   !
136   !
137   !
```

Figure 11. Programming Example (h_{FE}) Using HP-IB Commands

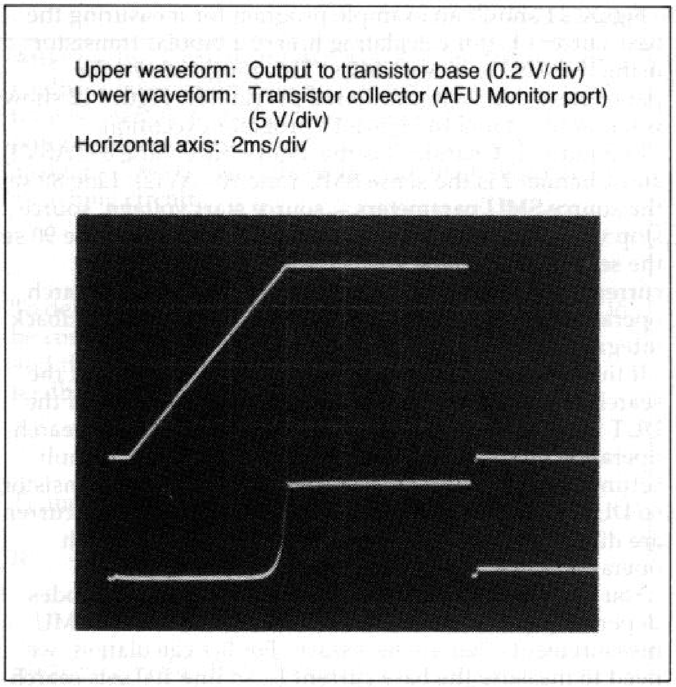


Figure 12. Waveforms Related to Figure 11 Program Execution

Line 90 sets the search SMU, and line 100 sets the sense SMU. Line 110 performs the I_b measurement, and line 120 displays the measurement value.

```
62    !
63    !
64    Icmax=1.15E-3
65    Vstart=0
66    Vstop=1
67    Hfemin=100
68    Hfemax=300
70    Ft=2.00E+8
71    Cin=8.E-12
72    Cbc=4.E-12
73    !
80    Para_hfe(5,1.E-3,Icmax,Vstart,Vstop,Hfemin,Hfemax,Ft,Cin,Cbc,Ib,
      Ibmax,Tau, Rs,Dt)
90    Set_asource(3,Vstart,Vstop,Rs,1.E-3,Dt,Ibmax)
100   Set_amonitor(2,1,5,1.E-3,Icmax)
110   Measure_asearch(1,2,Tau,Ib_meas)
120   PRINT Ib_meas
137   !
138   !
```

Figure 13. Programming Example (h_{FE}) using Furnished Subprograms

(b) FET

Here, we'll use the AFU to measure V_{th} of an FET with the characteristics shown in Table 10.

Table 10. FET Characteristics

V_d	I_d	$V_{TH\ min}$	$V_{TH\ max}$	C_{iss}	C_{rss}	I_{gss}
6V	10μA	1V	2V	3pF	1.3pF	100pA

① **Search start and stop voltage determination**

The following search start and stop voltages should allow V_{th} to be reached.

Start voltage: 0 V
Stop voltage: 2 V

② **Current range determination**

To determine V_{th}, it is not necessary to measure the search SMU current, therefore set the current range as large as possible to increase SMU response speed. We will set current compliance to 11.5mA to select the 10mA range.

For the sense SMU, select a current range using the same principles as described for bipolar transistors. Set the current compliance value to 11.5μA to select the 10μA range.

③ **Feedback integration time determination (see Table 6)**

- Assuming that the FET input resistance is very high, then $I_{bmax} = 0$, thus $\tau_1 \fallingdotseq 0$.
- $C_{ISS} = C_{IN} = 3pF$, which is less than 100pF. Current range = 10mA. So using Table 6-1, $\tau_2 = 0.9\mu s$.
- The sense SMU current range is 10μA, so using Table 6-2, $\tau_3 = 11\mu s$.
- τ_4 does not apply to FETs.
- C_{rss} for an FET corresponds to C_{bc} for a bipolar transistor, so

$$\tau_5 = 2 \cdot C_{rss}/I_{rm} = 2 \cdot 1.3pF/10\ \mu A = 0.26\ \mu s$$

- Assume that the DUT gain in the subthreshold region is 40.

Therefore,

$$\tau_{AF} = 80 \cdot \tau_{max} = 80 \cdot \tau_3 = 0.88ms$$

④ **Ramp rate determination (see Table 7)**

- $C_{ISS} = C_{IN} = 3pF$ and the search SMU current range is 10mA, so using Table 7-1, $RS_1 = 280V/ms = 280 \times 10^3 V/s$
- $D = \max(\tau_1, \tau_2, 20\ \mu s) = 20\ \mu s$, and using Id for Ic,

$$\begin{aligned} RS_2 &= (I_{comp}/I_d - 1)/(40 \cdot D) \\ &= (11.5/10 - 1)/(40 \cdot 20\ \mu s) \\ &= 188\ V/s \end{aligned}$$

- Using C_{rss} and I_d for C_{bc} and I_c.

$$\begin{aligned} RS_3 &= I_d/(100 \cdot C_{rss}) = 10\ \mu A/(100 \cdot 1.3pF) \\ &= 77 \times 10^3\ V/s \end{aligned}$$

$$\begin{aligned} RS_4 &= \sqrt{8 \cdot |V_{stop} - V_{start}| / \tau_{AF} \cdot D} \\ &= \sqrt{8 \cdot 2/0.88ms \cdot 20\ \mu s} \\ &= 30 \times 10^3\ V/s. \end{aligned}$$

From the above values, pick the minimum value as the ramp rate.

$$RS = \min\{RS_1 \sim RS_4\} = RS_2 = 188\ V/s$$

⑤ **Delay time determination**
Determine T_1 and T_2 from Table 8.

$$T_1 = RS \cdot D \cdot \tau_{AF}/8 = 188V/s \cdot 20\mu s \cdot 0.88ms/8 = 3.3\ \mu s$$
$$T_2 = 6 \cdot \tau_{AF}/A_{dut} = 6 \cdot 0.88ms/40 = 132\ \mu s$$

As described in Table 8, $T_{do} = \tau_{AF} = 0.88ms$, so

$$T_d = T_1 + T_2 = 135.3\ \mu s < T_{do} = 0.88ms$$

Therefore, the delay time should be the default value (0s).

⑥ **Programming example**
Figure 14 and Figure 15 show programming examples for specifying parameters using HP-IB commands and furnished library software subprograms, respectively. For explanations, refer to the previous bipolar transistor programming example paragraphs.

```
62    !
63    !
70    !
80    OUTPUT @Hp4142;"ASV3,0,3,188,11.5E-3"
90    OUTPUT @Hp4142;"AVI2,6,1E-5,11.5E-6"
100   OUTPUT @Hp4142;"ASM1,1,0.88E-3"
110   OUTPUT @Hp4142;"MM6"
120   OUTPUT @Hp4142;"XE"
130   !
132   ENTER @Hp4142;A$
135   Vth=VAL(A$[4,15])
136   PRINT Vth
137   !
138   !
139   !
```

Figure 14. Programming Example (V_{TH}) using HP-IB Commands

```
62    !
63    !
70    !
80    Vd=6
90    Id=1.E-5
100   Idmax=1.15*Id
110   Vstart=0
120   Vstop=2
130   Igmax=1.15E-2
131   Cin=3.E-12
132   Cgd=1.3E-12
133   !
134   Para_vth(Vd,Id,Idmax,Vstart,Vstop,Igmax,Cin,Cgd,Tau,Rs,Dt)
135   Set_asource(3,Vstart,Vstop,Rs,1.E-3,Dt,Igmax)
136   Set_amonitor(2,1,Vd,Id,Idmax)
137   Measure_asearch(1,1,Tau,Vth)
138   PRINT Vth
141   !
142   !
143   !
```

Figure 15. Programming Example (V_{TH}) using Furnished Subprograms

(4) AFU operation tips

① **Changing parameters if errors occur**
If the feedback integration time, ramp rate, and delay time are not specified, the following default values are automatically used.

Feedback integration time = 5ms
Ramp rate = 500V/s
Delay time = 0s

Usually no errors (oscillation, etc.) will occur if the above settings are used. However, if errors do occur, change the parameters as follows.

- If the target value is not reached, make sure that the start and stop voltages are appropriate.
- Set the ramp rate to 10% of its present value.
- Double the feedback integration time.
- If the measurement value (I_c or I_d) is not within ±2% of the target value, repeat this sequence.

② **Measurement range selection**
•Sense SMU[1]
To ensure accurate measurement sensitivity and a reasonable settling time, set a moderate current compliance/target value ratio. The recommended ratio is 1.15 to 10.

•Search SMU
To increase measurement speed, set the highest current range that still allows an acceptable resolution.

③ **AFU MONITOR port**
You can monitor the sense SMU measurement output at the AFU MONITOR port. If a low current range (less than 10μA) is set, no overshoot may be observed at the AFU Monitor port due to measurement circuit delay[2], even if overshoot occurs. Therefore, even if no overshoot is observed, do not set the feedback integration time too short or the ramp rate too high.

[1] *If the condition indicated below is satisfied, change to the next higher range.*
Target value > Range full scale and
Current compliance value > Range full-scale × 1.15

[2] *The measurement is not affected by this delay because it is corrected by the AFU error amplifier.*

3. APPLICATION EXAMPLES

3.1 Characteristic Curve Measurement Methods for Bipolar Transistors and FETs

Table 11 shows the force modes, measurement circuits, relevant HP-IB commands, and relevant library subprogram names that are necessary for performing various characteristic curve measurements.

Figure 16 shows the test fixture, DUT, and controller connections for measuring characteristics curves.

