BSIM PARAMETER EXTRACTION - ALGORITHMS AND USER'S GUIDE

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I. INTRODUCTION

It is indispensable for integrated circuit designers to have an accurate computationally-efficient circuit simulation model, especially for designing complex VLSI circuits. BSIM (Berkeley Short-channel IGFET Model) [1,2] is developed for such purpose. It provides good accuracy over a wide range of device geometries as well as high speed due to its compact mathematical formulation. To sustain high simulation accuracy, a suitable set of parameter values are required. In this report, an automated MOS device characterization and circuit simulation system developed for BSIM will be described. This characterization system has the ability to measure both the dc strong-inversion and weak-inversion characteristics from devices of different sizes, then generates a process file which will be sent to a main frame computer for future circuit simulations. This integrated system can greatly alleviate circuit designers' burden and expedite circuit designs.

The extraction program is written in HP Pascal. The program is partitioned into six major modules which makes maintenance and updating simple. These major modules are: initial display and measurement, parameter extraction, process-file development, I-V playback, parameters vs. L and W plots, and main program.

The measurement system has three major components [3] (Fig. 1): the HP-200 series computer (HP9836 in our system), the HP4145A parameter analyzer and the probe station. The computer controls and coordinates data transfer between the parameter analyzer and probe station, it also stores and optimizes the extracted parameters in the HP9888 bus expander. Other mass-storage unit can be used in place of the bus expander. The parameter analyzer supplies dc biases and monitors currents. The probe station can be either an automatic or a manual one. In the case of an automatic probe station (eg. Electroglas 2001X), the computer also drives the prober to those devices specified in the probe file. Data transfer between HP9836 and HP4145 is through HPIB interface bus and the connection between HP9836 and a VAX computer is via the RS232 bus. After measurements, each extracted parameter can be plotted out as functions of W and L which is optional at the choice of the user. Such information is useful in selecting the optimized range of device sizes per process file, so that even higher accuracy can be achieved. The final process file can be either stored in a floppy disk for future use or transferred to a larger computer where SPICE is located. Modeled and measured results for any device can also be plotted on the same figure for easy comparison.

The strong inversion measurement takes about three minutes for each device. The subthreshold measurement is optional. In measuring the subthreshold current, a good electrical and light shieldings for the prober are required.

There are four operation modes which can satisfy a variety of purposes, which are summarized in Fig. A1. When the program is executed, the user will be asked to enter the proper mode of operation. Mode 1 and 2 use an automatic prober. Mode 2 requires the operator to move the prober to a new device every time it finishs measuring a device. This mode provides the user a more flexible way to use the automatic prober. Any improper measurement (eg. due to bad contact which is quite usual for automatic prober) in the course of measuring can be handled and re-measured without disturbing previous measurements. Mode 3 is similar to mode 2 except that a manual prober is used. Mode 4 measures and extracts parameters from a single device.

Except for the fully automatic mode, the program communicates with the user through inquiries after measuring each device. The user can control the quality of measurements. This feature is essential in sustaining high-accuracy simulations. Examples of the interactions between the program and users can be found in chapter III. Some samples of measured and calculated results are shown in Fig. 2.

Flowcharts of the main program and the extraction subroutine are shown in Fig. 3 and 4, respectively. Most of the inputs to the program are specified in the probe file to minimize the unnecessary user-machine interaction. A device information menu will be displayed at the beginning for the user to input information. The only required inputs to the program are the name of the probe file and the drain voltage range. Other inputs are just for future reference and have no effect on the extraction process. Default values will be given if not specified. For the single device mode, (Mode 4), the surface potential or substrate doping also needs to be supplied in addition to those mentioned above. In other modes, the surface potential parameter is extracted from the largest device.

Before extracting device parameters, a series of tests are automatically performed to ensure the proper functionality of the test device. The device type is also identified at this time. If the device does not pass all of the tests, an error message will be given. This allows the user to check the probing contact or switch to another device. The extracted parameters of each device are also examined. If any of these parameter values are not within the built-in range, none of these parameter values will be saved. The user can choose to discard or remeasure this device. All these parameters will be displayed on the screen for the users to check. The maximum number of devices that can be extracted in this program is 40 and can be expanded easily. The limit is set by the available memory in the mass storage unit.

The following sections contain the detailed descriptions of the structure, operation of the BSIM parameter extraction program, as well as a brief summary of BSIM equations.

II. BSIM FORMULATION

In this chapter, BSIM equations are listed [3]. Twenty parameters per transistor size are used for both the NMOS and PMOS transistors. Among the twenty BSIM parameters, seven parameters model the threshold voltage, ten parameters model the drain current, three parameters model the subthreshold current.

(A). Threshold voltage

The threshold voltage can be expressed as:

$$V_{th} = V_{FB} + \phi_s + K_1\sqrt{\phi_s - V_{BS}} - K_2(\phi_s - V_{BS}) - \eta V_{DS} \tag{1}$$

where V_{FB} is the flat-band voltage, ϕ_s is the surface-inversion potential, K_1 is the body effect coefficient, K_2 is the source/drain depletion-charge-sharing effect coefficient, η accounts for the drain-induced-barrier-lowering effect.

V_{FB}, ϕ_s, K_1 and K_2 are bias-independent, while η can further be modeled by three parameters:

$$\eta = \eta_0 + \eta_B\, V_{BS} + \eta_D\, (\, V_{DS} - V_{DD}\,) \tag{2}$$

(B). Drain current

In the linear region, the drain current can be expressed as:

$$I_{DS} = \frac{\beta}{(\, 1 + U_1 * V_{DS}\,)} \left| (\, V_{GS} - V_{th}\,)\, V_{DS} - \frac{a}{2}\, V_{DS}^2 \right| \tag{3}$$

where

$$\beta = \frac{\beta_0}{[\, 1 + U_0\, (\, V_{GS} - V_{th}\,)\,]} \tag{4}$$

In the saturation region, the drain current can be expressed as:

$$I_{DSAT} = \frac{\beta (V_{GS} - V_{th})^2}{2aK} \tag{5}$$

where

$$a = 1 + \frac{gK_1}{2\sqrt{\phi_s - V_{BS}}} \tag{6}$$

$$g = 1 - \frac{1}{1.744 + 0.8364\,(\phi_s - V_{BS})} \tag{7}$$

$$K = \frac{U_1\,(V_{GS} - V_{th})}{2a} \tag{8}$$

$$V_{DSAT} = \frac{V_{GS} - V_{th}}{a\sqrt{K}} \tag{9}$$

U_0 and U_1 account for the mobility degradation effects due to the vertical and horizontal electric fields, respectively. The factor "a" represents the bulk doping effect. β_0 is the low-field conductance coefficient.

U_0 and U_1 are bias-dependent and are modeled as follows:

$$U_0 = U_{0Z} + U_{0B}\,V_{BS} \tag{10}$$

$$U_1 = U_{1Z} + U_{1B}\,V_{BS} + U_{1D}\,(V_{DS} - V_{DD}) \tag{11}$$

The calculation of β_0 is slightly different from other parameters. β_0 is obtained by quadratic interpolation through three data, i.e., β_0 at $V_{DS} = 0$ ($\equiv \beta_1$), β_0 at $V_{DS} = V_{DD}$ ($\equiv \beta_2$), and the sensitivity of β_0 to V_{DS} at $V_{DS} = V_{DD}$ ($\equiv \beta_3$). Both β_1 and β_2 are functions of V_{DS}, and are modeled by

$$\beta_1 = \beta_Z + \beta_{ZB}\,V_{BS} \tag{12}$$

$$\beta_2 = \beta_S + \beta_{SB}\,V_{BS} \tag{13}$$

The final value of β is given by Eq. (14)

$$\beta = \beta_1\left(\frac{V_{DS}}{V_{DD}} - 1\right) + \beta_2\left(2 - \frac{V_{DS}}{V_{DD}}\right) + \beta_3\,V_{DS}\left(\frac{V_{DS}}{V_{DD}} - 1\right) \tag{14}$$

A plot of β_0 vs. V_{DS} is shown in Fig. 5. The relationship between β, β_1, β_2, and β_3 can easily be observed in this figure.

(C). Subthreshold current

$$I_{exp} = \beta \, (V_{tm})^2 \, e^{1.8} \, e^{\frac{V_{GS} - V_{th}}{nV_{tm}}} \left[1 - e^{-\frac{V_{DS}}{V_{tm}}} \right] \tag{15}$$

$$I_{lim} = \beta \, \frac{(3V_{tm})^2}{2} \tag{16}$$

$$I_{subthreshold} = \frac{I_{exp} \, I_{lim}}{I_{exp} + I_{lim}} \tag{17}$$

where V_{tm} is equal to kT/q and n is the subthreshold swing coefficient. I_{lim} is used to set an upper limit on the subthreshold current. The subthreshold swing coefficient n is a function of V_{DS} and V_{BS}, and is modeled by

$$n = n_0 + n_B * V_{BS} + n_D * V_{DS} \tag{18}$$

N_0, N_B and N_D are the three BSIM subthreshold parameters. A more complete description of the BSIM subthreshold current model can be found in [4].

