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Table 1. 4145B Major Specifications

Function	Specifications	Function	Specifications
Measurement	• Stimulus/Measurement Unit (SMU) ...... 4 channels Voltage Output/Voltage Measurement Range: ±100V Max. Resolution: 1mV Basic Accuracy: 0.1% Current Output/Current Measurement Range: ±100mA Max. Resolution: 1pA Basic Accuracy: 0.3% • Voltage Monitors .... 2 channels Voltage Measurement Range: ±20V Max. Resolution: 100μV Basic Accuracy: 0.2% • Voltage Sources .... 2 channels Voltage Output Range: ±20V Max. Resolution: 1mV Basic Accuracy: 0.5%	Display	6-inch, high resolution CRT. Four display modes: Graphics, List, Matrix, and Schmoo.
		Graphics Analysis	Softkeys, User Function, Built-in calculator.
		Miscellaneous	Flexible Disk, HP-IB Interface, Plotter Output Function, External CRT Monitor Terminals, Special Test Fixtures.

1. INTRODUCTION

The HP Model 4145B Semiconductor Parameter Analyzer is a fully automatic, high performance instrument designed to measure, analyze, and graphically display the DC parameters and characteristics of diodes, transistors, ICs, solar cells, and wafers during the fabrication process.

In semiconductor R and D laboratories, the 4145B provides precise characteristics evaluation, an important step in the development of new high performance devices, and gives design engineers an easy to use method of device parameter acquisition – an essential element in Computer Aided Design (CAD).

On the production line, the 4145B provides real-time feedback on wafer evaluation, improving the semiconductor process and increasing production yields.

For semiconductor end users, the 4145B is ideal for circuit design applications and incoming inspection.

This Application Note is intended for first-time users of the 4145B. It contains fairly detailed descriptions of the 4145B's basic functions and capabilities, plus many examples of actual measurements, specifically those for bipolar transistors, MOSFETs, and solar cells. It is intended, also, to help semiconductor R and D labs and production facilities produce new devices with higher quality and more functions.
Table 1 lists the major specifications of the 4145B.

2. HP 4145B FUNCTIONS AND OPERATION

Until recently, semiconductor laboratories and manufacturers interested in automatic evaluation of the various DC parameters of semiconductors and other electronic devices had to purchase an expensive, complex test system consisting of many discrete instruments. Although fast and powerful, such systems have several inherent drawbacks that can't be overlooked if accurate, repeatable, and truly automatic measurements are to be made.

Software development, for example, requires a considerable investment in time and engineering manpower. Also, switching is performed by a relay matrix, which, although automatic, is a prime source of measurement error, especially in low-current measurements.

The 4145B solves these problems and in doing so provides an attractive alternative to an expensive test system. It is fast, easy to operate, fully automatic, and offers accuracy and resolution that equal or surpass those of many sophisticated test systems.

2. 1 Features

- **The complete range of semiconductor DC parameters can be quickly and accurately evaluated with this one stand-alone instrument.**

Measurement, analysis, and display of parameters such as V_T, gm, h_{FE}, early voltage, and many more are easily obtained. Operator responsibilities consist of keying in information (channel names, source modes and functions, output parameters, graphic scaling factors, etc.) as instructed by system messages appearing on the CRT.
For device measurement and stimulation, the 4145B is equipped with four programmable source/monitor units (SMUs).
Each SMU can be programmed to function as a voltage source/current monitor (V mode) or a current source/voltage monitor (I mode). Mode changes and channel reassignment are fully automatic, eliminating test lead connection changes. This feature simplifies operation and significantly increases measurement speed and reliability.

- **High resolution and sensitivity**

Each SMU can output and measure up to 100mA and 100V. Resolution is extremely high – 1pA (full 4-digits) and 1mV (4-½ digits), respectively. Resolution of the voltage monitors is particularly high – 100μV – making the system a valuable asset in measuring resistivity and sheet resistance of devices stimulated by low current sources. This feature is also valuable in evaluating the offset voltage characteristics of paired transistors and operational amplifiers.

- **The built-in flexible-disc drive allows you to store your own measurement setups and measurement results.**

Up to 240 user-generated measurement setups or 105 sets of measurement results can be stored on a single disc. Stored measurement setups can be quickly recalled with a few simple keystrokes, significantly reducing the setup time for new measurements. The auto-sequence function (described in Section 5) allows you to link stored measurement setups for complete, one-step characterization of a device.

- **HP-IB* lets you build an automatic test system tailor-made to meet the requirements of your operation.**

The 4145B can be remotely controlled via the HP-IB (Hewlett-Packard Interface Bus), a carefully defined instrument interface which simplifies systemization of programmable instruments and computers. Clear, multi-colored hard-copies of information displayed on the CRT can be obtained by simply connecting an HP-IB compatible plotter/printer to the 4145B. No controller is required. By connecting a controller and using simple HP-GL (Hewlett-Packard Graphics Language) commands, you can display additional information (notes, comments, overlay plots, etc.) on the CRT, or you can blank the CRT and use it as an independent graphics display. The 4145B has the functional capabilities and HP-IB provides the means for building a powerful semiconductor test system. For more details on systemization, refer Section 6.

2.2 Getting Started

Throughout this application note, [ ] will represent a softkey function and ( ) will represent a front panel key. Softkey functions are displayed on the CRT and change depending on the page being displayed. Additional softkey functions are displayed by pressing the [EXTN] softkey.

① Measurement Setup

Setting up, or programming, a measurement is si ilar to filling out a blank form. On the 4145B, though, the blank forms are called pages, and for measurement setup there are three: CHANNEL DEFINITION page (Figure 5), SOURCE SET UP page (Figure 6), and MEAS & DISP MODE SET UP page (Figure 7). A moveable field-pointer (▶) is displayed on each page and is used to select the field into which data is to be entered. System messages are displayed on the CRT and guide the operator through the setup procedure. Depending on the location of the field-pointer, data is entered with the softkeys, alphabetic keys, or numeric keys. Paging is contolled by the (NEXT) and (PREV) keys. The (MENU) key can be pressed at any time to return to the MENU page.

② Measurement

Measurement can be executed only when the GRAPHICS PLOT, LIST DISPLAY, MATRIX DISPLAY, or SCHMOO PLOT page is displayed. Measurement is executed by the (SINGLE), (REPEAT), or (APPEND) key, and is stopped by the (STOP) key. When (SINGLE) is pressed, the results of the previous measurement are cleared from the display and data buffers before measurement is made. When (APPEND) is pressed, however, the display and data buffers are not cleared and the new measurement results are displayed over the results of the previous measurement. Measurement integration time is selectable with the (SHORT), (MED), and (LONG) keys. The (AUTO CAL) key turns on the SMU auto-calibration function. With this function turned on, the SMUs perform self-calibration every five minutes.

③ Auto-Sequence Function

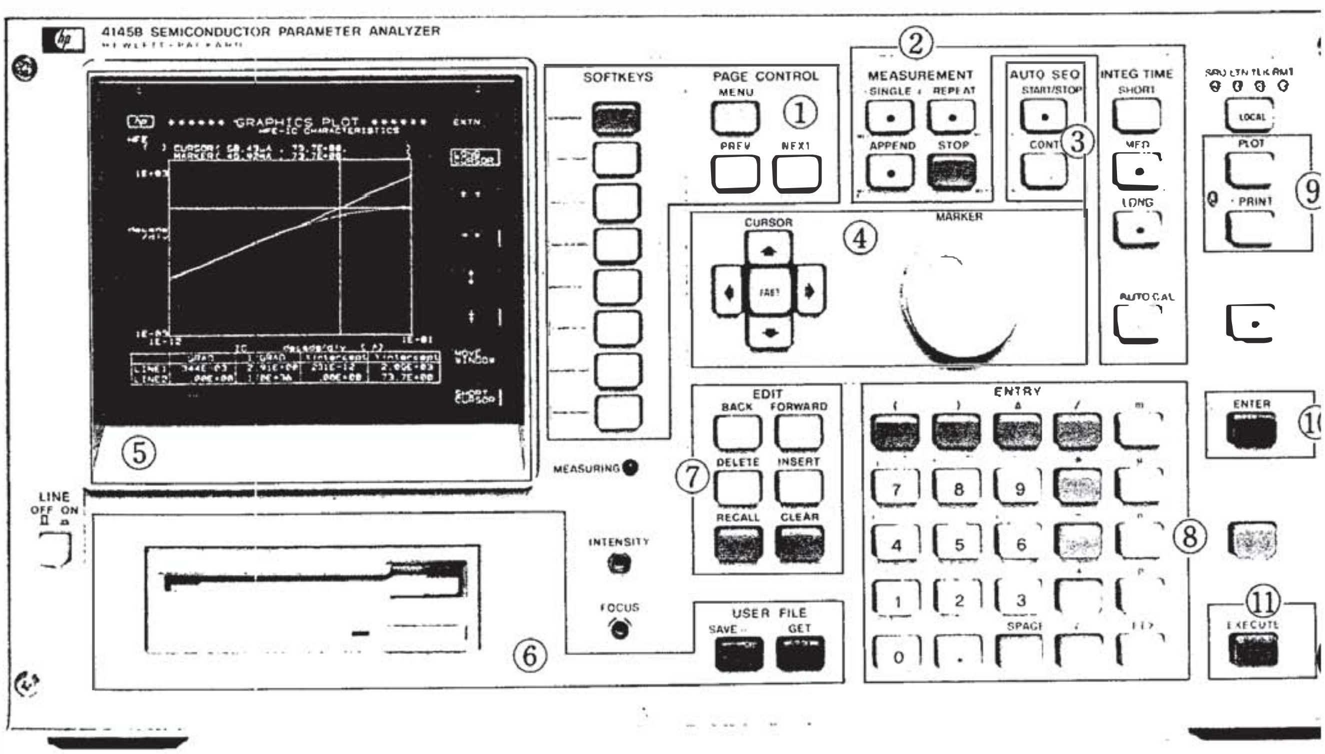
Pressing the AUTO SEQ (START/STOP) keystarts the Auto-Sequence program. Pressing it again during program execution stops the program. When Auto-Sequence executes a PAUSE command, it temporarily halts execution of the measurement procedure. Pressing the (CONT) key restarts the p ogram. For further details, see Section 5.

④ Analysis Functions

The MARKER dial and CURSOR keys control the marker and cursors (SHORT and LONG) on the measurement display pages. Pressing the [MARKER] softkey displays a marker which can be positioned at any measurement point along a plotted curve.

Pressing the [SHORT CURSOR] or [LONG CURSOR] softkey displayes a cursor which can be positioned at any point in the plot area. The X-axis, Y_1-axis, Y_2-axis values of the marker and cursor locations are displayed on the CRT, above the plot area. When [LINE 1] or [LINE 2] is pressed, two short cursors connected by a straight line are displayed. The gradient (GRAD) and inverse gradient (1/GRAD) of the line and the X and Y intercepts are displayed below the plot area. One of the cursors is highlighted and can be moved with the CURSOR keys. To move the other cursor, press the [CHANGE POINT] softkey.

The long and short cursors can also be used for horizontal



and vertical zoom-in/zoom-out ([⟷], [→←], [↕], [⇕]) and for recentering ([MOVE WINDOW]) the plot area. When [MOVE WINDOW] is pressed, the plot area is automatically centered on the cursor, without changing the relative position of the cursor and plotted curves. Displayed plots can be temporarily stored and redisplayed by the [STORE] and [RECALL] softkeys. Thus, overlay plots can be easily obtained.

⑤ Display

Measurement setup pages, softkey functions, and measurement results are displayed on a built-in CRT. Measurement results can be displayed in one of four display modes: Graphics, List, Matrix, or Schmoo.

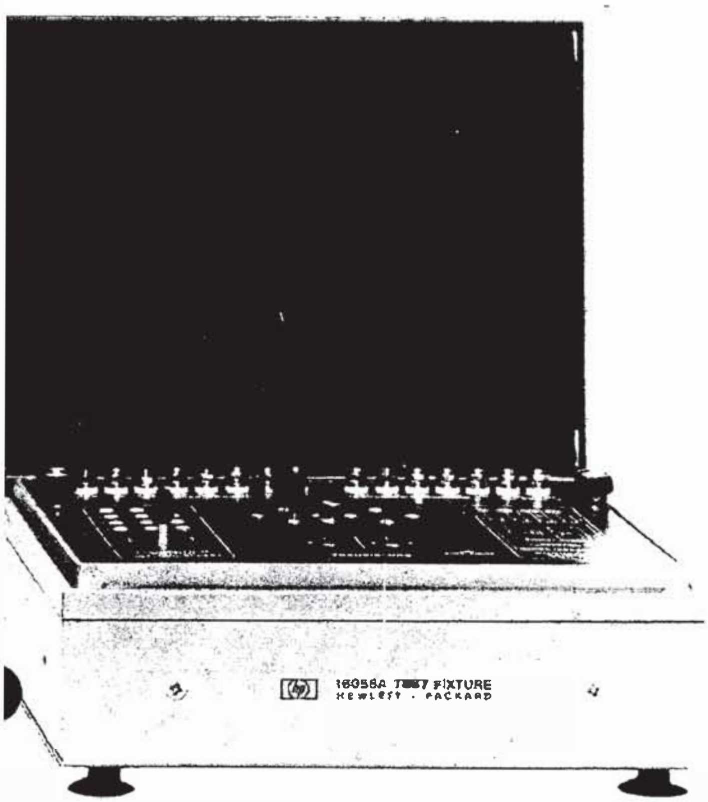
⑥ Flexible-Disc Drive

The built-in flexible-disc drive accommodates one double-sided, double density microflexible disc. Each disc furnished with the 4145B contains the necessary operating system software, four general purpose measurement setups, and enough space to store up to 240 user-generated measurement setups or 105 sets of measurement results. Data filing (store and recall) is performed by the (SAVE), (GET), and (EXECUTE) keys. Examples of storing and recalling a measurement setup and measurement results are given below.

- Measurement Setup (Program file, File type P) :

  (Store) (SAVE)(P)(H)(F)(E)(EXECUTE)
  (Recall) (GET)(P)(H)(F)(E)(EXECUTE)

  Here, P is the file type and HFE is the file name. The file name must be unique, must begin with an alphabetic character, must contain alphanumeric characters only, and must not exceed six characters.