Table 11. Characteristic Curve Measurement Methods

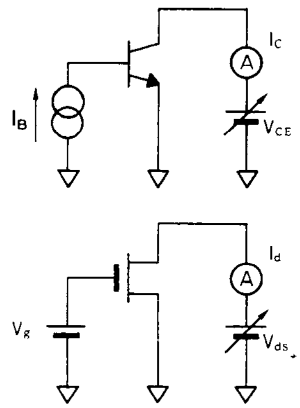
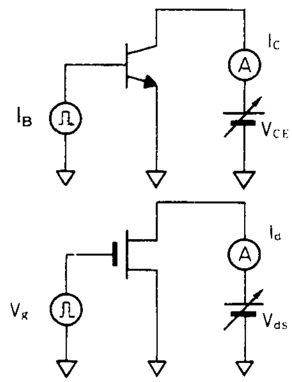
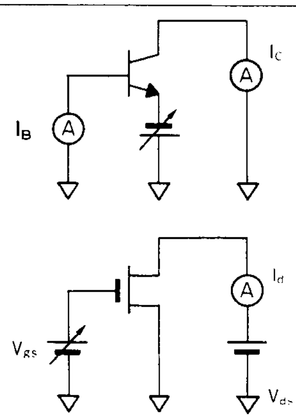
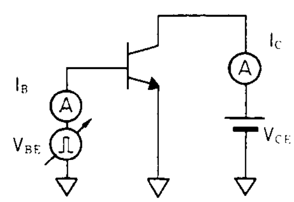
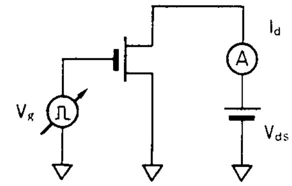
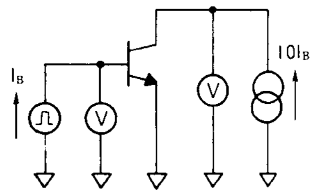
Characteristic curve		Force mode	Measurement circuit	Associated command	
Bipolar transistor	FET			HP-IB command	Subprogram name
I_C-V_{CE}	I_d-V_{ds}	Staircase sweep (from low to medium current region)		WV WI WSV WSI WT WM	Sweep_iv Sweep_miv Set_iv Sweep_mode
		Staircase sweep with pulsed bias (high current region)		WV WI WM PV PI PT	Pulse_v Pulse_i Set_iv Sweep_pbias
I_C-V_{BE} I_B-V_{BE} $h_{FE}-I_C$	I_d-V_{gs}	Staircase sweep (from low to medium current region)		WV WI WSV WSI WT WM	Sweep_iv Sweep_miv Set_iv Sweep_mode
		Pulsed sweep (high current region)	 Note: I_B and I_C cannot be measured at the same time.	PWV PWI	Set_piv Sweep_piv

Table 11. Characteristic Curve Measurement Methods (continued)

Characteristic curve		Force mode	Measurement circuit	Associated command	
Bipolar transistor	FET			HP-IB command	Subprogram name
	$g_m - V_{gs}$ $g_m - I_d$	Pulsed sweep (high current region)		PWV PWI	Set_piv Sweep_piv
$V_{CE(sat)}$ $-I_C$ $V_{BE(sat)}$ $-I_C$		Pulsed spot (high current region)		PV PI PT	Pulse_v Pulse_i

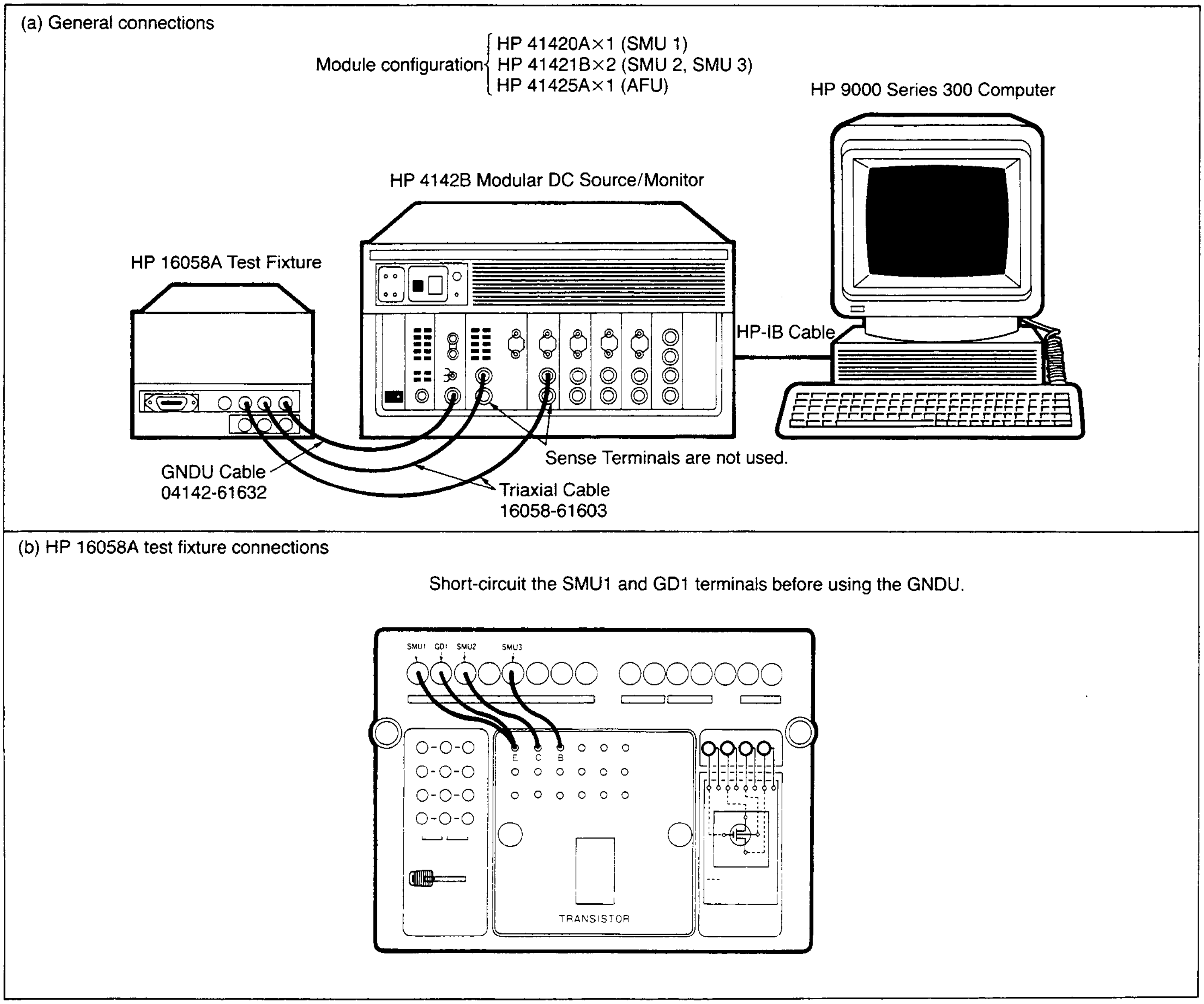


Figure 16. Test Fixture, DUT, and Controller Connections

3.2 GaAs MESFET Characterization

Figure 17 shows that a GaAs MESFET has 3 electrodes (source, gate, and drain), a thin active layer, and a semi-insulating GaAs substrate. GaAs MESFETs can operate at a high frequency, and are thus used in microwave applications. GaAs MESFETs are very small, and the thermal conductivity is very low (about 1/3 that of silicon), so heat generated by high voltage or current application causes problems. Using the HP 4142B's pulsed output, $I_d - V_{ds}$ characteristics in the high current region can be correctly measured because thermal drift is reduced.

Figure 18 shows a CURTICE model that is often used in circuit simulations for MESFETs. The rising edge drain current I_d is a hyperbolic function (tanh) of V_{ds}, which determines electron velocity saturation.

Sweep measurement techniques can be used to determine the circuit model parameters and the following property parameters.

- •K: Gain factor
- •V_{TO}: Threshold voltage
- •R_s, R_d, R_g: Ohmic contact resistances
- •n: Ideal factor of Schottky junction
- •I_{gs}: Saturation current at the Schottky junction
- •V_{bi}: Built- in potential
- •N_N: Active layer electron density
- •a: Active layer thickness
- • μ_o: Active layer electron mobility
- •g_m: Mutual conductance
- •F_{min}: Minimum noise figure

(1) K and V_{TO} measurement

Figure 19 shows the K and V_{TO} measurement circuit. The device is a depletion-type FET. Apply about .05V to the drain, then perform a staircase sweep of the gate voltage, and measure the drain current for each step.

Plot measurement values on the $\sqrt{I_d} - V_{gs}$ graph (Figure 20). The gain factor K is the slope of the straight line section, and the threshold voltage V_{TO} is the voltage where the extrapolated straight line intersects the x-axis (V_{gs}).