In the extraction program, the parameters which account for the sensitivity to V_{BS} are prefixed by "x2", and the sensitivity to V_{DS} are prefixed by "x3". For example, η_B in Eq. (2) is denoted by x2eta. β_2 in Eq. (13) is denoted by x3beta0sat, the suffix "sat" means this parameter is extracted in the saturation region.

The variable names for these twenty BSIM parameters used in the extraction program are slightly different from what used here. For user's convenience, a summary of these twenty BSIM parameters and their corresponding names in the extraction program is listed below by the order they appear in the process file. The variable names used in the extraction program are parenthesized.

1. V_{FB} (c1_vfb): the flat-band voltage.

2. ϕ_s (c2_phif2): the surface inversion potential.

3. K_1 (c3_k1): the body effect coefficient.

4. K_2 (c4_k2): the source/drain charge sharing effect coefficient.

5. η_Z (c5_eta): the value of η at zero substrate bias and $V_{DS} = V_{DD}$.

6. β_Z (c6_beta0): the value of β at zero substrate and drain-source biases.

7. U_{0Z} (c7_u0): the value of U_0 at zero substrate bias.

8. U_{1Z} (c8_u1): the value of U_1 at zero substrate bias.

9. β_{ZB} (c9_x2beta0): the sensitivity of β to substrate bias at $V_{DS} = 0$.

10. η_B (c10_x2eta): the sensitivity of η to substrate bias.

11. η_D (c11_x3eta): the sensitivity of η to drain voltage at $V_{DS} = V_{DD}$.

12. β_{ZB} (c12_x2u0): the sensitivity of β to substrate bias at $V_{DS} = 0$.

13. U_{1B} (c13_x2u1): the sensitivity of U_1 to substrate bias.

14. β_S (c14_beta0sat): the value of β at zero substrate bias and at $V_{DS} = V_{DD}$.

15. β_{SB} (c15_x2beta0sat): the sensitivity of β to substrate bias at $V_{DS} = V_{DD}$.

16. β_{SD} (c16_x3beta0sat): the sensitivity of β to drain voltage at $V_{DS} = V_{DD}$.

17. U_{1D} (c17_x3u1): the sensitivity of U_1 to drain voltage at $V_{DS} = V_{DD}$.

18. n_0 (n0par): the value of N at zero substrate and drain biases.

19. n_B (nbpar): the sensitivity of N to substrate bias.

20. n_D (ndpar): the sensitivity of N to drain voltage.

III. BSIM EXTRACTION PROGRAM USER'S GUIDE

This chapter describes how to load and run the extraction program step by step, and how to set up the environment required by the extraction program. The new users are recommended to read this user's guide thoroughly before they start running the BSIM parameter extraction program.

SYSTEM SETUP

The parameter extraction system consists of an HP 9836 computer with one mega byte memory (with the addition of HP 9888A Bus Expander). (Note: the minimum recommended memory size for the HP PASCAL system is 512K bytes.), a 4145A parameter analyzer and either an automatic prober or a manual prober. This system has to be properly setup before the parameter extraction program can be used. In the following descriptions, user actions are in **BOLD** print. Program prompts are in *italic* letters.

1. 4145 SETUP INSTRUCTIONS

A) **Place** the Software Diskett Revision A5 in the floppy disc drive slot on the lower left side of the 4145. The disc label should be up and towards you. Close the floppy disc drive door.

B) **Press** the "ON" switch on the left side of the 4145, and the machine should display a menu after it calibrates itself.

2. 2001X PROBER SETUP INSTRUCTIONS

If you are using the automatic mode (Mode 1) or semi-automatic mode with automatic prober (Mode 2)*, the following instructions should be followed. For Mode 3 and Mode 4 operations, this section can be skipped.

A) Make sure that no foreign objects are on the prober stage, or on the wafer chuck.

B) If the probe card you want to use is not in the probe card rack, put the probe card you want to use in the rack and press it back into the edge connector. Make sure that all four screws which hold the probe card are securely tightened down.

C) **Press** the "ON" switch on the lower right front of the prober front panel.

D) Look at the Prober Video Display and answer the following questions as shown below. If you do not respond fast enough, a default response will be

---

* The instruction listed here are specifically for the 2001 automatic prober.

chosen by the prober, and it will move on to the next question.

Type Message Plus Enter=> **ENTER**

Wait for Pattern Rec I/O Test... **Wait about 30 seconds**

Rom Test? **Y**

Repeat Test? **ENTER**

E) When the standard display comes up it should say ***XY MOTOR BLANK*** at the bottom of the screen. This means that the stage is floating on the platform and can be moved around. Pull the stage so that it is touching the front cushion on the prober platform. Now slide the stage along the front cushion to the right until it is contacting both the front and the right cushions. To hold the stage in place, hit the button inside the left side of the joystick control panel. (This button is recessed, and is in a cutout hole on the left vertical side of the joystick box)

F) On the front panel of the prober, above the label saying Model 2001X, is a small vacuum lever with a black handle. Pull the lever out so that it is perpendicular to the panel, and you should here a hissing noise as the vacuum turns on.

G) At this point, the I/O Mode should be set for the Prober. Turn to the control panel with the video monitor, and perform the **bold** actions to the *italic* video monitor requests
Press the blue 'Set Mode' key.
Select Line?= **7 and ENTER**
IOMODE? 0=OFF, 1=SERIAL, 2=GPIB **2 and ENTER**
If the line 9 GPIB (IEEE-488) address is not equal to 14, then set it to 14 as follows
Select Line?= **9 and ENTER**
GPIB ADDRESS=? 1 TO 15 **14 and ENTER**
Press the Yellow *ON LINE* Key on the monitor panel, which sets the prober up to receive signals from the 9836.

H) The stage up and down limits must now be either set or verified depending upon whether a new probe card will be used. Press the blue *SET PRMTR* key on the monitor panel, and observe the Z UP LIMIT and the Z DOWN LIMIT. The Z UP LIMIT should be about 30MILS above the Z DOWN LIMIT. Typical values might be Z UP LIMIT=370MILS and Z DOWN LIMIT=340MILS. If the probe card has not been changed, these values should have been previously setup, and require only verification. Using a new probe card requires that the LIMITS be lowered significantly, and then adjusted by raising the LIMITS incrementally until the probes barely touch the wafer when the chuck is up. This should be done by an experienced person. After the probes just touch the wafer, the Z UP LIMIT should be raised by 2.5 to 3.0 MILS to provide sufficient overdrive.

I) Place the wafer on the stage, and press both the *VAC* and the *LAMP* buttons on the joystick control panel. The video dislay should show that the wafer and chuck vacuum are on.

J) Press the *Align Scan* button on the panel with the joystick, and the stage should move under the probes. The index, jog and scan modes are selected by twisting the joystick. Faster movement is provided by pressing the red button on the joystick. The wafer is aligned by pressing the *Pause* key twice so that the stage is moving back and forth under the probes. The twist knob on the joystick control box is a theta adjust, and is used to align the wafer. Alignment is done by watching the wafer pass under a probe and using the theta adjust until patterns are tracking the probe across the wafer.

K) Once the wafer is aligned, the wafer should be moved so that the probes are over the device to be tested, and then the stage is raised with the *Z* button. The stage may have to be lowered and moved so that the probes will contact the center of the pads.

L) The Prober is setup for Automatic Operation

3. HP 9836 SETUP INSTRUCTIONS

Four operating system disks are needed to set up HP 9836: Pascal 2.0 BOOT Disc, Pascal 2.0 SYSVOL Disc, Pascal 2.0 ACCESS Disc and Pascal 2.0 CMPASM Disc. These disks should come with the machine (HP 9836). To make HP 9836 setup procedure easier to follow, a specially modified version of PASCAL 2.0 SYSVOL (provided in the BSIM package) is used. The setup procedures described below refer to the modified version.

SETUP HP9836 WITH MODIFIED HP PASCAL 2.0 SYSVOL

(a) **INSERT** Pascal 2.0 SYSVOL in the left disc drive (unit#4).

INSERT Pascal 2.0 BOOT in right disc drive (unit#3).

TURN ON HP 9888A Bus Expander (RAM).

PRESS the switch located on the front bottom right of the keyboard in to turn on the HP 9836.

(b) The operating system is now being loaded. Messages indicating the loading of OS are flashed on the screen.

DO NOTHING until the following message appears on the top of the screen.

```
Press 'ENTER' to P-load EDITOR, FILER, VT2 & Put LIBRARY->RAM
```

PRESS [ENTER] key.

(c) Another sequence of messages will be flashed on the screen.

DO NOTHING until the following messages appear on the screen.

```
Stream what file? SYSVOL:AUTO1
 Replace BOOT with ACCESS and Press 'ENTER'
```

TAKE Pascal 2.0 BOOT out of the right disc drive (unit#3).