- Measurement Results (Data file, file type D) :

  (Store) (SAVE)(D)(D)(M)(EXECUTE)
  (Recall) (GET)(D)(G)(M)(EXECUTE)

⑦ Edit Functions

Data and commands keyed in from key-groups 6, 8, and 9 are displayed on the CRT's keyboard input line until (ENTER) or (EXECUTE) is pressed. Displayed data can be edited by using the (BACK), (FORWARD), (DELETE), and (INSERT) keys. Pressing (CLEAR) erases all data from the keyboard input line. Pressing (RECALL) redisplays previously entered or executed data.

⑧ Data Entry and Calculator Functions

Numeric values, alphabetic characters, arithmetic operators, engineering units, and certain physical constants for measurement setup, user function definition, keyboard calculations, and other instrument operations are entered from this key group. Key functions labelled in blue and green are available only when the (Blue) key or (Green) key has been pressed. Additional arithmetic operators – LOG, LN, ABS, EXP (base of natural logs) and ** (exponentiation) – are also available. For example, to calculate $e^{\frac{qv}{kT}}$ (frequently used in semiconductor work), key in (Blue)(E)(X)(P)(Blue)(()(Green)(q)(*)(0)(.)(0)(/)(()(Green)(k)(*)(3)(0)(0)())())(EXECUTE)

The result, 12.010E + 09, will be displayed on the CRT. To enter a number using scientific notation, 5×10^{-11} for example, key in (5)(GET)(−)(1)(1). Also, implied multiplication is not allowed.

⑨ Hard-Copy Function

Hard-copies of information displayed on the CRT can be made by connecting an HP-IB compatible plotter or plotter/printer to the 4145B, pressing (PLOT) or (PRINT), and then pressing (EXECUTE). Plot area is user-specifiable within the limits of the plotter. The format is as follows:

PLOT X_{min}, Y_{min}, X_{max}, Y_{max}

To stop a PLOT or PRINT operation press the (PLOT) key or (PRINT) key again.

Recommended plotters are the HP7440A Plotter, and HP7475A Plotter. Others may be used but they must have a LISTEN ONLY mode. Refer to Figure 1 on the next page for more details.

⑩ Data Entry Key

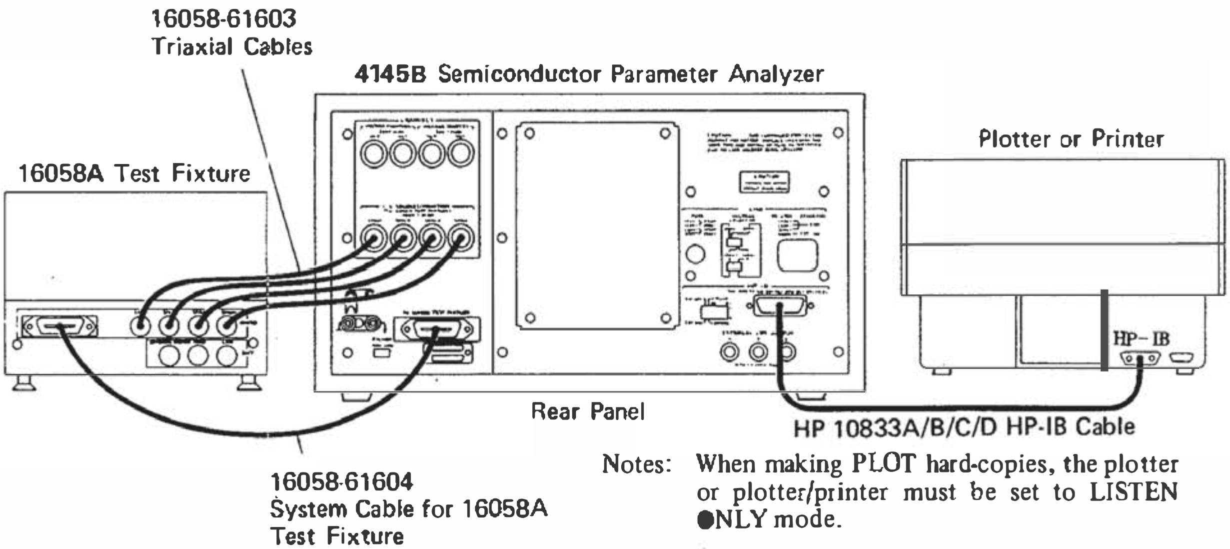
The (ENTER) key is used to enter channel names, user-function names and expressions, output parameters, comments, etc.

⑪ Execute Key

The (EXECUTE) key is used to execute GET, SAVE, PRINT, PLOT, PURGE, and REPACK commands, and keyboard calculations.

2. 3 Measurement Preparation

2. 3. 1 Test Fixture, DUT, and Plotter Connections



Notes: When making PLOT hard-copies, the plotter or plotter/printer must be set to LISTEN ONLY mode.

Figure 1.

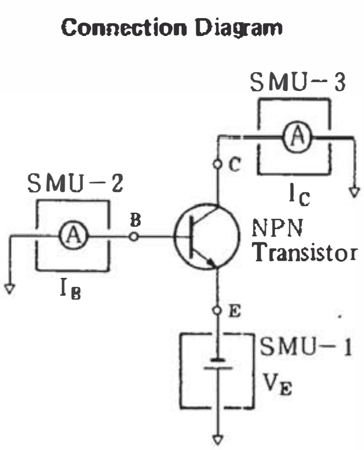


Figure 2.

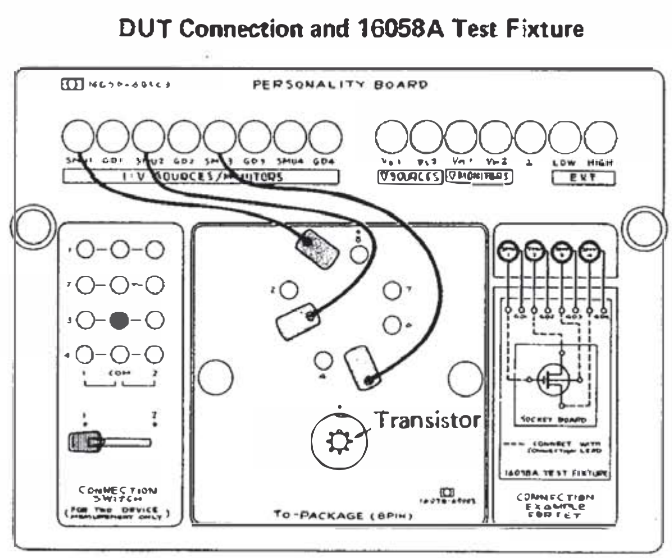


Figure 3.

2. 3. 2 Measurement Example

The basic measurement procedure of the 4145B is best described by making an actual measurement. In the following example we will measure and graphically display the characteristics of an NPN transistor connected for common emitter operation. Base-emitter voltage will be swept and the resultant base and collector currents will be measured.

① Test Fixture and DUT Connections

Turn off the 4145B and connect the 16058A Test Fixture as shown in Figure 1. Set the 4145B's VOLTAGE SELECTOR switch and FILTER switch as appropriate for the AC line-voltage and frequency. Set up the 16058A's Personality Board as shown in Figure 3 and insert a transistor into the DUT socket. Insert one of the furnished discs into the 4145B (label facing up), then turn on the 4145B.

② Menu Page

When the 4145B is turned on, it will first read a portion of the operating system software stored on the disc and will then perform a brief self-test, after which it will display the MENU page shown in Figure 4. The softkey functions displayed on this page are for page selection. Any page listed on the MENU can be displayed by pressing the corresponding softkey. (The softkey for the DIAGNOSTICS page is displayed by pressing the [EXTN] softkey.) For our measurement, we will use only the CHANNEL DEFINITION page, SOURCE SET UP page, and MEAS & DISP MODE SET UP page. The CHANNEL DEFINITION page must be set up first, so press the [1 CHAN DEF] softkey or the (NEXT) key.

③ CHANNEL DEFINITION

On this page we will select the channels (SMUs, voltage sources, and voltage monitors) to be used in the measurement, assign source and monitor names, and specify source modes and functions. The initial setup on this page is for general use and is not appropriate for the measurement we want to make. It must be changed to the setup shown in Figure 5. To do this, move the field-pointer (▶) to the NAME V field of SMU1 and then press the [Bi-Tr VCE-IC] softkey. This will automatically change the measurement setup to one that is more appropriate for measurement of bipolar transistors. A few simple changes remain to be made, however. To make these changes, first make sure that the field-pointer is in the NAME V field of SMU1, then perform the following key sequence:

(⇨) (⇨) [V] [VAR 1] (⇨) (⇨) (COM)
(V) (C) (ENTER) (⇨) (COM)

The CHANNEL DEFINITION page should now look as that shown in Figure 5. Note that one of the user functions has been defined as $H_{FE} = I_C/I_B$. It can be quickly changed by moving the field-pointer to the USER FCTN NAME field and entering the NAME, UNIT, and EXPRESSION. Variables can be used in the expression but are limited to the channel names specified in the NAME V and NAME I fields. With the present setup, for example, the only variables that can be used in a user-function expression are V_E, V_B, V_C, I_E, I_B, and I_C.

The next step in setting up the measurement is to define the output parameters (output voltage, current, compliance, etc.) for the source channels. This is done on the SOURCE SET UP page. To display the SOURCE SET UP page, press (NEXT).

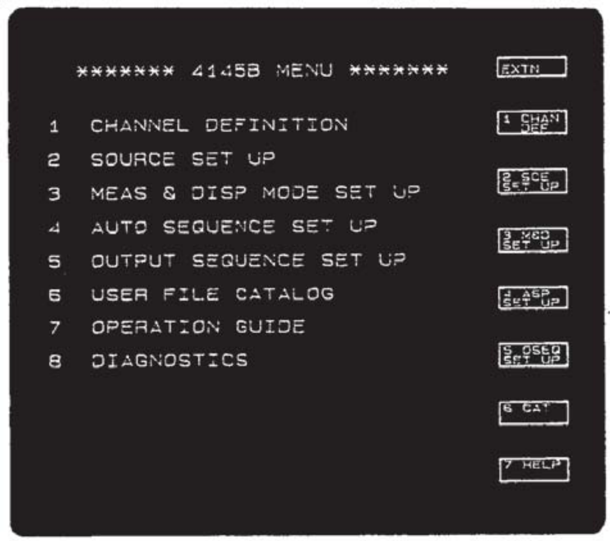


Figure 5.

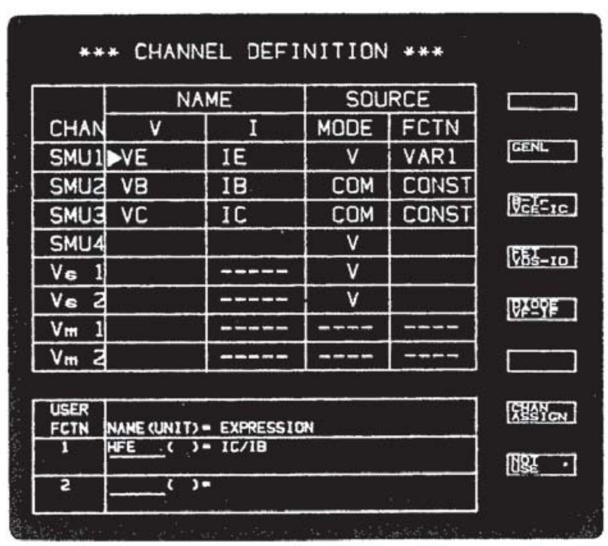


Figure 4.

④ **Source Setup**

On this page we will set the output parameters for each SMU selected on the CHANNEL DEFINITION page. Note that the source names – V_E, V_B, and V_C – are already entered in the appropriate fields. V_E is entered in the VARI NAME field because it is the V name of a voltage source (V MODE) whose SOURCE FCTN is VARI. Similarly, V_B and V_C are listed under CONSTANT because they are the V names of common sources (COM MODE) whose SOURCE FCTN's are CONST.

For our measurement, we must set up this page as shown in Figure 6. To do this, move the field-pointer to the VARI SWEEP MODE field and then perform the following key sequence:

[LINEAR] (0) (ENTER) (−) (0) (.) (9) (ENTER) (−) (0) (.) (0) (1) (ENTER) (1) (0) (0) (m) (ENTER)

When measurement is made, the base-emitter voltage, V_E, will be linearly swept from 0V to −0.9V in −10mV steps.

After all conditions have been set, press (NEXT) to display the MEAS & DISP MODE SET UP page.

⑤ **Display Mode Selection and Setup**

On this page we will select the mode for displaying the measurement results. Four modes are available – GRAPHICS, LIST, MATRIX, and SCHMOO. For our measurement, we will use the GRAPHICS display mode. Base-emitter voltage (V_E) will be plotted along the X-axis, collector current (I_C) along the Y_1-axis, and base current (I_B) along the Y_2-axis. See Figure 8.

To set up this page as shown in Figure 7, perform the following key sequence:

[GRAPHICS] [VE] [LINEAR] (0) (ENTER) (−) (1) (ENTER)

[IC] [LOG] (1) (p) (ENTER) (1) (0) (0) (m) (ENTER)

[IB] [LOG] (1) (p) (ENTER) (1) (0) (0) (m) (ENTER)

After all conditions have been set, press (NEXT) to display the GRAPHICS PLOT page.

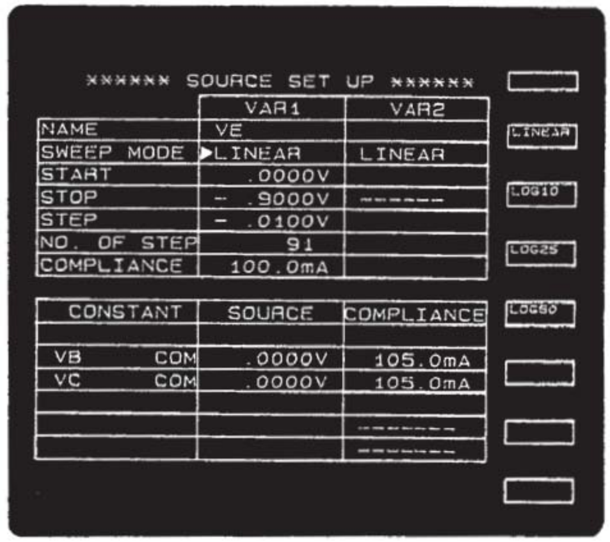


Figure 6.