$$V_{TO} = -3.5V$$

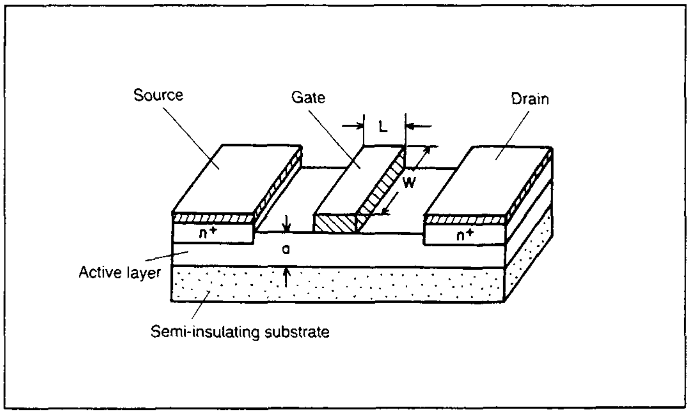


Figure 17. GaAs MESFET Structure

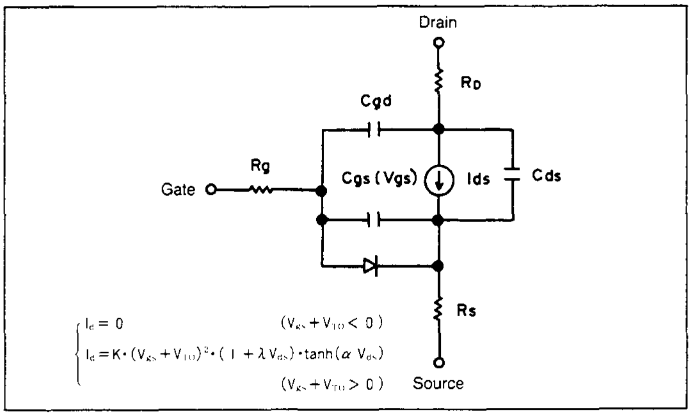


Figure 18. GaAs MESFET Circuit Model

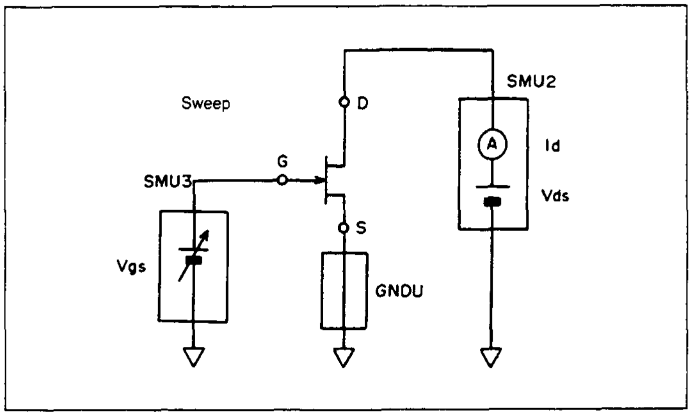


Figure 19. K, V_{TO} Measurement Circuit

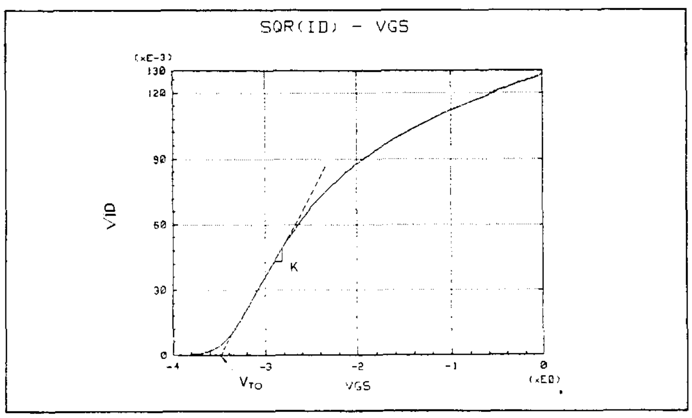


Figure 20. K, V_{TO} Extraction

(2) R_s, R_d, and R_g measurement

Figure 21 shows the R_s measurement circuit. With a 100μA gate-source current, staircase sweep the drain voltage, and measure drain current and gate voltage. Plot the measured values on the $V_{gs} - I_d$ graph (Figure 22). R_s is the slope of the straight line section. To determine R_d, switch the positions of SMU2 and GNDU, and perform the measurement in the same way.

Figure 23 shows the R_g measurement circuit and results. With $I_d = 0$, pulse sweep the gate voltage from 0V to 1.2V and measure I_g. Plot the results on an $I_g - V_{gs}$ graph and determine the slope of the straight line section shown in Figure 23. This slope is the sum of R_s and R_g. Subtract R_s from this number to determine R_g.

(3) n, I_{gs}, V_{bi}, N_N, and a

The current density at the Schottky junction between the gate and the source is expressed as follows:

$$J_g = A^* \cdot T^2 \cdot \exp\left[-\frac{qV_{bi}}{kT}\right] \cdot \exp\left[\frac{qV_{gs}}{nkT}\right]$$

where A^*: Effective Richardson constant (8.7 $A/cm^2/K^2$)
n: Ideal factor
V_{bi}: Schottky barrier built-in potential

The measurement circuit is the same as Figure 23, except the gate voltage sweep is a staircase sweep instead of a pulse sweep. For this measurement, the low current region is important, so pulse sweep is unnecessary.

Plot Log $I_g - V_{gs}$ as shown in Figure 24, and n is determined by the slope of the straight line section. I_{gs} is the current where the extrapolated straight line intersects the y-axis (I_g).

$$n = 1.197$$
$$I_{gs} = 3.13 \times 10^{-12}$$

The built-in potential V_{bi}, electron density N_N, and active layer thickness can be calculated from I_{gs}, the channel length L, and the channel width W, using the equations in Table 12. Assuming L = 1.5μm and W = 1,500μm, these parameters are calculated as follows:

$$V_{bi} = 26 \times 10^{-3} \ln\left[\frac{8.7 \cdot 300^2 \cdot 1.5 \cdot 1500 \times 10^{-8}}{3.13 \times 10^{-12}}\right]$$

$$= 0.763 \text{ V}$$

$$N_N = \exp\left[\frac{0.763 - 0.706}{0.026}\right] = 8.96\ (10^{16}/cm^3)$$

$$a = \sqrt{\frac{3.5 + 0.763}{7.23 \cdot 8.96}} = 0.26\ \mu m$$

Table 12. V_{bi}, N_N, and a Equations

$$V_{bi} = \frac{kT}{q} \cdot \ln\left[\frac{A^* \cdot T^2 \cdot L \cdot W}{I_{gs}}\right]$$

$$N_N = \exp\left[\frac{V_{bi} - 0.706}{kT/q}\right]$$

$$a = \sqrt{\frac{|V_{TO}| + V_{bi}}{7.23 \cdot N_N}}$$

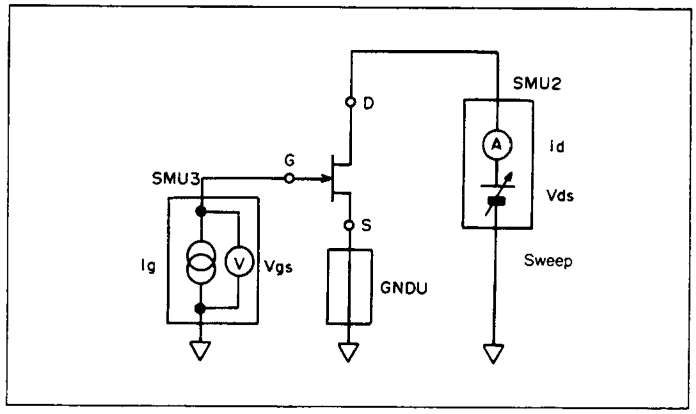


Figure 21. R_s Measurement Circuit

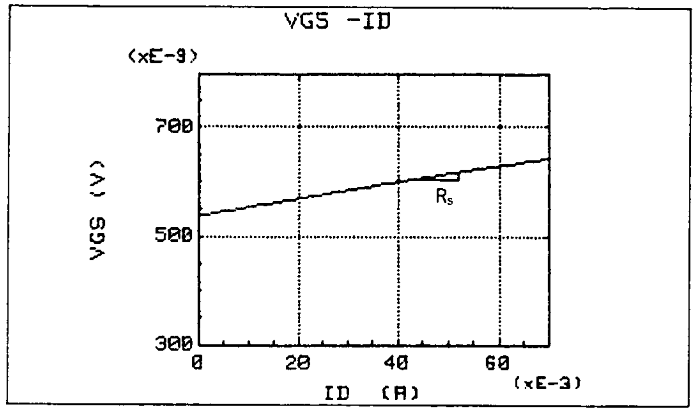


Figure 22. R_s Extraction

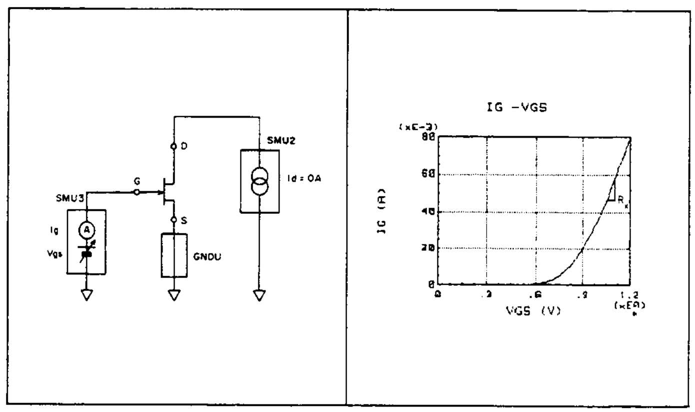


Figure 23. R_g Measurement Circuit and Extraction

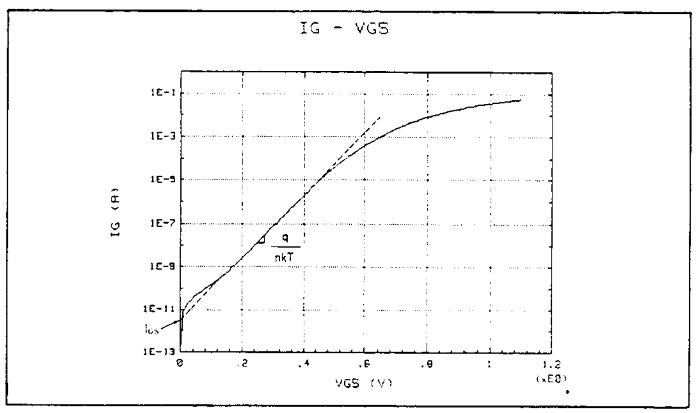


Figure 24. I_{gs}, n Extraction

(4) R_o and μ_o

When the drain voltage is about 0V in the nonsaturation region, the approximate drain current expression is as follows:

$$I_d \fallingdotseq G_0 \cdot \left\{ 1 - \sqrt{\frac{V_{bi}-V_{gs}}{V_{bi}-V_{TO}}} \right\} \cdot V_{ds}$$

where $G_o = \dfrac{1}{R_o}$ = open channel conductance.