INSERT Pascal 2.0 ACCESS in the right disc drive (unit#3).

PRESS [ENTER] key.

(d) **IGNORE** messages flashed on the screen until the following messages appear.

```
Stream what file? SYSVOL:AUTO2
 Replace ACCESS with CMPASM and Press 'ENTER'
```

TAKE Pascal 2.0 ACCESS out of the right disc drive (unit#3).

INSERT Pascal 2.0 CMPASM in the right disc drive (unit#3).

PRESS [ENTER] key.

(e) **DO NOTHING** until the following appears on the screen.

```
>Edit: Adjust Cpy Delete Find Insert Jmp Rplace Quit Xchg Zap?
=A Press 'ENTER' to P-load EDITOR, FILER, VT2 & Put LIBRARY->RAM
7-FEB-85
12:00
M#45
2500
0
SYSVOL:AUTO1
```

NOTE that the operating system has been successfully loaded at this point. You are now in the Pascal 2.0 EDITOR. It is strongly recommended that you only change the date to today's date on this page and leave everything else as it is. The second line always shows the date when you made the last change on this line. YOU MAY CHOOSE NOT TO CHANGE ANYTHING AT ALL. In either case (date changed or unchanged).

HIT [Q] key.

(f) You should be prompted with the following page on the screen.

```
>Quit:
   Update the workfile and leave
   Exit without updating
   Return to the editor without updating
   Write to a file name and return
   Save as file new file SYSVOL:AUTOSTART
   Overwrite as file SYSVOL:AUTOSTART
```

HIT [E] key if you DID NOT make date change in step e.

HIT [O] key if you DID make date change in step e.

If you made date change in step e, you will be prompted with this message.

```
>Quit:
Writing..
Your file is 125 bytes long
Exit from or Return to the editor?
```

HIT [E] key.

(g) HP 9836 is now successfully setup and the following line should be shown on the top of the screen.

```
Command: Compiler Editor Filer Initialize Librarian Run eXecute Version?
```

TAKE Pascal 2.0 SYSVOL out of the left disc drive (unit#4).

TAKE Pascal 2.0 CMPASM out of the right disc drive (unit#3).

4. LOAD, COMPILE and EXECUTE the BSIM PARAMETER EXTRACTION PROGRAM

Once the system is setup according to what is described above, the program is ready to be loaded into the system, then compiled and executed. The complete text of the extraction program is stored on one disk under the file name "bsim.TEXT". The following describes the procedure need to be followed in loading, compiling and executing the extraction program. If you have the BSIM extraction program object code on a disk, skip step 1 and step 2 in the following procedure. If you do not have the BSIM extraction program object code on a disk, skip step 0 in the following procedure.

(0) LOAD THE CODE FILE INTO RAM

(A) **INSERT** the disk that contains the file bsim.CODE in the right disk drive.

CLOSE the disk drive's door.

(B) **HIT** [F] key to invoke FILER.

(C) **HIT** [F] key again to invoke FILECOPY.

(D) You should now be prompted with the following message

Filecopy what file?

TYPE #3:bsim.CODE

HIT [ENTER] key.

(E) The following message should appear below the prompting message in step D.

Filecopy to what?

TYPE RAM:bsim.CODE (Note that bsim.CODE can be any file name you would like the CODE file in RAM to be called followed by .CODE)

HIT [ENTER] key.

(F) The object code file is now in RAM. You are ready now to execute the BSIM extraction program.

SKIP step 1 and step 2.

(1) LOAD THE COMPLETE EXTRACTION PROGRAM INTO RAM

(A) **INSERT** the extraction program (bsim.TEXT) in the right disc drive (unit#3).

CLOSE both disc drive's door.

(B) **HIT** [F] key to invoke FILER.

(C) **HIT** [F] key again to invoke filecopy.

(D) You should now be prompted with the following message

Filecopy what file?

TYPE #3:bsim.TEXT (Note that bsim is in lower case letters)

HIT [ENTER] key.

(E) The following message should appear below the prompting message in step D.

Filecopy to what?

TYPE RAM:bsim.TEXT (Note that bsim.TEXT can be any file name you would like the complete text file to be named followed by .TEXT)

HIT [ENTER] key.

(F) The content stored on bsim.TEXT disc in the right disc drive is now being copied into RAM and stored under the file name bsim.TEXT. When the copying is completed, you will be prompted with the FILER command line at the top of the screen.

Filer: Change Get Ldir New Quit Remove Save Translate Vols What Access Udir?

HIT [Q] key.

(G) The main command line should now appear.

Command: Compiler Editor Filer Initialize Librarian Run eXecute Version?

(2) COMPILE THE EXTRACTION PROGRAM

You now have the program in the RAM ready to be compiled.

(A)**HIT** [C] key.

(B) You are prompted with this line

Compile what text?

TYPE bsim.TEXT (or your .TEXT file name)

HIT [ENTER] key.

Another line will appear.

Printer Listing (l/y/n/e)?

HIT [N] key.

Another line appears.

Output file (default is "RAM:bsim.CODE")?

HIT [ENTER] key for default (or TYPE any file name you like followed by .CODE).

(C) The program is now being compiled.

DO NOTHING until the main command line appears at the top of the screen again. THIS USUALLY TAKES A WHILE.

(D) When the main command line appears again, you now have the CODE file in your RAM along with your TEXT file. BSIM PARAMETER EXTRACTION PROGRAM is now ready to be executed.

(3) EXECUTE THE EXTRACTION PROGRAM

(A) **HIT** [X] key.

(B) You are prompted with the message.

Execute what file?

TYPE bsim.CODE

HIT [ENTER] key.

(C) The following message will appear on the screen

loading 'bsim.CODE'

followed by a screenful of BSIM MENU PAGE which is shown in Fig. A1

(D) **READ** the menu page. (if you wish)

ENTER the number of desired operation mode.

(E) Four different operation modes are provided. Operation selected depends on whether an automatic prober or a manual prober is used. The fifth operation mode gets you back to the main command level. >From this point on, different operation mode selected will prompt you differently. The following will describe different modes of operation separately.

Mode 1:
Fully Automatic

(see below)

Mode 2:
Semi Automatic -- [AUTOMATIC PROBER]

(see below)

Mode 3:
Semi Automatic -- [MANUAL PROBER]

Mode 1, 2, 3 have similar prompts from the program. In the following descriptions, if the program prompt (in italic letters) is preceded by '2', the prompt is displayed when running Mode 2 operation; if the program prompt is preceded by '3', it is displayed when running Mode 3 operation.

(a) Fig. A2 is displayed after the number key [1], [2] or [3] is pressed.

(b) **INPUT** all information requested. Output file can be defaulted to bsimout.TEXT. Prober File HAS TO BE in RAM. Section 6. describes how to load Prober File into RAM. Section 8 describes how to create prober files.

(c) **HIT** any key except [C] key to start measurements and extractions.

(d) Fig. A3 is now displayed.

OBSERVE CLOSELY the measurements displayed on HP 4145A screen.

Before the parameters are filled with values, you will be prompted with

Are the measurements satisfactory enough to proceed?(Y/N) >

HIT [Y] key to extract parameter values.

HIT [N] key if measurements are bad. You will be prompted with

Would you like to remeasure this device?(Y/N) >

HIT [Y] key, step d is repeated.

HIT [N] key, step e is skipped.

(e) If parameter values were extracted in step d, you will be prompted with

Are you interested in subthreshold measurements and extraction?(Y/N) >

HIT [Y] key for subthreshold measurements and extraction (n_0, n_B, n_D).

HIT [N] key, no subthreshold measurements are done.

(f) For Mode 1 skips this step.

For modes 2 and 3, you should be prompted with

Are probes on next device? If so, Press "ENTER" >

Move the probes to the next device and Press "ENTER"

MOVE the probes to the next device

HIT [ENTER] key.

(g) Step d, step e and step f are repeated until there is no more device on the die to be tested.

(h) For Mode 1 skips this step.

For modes 2 and 3, if there is no more die on the wafer to be characterized, skip this step. If there are still dies on the wafer to be characterized, you will be prompted with

Are probes on first device of next die? If so, Hit "ENTER" >

Move the probes to the first device of next die then hit 'ENTER'

MOVE the probes to the first device of next die.

HIT [ENTER] key.. Steps starting at d are repeated.

(i) You will now be prompted with

Would you like to view IV curves?(Y/N) >

HIT [N] key, BSIM MENU PAGE (Fig. A1) will appear. Skip the rest of the steps.

HIT [Y] key will bring you to the graphics mode. Fig. A4 will be displayed on the screen.

INPUT all information requested for your desired graph.

(j) Fig. A5 should now appear. After selecting your desired graph, you will be prompted with

New SMU connections?(Y/N)

HIT [Y] key will give you a chance to specify the SMU connection.

HIT [N] key, you will be given the connections you made last and you have a chance to make the right connections if they are not what the program thought they are.

(k) You should now be prompted with

Place probes on device and Press "ENTER"

PROBE the device you want to graph.