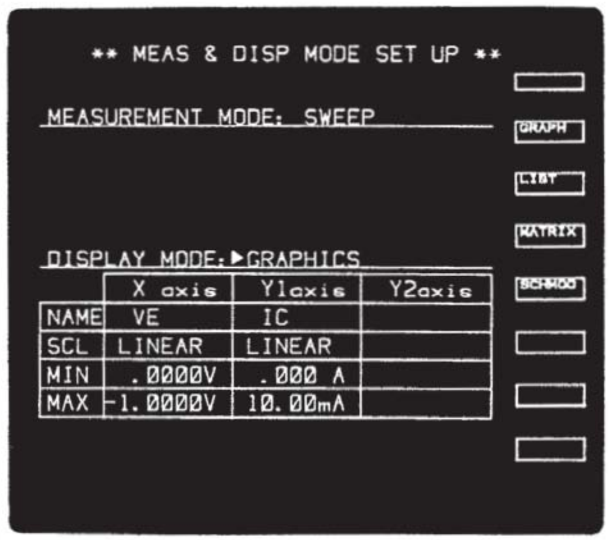


Figure 7.

⑥ Measurement and Display

All measurement conditions have been set and the 4145B is now ready to make the measurement. Close the test fixture lid (shields the DUT from RFI and EMI sources) and press the (SINGLE) key. The 4145B will begin sweeping the base-emitter voltage, V_E, from 0V to −0.9V in −10mV steps. The resultant collector current, I_C, and base current, I_B, will be measured at each V_E step and plotted on the CRT as shown in Figure 8. The curve with the more acute slope is collector current, and the other curve is base current.

Pressing the [EXTN] softkey displays additional softkey functions. For example, the [GRTCL TICK] softkey replaces the grid lines with tick-marks along each axis; the [COMMNT] softkey allows entry of comments of up to 30 characters; the [AUTO SCALE] softkey rescales the plot area to provide optimum display of measurement results.

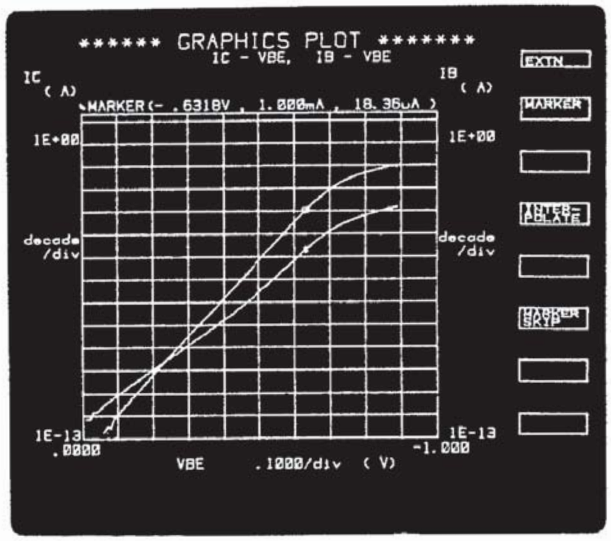


Figure 8.

⑦ Marker Function

Measurement results at each measurement step can be digitally displayed by pressing the [MARKER] softkey. When the MARKER dial is rotated, the marker will move along the plotted curve and the X, Y_1 and Y_2 coordinates will be displayed above the plot area.

The [MARKER SKIP] softkey moves the marker to the next curve in multi-curve measurements (see Figure 12).

The marker can be used to simplify keyboard calculations. For example, to calculate h_{FE} at the marker position in Figure 8, key in (I) (C) (/) (I) (B) (EXECUTE). It is not necessary to input the numeric values.

● Line and Cursor Functions

Pressing the [LINE ON] softkey displays a solid straight line (LINE 1) or a dashed straight line (LINE 2) between two short cursors, as shown in Figure 9. Both lines can be displayed at the same time but only one can be moved. The gradient (GRAD), inverse gradient (1/GRAD), X-axis intercept, and Y-axis intercept of each line are displayed below the plot area. Of the two cursors displayed with each line, one will be highlighted and can be moved (line also moves) by the CURSOR keys ((⇦), (⇧), (➡), (⬇), and (FAST)).

To move the other cursor, press the [CHANGE POINT] softkey. The line gradient can be input directly from the keyboard by first pressing the [GRAD VALUE] softkey. For example, to display a line whose gradient is e^2, perform the following key sequence:

[LINE ON] [GRAD VALUE] (CLEAR) (Blue) (E) (X) (P) (Blue) (() (2) ()) (EXECUTE) (ENTER)

Another helpful function is the [CURSOR → O] softkey. When pressed (marker must be on), the cursor will automatically move to the marker position.

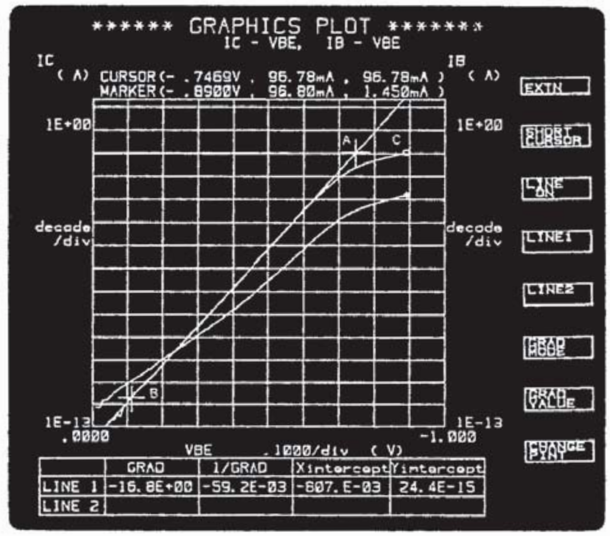


Figure 9.

3. IMPORTANCE OF DC PARAMETRIC EVALUATION

The need for accurate measurement and evaluation procedures in the design and fabrication of integrated circuits is widely recognized in the semiconductor industry. The 4145B provides the R & D lab or production facility with a powerful tool for use in evaluating DC parameters of ICs in the design stage, or for use on the production line to evaluate processes. It is also a valuable asset in the design of electronic circuits employing semiconductors in their circuitry.

- **Evaluating DC parameters in IC design**

In order to design an effective integrated circuit, it is important for the design engineer to have a thorough understanding of the electrical characteristics of the devices going into the IC. (And this includes both their performance and limitations.) To properly evaluate a diode, saturation current (Is), dynamic resistance (rd), and breakdown voltage (BV) must be known. And in evaluating bipolar transistors, it is important to know forward current gain (h_{FE}) at the collector, collector saturation voltage ($V_{CE(sat)}$), early voltage (V_A), and breakdown voltage (BV_{CEO} and others). Punch-through voltage and characteristics under stimulation by a constant-current source, as well as paired characteristics (ΔV_{BE}) of a transistor must also be known.

In evaluating MOS transistors, drain characteristics and threshold voltage (V_T) must be known, along with their basic effects. Channel conductance (Gds), load current characteristics, the relationship between beta and transmission characteristics when used in an inverter circuit, and sub-threshold voltage characteristics must also be measured.

- **Evaluating DC parameters as a process monitoring step in semiconductor fabrication**

The effectiveness of the 4145B in process evaluation during semiconductor fabrication is enhanced by the use of TEG (Test Element Group), a special evaluation device using DC parameter and C–V characteristics data to obtain a wafer profile.

However, not only does it make good sense to evaluate electrical parameters during the fabrication process, but physical parameters are important as well. An example of how the 4145B can be used here is through the use of sheet resistance (Rs), breakdown voltage, leakage current, threshold voltage and other DC parameters. Add these to C–V measurements and you can see that they become very useful in evaluating physical parameters such as oxide layer capacitance (C_{OX}), oxide layer thickness (t_{OX}), surface charge density (Q_{ss}), flat band voltage (V_{FB}) and others. Statistical data can be compiled and analyzed, reducing process fluctuations to a minimum.

- **Evaluating DC parameters in the design of electronic response circuits**

In designing higher performance and better reliability into electronic circuits, it is of foremost importance to know whether the semiconductor devices (IC's transistors, etc.) are capable of doing the job. Ideal operating points must be established under actual operating conditions, and environmental factors (temperature, humidity) must be characterized and accounted for.

Figure 10 shows the development/production flow of an IC, and Table 2 lists the major DC parameters and characteristics requiring evaluation during the design and fabrication stage.

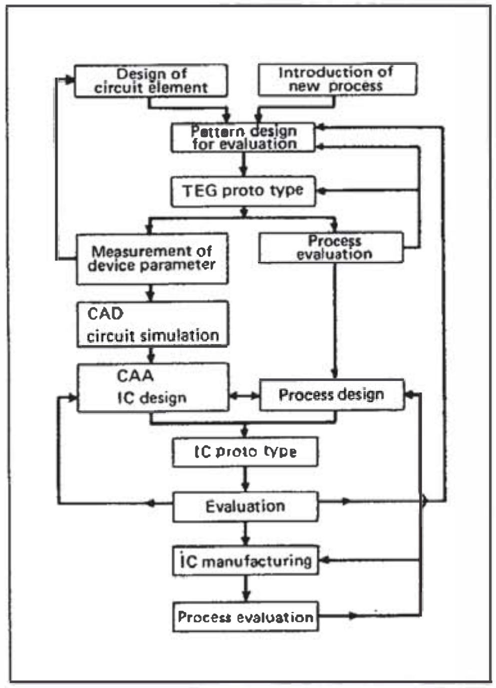


Figure 10. Flow of IC design/manufacturing

Table 2. Important DC Parameters/Characteristics

Bipolar		MOS	
Resistivity	ρ	Resistivity	ρ
Sheet Resistance	R_S	Sheet Resistance	R_S
Breakdown	BV	Breakdown	BV
Current gain	h_{FE}	Transconductance	gm
Saturation V	$V_{CE(sat)}$	Threshold V	V_T
Saturation I	I_s	On resistance	r_{on}
Collector output R	R_C	Leakage current	I_L
Collector R	r_c		
Emitter R	r_e		
Base R	r_b		
Base-Emitter	V_{BE}		
$I_C - V_{CE} \mid I_B$		$I_D - V_{DS} \mid V_{GS}$	
$h_{FE} - I_C$		$V_T - V_{SUB}$	
$V_{BE} - I_C$			
$V_{BE} - I_B$			

4. APPLICATION

4. 1 Evaluating Bipolar Devices

Application Example 1: Static Collector Characteristics

In this example, the static collector characteristics of an NPN transistor will be measured and graphically displayed. Results will be analyzed to obtain early voltage (V_A) and collector output resistance (Rc).

Connect the DUT as shown in Figure 11 and set up the CHANNEL DEFINITION, SOURCE SET UP, and MEAS & DISP MODE SET UP pages as shown at the right. Next, display the GRAPHICS PLOT page and press the (SINGLE) key.

Using the Line Function, draw a straight line between points A and B (see Figure 12). Collector output resistance and early voltage can now be read directly from the CRT from the 1/GRAD and X intercept values, respectively. In this example, output resistance is 2.81 kΩ and early voltage is −16.1 V.

Early voltage is a particularly important DC parameter for computer-aided design. On many systems, however, it can be obtained only by manual line-extrapolation techniques. As shown here, though, the 4145B calculates this parameter and displays the result on the CRT, allowing direct readout.

We will use this measurement setup again in Section 5, so now would be a good time to store it on the disc. Perform the following key sequence:

(SAVE) (P) (N) (P) (N) (I) (EXECUTE)

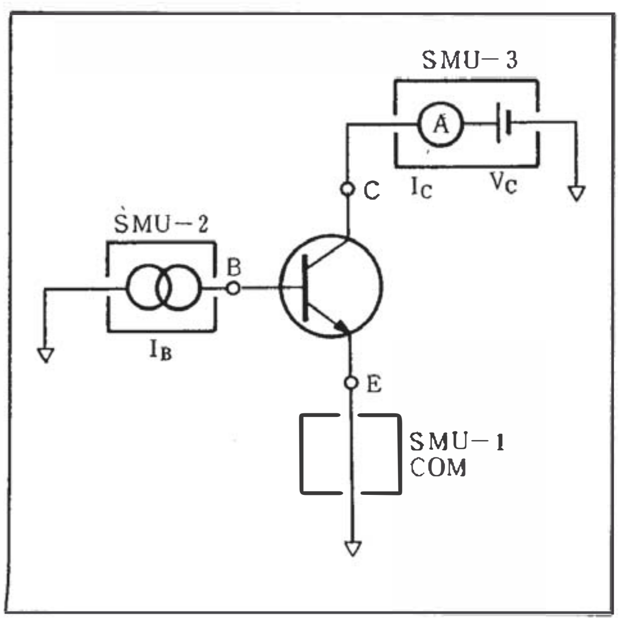
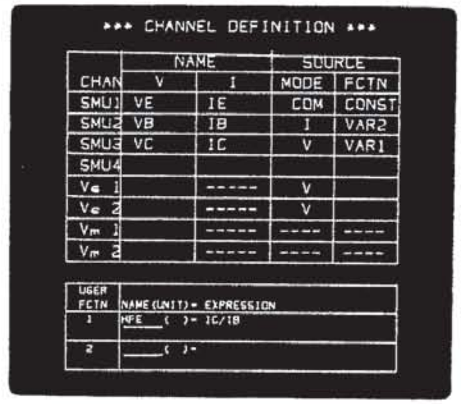
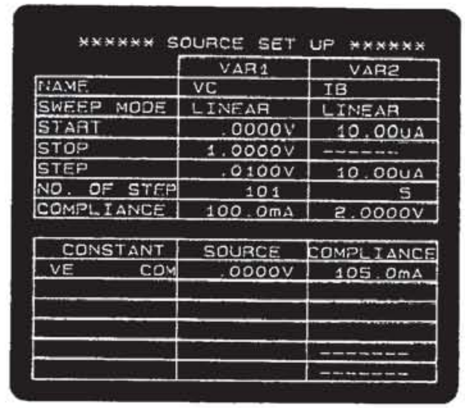
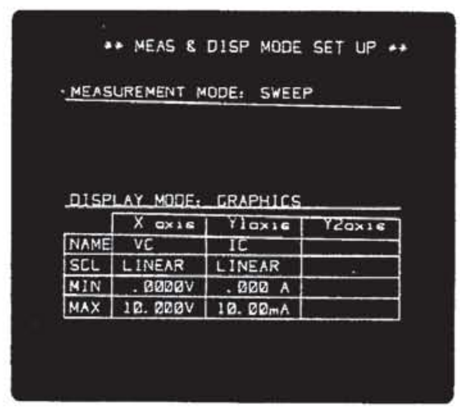


Figure 11.