$$\text{Using } XX \equiv \left[1 - \sqrt{\frac{V_{bi}-V_{gs}}{V_{bi}-V_{TO}}} \right]^{-1}$$

$$\text{then } R_o = \frac{V_{ds}}{I_d\, XX}$$

Figure 25 shows the measurement circuit. With a constant voltage of 0.05V applied to the drain, pulse sweep the gate voltage and measure the drain current. Plot the measurement values on the $V_{ds}/I_d - XX$ graph (Figure 26). If the characteristic curve is not a straight line, it means that the V_{bi} or V_{TO} value is not appropriate. If this occurs, measure V_{TO} and I_{gs} again. The open channel resistance R_o is the slope of the straight line characteristic curve and is 1.08Ω from our measurement.

The weak electric field electron mobility is determined by the following equation.

$$\mu_o = \frac{L}{R_0 \cdot q \cdot N_N \cdot a \cdot W}$$

Using R_o, a, and N_N that we determined earlier,

$$\mu_o = \frac{1.5}{1.08 \cdot 1.9\times10^{-19} \cdot 8.96\times10^{16} \cdot 0.26\times10^{-4} \cdot 1500}$$

$$= 2091.9\ (\text{cm}^2/\text{V} \cdot \text{sec})$$

(5) g_m and F_{min}

Figure 27 shows the g'_m measurement circuit. With constant voltage applied to the drain, pulse sweep the gate voltage and measure I_d. This circuit measures the actual mutual conductance g'_m, which has been degraded from the intrinsic mutual conductance g_m by R_s. Use the measurement points and the following equation to determine g'_m for various V_{gs} values, then plot g'_m vs V_{gs} as shown in Figure 28.

$$g'_m = \frac{\Delta I_d}{\Delta V_{gs}}$$

The intrinsic mutual conductance g_m is calculated by the following equation.

$$g_m = \frac{g'_m}{1 - g'_m R_s}$$

The minimum noise Figure F_{min} occurs for drain current I_{dss} (V_{gs} = 0). From Figure 28, at V_{gs} = 0V, $g'_m \fallingdotseq .095$S, so from the above equation $g_m \fallingdotseq 0.11$S. The minimum noise Figure F_{min} is expressed by the following equation.

$$F_{min} \fallingdotseq 10 \cdot \log\left[1 + K \cdot f \cdot L \cdot \sqrt{g_m(R_g+R_s)}\right]\ (\text{dB})$$

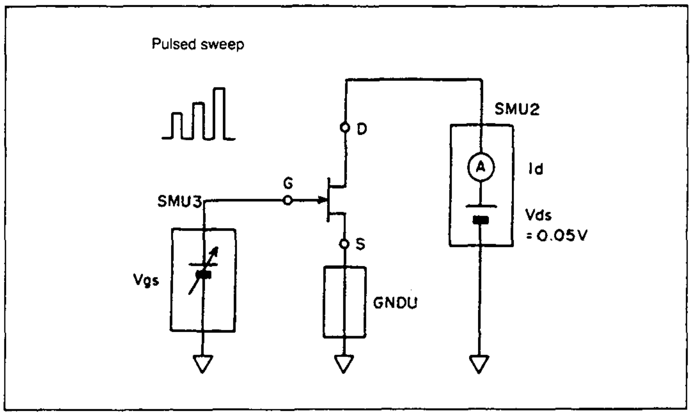


Figure 25. R_o Measurement Circuit

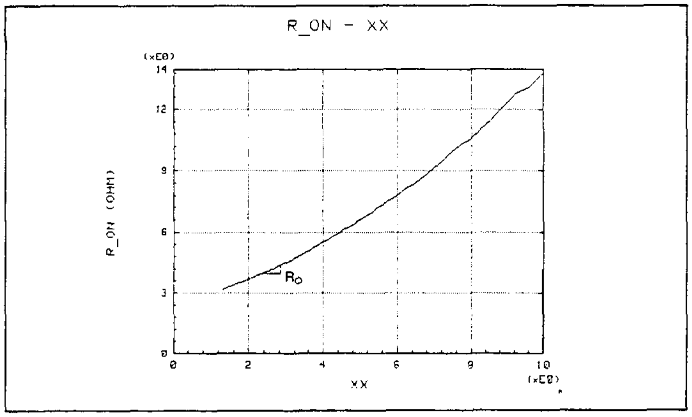


Figure 26. R_o Extraction

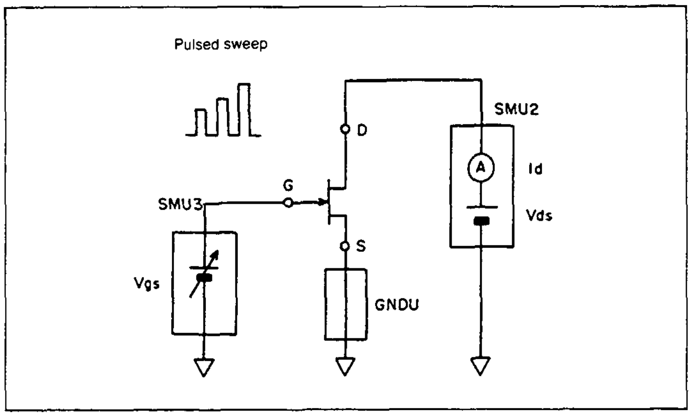


Figure 27. g'_m Measurement Circuit

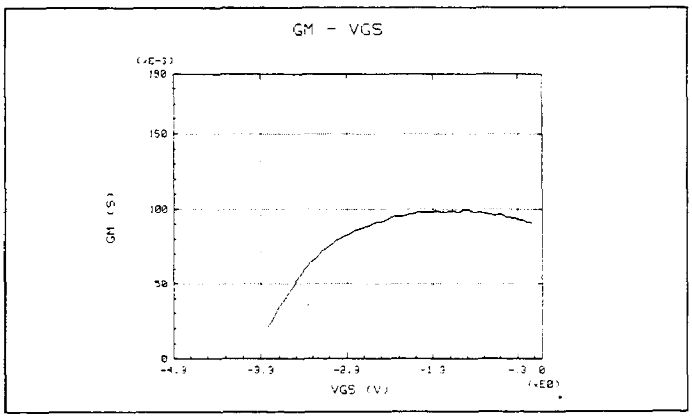


Figure 28. g'_m Measurement Plot

where K: Constant with value 0.25 to 0.3
f: Operation frequency (GHz)
L: Channel length
R_g: 3.96Ω and R_s = 1.5Ω from previous measurement (See Figures 22 and 23, respectively).

Using f = 5.92GHz and g_m obtained above, and assuming K = 0.27, the minimum noise figure is calculated as follows:

$$F_{min} = 10 \cdot \log [1+0.27 \cdot 5.92\text{GHz} \cdot 1.5\mu\text{m} \cdot \sqrt{0.11 \cdot (3.96\Omega+1.5\Omega)}] = 4.5 \text{ (dB)}$$

3.3 Power MOSFET Characterization

Unlike general MOSFETs, the power MOSFET has a vertical structure (Figure 29) and a parasitic capacitance between the source and the drain as shown in the circuit model in Figure 30.

The drain current expressions are as follows:

I. Linear region (nonsaturation region)

$$I_D = 2 \cdot K \cdot V_{ds} \cdot [(V_{gs}-V_T)-V_{ds}/2]\,(1+\lambda V_{ds})$$

II. Saturation region

$$I_D = K \cdot (V_{gs}-V_T)^2 \cdot (1+\lambda V_{ds})$$

The gain factor K, threshold voltage V_T, channel length modulation parameter λ, source resistance R_s, and drain resistance R_D are determined as follows:

(1) K and V_T

Figure 31 shows the measurement circuit. Perform a synchronous staircase sweep of the gate-source and the drain-source voltages. Measure the drain current I_d, and plot measurement values on the $\sqrt{I_d} - V_{gs}$ graph (Figure 32).

The gain factor K is the slope of the straight line section, and the threshold voltage V_T is the voltage where the extrapolated straight line intersects the x-axis (V_{gs}).