PRESS [ENTER] key.

(l) IV graphics actions are described in '4':SINGLE DEVICE mode step h.

(m) After you exit IV graphics routine, you will be prompted with

Would you like to view plots of BSIM PARAMETER vs W or L?(Y/N) >

If you have answered YES to the above question, you will now be prompted with Fig. A6.

READ instructions.

HIT the number key corresponding to desired device type.

(n) Fig. A7 should appear on the screen.

HIT the number key corresponding to desired graph.

ENTER length or width value if number 3 or 4 is selected.

(o) Fig. A8 should appear.

HIT the number key corresponding to the desired parameter to be graphed.

(p) You should be prompted with

Press 'c' to make change or press 'ENTER' >

HIT [C] key to change.

HIT [ENTER] key to continue.

(q) Requested graph is now displayed along with the selection menu shown in Fig. A9. Selections '1', '2' are explained when I-V Graphics is explained in SINGLE DEVICE operation. Selection '3]'brings Fig. A6 back onto the screen and steps h through k are repeated.

'4': SINGLE DEVICE

(a) Fig. A10 is displayed after the number key '4' is pressed.

(b) **INPUT** all information requested. Output File may be defaulted to bsimout.TEXT. SMU outlets are specified on the back panel of the HP 4145A.

(c) **HIT** any key except [C] key to start measurements and extractions.

(d) Fig. A3 is displayed on the screen. All parameter values will be filled once the extractions are done except n_0, n_B, n_D which are used for modeling the subthreshold conduction.

(e) When prompted with

Are you interested in subthreshold measurements and extraction?(Y/N) >

HIT [Y] key if interested.

HIT [N] key if not interested.

(f) If [Y] key was hit in step e, the remaining 3 parameter values will be filled after subthreshold region measurements and extractions are done. Otherwise, the 3 parameters will be left blanks.

(g) **DO NOTHING** until you see this message appeared at the bottom of the screen.

Would you like to view I-V curves?(Y/N)

HIT [Y] key if interested.

HIT [N] key if not interested. Skip the rest of the steps.

(h) Fig. A5 will be displayed.

ENTER information requested for graph desired.

HIT [ENTER] key when prompted by

Press "ENTER" to continue >

(i) **BE PATIENT** at this point. Measurements and calculations take time.

DO NOTHING until desired graph is displayed on the screen along with a selection menu of selections that may be made about the graph.

(j) 5 selections may be made about the graph selected (Fig. A11)

(1)**Zoom Using Knob and Keys:** Activated by hitting the number key can be moved horizontally by turning the knob which is located at the upper left corner of the HP 9836 keyboard. It can also be moved vertically by pressing the [SHIFT] key and turning the knob simultaneously. To zoom a portion of the current graph, a box which encloses the portion has to be defined. Move the cross hair to a point where one of the four corners is there to be, then hit [ENTER] key to define that corner. Move the cross hair horizontally and vertically to define the box and hit [ENTER] key again to zoom the portion contained in the box. Selection menu is then displayed again along with zoomed graph.

(2)**Redraw Full Graph:** Activated by hitting the number key '2'. When a portion of a graph has been zoomed, this option can get the full scaled graph back onto the screen again, as if no zooming has ever been done.

(3)**Select New Graph for Current Device:** Activated by hitting the number key '3'. Fig. A5 is displayed again. Steps h, i, j are repeated for the new graph.

(4)**Select New Device:** Activated by hitting the number key '4'. Fig. A4 is then displayed. This option is only meaningful when more than one device has been tested, i.e. when automatic or semi-automatic mode has been selected. Input all information requested by Fig. A4 about the device to be graphed. Steps select desired graph.

(5)**Exit I-V Graphics Menu:** Activated by hitting the number key displayed.

5. STORE PROCESS FILE ONTO A DISK

When the execution of the extraction program is completed, a process file is created in the RAM under the name you input for the prompt "output file >" when Fig. A2 was displayed. This process file has to be stored onto a disk before it can be transferred to VAX and used as input for SPICE simulation. This section describes the procedure to be followed.

(1) **INSERT** an initialized blank disk into the right disc drive (unit#3).

(2) **MAKE SURE** the main command line is displayed at the top of the screen.

HIT [F] key to invoke FILER.

HIT [F] key again to invoke Filecopy.

(3) You should be prompted with

Filecopy what file?

TYPE RAM:bsimout.TEXT (or whatever name you used for output file name)

HIT [ENTER] key.

(4) You should now be prompted with

Filecopy to what?

TYPE #3:bsimout.TEXT (or whatever you would like the file to be named on the disk)

HIT [ENTER] key.

(5) When the copying is done, you will see the FILER command line at the top of the screen and the following message beneath it.

RAM:bsimout.TEXT => V3:bsimout.TEXT (or V4:bsimout.TEXT)

NOTE that V3 or V4 is the disk directory name selected by the system. You may change the directory name by doing the following.

HIT [C] key.

You should be prompted by

Change what file?

TYPE V3: (or V4: depends on which one was shown)

HIT [ENTER] key.

You should be prompted by

Change to what?

TYPE any directory name followed by a colon (:); directory name should not exceed 5 characters.

HIT [ENTER] key.

The FILER command line should again appear at the top of the screen. To get back to the main command level

HIT [Q] key.

6. LOAD PROBER FILE INTO RAM

(1) **INSERT** the disk containing the prober file in the right disk drive (unit#3).

(2) **MAKE SURE** that you are at the main command level.

HIT [F] key to invoke FILER.

HIT [F] key again to invoke Filecopy.

(3) You should be prompted by

Filecopy what file?

TYPE #3:probe.TEXT (or the name of the prober file stored on the disk)

(4) You should now be prompted by

Filecopy to what?

TYPE RAM:probe.TEXT (or any name you would like to name the file)

HIT [ENTER] key.

(5) When the loading is completed, the FILER command line should appear at the top of the screen. And now you have the prober file in RAM ready to be used.

7. LINK HP9836 to VAX

A) To transfer file to the VAX, the RS232 Data Communication Board must be in the back of the HP9836, and it must be connected to a port selector or a modem.

B) **INSERT** the Pascal VT2 Disc in the right Disc Drive.

C) Return to the main command line of the operating system.

D) **PRESS** [P] {this selects the permanent load operating system option.}
Load what code file ? **#3:NEWKBD**

E) **PRESS** [X]
Execute what file? **#3:VT2**

F) When the program is loaded, a menu will appear, and the user must load in the configuration as follows:

Main> **4** {option to creat a configuration}
Selection? **1** {VAX/UNIX}
Rate? **9600** {baud rate}
Selection? **3** {modem}
Main> **1** {go to emulator mode}

G) **PRESS** the port selector switch, and log into a VAX account as using normal procedures. The terminal type is 2648. To perform file transfer, **PRESS** CTRL and EXECUTE at the same time. This returns the program to an execution menu.

Execute> **3** {file transfer to host}
Enter host file name: **Your VAX FILE NAME**
Enter local file name: **A name like RAM:bsimout.TEXT**

Multiple files can be transferred, or the HP9836 can be used as a VAX terminal. To xit the program, select the terminate emulator option.

8. INSTRUCTIONS FOR CREATING PROBER FILES

An automatic prober file should be constructed exactly as follows. All comments are surrounded by parenthesis, while all lines should begin at the left margin, and no blank lines should be present.

```
8200                  {The x-direction die size dimension in microns}
8200                  {The y-direction die size dimension in microns}
00000000000000000000  {the first two lines should be  omitted  when }
00000000000000000000  {using Mode 3 ( semi-automatic with manual }
00000000000000000000  {probe station}
00000000000000000000
00000010000010000000
000X0000000000000000
00000000000000000000  {This is the 20 by 20 array to designate the}
10000100000100000000  {die which are to be tested. All locations}
00000000000000000000  {marked with a "1" will be probed, and the}
00000000000000000000  {location marked with "X" is the origin die}
00000001000000010000
00000000000000000000  {The upper left corner of the array represents}
00000000000000000000  {location(1,1), and the x-values increase towards}
10000000001000000000  {the right, while the y-values increase towards}
00000000000000000000  {the bottom}
00001000000100000000
00000000000000000000  {In this example, the origin is (4,6)}
00000000000000000000
00000000000000000000
10000000010000000000
**               {Device to device delimiters}
mx=800            {Distance in x-direction from die origin to device}
my=920            {Distance in y-direction from die origin to device}
w=50             {Width of device #1 in microns}
l=1              {Length of device #1 in microns}
dt=1             {Device #1 is a NMOS device}
ed=1             {Device #1 is an enhancement device}
sd=1             {Drain of device #1 is connected to SMU 1}
sg=2             {Gate of device #1 is connected to SMU 2}
ss=3             {Source of device #1 is connected to SMU 3}
sb=4             {Substrate of device #1 is connected to SMU 4}
**
{Values for the next device are listed here, if multiple devices will be analyzed.}
{The last line of the prober file must be "**"}
{The devices can be in any order, and all device descriptions such as "mx=800"}
{can be in any arbitrary sequence, as long as they are all included}
```

Acceptable device description values are:

mx,my	{in microns}
w,l	{in microns}
dt	{1=NMOS, -1=PMOS}
ed	{1=enhancement, 0=zero-threshold, and -1=depletion}
sd,sg,ss,sb	{any value from 1 to 4 which is not the value of} {any one of the remaining three}

IV. EXTRACTION THEORY AND ALGORITHM

IV.1 MEASUREMENT ROUTINE

The measurement routine of the extraction program is composed of three parts: device type test, device functionality test, and drain-current measurement for parameter extraction. It is important to find out the abnormal electrical behaviors of the device-under-test either due to improper probing or device defects before useful data can be stored. This can save valuable testing time and help eliminating faulty devices, which may cause large errors in the process files developed. The program employs the user specified maximum voltage (V_{DD}) to set up the HP4145, prior to parameter extraction, for checking error conditions and determining device type and functionality.