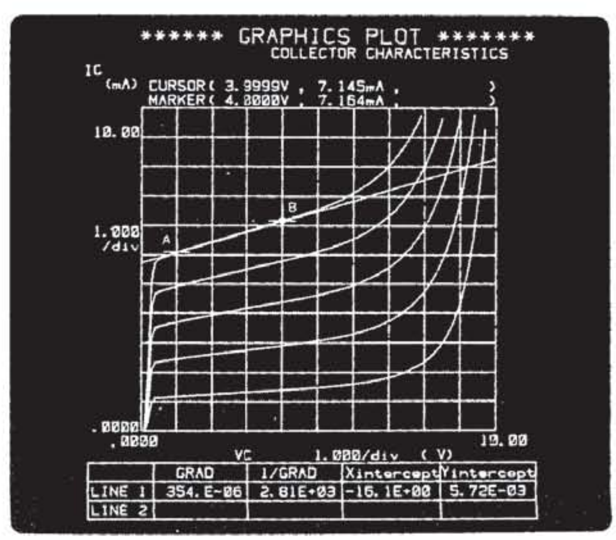


Figure 12.

Application Example 2: $I_c - V_{BE}$ and $I_B - V_{BE}$ Characteristics

One of the most important steps in evaluating semiconductor parameters is measuring collector current and base current as a function of base-emitter voltage. These measurements can be graphically analyzed to obtain saturation current, collector current constant, $h_{FE} - Ic$ characteristics, along with base resistance and recombination current characteristics.

Here, connect the DUT as shown in Figure 13, then execute the measurement to display the collector current characteristics and base current characteristics illustrated in Figure 14. The upper characteristics curve represents collector current, which is usually expressed as $Ic \doteq I_1 e^{(q(V_{BE} - I_B r_b)/KT)} + I_2$.

In the above expression, I_2 represents saturation current, I_1 is the collector current constant, and r_b is the equivalent base resistance when large DC signals are applied to the base.

Next, using the Line Function, connect points A and B with a straight line. The Y-axis intercept data can be read directly as I_1 ($I_1 = 24.4 \times 10^{-15}$ A). In this example, $I_2 = 0$ A, and can be ignored.

To obtain r_b, move the marker to a point (point C in Figure 14) where the collector current is the same as that at point A. Then using the cursor and marker data, calculate the voltage difference between points A and C and divide the result by the base current at point C to obtain base resistance r_b. (( ) (0) (.) (8) (9) (−) (0) (.) (7) (5) ( )) (/) (1) (.) (4) (5) (m) (EXECUTE)

The value for r_b is 96Ω in this example.

Other applications using these settings and connections include obtaining forward current gain (h_{FE}) at any point on the characteristics curve. This can be done by using the marker and keyboard calculations.

*** CHANNEL DEFINITION ***

CHAN	NAME V	NAME I	SOURCE MODE	SOURCE FCTN
SMU1	VE	IE	V	VAR1
SMU2	VB	IB	COM	CONST
SMU3	VC	IC	COM	CONST
SMU4				
Vs 1		------	V	
Vs 2		------	V	
Vm 1		------	-----	-----
Vm 2		------	-----	-----

USER FCTN	NAME (UNIT) = EXPRESSION
1	HFE ( ) = IC/IB
2	( ) =

****** SOURCE SET UP ******

	VAR1	VAR2
NAME	VE	
SWEEP MODE	LINEAR	LINEAR
START	.0000V	
STOP	− .9000V	------
STEP	− .0100V	
NO. OF STEP	91	
COMPLIANCE	100.0mA	

CONSTANT	SOURCE	COMPLIANCE
VB COM	.0000V	105.0mA
VC COM	.0000V	105.0mA

** MEAS & DISP MODE SET UP **

MEASUREMENT MODE: SWEEP

DISPLAY MODE: GRAPHICS

	X axis	Y1axis	Y2axis
NAME	VE	IC	IB
SCL	LINEAR	LOG	LOG
MIN	.0000V	1.000pA	1.000pA
MAX	-1.0000V	100.0mA	100.0mA

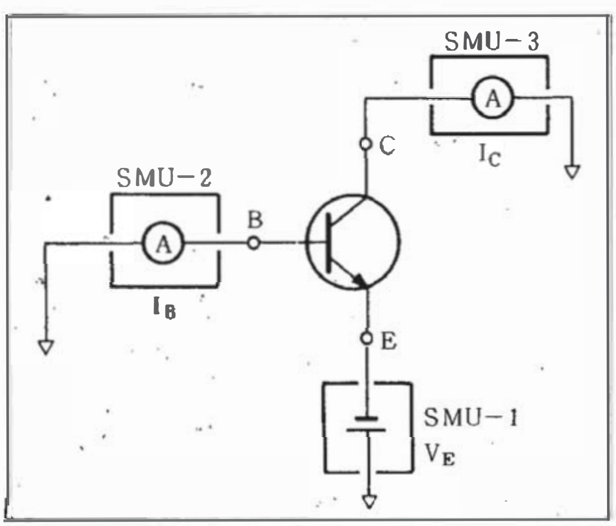
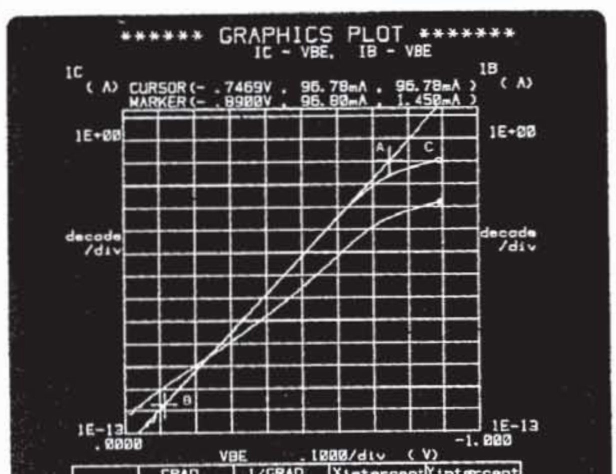


Figure 13.



	GRAD	1/GRAD	Xintercept	Yintercept
LINE 1	-16.8E+00	-59.2E-03	-807.E-03	24.4E-15
LINE 2				

Figure 14.

For example, key in

[9] [6] [.] [8] [/] [1] [.] [4] [5] [EXECUTE]

or [1] [C] [/] [1] [8] [EXECUTE]. (Refer to Application Example 5 for the procedure on graphing h_{FE}.)

Also, the Line Function can be used to draw a straight line with a gradient of q/2kT across the base current characteristics curve in the low current region to evaluate recombination current characteristics in the surface and depletion layers. With a q/2kT gradient at 300 kelvin, the key entries are as follows:

[LINE ON], [GRAD VALUE], [CLEAR] [−] [Green] [V] [/] [1] [2] [.] [Green] [k] [*] [3] [0] [0] [*] [2] [.] [3] [0] [3] [)] [EXECUTE] [ENTER]

Now, store this measurement setup on the disc.

[SAVE] [P] [I] [C] [B] [V] [B] [E] [EXECUTE]

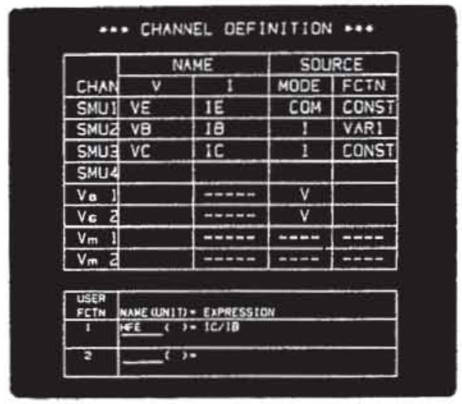
Application Example 3: Emitter Resistance

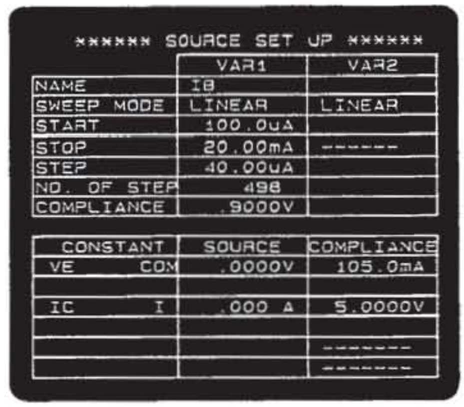
The series resistance of the emitter (r_e) of a bipolar transistor can be determined by stimulating the base with current and measuring the voltage between the collector and emitter. The inverse of the characteristics curve gradient can thus be obtained. The connections for this setup are shown in Figure 15.

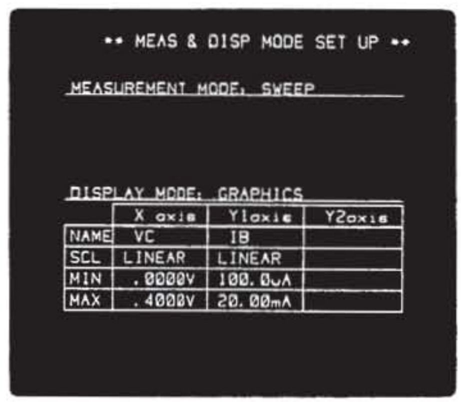
The voltage between the collector and emitter (V_{CE}) will be shown on the X-axis, and the Y-axis will graph the base current (I_B). Figure 16 shows the measurement results.

Using the Line Function, connect points A and B with a straight line. The inverse gradient of the line can be read directly. The figure shows r_e to be 2.25Ω.

Name this measurement setup EMTR and store it on the disc for use in the Auto Sequence application examples in Section 5.







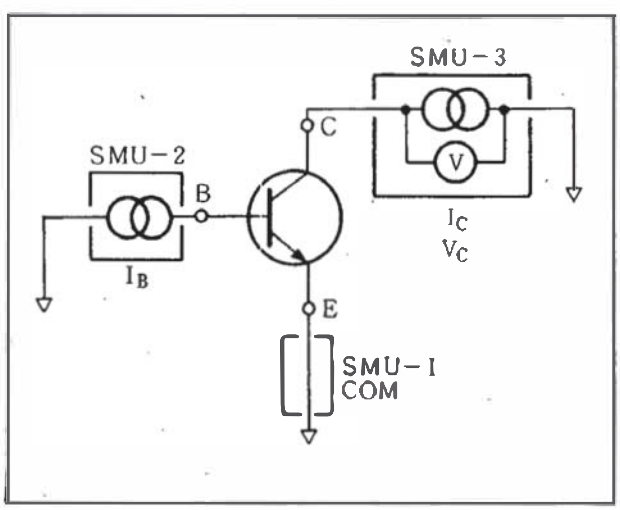


Figure 15.

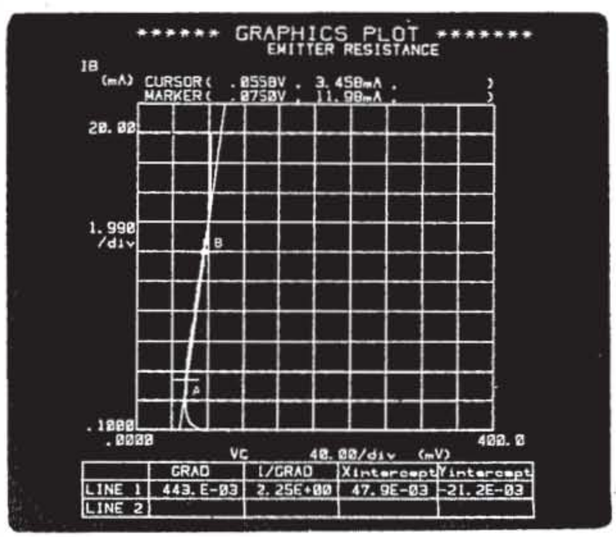


Figure 16.

Application Example 4: Collector Resistance

Measurement of the series resistance of the collector (r_c) in a bipolar transisitor is similar to measuring emitter resistance r_e (previous example). Here, current is applied to the base and collector, and the collector-emitter voltage (V_{CE}) is measured.

To characterize $I_B - V_{CE}$, two collector current values (I_{C1} and I_{C2}) will be measured. The relationship between points $I_{C1} - I_{B1}$ and $I_{C2} - I_{B2}$ on the characteristics curve will be equality ($I_{C1}/I_{B1} = I_{C2}/I_{B2}$), and measuring the V_{CE} voltage difference (ΔV) between these points will give the values required for obtaining collector resistance, which is calculated as $r_c = \Delta V/(I_{C2} - I_{C1})$.
Connect the DUT as shown in Figure 17. Figure 18 shows the measurement results.

In this example, $I_{C1} = 4mA$, $I_{C2} = 8mA$, $I_{B1} = 6mA$, and $I_{B2} = 12mA$. Data at the marker and cursor points show the voltage change (ΔV) to be 0.028 volts, so an r_c of 7.0Ω is obtained.

This example clearly shows that the 4145B can be used to accurately measure series collector resistances in low voltage regions, making it particularly valuable in parametric analysis of CAD models.

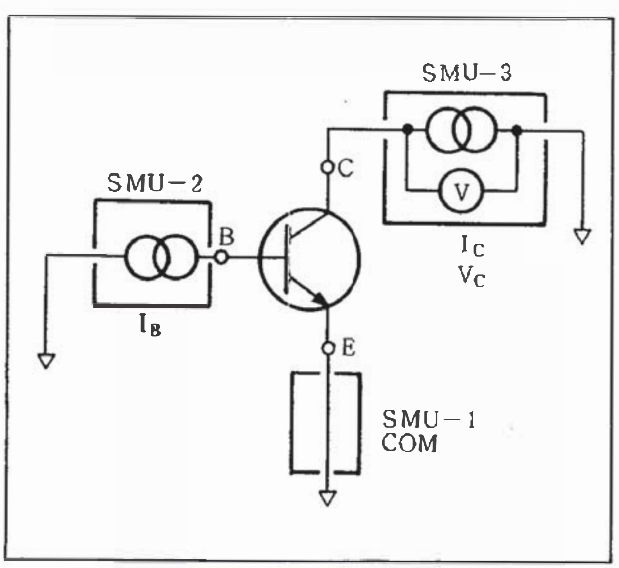


Figure 17.