(2) λ

Figure 33 (a) shows the measurement circuit. With pulsed voltage applied to the gate, staircase sweep the drain voltage. Plot measurement values on the I_d-V_{ds} graph (Figure 33 (b)). Select a point on the characteristic curve, and call the coordinates of this point (V_{ds1}, I_{d1}). Extrapolate a straight line from this point to the y-axis (I_d), and call the intersection point I_{do}. Determine λ from the following equation:

$$\lambda = \frac{I_{d1}-I_{do}}{I_{do} \cdot V_{ds1}}$$

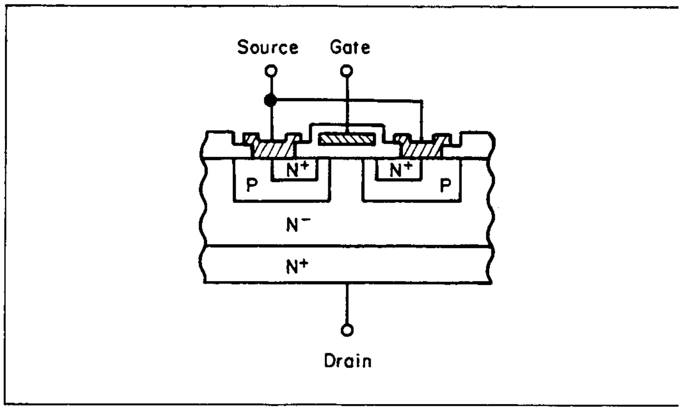


Figure 29. Power MOSFET Structure

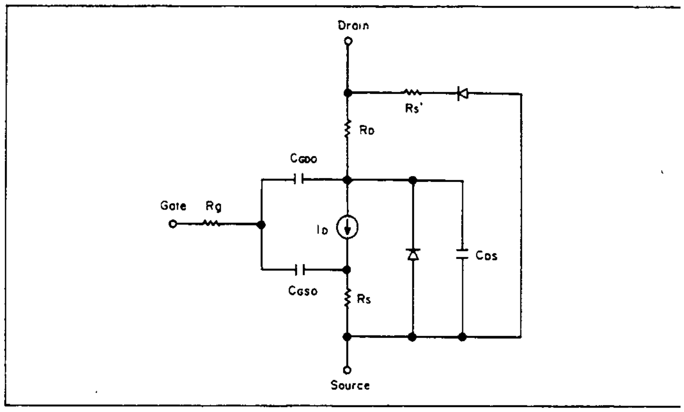


Figure 30. Power MOSFET Circuit Model

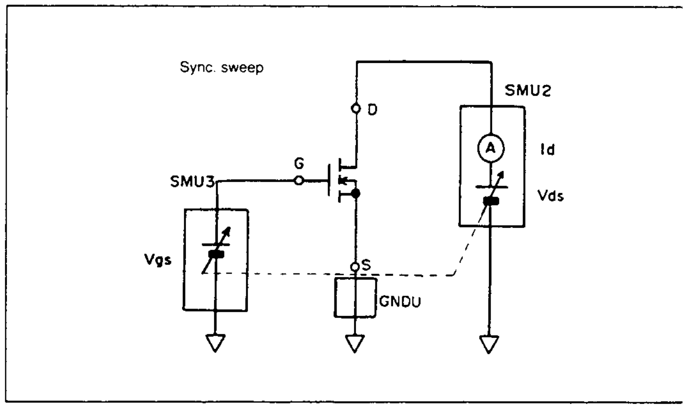


Figure 31. K, V_T Measurement Circuit

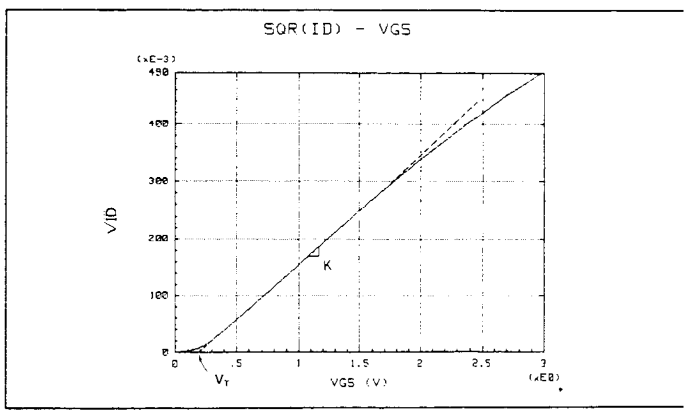


Figure 32. K, V_T Extraction

(3) R_s

To include the voltage drop due to the ohmic contact resistances R_s and R_d, replace V_{gs} and V_{ds} in Equations I and II (previous page) with the following expressions.

$$V_{gs} = V'_{gs} - I_d R_s$$
$$V_{ds} = V'_{ds} - I_d (R_s + R_D)$$

where V'_{gs} and V'_{ds} are the measurement values.

Using the measurement circuit in Figure 33 (a), perform measurements for two $V'_{ds} - I_d$ characteristic curves and plot the curves (Figure 34). Each curve has constant V'_{gs}. Choose a saturation region point from each curve (V_{ds1}, I_{d1}) and (V_{ds1}, I_{d2}), and substitute these points to make 2 versions of Equation II. If these two versions are combined, the following equation can be derived. Plug in the values to calculate R_s.

$$R_s = \frac{V_{gs1} - bV_{gs2} - V_T (1-b)}{I_{d1} (1 - 1/b)}$$

$$b = \frac{I_{d1}}{I_{d2}}$$

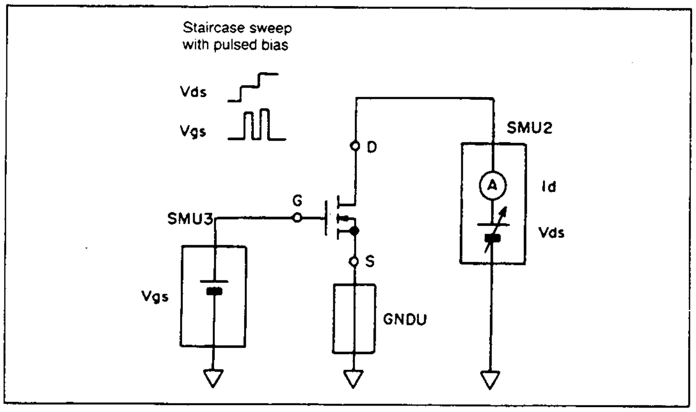


Figure 33 (a). λ Measurement Circuit

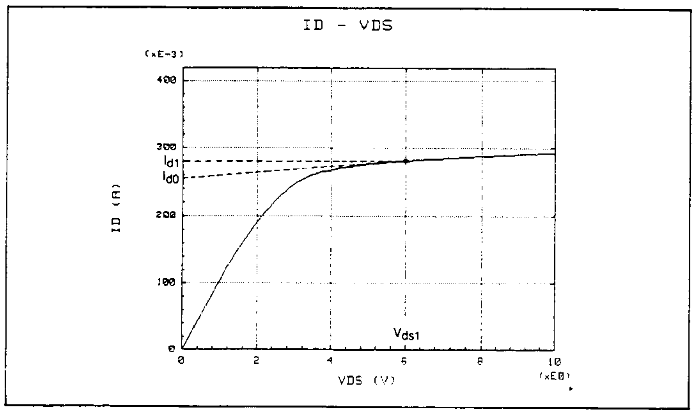


Figure 33 (b). λ Extraction

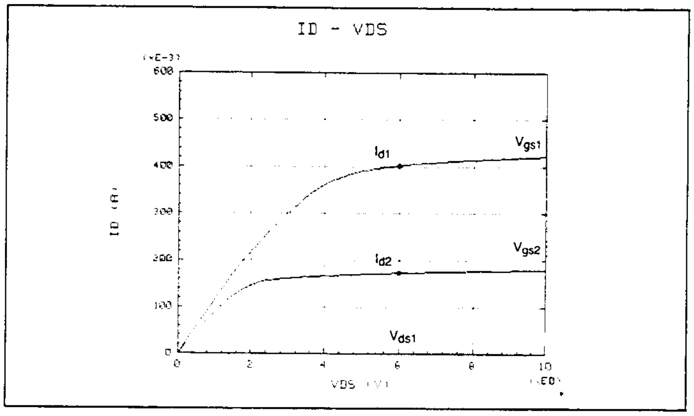


Figure 34. R_s Extraction

(4) R_D

Figure 35 shows the measurement circuit for determining R_D. With 0.1V applied to the drain, pulse sweep the gate voltage, and mesure I_d. Plot the measurement values on the $V_{gs} - R_{ON}$ graph. $R_{ON} = V_{ds}/I_d$.

$$R_{ON} = R_s + R_D + \frac{1}{2 \cdot K \cdot (V_{gs} - V_T)}$$

Determine the drain resistance R_D from the following equation:

$$R_D = R_{ON} - R_s - \frac{1}{2 \cdot K \cdot (V_{gs} - V_T)}$$

Use the values of R_s, K, and V_T that you measured previously.

Use Figure 36 to select the R_{ON} and V_{gs} values: Use the R_{ON} value in the region where R_{ON} has become fairly constant. V_{gs} corresponds to the R_{ON} you choose.

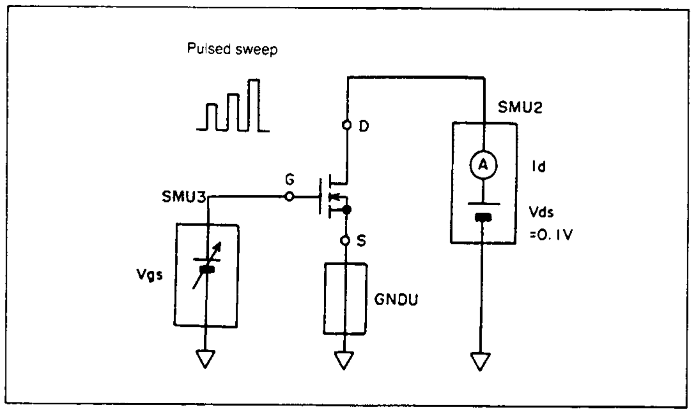


Figure 35. R_{ON} Measurement Circuit

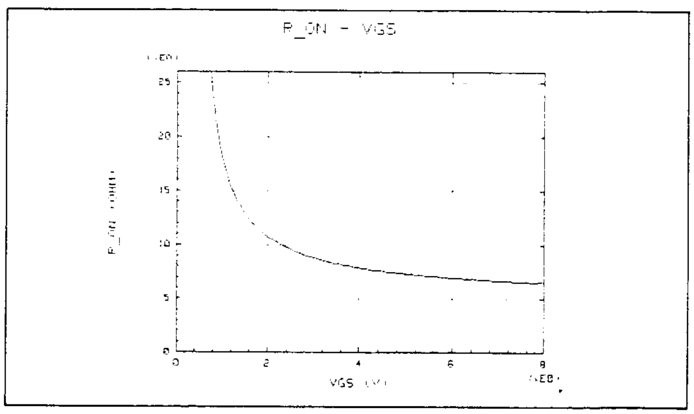


Figure 36. R_{ON} Measurement Plot

3.4 Bipolar Power Transistor Characterization

The knee current I_K, which produces high injection effects in the high current region, emitter resistance R_E, and collector resistance R_C are determined as follows.