1. Device-Type Test

In an MOS transistor, there are p-n junctions between source/drain and the substrate. The polarity of p-n junctions is used to determine the device type. The initial HP4145 measurement setup analyzes the source/drain-to-body junctions and checks for possible short-circuits between the gate and other terminals. In the test, the source and drain are connected to the ground, and the gate is connected to V_{DD}. Two voltages ($+V_{DD}$ and $-V_{DD}$) are applied to the substrate successively. Substrate currents (I_{Bpos} and I_{Bneg}) and gate currents (I_{Gpos} and I_{Gneg}) corresponding to these two substrate biases are measured. Bias conditions for an NMOS device in this test is shown in Fig. 6(a). A sample of the test results displayed on HP4145 in shown in Fig. 6(b). Notice that the gate potential is set at a different level with the source, drain and substrate. Any short-circuit between the gate and any of the other terminals can be detected. To find out the polarity of the source/drain-body junctions, I_{Bpos} and I_{Bneg} are compared to some pre-determined current level (e.g. 10 μA). A list of all possible results are summarized below.

(1) If $I_{Bpos} > 10\mu A$ and $I_{Bneg} < 10\mu A$, then the device is an N-channel device.

(2) If $I_{Bpos} < 10\mu A$ and $I_{Bneg} > 10\mu A$, then the device is a P-channel device.

(3) If both I_{Bpos} and I_{Bneg} are less than $10\mu A$, then it is open-circuited between the source/drain and the substrate.

(4) If both I_{Bpos} and I_{Bneg} are larger than $10\ \mu A$, then it is short-circuited between the source/drain and the substrate. (Note: because of this test, devices with butting source and substrate contact will be rejected.)

(5) If either I_{Gpos} or I_{Gneg} is larger than $0.1\mu A$, then the quality of the gate oxide is not within the acceptable range.

Should any error occurs, the program will pause and wait for user's action. The user can readjust the probes or skip the present device according to the error message. The reference current levels used to judge device behaviors are set for the purpose of detecting obvious shorts and are not intended for screening junction or gate leakage currents. For devices with large leakage currents and/or high noise level, these reference levels should be changed accordingly.

2. Device-Functionality Test

If no error is detected in the Device-Type-Test procedure, the device type determined in the previous step is used to set up HP4145 in determining the device functionality. The test principle is based on the relationship between the drain saturation current and the gate voltage. The source is set to ground potential. The drain voltage is set to V_{DD}. The gate is set to 0 V and V_{DD}. For a P-channel device, the polarity of the voltages are reversed accordingly. Two drain current values, I_{DS0} and I_{DSVDD}, corresponding to the two gate voltages are measured. The bias condition for an NMOS transistor in this test is illustrated in Fig. 7(a). A sample of the test results is shown in Fig. 7(b). Syndromes are listed below.

(1) If $I_{DS0} > 0.95 I_{DSVDD}$, it indicates a short circuit between the source and drain.

(2) If $I_{DS0} < 10(W_{MK}/ L_{MK}) \mu A$, it indicates an open circuit between the source and the drain.

(3) Otherwise, the device is functional.

where W_{MK} and L_{MK} denote the mask-level channel width and length, respectively. If an error occurs, the program will pause and wait for the user's action as in last procedure.

3. Device Measurements for Parameter Extraction

If the device is functional, HP4145 is set to measure I_{DS}-V_{GS} data with V_{BS} as the Z-axis variable. V_{GS} is chosen to increase from 0 to V_{DD} with voltage steps ranging from 0.05 to 0.5 volt depending on the magnitude of V_{DD} (V_{Gstep} = 0.05 V for $V_{DD} \leqslant 3V$, V_{Gstep} = 0.1 V for $V_{DD} \leqslant 5V$, V_{Gstep} = 0.2 V for $V_{DD} \leqslant$ 10 V, V_{Gstep} = 0.5 V for $V_{DD} \geqslant 10$ V) V_{BS} is equally spaced between 0 and V_{DD}. V_{DS} is biased at five values: 0.1, 0.2, $0.4V_{DD}$, $0.9V_{DD}$, and V_{DD}. Data with V_{DS}=0.1 and 0.2 are used to extract linear-region parameters. The data with $V_{DS} = 0.9V_{DD}$ and V_{DD} are used to extract saturation-region parameters. After the 17 strong-inversion parameter values are extracted, the data with $V_{DS} = 0.4V_{DD}$ are used to refine them. This refinement procedure improves the extracted parameter set. At each V_{DS} bias, thirty I_{DS} values corresponding to five equally spaced V_{GS} between the threshold voltage and V_{DD}, and six V_{BS} values are measured. They are stored in a three-dimensional array, and are passed to the extraction routine for parameter extraction.

The first V_{GS} value of the five equally-spaced biases is selected to be 5 V_{Gstep} above the threshold. This is to ensure that none of the stored I_{DS} data is in the subthreshold region. Depending on the fabrication process and bias conditions, the threshold voltage of MOS transistors may widely distributed below V_{DD}. A threshold current level is used to determine the approximate threshold voltage. The threshold current is set to be

$$I_{threshold} = 0.1 \frac{W_{MK}}{L_{MK}} \mu A \qquad \text{for} V_{DS} = 0.1 \text{ and } 0.2 \text{ volt} \tag{19}$$

$$I_{threshold} = 0.1 \left(\frac{V_{DS}}{0.1}\right)^{1/2} \frac{W_{MK}}{L_{MK}} \mu A \qquad \text{for } V_{DS} = 0.4V_{DD}, 0.9V_{DD} \text{ and } V_{DD} \tag{20}$$

During the measurement, $I_{DS}-V_{GS}$ curves are displayed on the screen of HP4145. If the user does not satisfy the quality of measured data, re-measurement of the device is possible at the end of each measurement. A typical display on the screen of HP4145 during the measurement is shown in Fig. 8.

4. Measurement for Subthreshold Parameter Extraction

After the 17 strong-inversion parameters have been extracted, the user has the option to extract subthreshold parameters. The setup of HP4145 for subthreshold measurement is the same as that for strong inversion except that V_{GS} scans from V_{th} - 0.5 to V_{th} - $3V_{tm}$ and y-axis scale is set to be logarithmic rather than linear, where $V_{tm} \equiv kT/q$, V_{th} is calculated from the strong inversion parameters just extracted. The gate bias range is selected to be such that the device is operating in the subthreshold region, and the measured drain current is above noise level. Since threshold voltages are different for different drain and substrate biases, HP4145 has to be set up again every time V_{DS} or V_{BS} changes. The subthreshold swing coefficient n for five drain biases and six substrate biases are calculated from the measured subthreshold current in this routine and stored in an array named "npar". The subthreshold swing coefficient n is calculated according to the following equation.

$$n = \frac{1}{V_{tm} \ln(10)} S \tag{21}$$

where S is the subthreshold swing defined by

$$S = \ln(10) \frac{dV_{GS}}{d[\ln(I_{DS})]} \tag{22}$$

A typical log(I_{DS}) vs. V_{GS} curve is shown in Fig. 9. The slope of the transistor characteristics in the subthreshold region is the subthreshold swing S.

IV.2 PARAMETER EXTRACTION

This routine is the most sophisticated portion of the BSIM parameter extraction program. It uses the I_{DS}–V_{GS} data stored in the measurement routine to extract all the 20 BSIM parameters. The extraction routine can be divided into four parts: linear-region analysis, saturation-region analysis, parameter refinement, and subthreshold parameter extraction. Local optimizations are performed by a combination of Newton-Raphson and Linear-Least-Square algorithms to achieve fast convergence.

5. Linear-Region Analysis

In this part, six parameters are extracted, namely, V_{FB}, ϕ_{2f}, K_1, K_2, U_0, and x2u0. The data used in this procedure are I_{DS} values stored in the measurement routine corresponding to V_{DS} = 0.1 and 0.2 V.