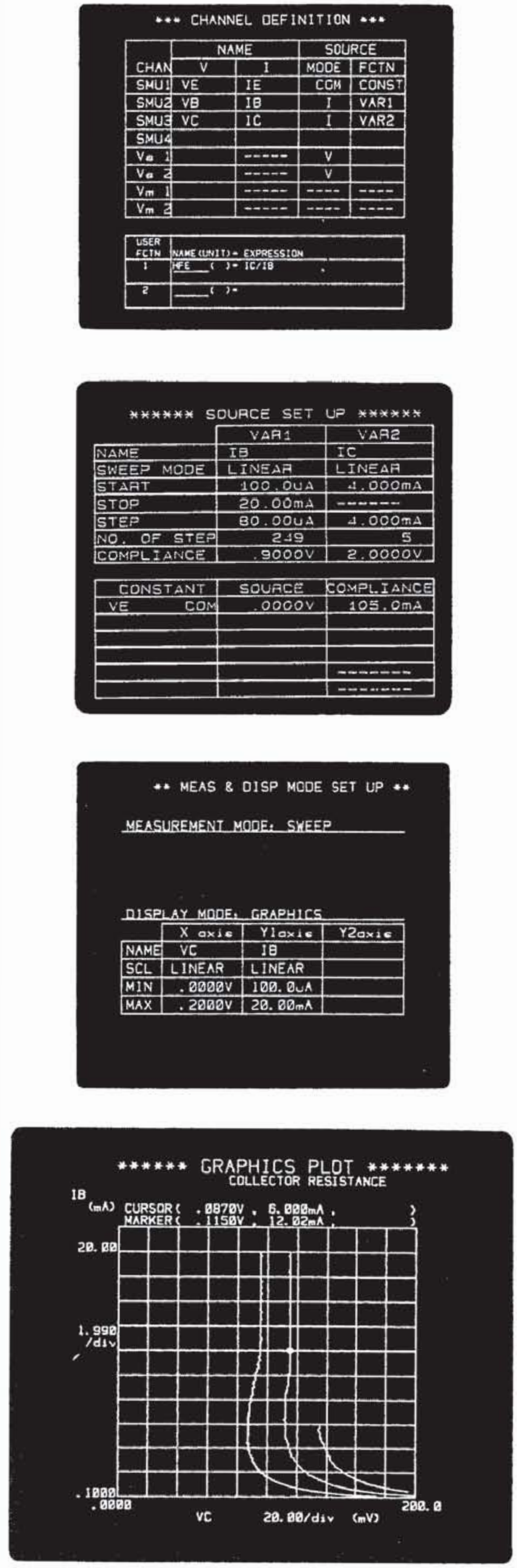


Figure 18.

Application Example 5: h_{FE} — Ic Characteristics

By ma ing a few simple changes on the MEAS & DISP MODE SET UP page of the measurement setup used in Application Example 2, the transistor's h_{FE}-Ic characteristics can be quic ly obtained. The measurement setup is stored on the disc under file name ICBVBE, and can be recalled by performing the following key sequence:

(GET) (P) (I) (C) (B) (V) (B) (E) (EXECUTE)

Next, display the MEAS & DISP MODE SET UP page and perform the following key sequence:

[GRAPHICS] [IC] [LOG] (1) (0) (ENTER) (1) (0) (0) (m)

(ENTER) [EXTN] [HFE] [LOG] (1) (m) (ENTER) (1) (0)

(0) (0) (ENTER) [EXTN] [NOT USE] (NEXT) (SINGLE)

The plotted h_{FE}-Ic curve will be similar to that shown in Figure 19. If the marker is used, h_{FE} at various values of collector current can be read directly from the display. The h_{FE} decay constant can be read directly from the display by using the line function to draw a line tangent to the linear portion of the h_{FE}-Ic curve as shown in Figure 19. The line slope (GRAD) is equal to the decay constant.

This measurement setup will be used again in Section 5, so store it on the disc under file name HFE1.

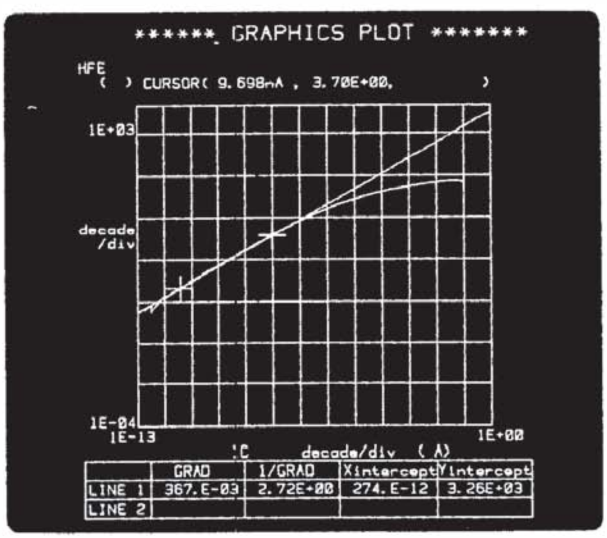


Figure 19.

Application Example 6: List Display

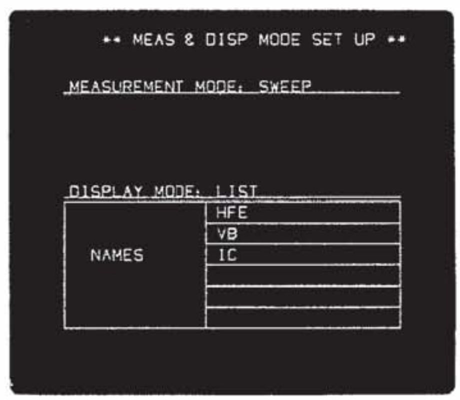
In the preceding examples, measurement results were plotted on the GRAPHICS PLOT page. In this example, however, measurement results will be displayed in a list format.

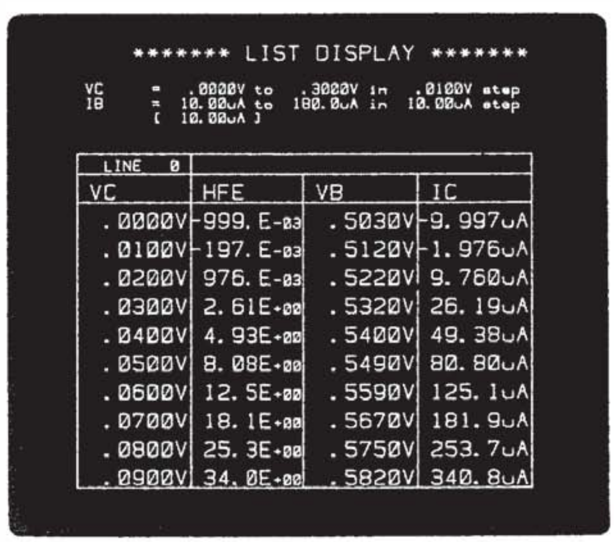
In this example, VAR2 will sweep base current and VAR1 will sweep collector-emitter voltage (V_C) and h_{FE} will be measured.

Display the MEAS & DISP MODE SET UP page and perform the following key sequence:

[LIST] [HFE] [VB] [IC]

The page will be as shown below. Press the (NEXT) key and then the (SINGLE) key. Each step value of the VAR1 source VC will be listed in the left-most column; the step value of the VAR2 source I_B will be enclosed in brackets above the table. Measurement results for h_{FE}, V_B, and Ic will be listed in the remaining three columns. Only ten measurement steps can be displayed at one time. Use the [RIGHT], [LEFT], [ROLL UP], and [ROLL DOWN] softkeys to display additional measurement results. The LIST DISPLAY is shown in Figure 20.





******* LIST DISPLAY *******

VC = .0000V to .3000V in .0100V step
IB = 10.00uA to 100.0uA in 10.00uA step
[10.00uA]

LINE 0

VC	HFE	VB	IC
.0000V	-999.E-03	.5030V	-9.997uA
.0100V	-197.E-03	.5120V	-1.976uA
.0200V	976.E-03	.5220V	9.760uA
.0300V	2.61E+00	.5320V	26.19uA
.0400V	4.93E+00	.5400V	49.38uA
.0500V	8.08E+00	.5490V	80.80uA
.0600V	12.5E+00	.5590V	125.1uA
.0700V	18.1E+00	.5670V	181.9uA
.0800V	25.3E+00	.5750V	253.7uA
.0900V	34.0E+00	.5820V	340.8uA

Figure 20.

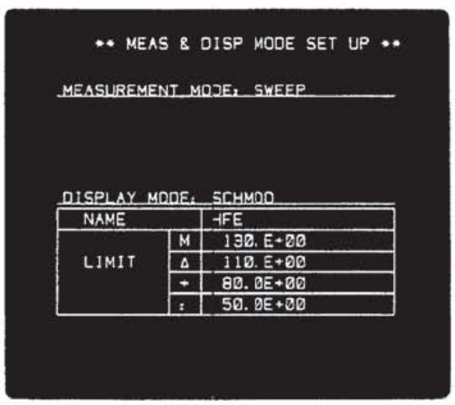
Application Example 7: Schmoo Plot

The Schmoo Plot is a three-dimensional (X-Y-Z) display in which five level-dependent, weighted symbols are used to indicate the relative values the measurement results along the Z-axis. When SCHMOO is selected on the MEAS & DISP MODE SET UP page, the VAR1 source and VAR2 source are automatically selected for the X-axis and Y-axis, respectively. The same measurement setup used in example 7 will be used in th s example. Display the MEAS & DISP MODE SET UP page and then perform the following key sequence: [SCHMOO] [EXTN] [HFE]

We must now define the lower limit value that each symbol is to have. The weighting relationships are as follows:

M > Δ > + > : > –

Define the lower limit of each symbol in accordance with the figure below. (The lower limit of – is always zero.) When measurement is made, all h_{FE} values higher than 130 will be displayed as M, all values between 110 and 130 will be displayed as Δ, and so on. Now press (NEXT) and (SINGLE). The resulting display will be similar to the one shown in Figure 21. To obtain the exact value of h_{FE} at each measurement point, press the [CURSOR] softkey. This will highlight the symbol at the first measurement point and will display the Z-axis value, above the plot area. When looking at a Sclunoo Plot, think of the Z-axis as projecting out from the screen.



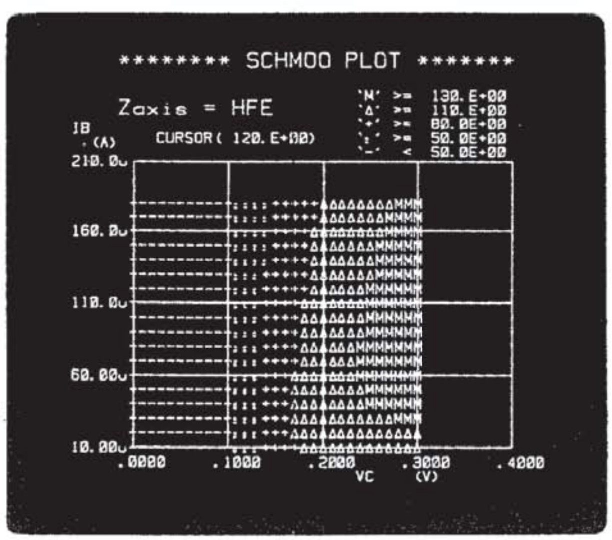


Figure 21.

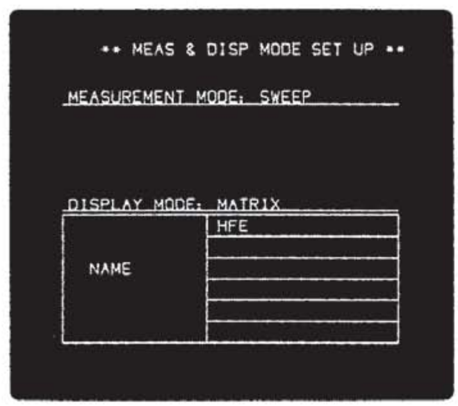
Application Example 8: Matrix Display

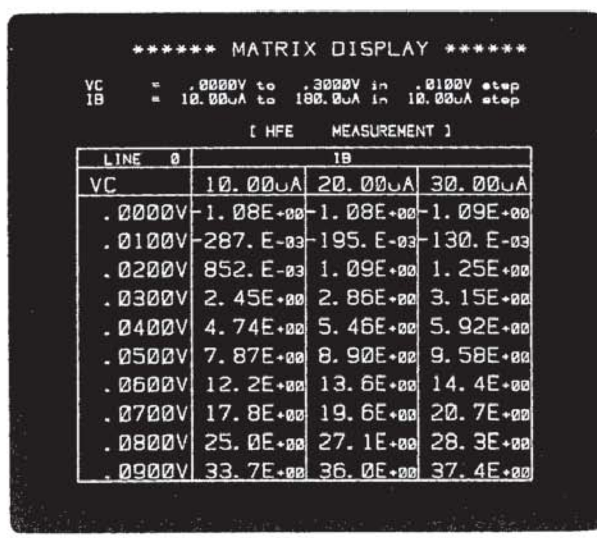
When MATRIX is selected on the MEAS & DISP MODE SET UP page, measurement results obtained from one monitor channel or user function are displayed as a function of the VAR1 source and the VAR2 source.

The same measurement setup that was used in example 7 will be used in this example. Display the MEAS & DISP MODE SET UP page and perform the following key sequence: [MATRIX] [EXTN] [HFE]

Only one monitor channel or user function can be selected.

Press the (NEXT) key and then the (SINGLE) key. The resulting display will be sim lar to the one shown in Figure 22. Each step value of the VAR1 source V_C will be listed in the left-most column; each step value of the VAR2 source I_B will be displayed in the top row of the table. h_{FE} at each VAR1-VAR2 step combination is displayed as shown in Figure 22. Only ten VAR1 measurement steps and three VAR2 measurement steps can be displayed at one time. Use the [RIGHT], [LEFT], [ROLL UP], and [ROLL DOWN] softkeys to display additional measurement results.