(1) I_K

Use the circuit in Figure 37 to measure values for the high current $I_c - V_{BE}$ and $I_B - V_{BE}$ characteristic curves. With $V_{CE}=1V$, pulse sweep the base voltage, and measure I_B and I_C. Plot measurement values on a semilogarithmic graph. In the high current region (>10mA), the curve is not a straight line. This is caused by the ohmic resistance at the base and emitter terminal and by voltage drop due to the base-spreading resistance. The drop-away voltage ΔV_{BE} is expressed by the following equation:

$$\Delta V_{BE} = V_{BE} - V'_{BE} = I_B R_B + I_E R_E$$

where V_{BE}: Measured value
V'_{BE}: Transistor intrinsic value (Ignoring R_B and R_E)

The theoretical expression for the base current is:

$$I_B = I_{BS} \cdot \exp\left[\frac{qV'_{BE}}{nkT}\right]$$

You can determine the saturation current I_{BS} and the ideal factor n from the $I_B - V_{BE}$ characteristic curve in the medium and low current region. Perform a synchronous staircase sweep of the base-emitter and collector-emitter voltages to obtain measurement values for plotting an $I_B - V_{BE}$ characteristic curve. Plot measurement values on a semilogarithmic graph (Figure 40). Determine n from the slope of the straight line section in the medium current region. I_{BS} is the current where the extrapolated straight line intersects the y-axis (I_B).

Intrinsic voltage V'_{BE} can now be determined by the following equation.

$$V'_{BE} = \frac{nkT}{q} \ln\left[\frac{I_B}{I_{BS}}\right]$$

Pick $I_B - I_C$ pairs (same V_{BE}) from Figure 38, and use the I_B values in the above equation to calculate corresponding V'_{BE} values. Then, plot I_C and I_B vs. V'_{BE} as shown in Figure 39. The I_B curve is now corrected to a straight line, and the I_C curve has a discontinuity (slope changes drastically). The current at this discontinuity is the knee current I_K.

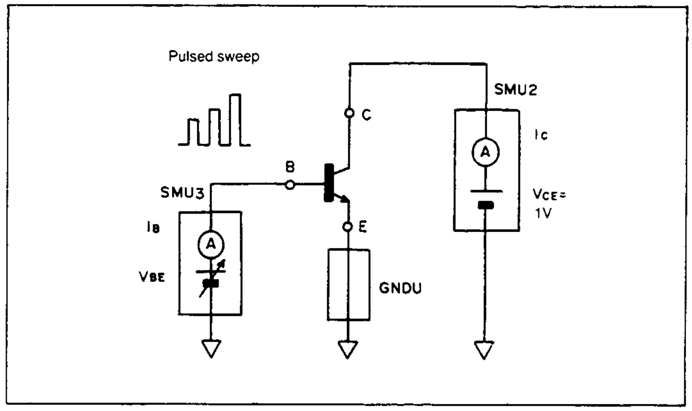


Figure 37. I_C, $I_B - V_{BE}$ Measurement Circuit

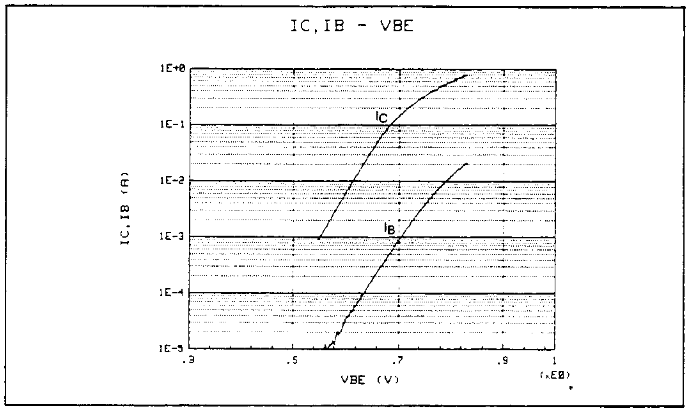


Figure 38. Measured I_C, $I_B - V_{BE}$

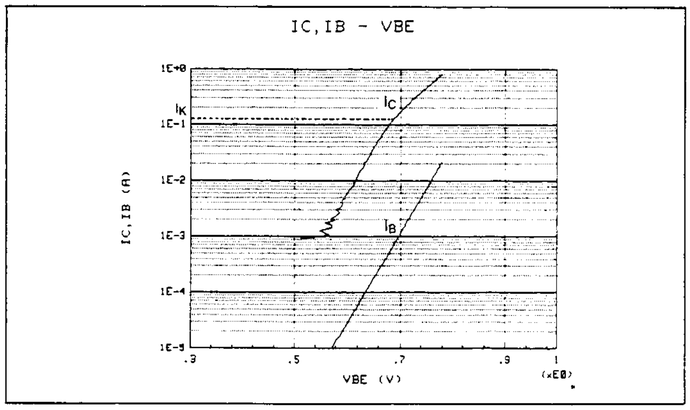


Figure 39. Corrected I_C, $I_B - V'_{BE}$ (I_K Extraction)

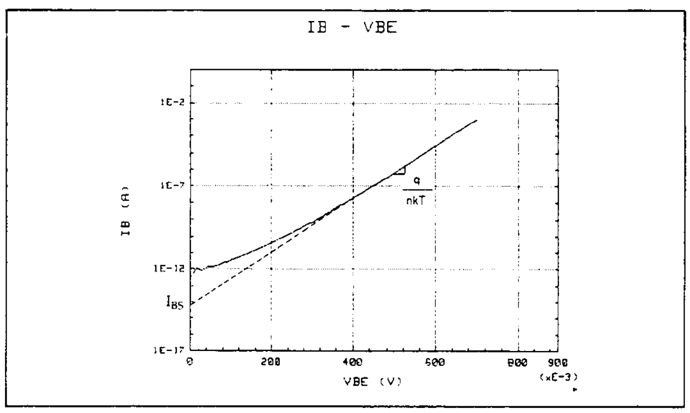


Figure 40. n, I_{BS} Extraction

(2) R_E

Figure 41 shows the measurement circuit. With collector current set to 0 (open collector), pulse sweep current to the base, and measure V_{CE}. Plot measured values on the $V_{CE}-I_B$ graph. Determine the emitter resistance R_E from the slope of the straight line section.

(3) R_C

The output resistance (V_{CE}/I_C) in the saturation region is expressed by the following equation:

$$R_o \fallingdotseq R_C + \left(1+\frac{I_C}{I_B}\right) R_E$$

Plot the $V_{CE}-I_C$ characteristic curve with I_C/I_B constant. Figure 43 shows the measurement circuit. For various values of I_B, but with $I_C/I_B = 10$, perform repeated pulsed spot mode measurements. Plot measured values on the $V_{CE}-I_C$ graph. The slope of the curve in the high current region is R_o, and collector resistance R_c can be calculated from the following equation.

$$R_C = R_o - \left(1+\frac{I_C}{I_B}\right) R_E$$

$$= R_o - 11R_E$$

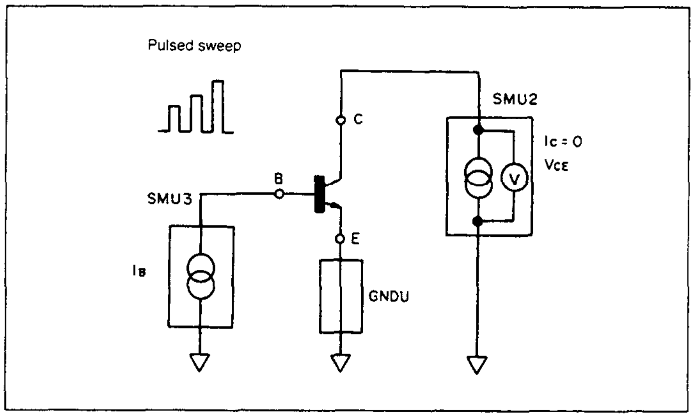


Figure 41. R_E Measurement Circuit

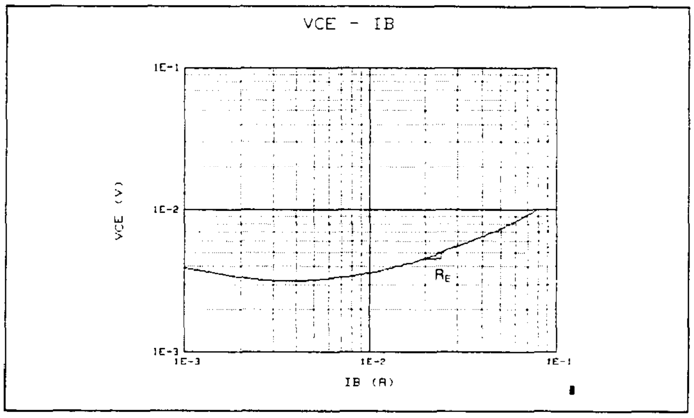


Figure 42. R_E Extraction

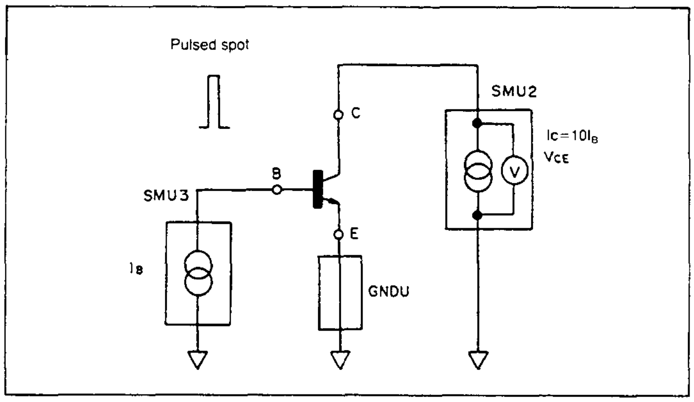


Figure 43. R_C Measurement Circuit

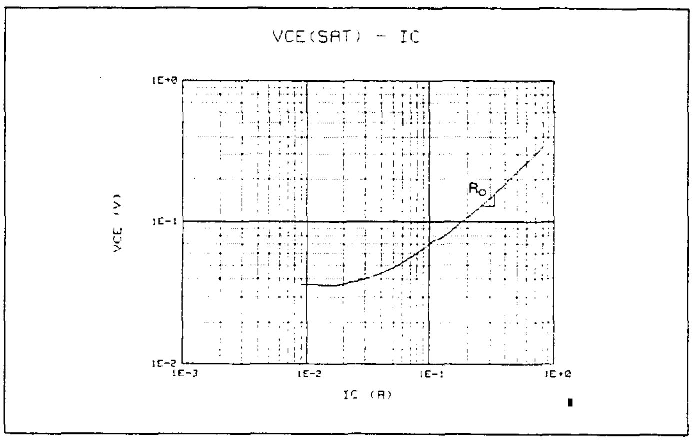


Figure 44. R_C Extraction

References

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2. M. Ohmori, "Ultra High Speed Compound Semiconductor Devices", 1986
3. H. Fukui, "Determination of the Basic Device Parameter of a GaAs MESFET"
   BSTJ, Vol. 58, No. 3, pp. 771–797, 1979
4. W.R. Curtice, "A MESFET Model for Use in the Design of GaAs Integrated Circuits"
   MTT-28, No. 5, pp. 448–455, 1980
5. "SPICE-2 Computer Models for HEXFETs®"
   IR Corp. Application Note 954A
6. I. Getreu, "Modeling the Bipolar Transistor"

APPENDIX GaAs MESFET Measurement Program Example

(1) Program description

This program example uses subprograms from the furnished library. For parameter meanings, see the text.