(a) Procedure "Linear-Region-Extraction"

This procedure calculates β, V_{th} and U_0 in the linear region. Since the smallest V_{GS} was chosen to be 5 V_{Gstep} above the threshold level, the drain current characteristics can be expressed as

$$I_{DS} = \frac{\beta}{1 + U_0 (V_{GS} - V_{th})} (V_{GS} - V_{th} - \frac{a}{2} V_{DS}) V_{DS} \tag{3}$$

where a is given by Eq. (5). Eq. (3) can be rewritten as:

$$f(\beta, V_{th}, U_0) = \frac{G + G\, U_0 (V_{GS} - V_{th})}{V_{GS} - V_{th} - \frac{a}{2} V_{DS}} - \beta = 0 \tag{23}$$

where $G \equiv I_{DS}/ V_{GS}$. By taking the total derivative, Eq. (23) becomes

$$f(\beta, V_{th}, U_0) = \Delta\beta - \frac{\partial f}{\partial V_{th}} \Delta V_{th} - \frac{\partial f}{\partial U_0} \Delta U_0 \tag{24}$$

where

$$\frac{\partial f(x)}{\partial V_{th}} = \frac{G(1 + U_0 \frac{a}{2} V_{DS})}{(V_{GS} - V_{th} - \frac{a}{2} V_{DS})^2} \tag{25}$$

$$\frac{\partial f(x)}{\partial U_0} = \frac{G(V_{GS} - V_{th})}{V_{GS} - V_{th} - \frac{a}{2} V_{DS}} \tag{26}$$

Eq. (24) is used in Newton-Raphson's iteration.

To solve Eq. (24), initial values of β, U_0 and V_{th} have to be calculated first. A typical curve for $G - V_{GS}$ in the linear region is shown in Fig. 10. For low V_{GS} values, Eq. (22) can be simplified to Eq. (27)

$$G \approx \beta(V_{GS} - V_{th}) \equiv \text{const} + \text{linear} * V_{GS} \tag{27}$$

Therefore, the intercept of the curve with the x-axis is a good approximation to the threshold voltage and the slope at the intercept is also a good approximation to β. The initial values of V_{th} and β for Newton-Raphson's iteration can then be obtained by fitting the drain currents at low V_{GS} into Eq. (27). The program uses three stored I_{DS} data corresponding to the first three lower V_{GS} values to do the initial estimates for each substrate bias. After the Linear-Least-Square fit, the initial value of β is equal to "linear" , while the initial value of V_{th} is equal to "-const/linear".

Rearranging Eq. (3) again, we can write

$$\frac{V_{GS} - V_{th} - \frac{a}{2} V_{DS}}{G} = \frac{1}{\beta} + \frac{U_0(V_{GS} - V_{th})}{\beta} \equiv \text{const} + \text{linear} * V_{GS} \tag{28}$$

By applying Linear-Least-Square algorithm to Eq. (28) again at large V_{GS} values, the initial estimate of U_0 can be set to "linear/const". Since the exact value of a is unknown for the time being, an approximate value of a (corresponding to Nsub = 1.0E16) is used. This is a very good approximation, because the value of a V_{DS} is usually much smaller than V_{GS} values in the linear region.

By solving Eq. (24), the updated values of β, U_0 and V_{th} can be obtained. A combination of Linear-Least-Square algorithm with three variables and Newton-Raphson's algorithm is used to solve Eq. (24). The Linear-Least-Square algorithm is used to determine the increments of the variables and evaluate new partial derivatives for the next Newton-Raphson's iteration. At the end of each iteration, a test is made to detect whether convergence has been reached. The convergence criterion scales with accuracy requirements. When either convergence is reached or the maximum allowable number of iteration is encountered, the iteration will be terminated and the final values of β, V_{th}, and U_0 are stored in two-dimensional arrays corresponding to different drain and substrate biases. If the maximum number of iteration is encountered, a warning message "**WARNING: NEWTON-RAPHSON'S ITERATION DOES NOT CONVERGE**" will be displayed on the screen.

The low-field conductance coefficient β_0 can be calculated from extracted β values using Eq. (4). This is done in the "saturation_region_data_reduction procedure" where the parameter U_1 is extracted.

To help the convergence of Newton-Raphson's iteration process, the value of U_0 is limited to be within 0 and 3, the value of β is limited to be less than 0.05, and the value of V_{th} is limited to be less than V_{DD} during the iteration. These limits are based on practical considerations of MOS transistor behaviors over a wide range of device dimensions. The maximum number of iteration is set to be 15 in this procedure.

(b) Extraction of Surface Potential (phif2)

The name of this procedure in the extraction program is "large_device_20f_extraction" which is mutually exclusive with another similar procedure named "linear_region_threshold_analysis". Only one of these two procedures will be called during extraction. The parameter 2phif is a direct measure of the effective channel doping concentration, and its accurate determination is essential for process analysis. Therefore two procedures were used in the extraction program to achieve high accuracy. The threshold voltage extracted in the last procedure for different substrate biases are used to extract another three parameters, K_1, K_2, and V_{FB}. The only difference between procedures "large_device_20f_extraction" and "linear_region_threshold_analysis" is that in the former procedure, the parameter phif2 is extracted from measured data, while in the latter procedure, it uses the values of phif2 of the largest devices previously measured.

The relationship between body-effect coefficient K_1, channel-doping concentration N_a, and surface potential are given by the following equations.

$$N_a = n_i \exp\left(\frac{\phi_{2f}}{2V_{tm}} \right) \tag{29}$$

$$K_1 = s \, \frac{2\, q\, \epsilon\, N_a{}^{\frac{1}{2}}}{C_{ox}} \tag{30}$$

where s is the geometry factor given by

$$s = 1 + \frac{L_{K_1}}{L_{MK} - \Delta L} + \frac{W_{K_1}}{W_{MK} - \Delta W} \tag{31}$$

L_{K_1} and W_{K_1} are parameters derived from process files of previous dies. The value of s is approximately equal to unity for devices with large W_{MK} and L_{MK}. Therefore, the most accurate value of ϕ_{2f} is obtained from the largest device on each die. The rest of the devices should use the the value of ϕ_{2f} extracted from the largest device on that die. For the first die measured on a chip, no process file is available, the value of s defaults to one. For all subsequent dies, the geometry factor s is evaluated from Eq. (31), and can be used to derive a more accurate value of ϕ_{2f} for the largest device on the die.

For the single device operation mode, only procedure "linear_region_threshold_analysis" will be called, since the value of ϕ_{2f} is specified by the user in the initial input page. For fully automatic operation mode (Mode 1), the largest device of each device type will be switched automatically to the first test device. Hence, the procedure "large_device_20f_extraction" will be called only once for each device type, i.e. the first measured device of each device type on each die. For the rest of devices on the die, procedure "linear_region_threshold_analysis" is called and the value of ϕ_{2f} from the first device is used. For semi-automatic operation modes (Mode 2 and 3), the first device measured is not necessarily the largest device. In this case, the parameter ϕ_{2f} is extracted from the first device and used by other devices until the largest device is encountered, then a new ϕ_{2f} is extracted again from the largest device and used throughout the rest of devices on the die. Therefore, the procedure "large_device_20f_extraction" will be called twice if the first test device is not the largest device on the die. This causes slight inconsistency in evaluating K_1, K_2 and V_{FB}. Therefore, it is recommended that the largest device be always included at the top of the device list in the probe file.

The extraction theory in this procedure is based on Eq. (1).

$$f(x) \equiv V_{th} = (V_{FB} - \eta * V_{DS}) + \phi_{2f} + K_1 * \sqrt{\phi_{2f} + V_{BS}} - K_2 * (\phi_{2f} - V_{BS}) \qquad (1)$$

A combination of Newton-Raphson and Linear-Least-Square algorithms are used to obtain the updated parameter values. The equation used in Newton-Raphson's iteration is

$$V_{th} - f(x) = \frac{\partial f(x)}{\partial \phi_{2f}} \Delta\phi_{2f} \qquad (32)$$

where

$$\frac{\partial f(x)}{\partial \phi_{2f}} = 1 - K_2 + \frac{K_1}{2\sqrt{\phi_{2f} - V_{BS}}} + \frac{K_1\sqrt{\phi_{2f}}}{4V_{tm}} \qquad (33)$$

Substituting Eq. (1) and (33) into Eq. (32), we have

$$V_{th} - \phi_{2f} - K_1 \sqrt{\phi_{2f} - V_{BS}} = (V_{FB} - \eta\, V_{DS}) + (1 - K_2 + \frac{K_1}{2\sqrt{\phi_{2f} - V_{BS}}} + \frac{K_1\sqrt{\phi_{2f}}}{4V_{tm}}) \Delta\phi_{2f} + (\phi_{2f} - V_{BS}) K_2 \qquad (34)$$

By applying Linear-Least-Square algorithm to Eq. (34) with $\Delta\phi_{2f}$ and K_2 as variables, the values of K_1, K_2, ϕ_{2f}, and $V_{FB} - \eta * V_{DS}$ for the next iteration can be calculated. The final values of these parameters for two different drain biases are stored in arrays for future analysis. Again, a convergence test is performed at the end of each iteration. If the maximum iteration number (15) is reached, a warning message will be displayed on the screen.