LINE 0	IB		
VC	10. 00uA	20. 00uA	30. 00uA
.0000V	-1. 08E+00	-1. 08E+00	-1. 09E+00
.0100V	-287. E-03	-195. E-03	-130. E-03
.0200V	852. E-03	1. 09E+00	1. 25E+00
.0300V	2. 45E+00	2. 86E+00	3. 15E+00
.0400V	4. 74E+00	5. 46E+00	5. 92E+00
.0500V	7. 87E+00	8. 90E+00	9. 58E+00
.0600V	12. 2E+00	13. 6E+00	14. 4E+00
.0700V	17. 8E+00	19. 6E+00	20. 7E+00
.0800V	25. 0E+00	27. 1E+00	28. 3E+00
.0900V	33. 7E+00	36. 0E+00	37. 4E+00

Figure 22.

4. 2 Evaluating MOS Devices

Application Example 9: Measuring Threshold Voltage (V_T) of MOSFETs

The threshold voltage of an enhancement type MOSFET is defined as the gate voltage required to cause a predetermined value of drain current to flow. In this example, V_T is the gate voltage required to cause $10\mu A$ of drain current.

Connect the DUT as shown in Figure 23, and setup the CHANNEL DEFINITION, SOURCE SET UP, and MEAS & DISP MODE SET UP pages as shown at the right. The VAR1 source will sweep the gate voltage (V_G), and the VAR2 source will sweep the source-substrate voltage (V_{SB}). Gate voltage (V_G) will be linearly plotted along the X-axis and drain current (I_D) will be logarithmically plotted along the Y-axis.

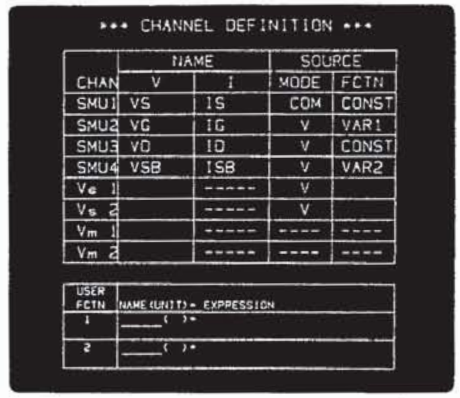
Measurement results are shown in Figure 24. Here, the left-most curve shows the drain current variations when substrate voltage (V_{SB}) is constant at 0V. To obtain V_T, move the marker along the left-most curve until $I_D = 10\mu A$, then read the gate voltage (X-axis) displayed above the plot area. In Figure 24, V_T is 2.017 volts.

Because of the device's body effect, threshold voltage changes as substrate voltage changes. Thus, if $V_T | V_{SB=0}$ is known, V_T at any value of V_{SB} can be calculated as

$$V_T = V_{TO} - \gamma \left[(V_{SB} + 2\phi f)^{1/2} - (2\phi f)^{1/2} \right]$$

where V_{TO} is threshold voltage when V_{SB} is zero, γ is the body effect coefficient, and ϕf is the Fermi potential. Also, the body effect coefficient, γ, can be obtained from this equation.

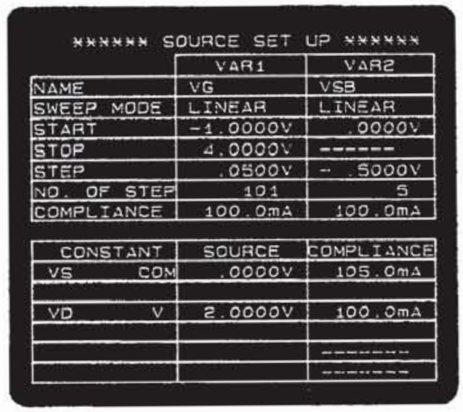
Note that the 4145B is capable of stable current measurements down to 1pA.



*** CHANNEL DEFINITION ***

CHAN	NAME V	NAME I	SOURCE MODE	SOURCE FCTN
SMU1	VS	IS	COM	CONST
SMU2	VG	IG	V	VAR1
SMU3	VD	ID	V	CONST
SMU4	VSB	ISB	V	VAR2
Vs 1		-----	V	
Vs 2		-----	V	
Vm 1		-----	----	----
Vm 2		-----	----	----

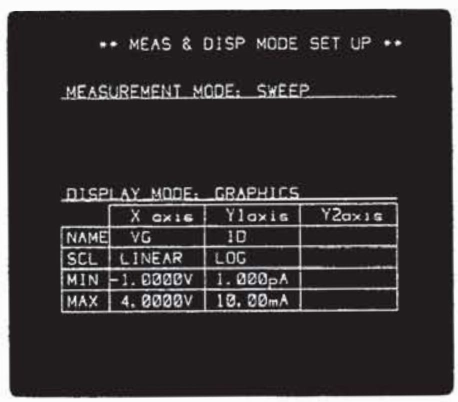
USER FCTN	NAME (UNIT) = EXPRESSION
1	____( )=
2	____( )=



****** SOURCE SET UP ******

	VAR1	VAR2
NAME	VG	VSB
SWEEP MODE	LINEAR	LINEAR
START	-1.0000V	.0000V
STOP	4.0000V	------
STEP	.0500V	- .5000V
NO. OF STEP	101	5
COMPLIANCE	100.0mA	100.0mA

CONSTANT		SOURCE	COMPLIANCE
VS	COM	.0000V	105.0mA
VD	V	2.0000V	100.0mA



** MEAS & DISP MODE SET UP **

MEASUREMENT MODE: SWEEP

DISPLAY MODE: GRAPHICS

	X axis	Y1axis	Y2axis
NAME	VG	ID	
SCL	LINEAR	LOG	
MIN	-1.0000V	1.000pA	
MAX	4.0000V	10.00mA	

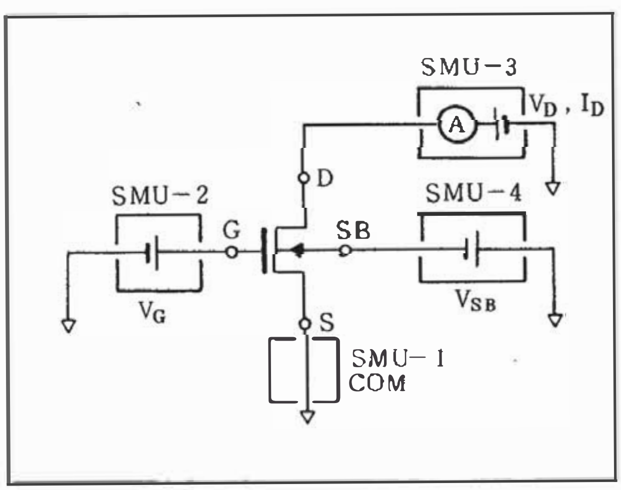


Figure 23.

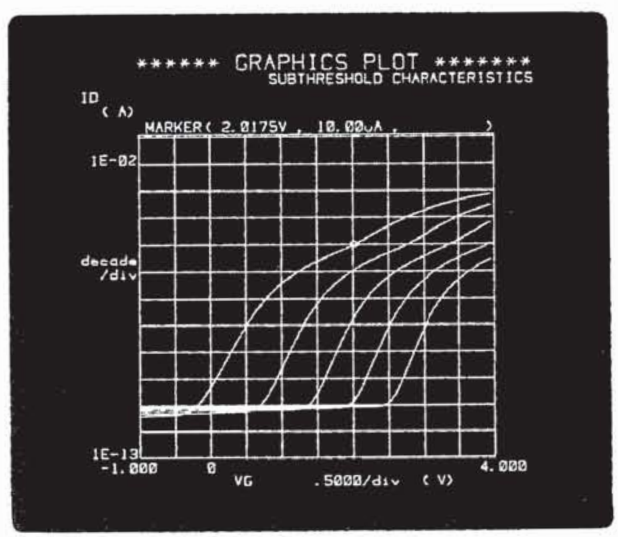


Figure 24.

Application Example 10: Measuring Threshold Voltage (V_T) of MOSFETs

A frequently used method of measuring a MOSFET's threshold voltage is to bias the device such that the gate and drain are always at the same potential and measure its characteristics in the saturation region. Drain current in the saturation region is calculated as

$$I_D = \beta (V_{GS} - V_T)^2$$

where β is the gain factor of the device and is expressed as

$$-\frac{1}{2}\mu\frac{W}{L}\,\frac{\epsilon_{OX}}{t_{OX}}$$

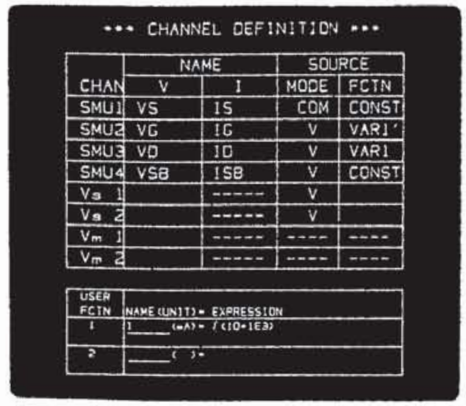
By taking the square root of both sides of the I_D equation, we find that the relationship between $\sqrt{I_D}$ and V_{GS} is linear, with a slope of $\sqrt{\beta}$ crossing the X-axis. The point at which the slope crosses the X-axis is the threshold voltage. Thus,

$$\sqrt{I_D} = \sqrt{\beta}\,(V_{GS} - V_T)$$

The user function can be used to perform this calculation during measurement. The Line Function can then be used to determine V_T and β.

Set up the CHANNEL DEFINITION, SOURCE SET UP, and MEAS & DISP MODE SET UP pages as shown at the right. The user function must be defined as I (mA) = $\sqrt{I_D * 1E3}$. Also, on the SOURCE SET UP page, the VAR1' ratio must be specified. To do this, move the field-pointer to the VAR1 START field and then perform the following key sequence: [VAR1 RATIO] (1) (ENTER)

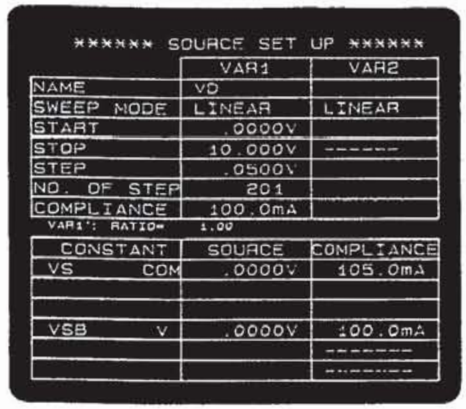
This will insure that the gate and drain voltages, V_G and V_D, will be equal throughout the measurement. Measurement results will be similar to those shown in Figure 26. To obtain V_T and β, draw a line along the linear portion of the curve. The X intercept (2.13 V in Figure 26) is V_T, and the square of the line gradient (GRAD) is β (0.25 in Figure 26).



*** CHANNEL DEFINITION ***

CHAN	NAME V	NAME I	SOURCE MODE	SOURCE FCTN
SMU1	VS	IS	COM	CONST
SMU2	VG	IG	V	VAR1'
SMU3	VD	ID	V	VAR1
SMU4	VSB	ISB	V	CONST
Vs 1		-----	V	
Vs 2		-----	V	
Vm 1		-----	----	----
Vm 2		-----	----	----

USER FCTN	NAME (UNIT) = EXPRESSION
1	I (mA) = √(ID*1E3)
2	( ) =

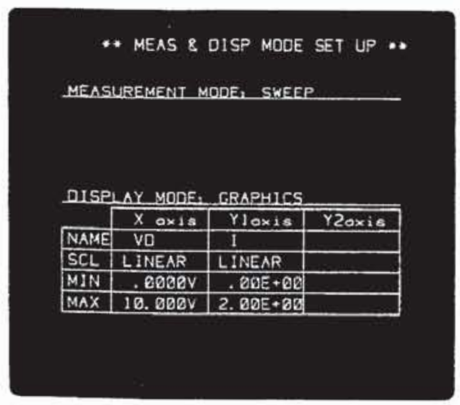


****** SOURCE SET UP ******

	VAR1	VAR2
NAME	VD	
SWEEP MODE	LINEAR	LINEAR
START	.0000V	
STOP	10.000V	-------
STEP	.0500V	
NO. OF STEP	201	
COMPLIANCE	100.0mA	

VAR1': RATIO= 1.00

CONSTANT		SOURCE	COMPLIANCE
VS	COM	.0000V	105.0mA
VSB	V	.0000V	100.0mA



** MEAS & DISP MODE SET UP **

MEASUREMENT MODE: SWEEP

DISPLAY MODE: GRAPHICS

	X axis	Y1axis	Y2axis
NAME	VD	I	
SCL	LINEAR	LINEAR	
MIN	.0000V	.00E+00	
MAX	10.000V	2.00E+00	

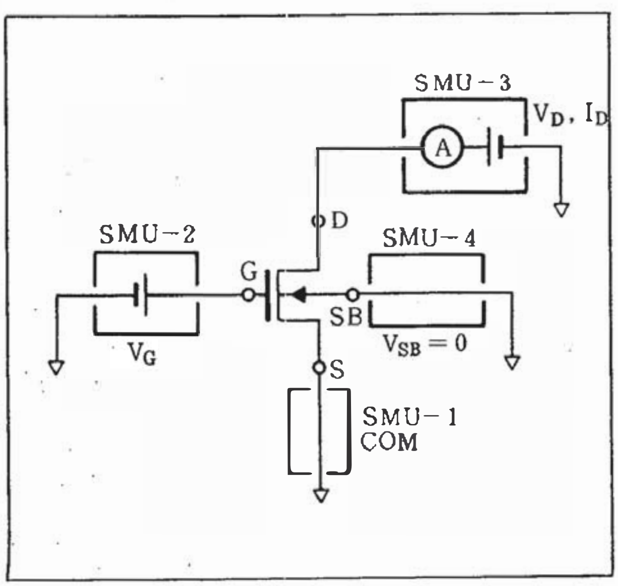
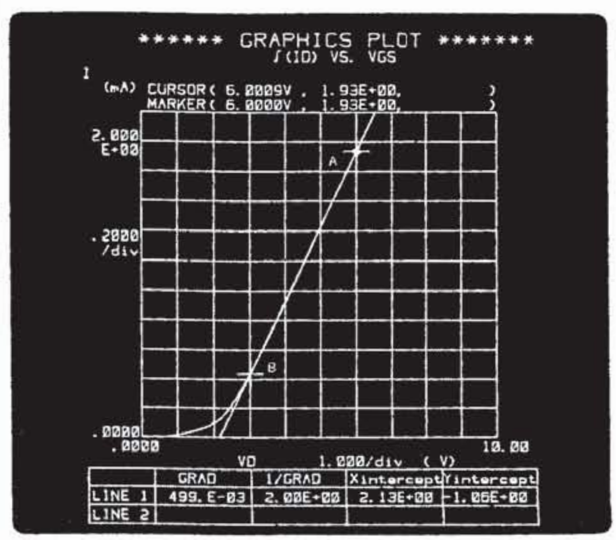


Figure 25.