70, 80: Loads furnished library.
130 to 190: Main program.
131, 132: Assigns GaAs channel length and width (cm).
140: Extracts K and V_{TO}.
150: Extracts R_s and R_g.
160: Extracts n, I_{gs}, V_{bi}, N_N, and a.
170: Extracts R_o and μ_o.
180: Extracts g_m and F_{min}.
190: Prepares results report.

Subprograms:

① Extract_k_vto

This subprogram extracts K and V_{TO}.
324 to 340: Sets V_{ds} = 0.05V, sweeps V_{gs} from −5V to 0V, and measures I_d.
400 to 440: Plots results on graph.
460: Searches for straight line section, and determines regression coefficient.
600: Calculates K.
610: Calculates V_{TO}.
614: Resets output to 0V.

② Extract_r

This subprogram extracts R_s and R_g.
873 to 880: Sets I_g = 100μA, sweeps V_{ds} from 0 to 0.2V, and measures V_{gs} and I_d.
936 to 970: Plots results on graph.
1001: Searches for straight line section, and determines regression coefficient.
1130: Calculates R_s.
1160 to 1170: Sets I_d = 0A (Drain open), pulse sweeps V_{gs} from 0 to 1.2V, and measures I_g.
1240: Searches for straight line section, and determines regression coefficient.
1250: Calculates R_g.

③ Extract_n_igs

This subprogram extracts n, I_{gs}, V_{bi}, N_N, and a.
1560: Sets number of samples for averaging.
1510 to 1580: Sets I_d = 0A (Drain open), staircase sweeps V_{gs} from 0 to 1.1V, and measures I_g.
1595 to 1630: Plots results.
1651 to 1683: Determines n from the straight line section in the intermediate current region.
1684: Extrapolates straight line to determine I_{gs}.
1691 to 1701: Calculates V_{bi}, N_N, and a.

④ Extract_ro

This subprogram extracts R_o and μ_o.
1741 to 1790: Sets V_{ds} = 0.05V, pulse sweeps V_{gs} from (V_{TO} + 0.8V) to 0.5V, and measures I_d.
1810 to 1811: Converts parameters for plotting.
1860 to 1910: Plots results on graph.
1940: Searches for straight line section, and determines regression coefficient.
1950: Calculates R_o.
1960: Calculates μ_o.

⑤ Extract_gm_fmin

This subprogram extracts g_m and F_{min}.
2020 to 2060: Sets V_{ds} = 1.5V, pulse sweeps V_{gs} from (V_{TO} + 0.2V) to 0V, and measures I_d.
2080 to 2100: Calculates g_m values.
2140 to 2180: Calculates g_m moving average for each point, and plots results on graph.
2200: Calculates R_s-corrected value for g_m (at V_{gs} = 0V).
2210: Calculates F_{min}.

⑥ Rline

Searches for straight line section, and determines the regression coefficient.

⑦ Least

Determines regression coefficient by the least squares method.

⑧ Report

This subprogram prepares the results report.

(2) Program listing

```
1     !*************************************************
10    ! APPLICATION SAMPLE PROGRAM
20    ! GAAS MESFET
30    !*************************************************
40    ASSIGN @Hp4142 TO 717
50    COM @Hp4142
60    !
70    !LOADSUB ALL FROM "HP4142_DRV"
80    !LOADSUB ALL FROM "GRAPHICS"
90    !
100   Init_hp4142
110   Init_computer
120   !
130   !MAIN PROGRAM
131   L=1.5E-4            ! CHANNEL LENGTH  (cm)
132   W=.15              ! GATE WIDTH (cm)
133   Ch_sw_on
140   Extract_k_vto(K,Vto)
150   Extract_r(Rs,Rg)
160   Extract_n_igs(L,W,Vto,N,Igs,Vbi,Nn,A)
170   Extract_ro(L,W,Vto,Vbi,Nn,A,Ro,U)
180   Extract_gm_fmin(L,Vto,Rs,Rg,Gm,Fmin)
183   WAIT 2
190   Report(L,W,K,Vto,Rs,Rg,N,Igs,Vbi,Nn,A,Ro,U,Gm,Fmin)
200   !
210   !
220   END
230   !*****************************************************
240   SUB Extract_k_vto(K,Vto)
241   !*****************************************************
242   !EXTRACTION K(Gain factor),VTO(Threshold voltage)
250   !CONNECTION   DRAIN:SMU2,GATE:SMU3,SOURCE:GNDU
251   OPTION BASE 1
252   COM @Hp4142
254   REAL Id(101),Vgs(101),X(5),Y(5),Sid(101)
270   Set_smu(1)
280   Ht=1.E-2                           ! HOLD TIME
281   Dt=1.E-3                           ! DELAY TIME
290   Vg_start=-5                        ! GATE V.SWEEP START VOLTAGE
300   Vg_stop=0                          !              STOP VOLTAGE
310   !
323   !
324   Force_v(2,.05,2,.1)                ! SET DRAIN VOLTAGE
330   Set_iv(3,1,20,Vg_start,Vg_stop,100,Ht,Dt,1.E-2)  !LINEAR SWEEP
340   Sweep_iv(2,2,0,Id(*),Vgs(*))       ! MEASURE DRAIN CURRENT
350   !
360   Xmin=-4
370   Xmax=0
380   Ymin=0
390   Ymax=SQR(ABS(Id(100)))
400   Lingraph(Xmin,Xmax,Ymin,Ymax,"VGS","/ID","SQR(ID) - VGS",1)
401   IF Id(1)=0 THEN Id(1)=1.E-13
410   MOVE Vgs(1),SQR(ABS(Id(1)))
420     FOR I=2 TO 100
421       IF Id(I)=0 THEN Id(I)=1.E-13
422       Sid(I)=SQR(ABS(Id(I)))
430       DRAW Vgs(I),Sid(I)
440     NEXT I
450   !
451   I=20
460   Rline(I,Vgs(*),Sid(*),A,B,L)       ! REGRESSION LINE
600   K=B*B
610   Vto=-A/B
614   Zero_output
620   !
621   SUBEND
```

```
631   !*****************************************************
780   SUB Extract_r(Rs,Rg)
781   !*****************************************************
790   ! EXTRACTION OHMIC RESISTANCE
791   OPTION BASE 1
792   INTEGER Ch(2),Mm(2)
793   REAL Mdata(2,101),Range(2),Id(101),Vgs(101),Ig(101)
794   !
796   Igb=1.00E-4
861   V_start=0
862   V_stop=.2
863   Ht=1.0E-2            !HOLD TIME
864   Dt=1.E-3             !DELAY TIME
865   Ch(1)=2
866   Ch(2)=3
867   Mm(1)=2
868   Mm(2)=1
869   Range(1)=0
870   Range(2)=2
871   !
873   Force_i(3,Igb,0,1)
874   Set_iv(2,1,2,V_start,V_stop,100,Ht,Dt,.1)
880   Sweep_miv(Ch(*),Mm(*),Range(*),Mdata(*))
890     FOR I=1 TO 100
900       Id(I)=Mdata(1,I)
910       Vgs(I)=Mdata(2,I)
920     NEXT I
930   !
931   GCLEAR
933   Id1=Id(100)
934   Vgs0=Vgs(1)-.2
935   Vgs1=Vgs(100)+.2
936   Lingraph(0,Id1,Vgs0,Vgs1,"ID  (A)","VGS (V)","VGS -ID",1,2)
940   MOVE Id(1),Vgs(1)
950     FOR I=1 TO 100
960       DRAW Id(I),Vgs(I)
970     NEXT I
980   !
991   I=10
1001  Rline(I,Id(*),Vgs(*),A,B,L)
1120  !
1130  Rs=B
1134  Zero_output
1140  !*******************************************************
1150  ! CALCULATE RG
1151  !*******************************************************
1152  P_width=1.E-3
1153  Period=1.E-2
1154  Ht=1.E-2
1156  V_start=0
1157  V_stop=1.2
1158  !
1160  Force_i(2,0,0,1)
1161  Set_piv(3,1,2,0,V_start,V_stop,100,P_width,Period,Ht,.1)
1170  Sweep_piv(3,2,0,Ig(*),Vgs(*))
1180  !
1181  Igmax=Ig(100)
1185  Lingraph(0,V_stop,0,Igmax,"VGS (V)","IG (A)","IG -VGS",1,4)
1190  MOVE Vgs(1),Ig(1)
1200    FOR I=1 TO 100
1210      DRAW Vgs(I),Ig(I)
1220    NEXT I
1230  !