(c) Linear Region Threshold Analysis

Except the largest and/or the first device, this procedure is usually called to extract K_1, K_2, V_{FB}. No iteration is needed in this procedure. Therefore, is easier and faster. K_1, K_2, and $V_{FB} - \eta V_{DS}$ are calculated by applying Linear-Least-Square algorithm to Eq. (35) over the range of measured substrate biases for two low V_{DS} values with $\sqrt{\phi_{2f} - V_{BS}}$ and $-(\phi_{2f} - V_{BS})$ as variables. ϕ_{2f} is obtained from the largest device.

$$V_{th} - \phi_{2f} = (V_{FB} - \eta V_{DS}) + (\sqrt{\phi_{2f}}) K_1 - (\phi_{2f} - V_{BS}) K_2 \tag{35}$$

(d) Linear-Region Data Reduction and Linear-Region Parameter Validity Check

All the linear-region parameters calculated previously except β are analyzed in this procedure to separate the parameter dependencies on substrate and drain biases. Linear-Least-Square algorithm is applied to the following equations to extract the seven parameters.

$$U_0(V_{DS},V_{BS}) = u0 + x2u0\, V_{BS} + x3u0\, V_{DS} \tag{36}$$
$$V_{FB}(V_{DS}) = V_{FB} + \eta V_{DS} \tag{37}$$
$$\phi_{2f}(V_{DS}) = \phi_{2f} + (\text{discarded term})\, V_{DS} \tag{38}$$
$$K_1(V_{DS}) = K_1 + (\text{discarded term})\, V_{DS} \tag{39}$$
$$K_2(V_{DS}) = K_2 + (\text{discarded term})\, V_{DS} \tag{40}$$

x3u0 in Eq. (36) is not saved as a parameter, but is used to help obtaining u0 and x2u0. The value of η calculated in Eq. (37) is discarded. More accurate values of η are obtained in the saturation region analysis which will be discussed later.

After parameters V_{FB}, ϕ_{2f}, K_1, K_2, u0, and x2u0 have been calculated, they are checked against certain bounds. If any of these parameters is not within the bounds, all the parameters will not be saved and the program skip to the next device. Also, an error message will be displayed on the screen to notify the user.

The bounds of the linear region parameters are listed below:

$-5.0 \leqslant V_{FB} \leqslant 1.0$

$0.2 \leqslant \phi_{2f} \leqslant 1.5$

$0 \leqslant K_1 \leqslant 5.0$

$-1.0 \leqslant K_2 \leqslant 1.0$

$-2.0 \leqslant u0 \leqslant 2.0$

$-2.0 \leqslant x2u0 \leqslant 2.0$

6. Saturation-Region Data Analysis

(a) Saturation-Region Analysis

The I_{DS} data measured corresponding to $V_{DS} = 0.9V_{DD}$ and $V_{DS} = V_{DD}$ are used to determine U_1, β, and V_{th} in the saturation region. Calculations are based on Eq. (3) and (4)

$$I_{DS} = \frac{\beta}{(1 + U_1 * V_{DS})} (V_{GS} - V_{th} - \frac{a}{2} V_{DS}) V_{DS} \tag{3}$$

$$I_{Dsat} = \frac{\beta (V_{GS} - V_{th})^2}{2 a K} \tag{4}$$

Expressions of β, a and K are referred to Eq. (4), (6) and (8). An equation suitable for the Newton-Raphson's algorithm can be obtained by differentiating Eq. (3) or (4).

$$I_{DSmeas} - I_{DSsim} = \frac{\partial I_{DSsim}}{\partial \beta_0} \Delta\beta_0 + \frac{\partial I_{DSsim}}{\partial V_{th}} \Delta V_{th} + \frac{\partial I_{DSsim}}{\partial U_1} \Delta U_1 \tag{41}$$

where I_{DSsim} represents the calculated drain current, I_{DSmeas} represents the measured data.

A combination of Newton-Raphson algorithm and Linear-Least-Square algorithm is used to solve Eq. (41). The initial values of β_0 and V_{th} in this procedure is calculated from the linear-region parameters with $V_{DS} = 0.2$ V. The initial value of U_1 is set to zero.

For depletion-mode devices, the drain saturation voltage can be as large as V_{DD}. As a result, the transistor may not operate in the saturation region within the bias range. Therefore, in each iteration, the drain saturation voltage is calculated and compared with the drain voltage to determine which equation for the drain current should be used.

If $V_{dsat} \geqslant V_{DS}$, the transistor is operated in the linear region. Then,

$$I_{DSsim} = I_{DS}. \tag{42}$$

$$\frac{\partial I_{DSsim}}{\partial \beta_0} = \frac{I_{DSsim}}{\beta_0} \tag{43}$$

$$\frac{\partial I_{DSsim}}{\partial V_{th}} = \frac{I_{DSsim}\, U_0}{(1 + U_0 V_{GS})} - \frac{\beta_0 V_{DS}}{[1 + U_0 (V_{GS} - V_{th})](1 + U_1 V_{DS})} \tag{44}$$

$$\frac{\partial I_{DSsim}}{\partial U_1} = -\frac{I_{DSsim}\, V_{DS}}{1 + U_1 V_{DS}} \tag{45}$$

If $V_{dsat} \geqslant V_{DS}$, the transistor is operated in the saturation region. Then,

$$I_{DSsim} = I_{Dsat} \tag{46}$$

$$\frac{\partial I_{DSsim}}{\partial \beta_0} = \frac{I_{DSsim}}{\beta_0} \tag{47}$$

$$\frac{\partial I_{DSsim}}{\partial V_{th}} = \frac{I_{DSsim}\, U_1 T}{a[1 + U_0 (V_{GS} - V_{th})]} + \frac{I_{DSsim}\, U_1 T}{a K} - \frac{\beta_0 (V_{GS} - V_{th})}{a K [1 + U_0 (V_{GS} - V_{th})]} \tag{48}$$

$$\frac{\partial I_{DSsim}}{\partial U_1} = \frac{I_{DSsim} (V_{GS} - V_{th}) T}{a K} \tag{49}$$

$$T = 0.5 + \frac{0.5}{\sqrt{1 + 2 V_c}} \tag{50}$$

$$V_c = \frac{U_1 (V_{GS} - V_{th})}{a} \tag{51}$$

During each iteration, the value of U_1 is limited to be between 0 and 3, and the value of β_0 at $V_{DS} = V_{DD} - 0.5$ is set to not exceed the value of β_0 at $V_{DS} = V_{DD}$. After each iteration, a convergence test is performed to determine whether the required accuracy is observed. If the maximum number of iteration is reached, a warning will be displayed on the screen. After the threshold voltage in the saturation region is obtained, the parameter η is calculated through the use of the following equation:

$$\eta(V_{DS}, V_{BS}) = \frac{[V_{FB} + \phi_{2f} + K_1 \sqrt{\phi_{2f} - V_{BS}} - K_2 (\phi_{2f} - V_{BS})] - V_{th}(V_{DS}, V_{BS})}{V_{DS}} \tag{52}$$

The final values of β_0, η, and U_1 corresponding to various V_{BS} and V_{DS} biases are stored in arrays for further analysis.

(b) Saturation-Region Extraction for Long-Channel Devices

For long-channel devices, U_1 becomes extremely small. During the iteration, if U_1 is less than 10^{-7} U_1 is set to zero and this procedure is called. The name of this procedure is "zero_u1_saturation_extraction". This procedure will extract β_0 and V_{th} values through the use of an equation similar to Eq. (41), but with U_1 terms and U_1 derivatives eliminated. This special procedure is necessary, because the final values of β_0 and V_{th} calculated from the original procedure may not be optimal when U_1 approaches zero. This procedure performs Linear-Least-Square Fit with two variables only. The maximum number of iteration in this procedure is 12.

(c) Saturation-Region Data Reduction and Parameter Validity Check

The dependencies of parameters, U_1, η, and β_0 on the drain and substrate biases are calculated in this procedure. Linear-Least-Square algorithm with two or three variables are used to extract the bias dependencies.