	GRAD	1/GRAD	Xintercept	Yintercept
LINE 1	499.E-03	2.00E+00	2.13E+00	-1.06E+00
LINE 2				

Figure 26.

Application Example 11: Measuring Transconductance (gm) of MOSFETs

The transconductance of a MOSFET is defined as the device's ability to vary drain current (output) in response to gate voltage (input) variations, with drain-source voltage constant. In equation form

$$gm = \frac{\Delta I_{DS}}{\Delta V_{GS}} \Big|_{V_{DS}\ \text{constant}}$$

In this example, we will measure I_D at five different values of drain voltage and use the user function to calculate and plot gm.

Set up the CHANNEL DEFINITION, SOURCE SET UP, and MEAS & DISP MODE SET UP pages as shown at the right. Define the user-function as

GM (S) = ΔID/ΔVG

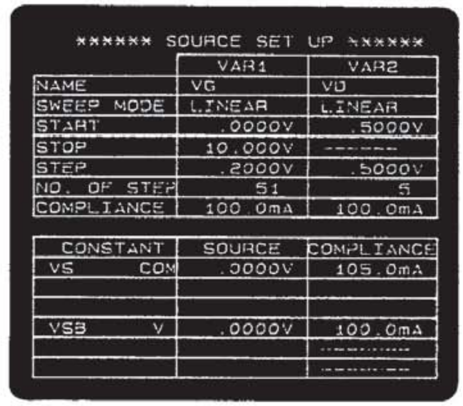
Measurement results will be similar to those shown in Figure 28.

The marker can be used to obtain direct read-out of gm at any bias point. Also, threshold voltage, V_T, can be obtained by drawing a line as shown in Figure 28 and reading the displayed X intercept value. In Figure 28, V_T is 2.18 volts.

*** CHANNEL DEFINITION ***

CHAN	NAME V	NAME I	SOURCE MODE	SOURCE FCTN
SMU1	VS	IS	COM	CONST
SMU2	VG	IG	V	VAR1
SMU3	VD	ID	V	VAR2
SMU4	VSB	ISB	V	CONST
Vs 1		-----	V	
Vs 2		-----	V	
Vm 1		-----	----	----
Vm 2		-----	----	----

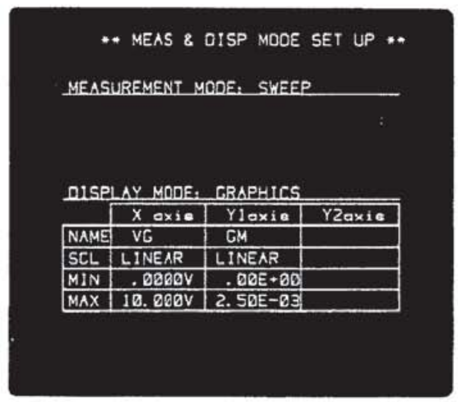
USER FCTN	NAME (UNIT) = EXPRESSION
1	GM (S) = ΔID/ΔVG
2	( ) =



****** SOURCE SET UP ******

	VAR1	VAR2
NAME	VG	VD
SWEEP MODE	LINEAR	LINEAR
START	.0000V	.5000V
STOP	10.000V	------
STEP	.2000V	.5000V
NO. OF STEP	51	5
COMPLIANCE	100.0mA	100.0mA

CONSTANT		SOURCE	COMPLIANCE
VS	COM	.0000V	105.0mA
VSB	V	.0000V	100.0mA



** MEAS & DISP MODE SET UP **

MEASUREMENT MODE: SWEEP

DISPLAY MODE: GRAPHICS

	X axis	Y1axis	Y2axis
NAME	VG	GM	
SCL	LINEAR	LINEAR	
MIN	.0000V	.00E+00	
MAX	10.000V	2.50E-03	

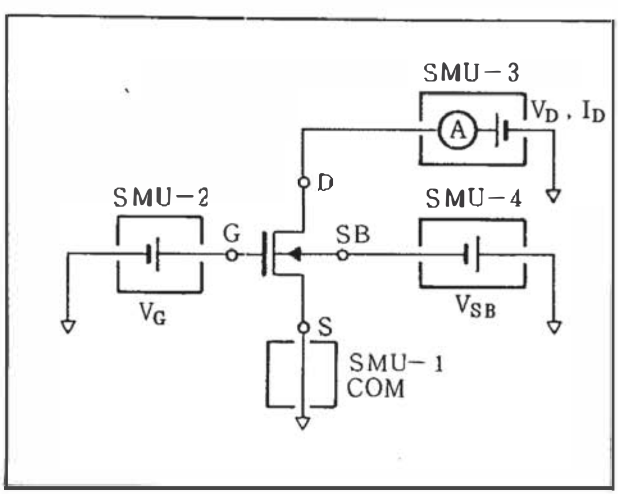
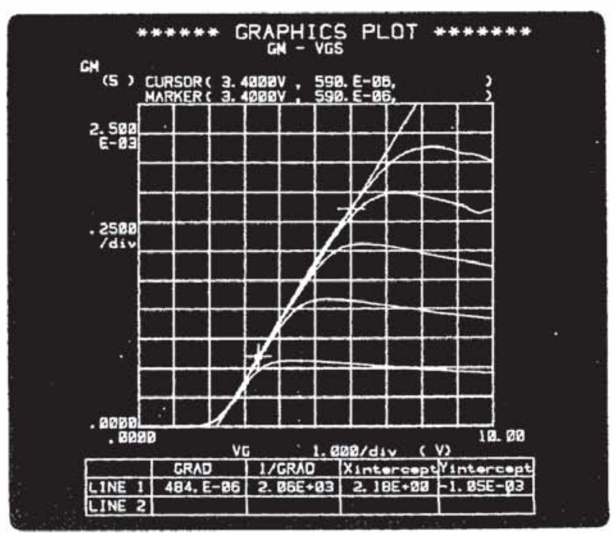


Figure 27.



	GRAD	1/GRAD	Xintercept	Yintercept
LINE 1	484.E-06	2.06E+03	2.18E+00	-1.05E-03
LINE 2				

Figure 28.

Application Example 12: Measuring Channel Conductance (Gds) of MOSFETs

Channel conductance (Gds) is one of the most important parameters used in the design of MOSFET analog switching circuits. For MOSFET biased for linear operation, Gds is defined as the ratio of drain current I_{DS} to drain-source voltage V_{DS} when V_{DS} is near zero. In equation form

$$Gds = \frac{I_{DS}}{V_{DS}}\Big|_{V_{DS} \to 0} = 2\beta(V_{GS} - V_T)$$

During measurement, the drain must be held constant at 50mV in order to operate the device in the linear region. Gate voltage V_G and substrate voltage V_{SB} will then be swept and drain current I_D will be measured. The user function will be used to calculate and plot Gds as a function of V_G.

Connect the DUT as shown in Figure 29 and set up the CHANNEL DEFINITION, SOURCE SET UP, and MEAS & DISP MODE SET UP pages as shown at the right. Define the user function as

GDS (S) = ID/VD

Measurement results will be similar to those in Figure 30. The marker can be used to obtain direct read-out of channel conductance at any value of gate voltage. For example, moving the marker along the V_{SB} = 0V curve until V_G = 3.5V obtains a Gds of 1.35mS (point B in Figure 30). Threshold voltage, also, can be obtained by drawing a line between points A and B and reading the X intercept of the line. In Figure 30, threshold voltage is 2.14 volts.

*** CHANNEL DEFINITION ***

CHAN	NAME V	NAME I	SOURCE MODE	SOURCE FCTN
SMU1	VS	IS	COM	CONST
SMU2	VG	IG	V	VAR1
SMU3	VD	ID	V	CONST
SMU4	VSB	ISB	V	VAR2
Vs 1		-----	V	
Vs 2		-----	V	
Vm 1		-----	----	----
Vm 2		-----	----	----

USER FCTN	NAME (UNIT) = EXPRESSION
1	GDS (S) = ID/VD
2	( ) =

****** SOURCE SET UP ******

	VAR1	VAR2
NAME	VG	VSB
SWEEP MODE	LINEAR	LINEAR
START	1.0000V	.0000V
STOP	11.000V	----------
STEP	.1000V	-2.0000V
NO. OF STEP	101	5
COMPLIANCE	100.0mA	100.0mA

CONSTANT		SOURCE	COMPLIANCE
VS	COM	.0000V	105.0mA
VD	V	.0500V	100.0mA

** MEAS & DISP MODE SET UP **

MEASUREMENT MODE: SWEEP

DISPLAY MODE: GRAPHICS

	X axis	Y1axis	Y2axis
NAME	VG	GDS	
SCL	LINEAR	LINEAR	
MIN	1.0000V	.00E+00	
MAX	11.000V	10.0E-03	

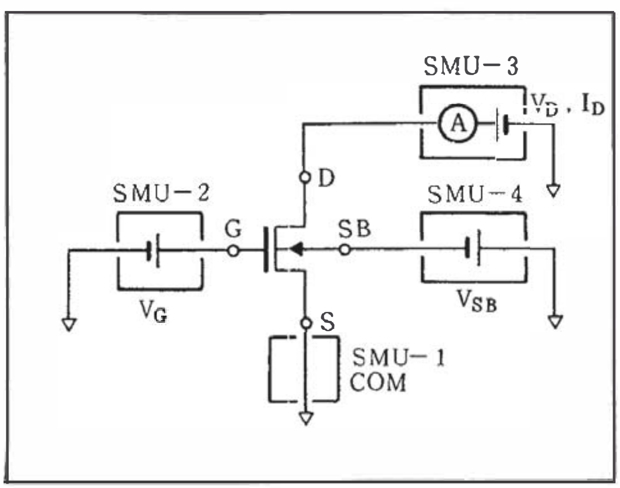
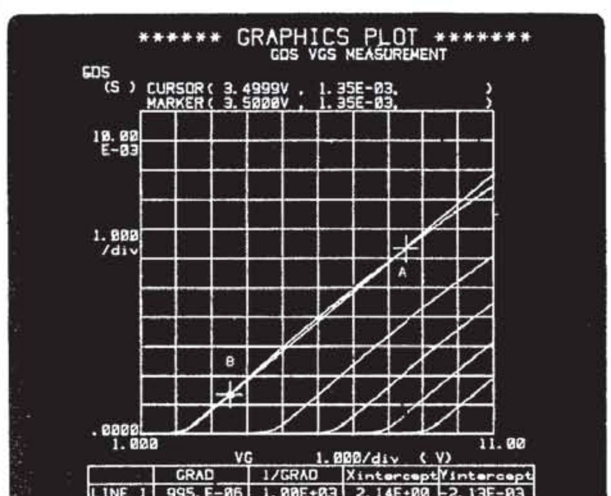


Figure 29.



	GRAD	1/GRAD	Xintercept	Yintercept
LINE 1	995.E-06	1.00E+03	2.14E+00	-2.13E-03
LINE 2				

Figure 30.

4. 3 Evaluating Solar Cells

This example shows how the 4145B can be used to evaluate solar cell parameters. The maximum output power, optimum operating voltage, and optimum operating current of both single crystal silicon and amorphous silicon structures can be easily obtained.

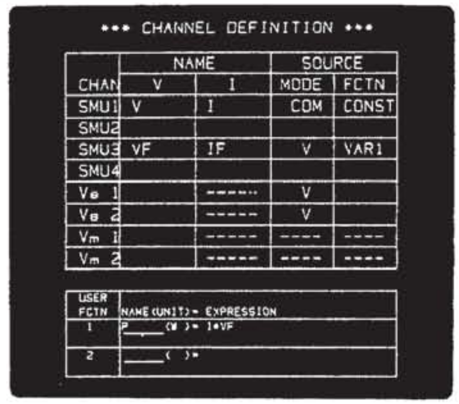
Connect the DUT as shown in Figure 31 and set up the CHANNEL DEFINITION, SOURCE SET UP, and MEAS & DISP MODE SET UP pages as shown at the right. Define the user function as

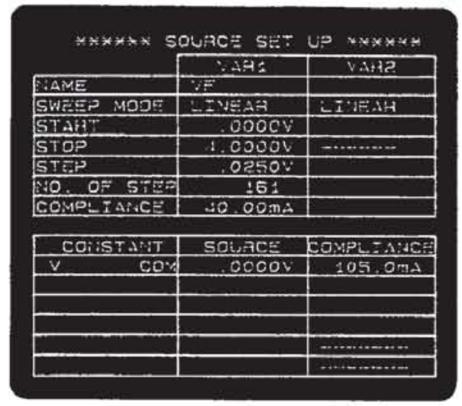
P (W) = I * VF

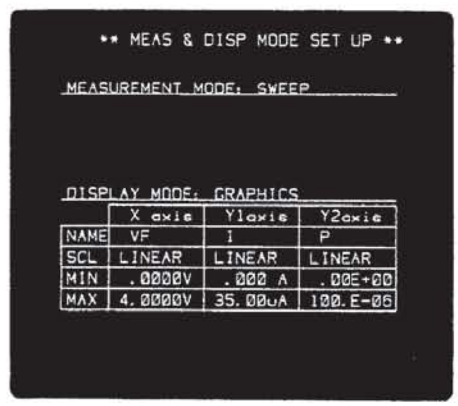
Figure 32 shows the output characteristics of a silicon solar cell under constant illumination by a solar simulator.