1231  I=50
1240  Rline(I,Vgs(*),Ig(*),A,B,L)
1250  Rg=1/B-Rs
```

```
1260  !
1264  Zero_output
1270  SUBEND
1280  !*****************************************************
1480   SUB Extract_n_igs(L,W,Vto,N,Igs,Vbi,Nn,A)
1481  !*****************************************************
1483   OPTION BASE 1
1484   REAL Ig(101),Vgs(101),Lig(101)
1490   !
1491   Q=1.602E-19
1492   K=1.38E-23
1493   Temp=300
1494   Vt=K*Temp/Q
1495   !
1497   Ht=1.0E-2
1500   Dt=1.0E-3
1501   V_start=0
1502   V_stop=1.1
1510   Force_i(2,0,0,1)
1550   !
1560   Set_smu(10)
1570   Set_iv(3,1,2,V_start,V_stop,100,Ht,Dt,.1)
1580   Sweep_iv(3,2,0,Ig(*),Vgs(*))
1590   !
1591   GCLEAR
1593   Ymin=1.E-13
1594   Ymax=.1
1595   Loggraph(0,1.2,Ymin,Ymax,"VGS (V)","IG (A)","IG - VGS",1,1)
1596   IF Ig(1)=0 THEN Ig(1)=1.E-13
1600   MOVE Vgs(1),LGT(ABS(Ig(1)))
1610     FOR I=2 TO 100
1611       IF Ig(I)=0 THEN Ig(I)=Ig(I-1)
1612       Lig(I)=LGT(ABS(Ig(I)))
1620       DRAW Vgs(I),Lig(I)
1630     NEXT I
1640   !
1641   N=2
1650   I=10
1651   WHILE N>1.3
1660    Rline(I,Vgs(*),Lig(*),A,B,L1)
1680    N=1/(B*Vt*LOG(10))
1681    I=L1
1683   END WHILE
1684   Igs=EXP(LOG(10)*A)
1690   !
1691   Aa=8.7                           ! RICHARDSON CONSTANT (AMP/cm^2/k^2)
1694   Vbi=Vt*LOG(Aa*Temp*Temp*L*W/Igs)
1697   Nn=EXP((Vbi-.706)/Vt)            ! ELECTRON DENSITY (10^16/cm^3)
1701   A=SQR((ABS(Vto)+Vbi)/(7.23*Nn))  ! THICKNESS OF ACTIVE LAYER (um)
1704   !
1705   Zero_output
1707   SUBEND
1710   !*****************************************************
1720   SUB Extract_ro(L,W,Vto,Vbi,Nn,Aa,Ro,U)
1730   !*****************************************************
1731   OPTION BASE 1
1732   REAL Id(101),Vgs(101),Xx(101),Ron(101)
1733   Q=1.602E-19
1735   Ht=1.0E-2
1736   Dt=1.E-3
1737   P_width=1.E-3
1738   Period=1.E-2
1740   !
1741   Vd1=.05
1748   Force_v(2,Vd1,2,1)
1750   V_start=Vto+.8
```

```
1760   V_stop=.5
1761   P_base=Vto-.5
1770   !
1780   Set_piv(3,1,20,P_base,V_start,V_stop,100,P_width,Period,Ht,.1)
1790   Sweep_piv(2,2,.1,Id(*),Vgs(*))
1791   !
1800    FOR I=1 TO 100
1810      Xx(I)=1/(1-SQR((Vbi-Vgs(I))/(Vbi-Vto)))
1811      Ron(I)=ABS(Vd1/Id(I))
1820    NEXT I
1823    !
1824    GCLEAR
1830    Xx_max=Xx(1)
1840    Ymax=Ron(1)
1850    !
1860    Lingraph(0,Xx_max,0,Ymax,"XX","R_ON (OHM)","R_ON - XX",1)
1870    !
1880    MOVE Xx(1),Ron(1)
1890     FOR I=2 TO 100
1900       DRAW Xx(I),Ron(I)
1910     NEXT I
1920    !
1921    I=10
1940    Rline(I,Xx(*),Ron(*),A,B,L1)
1950    Ro=B
1960    U=L/(Ro*Q*Nn*1.E+16*Aa*1.E-4*W)      ! MOBILITY (cm^2/V-SEC)
1970    !
1971    Zero_output
1980    SUBEND
1990    !*******************************************************
2000    SUB Extract_gm_fmin(L,Vto,Rs,Rg,Gm0,Fmin)
2010    !*******************************************************
2011    OPTION BASE 1
2012    REAL Id(101),Vgs(101),Gm(101)
2013    F=5.92
2014    Kk=.27
2016    Ht=1.E-2
2017    Dt=1.E-3
2020    Force_v(2,1.5,2,1)
2041    P_base=Vto-.5
2042    V_start=Vto+.2
2043    V_stop=0
2044    P_width=1.E-3
2045    Period=1.E-2
2050    Set_piv(3,1,20,P_base,V_start,V_stop,100,P_width,Period,Ht,.1)
2060    Sweep_piv(2,2,.1,Id(*),Vgs(*))
2070    !
2080    FOR I=2 TO 98
2090      Gm(I)=(Id(I+1)-Id(I-1))/(Vgs(I+1)-Vgs(I-1))
2100    NEXT I
2110    !
2111    GCLEAR
2120    Xmin=V_start-1
2130    Ymax=Gm(90)+1.E-1
2140    Lingraph(Xmin,0,0,Ymax,"VGS (V)","GM (S)","GM - VGS",1)
2150     MOVE Vgs(2),Gm(2)
2160     FOR I=4 TO 96
2165       Gm(I)=(Gm(I+2)+Gm(I+1)+Gm(I)+Gm(I-1)+Gm(I-2))/5
2170       DRAW Vgs(I),Gm(I)
2180     NEXT I
2190    !
2200    Gm0=Gm(96)/(1-Gm(96)*Rs)
2210    Fmin=10*LGT(1+Kk*F*L*1.E+4*SQR(Gm0*(Rs+Rg)))
2220    !
2230    Zero_output
2240    SUBEND
```

```
2250   !
2251   !**************************************************
2260   SUB Rline(I,X1(*),Y1(*),A,B,K)
2261   !**************************************************
2270   OPTION BASE 1
2280   REAL X(5),Y(5)
2290   R2=0
2300   K=I
2310    WHILE R2<.9995 AND K<93
2320     X(1)=X1(K)
2330     X(2)=X1(K+2)
2340     X(3)=X1(K+4)
2350     X(4)=X1(K+6)
2360     Y(1)=Y1(K)
2370     Y(2)=Y1(K+2)
2380     Y(3)=Y1(K+4)
2390     Y(4)=Y1(K+6)
2400       Least(X(*),Y(*),A,B,R2)
2410     K=K+6
2420    END WHILE
2430   !
2431   SUBEND
2432   !**************************************************
2440   SUB Least(X(*),Y(*),A,B,R2)
2441   !**************************************************
2450   OPTION BASE 1
2460   C=0
2470   D=0
2480   E=0
2490   F=0
2500   G=0
2510   FOR I=1 TO 4
2520     C=C+X(I)
2530     D=D+Y(I)
2540     E=E+X(I)*X(I)
2550     F=F+Y(I)*Y(I)
2560     G=G+X(I)*Y(I)
2570   NEXT I
2580   A=(E*D-C*G)/(4*E-C*C)
2590   B=(4*G-C*D)/(4*E-C*C)
2600   R2=(A*D+B*G-D*D/4)/(F-D*D/4)
2610   SUBEND
2620   !*****************************************************
2630   SUB Report(L,W,K,Vto,Rs,Rg,N,Igs,Vbi,Nn,A,Ro,U,Gm0,Fmin)
2640   !*****************************************************
2641   GCLEAR
2650   PRINT
2660   PRINT " GAAS MESFET PARAMETER (L=";L*1.E+4;"(um)  W=";W*1.E+4;"(um))"
2680   PRINT "  K (Gain factor) = ";K
2700   PRINT "  VTO (Threshold voltage) = ";Vto
2720   PRINT "  RS (SOURCE res.) = ";Rs
2740   PRINT "  RG (GATE res.) = ";Rg
2750   PRINT "  IGS (GATE SOURCE Saturation current) = ";Igs
2760   PRINT "  N (Ideality factor) = ";N
2770   PRINT
2780   PRINT "  Vbi (Built_in voltage) = ";Vbi
2800   PRINT "  Nc  (Electron density) = ";Nn*1.E+16;" (/cm^3)"
2810   PRINT "  a   (Active layer thickness) = ";A;" (um)"
2820   PRINT "  Ro (Open channel res.) = ";Ro
2840   PRINT "  Uo (Electron mobility) = ";U;" (cm^2/V-sec)"
2860   PRINT "  Gm (Mutual conductance) = ";Gm0
2870   PRINT
2880   PRINT "  Fmin (Minimum noise figure) = ";Fmin;" (DB)"
2890   SUBEND
2900   !
```

(3) Program output

```
GAAS MESFET PARAMETER (L= 1.5 (um)  W= 1500 (um))
 K (Gain factor) =  .00543758513218
 VTO (Threshold voltage) = -3.50556265484
 RS (SOURCE res.) =  1.52642028301
 RG (GATE res.) =  3.96724287099
 IGS (GATE SOURCE Saturation current) =  3.13104866241E-12
 N (Ideality factor) =  1.1967456158

 Vbi (Built_in voltage) =  .758703994078
 Nc  (Electron density) =  7.6861147595E+16  (/cm^3)
 a   (Active layer thickness) =  .277012646203  (um)
 Ro (Open channel res.) =  1.07935779521
 Uo (Electron mobility) =  2716.22408226  (cm^2/V-sec)
 Gm (Mutual conductance) =  .110592771787

 Fmin (Minimum noise figure) =  4.57705672169  (DB)
```

HEWLETT PACKARD

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