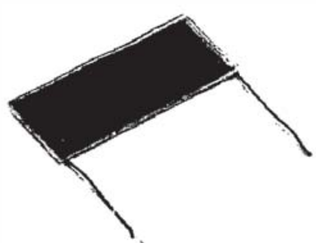
By positioning the marker at the maximum power point, optimum operating voltage and current can be read directly from the CRT. In this example, maximum output power is 87μW, optimum operating voltage is 2.975V, and optimum operating current is 29.26μA.

Additionally, by making a few simple changes to the measurement setup, short-circuit current Isc or open-circuit voltage Voc can be obtained.









Single Crystal Silicon
Solar Cell

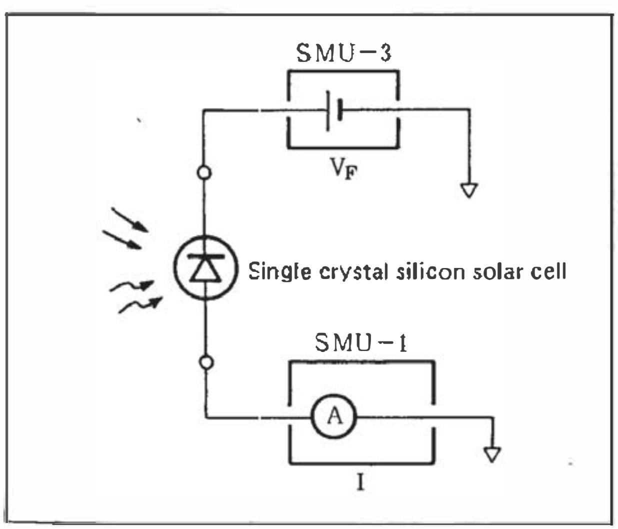


Figure 31.

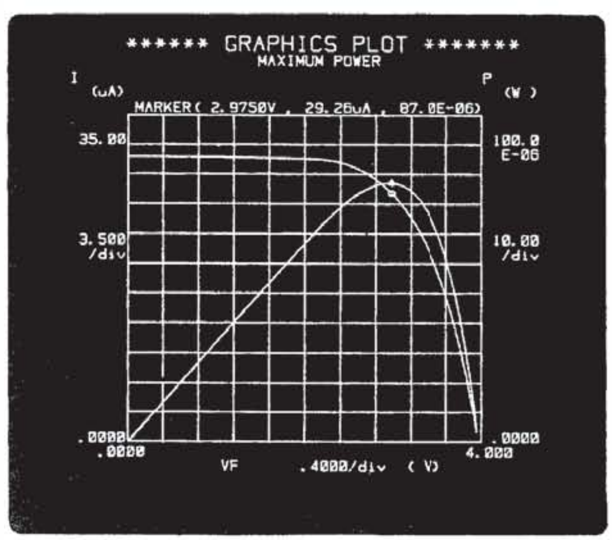


Figure 32.

5. AUTO-SEQUENCE PROGRAMMING EXAMPLE

This section describes the method of setting up the Auto-Sequence to obtain four different bipolar transistor parameter measurements, with a continuing plot connecting each measurement. The four measurement setups were stored in Application Examples 1, 2, 3, and 5. (Figure 33)

First, from the Menu page, press [4 ASP SET UP] to display the Auto-Sequence Setup page.

As shown in Figure 34, enter the various commands using the Softkeys and Data Entry Keys, then program Auto-Sequence by specifying the measurements, plot position and dimensions, and the measurement data recording sequence, etc. Repeat all steps as directed until the program is complete. At any point where program execution should be halted for analysis, insert a PAUSE command. (The program can be restarted with the (CONT) key.)

Execution of the Auto-Sequence program is started by pressing the AUTO SEQ (START/STOP).

Figure 35 shows how the various characteristics and DC parameters of a DUT can be automatically measured, plotted, and stored using the 4145B's auto-sequence function.

To store the Auto-Sequence program on the disc, attach the file name BIP to it and key in (SAVE) (3) (B) (I) (P) (EXECUTE). To recall it, key in (GET) (S) (B) (I) (P) (EXECUTE).

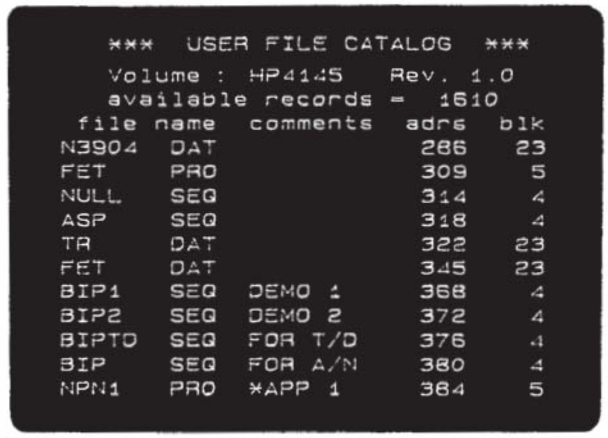


Figure 33.

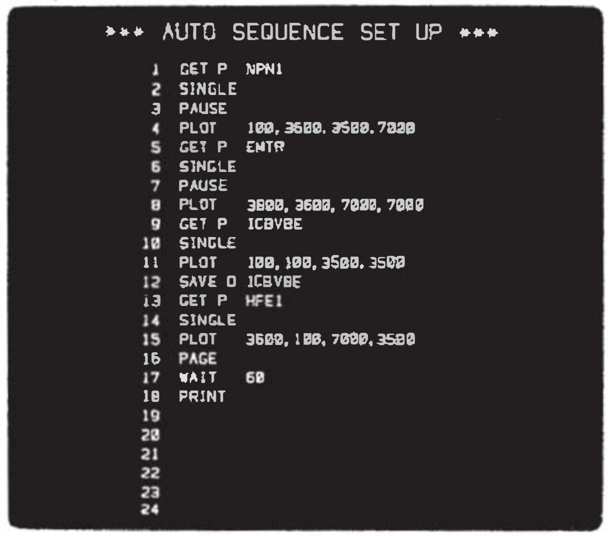


Figure 34.

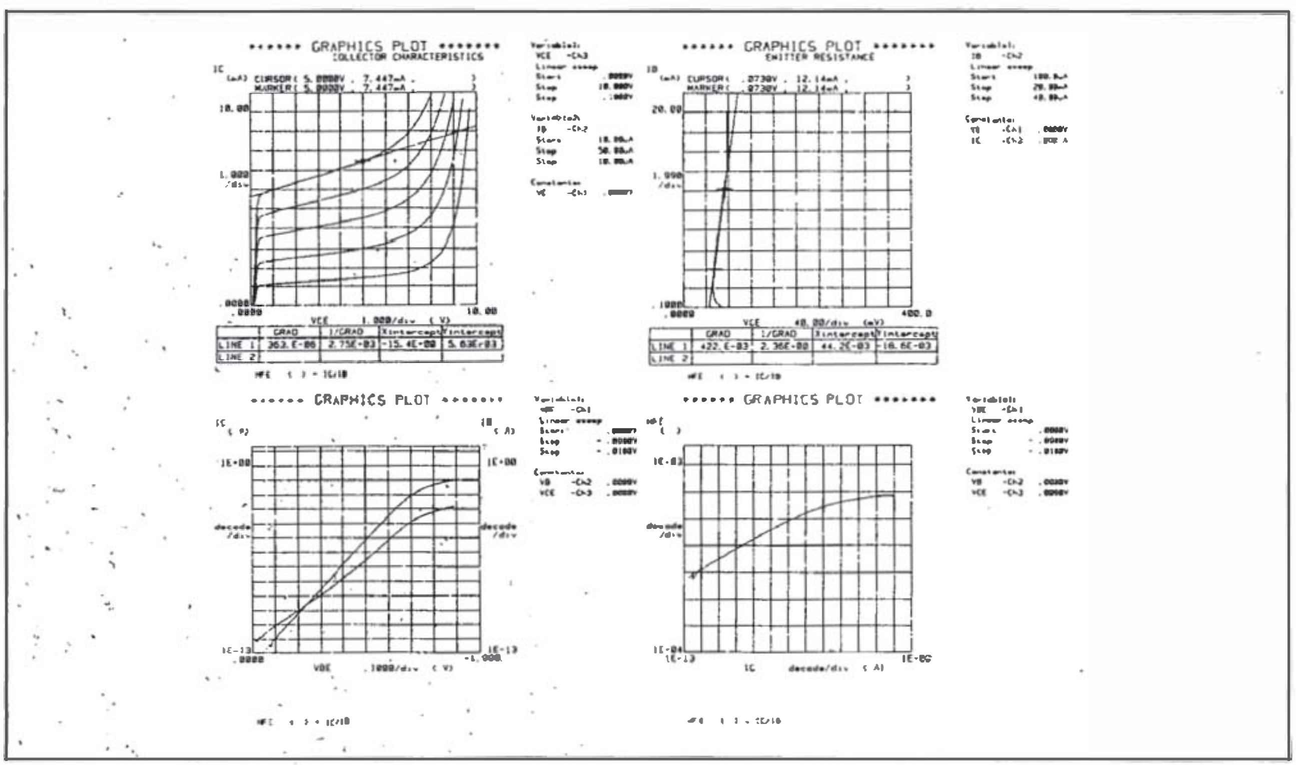


Figure 35. Example plot of Bipolar Transistor Characteristics

6. SYSTEMIZATION

One of the steps proven most effective in shortening the lead time between the conceptual stage and actual production of semiconductor devices is laboratory automation. A system capable of accurately measuring the various characteristics of a device and automatically extracting parameters for analysis to provide the design engineer with instant feedback is essential.

Furthermore, such a system becomes even more important as advances are made in VLSI techniques, and as more devices and circuits are designed using CAD simulation techniques. Here, a measurement system is called for that can extract model parameters constructed to duplicate the actual device with a high degree of accuracy, and feed them directly into the CAD system.

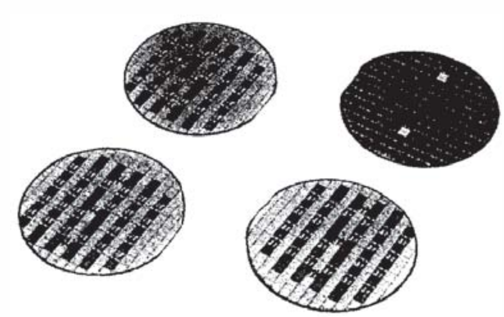
The 4145B is designed to function as the nucleus of a system that will meet these requirements and objectives. The configuration of an idealized system is shown in Figure 36.

With the ability to measure DC characteristics of semiconductor devices down to the $100\mu V$ and 1pA range – and its high sensitivity – a 4145B-based system will prove a valuable asset in both the R & D laboratory and in quality-control on the production line. Its capabilities in the latter application include C–V measurements at frequencies ranging from DC to 1MHz to evaluate junction and oxide layer capacitance, and to determine voltage dependence characteristics. Other possibilities with the 4145B – 4275A Multifrequency LCR Meter – 4140B pA Meter combination are the measurement of oxide layer thickness, and flat band voltage.

HP-IB is used to pass program control between the controller and the various instruments and wafer prober. And in a system where device characteristics evaluation is the primary objective, the controller can be used to initially process the measurement data, then transmit it to the host computer. The host computer can then use this data to attach numerical values to device parameters and determine distribution patterns. Interrelational diagrams between parameters can be constructed to give the design engineer a powerful tool for use in designing effective working circuits.

When the system is applied to model parameter extraction, the controller can use the measurement data to construct the model parameter for input into the CAD system.

As shown in the system configuration diagram (Figure 36), using the 4145B permits a completely automated semiconductor device measurement system to be assembled with far fewer individual instruments than previous systems, improving cost-performance and device reliability at the same time.



Silicon wafers

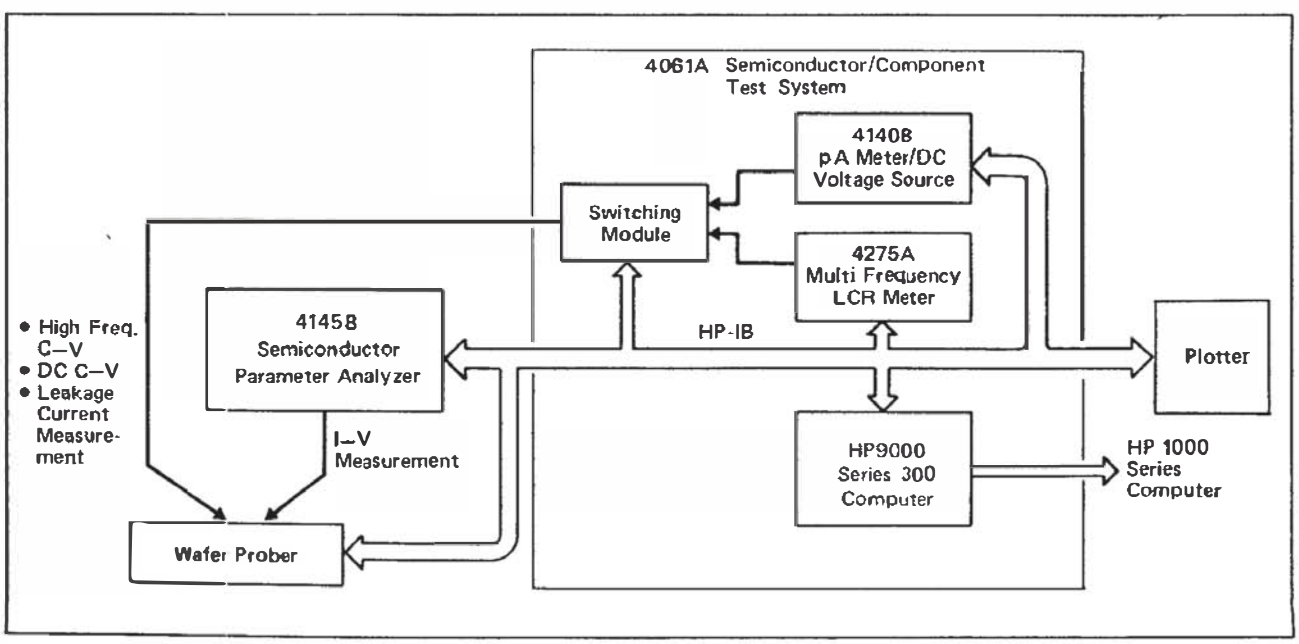


Figure 36. Automatic measurement system for CAD system