U_1 is modeled as

$$U_1(V_{DS},V_{BS}) = u1 + x2u1\ V_{BS} + x3u1\ (\ V_{DS} - V_{DD}\ ) \tag{53}$$

$\eta(V_{DS},V_{BS})$ is obtained from Eq. (52).

$$\eta(V_{DS},V_{BS}) = eta0 + x2eta\ (\ \phi_{2f} - V_{BS}\ ) + x3eta\ (\ V_{DS} - V_{DD}\ ) \tag{54}$$

The values of β_0 at low V_{DS} are calculated by Eq. (55).

$$\beta_0(V_{DS},V_{BS}) = \beta(V_{DS},V_{BS})\ [\ 1 + (\ u1 + x2u1\ V_{BS}\ )\ V_{DS}\ ] \tag{55}$$

Finally, β_0 in the linear region is model as

$$\beta_0(V_{DS},V_{BS}) = beta0 + x2beta0\ V_{BS} + (\ \text{discarded term}\ )\ V_{DS} \tag{56}$$

β_0 in the saturation region is modeled as

$$\beta_0(V_{DS},V_{BS}) = \text{beta0sat} + \text{x2beta0sat} * V_{BS} + \text{x3beta0sat} * (V_{DS} - V_{DD}) \qquad (57)$$

7. Saturation-Region Parameter Refinement

For very short-channel devices, substrate current becomes appreciable at large drain voltages. The extracted parameters from measured data for saturation analysis may not be correct throughout the drain voltage operating range due to the substrate current component in the measured data. Without this procedure, what usually happens for very short-channel devices is that the calculated drain currents match very well at small and large drain voltages, but introduce large errors at intermediate drain voltage values. This is because local optimization was used only at low and high V_{DS} values. This procedure uses the $I_{DS}-V_{GS}$ data measured at $V_{DS} = 0.4V_{DD}$ to iterate ten times with the parameters obtained in previous iteration. This guarantees the validity of the parameters for the full drain bias range.

The procedure consists of two parts. The first part corrects the U_1 parameters. The second part corrects the β_0 parameters. All other parameters are unchanged.

(a) U_1 refinement

By solving Eq. (3) and (4), U_1 in the linear region and saturation region are given by Eq. (58) and (59), respectively.

$$U_1(\text{linear}) = \frac{1}{V_{DS}} \left\{ \frac{\beta_0[\,(V_{GS} - V_{th})\,V_{DS} - \frac{a}{2}\,V_{DS}^2\,]}{I_{DS}[\,1 + U_0\,(V_{GS} - V_{th})\,]} - 1 \right\} \qquad (58)$$

$$U_1(\text{sat}) = \frac{2\,a\,(\,\alpha - \sqrt{\alpha}\,)}{V_{GS} - V_{th}} \qquad (59)$$

where

$$\alpha = \frac{\beta_0\,(\,V_{GS} - V_{th}\,)^2}{2\,a\,I_{DS}[\,1 + U_0\,(\,V_{GS} - V_{th}\,)\,]} \qquad (60)$$

New U_1 values are obtained from Eq. (54) and (55) for various gate and substrate biases.

The drain saturation voltages corresponding to the two new U_1 values are also calculated using Eq. (8) to determine which value of U_1 should be used for the corresponding data. Linear-Least-Square algorithm is then applied to extract new values of u1, x2u1 and x3u1.

(b) β_0 refinement

With the new U_1 parameter values calculated in (a), β_0 values of the linear region have to be corrected again with the new U_1 value.

$$\beta_0(V_{DS},V_{BS}) = \beta(V_{DS},V_{BS})\,(\,1 + U_1\,V_{DS}\,) \qquad (55)$$

β_0 values in the saturation region can be obtained by solving Eq. (4).

$$\beta_0(V_{DS},V_{BS}) = \frac{2\,a\,K\,I_{DS}}{(\,V_{GS} - V_{th}\,)^2} \qquad (61)$$

By applying Linear-Least-Square algorithm to β_0 for both the linear and saturation regions, new values for all five β_0-related parameters can be obtained.

Up to this point, the seventeen strong-inversion BSIM parameters have been extracted. The twelve parameters obtained in the saturation-region are compared with some pre-determined limits to warrant their validities. These limiting values are:

$-1.0 \leqslant$ eta $\leqslant 1.0$

$0 \leqslant$ beta0 $\leqslant 1.0$

$-1.0 \leqslant$ u1 $\leqslant 5.0$

$-1.0 \leqslant$ x2beta0 $\leqslant 1.0$

$-1.0 \leqslant$ x2eta $\leqslant 1.0$

$-1.0 \leqslant$ x3eta $\leqslant 1.0$

$-1.0 \leqslant$ x2u1 $\leqslant 1.0$

$0 \leqslant$ beta0sat $\leqslant 1.0$

$-1.0 \leqslant$ x2beta0sat $\leqslant 1.0$

$-1.0 \leqslant$ x3beta0sat $\leqslant 1.0$

$-1.0 \leqslant x3u1 \leqslant 1.0$

8. Subthrshold Parameters Extraction

This procedure is called only when the user have selected the option of subthreshold measurement. The BSIM subthreshold current expression is given in Eq. (16). Measured results of the subthreshold swing coefficient n for different substrate and drain biases have been stored in an array named "npar" during subthreshold current measurements. Three subthreshold parameters can be obtained by fitting the results into Eq. (17) through the use of Linear-Square-algorithm.

$$npar(V_{DS}, V_{BS}) = n_0 + n_D\, V_{BS} + n_D\, V_{DS} \qquad (17)$$

IV.3 PROCESS FILE DEVELOPMENT

After the 20 BSIM parameters have been calculated for each device, they, together with the mask length and width, are stored in a temporary file corresponding to the device type. Six temporary files are created for each device type at the begining of a new die measurement. These temporary files are:

NEDFILE (for NMOS enhancement devices)

NZDFILE (for NMOS zero-threshold devices)

NDDFILE (for NMOS depletion mode devices)

PEDFILE (for PMOS enhancement devices)

PZDFILE (for PMOS zero-threshold devices)

PDDFILE (for PMOS depletion mode devices)

If a file by any of these names exists on the prefixed directory, it will be overwritten after the execution of the extraction program. These files will be purged when the program is normally exited by the user. If the program is abnormally terminated for some reasons, the stored BSIM parameters for already measured devices are still retained in these files. When the testing of all devices on a die is complete, process files for every device type analyzed on that given die are generated from these six temporary files. These temporary files are also used to generate parameter vs. W & L plots. The minimum number of devices for each device type required to generate a process file is 3. The process file consists of 29 lines. A sample of the process file is shown at the end of this chapter. The first line of the process file indicates the device type and process file number which will be referred by SPICE. For example: NM1 may represents NMOS enhancement devices process file No. 1. Line 2 to 8 are just for user's reference and have no effect on the calculated results. Line 9 to 28 are the calculated 60 BSIM process file parameters. These 60 parameters are size-independent. A description of the order of these parameters can be found in [3]. Except the sixth parameter line (line 13 of the process file, which is beta0 parameter), these size-independent parameters are generated by applying Linear Least Square algorithm with three variables to Eq. (62).

$$P_i = P_0 + \frac{P_L}{L_{MK} - \Delta L} + \frac{P_W}{W_{MK} - \Delta W} \tag{62}$$

where ΔW and ΔL account for any process bias such as print bias, etch bias, and lateral diffusion of dopants. P_i are the parameters stored in temporary files. P_0, P_L and P_W are the size-independent parameters to be calculated. When parameter variations with respect to electrical channel length and channel width have been calculated from Eq. (62), they are stored in the first three column of line 9 to 28 of the process file. All the parameters are re-calculated with the three size-independent parameters for each device size that was measured. The re-calculated parameter values for each device size are then compared to the original extracted parameter values. The largest percent errors between the original parameter values and re-calculated values over the range of device sizes analyzed are reported in the fourth column. The values in fifth and sixth columns are the mask-level channel width and length of the device which experiences the largest percent error reported by the fourth column. The last three columns of line 9 to 28 just contain statistical information about BSIM parameters. They are not needed for circuit simulations. The values of ΔL and ΔW are obtained from the beta0 parameter (the low-field conductance coefficient at low drain bias). The relationship between beta0 and effective channel width and channel length is given by

$$\text{beta0} = \mu_n C_o \frac{W_{MK} - \Delta W}{L_{MK} - \Delta L} \tag{63}$$

If we plot of 1/beta0 vs. L_{MK}, a straight line would be observed. The x-intercept gives ΔL. Similarly, a plot of beta0 vs. W_{MK} reveals the information of ΔW. The schematic illustration for obtaining ΔL and ΔW is shown in Fig. 11. The values of ΔL and ΔW are stored in the second and third columns in line 13 of the process file. The values of the five β_0-related parameters in the process file are converted to the carrier mobility-related parameters on the die. The conversion factor is $C_{ox}\, W_{MK}/\, L_{MK}$. Three U_1-related parameters in the process file are also normalized by the effective channel length ($L_{MK} - \Delta L$.) Therefore, the values of these 8 parameters have different values from what shown on the screen during extraction. The last line in the process file contains the information of gate-oxide thickness, temperature and V_{DD}.

Once the process file has been created, the user can look at the I-V curves generated from the extracted parameters together with measured data. Device parameters vs. W & L plots on-line menu is also provided in another graphic section. A detailed description about the graphic ability of the extraction program can be found in [5].

```
NMOSE
*PROCESS=2s14
*RUN=
*WAFER=
*XPOS=6
*YPOS=5
*OPERATOR=
*DATE=
-9.1191E-001,4.50507E-002,8.07659E-002,7.86121E+000,1.00000E+002,3.00000E+001
7.15629E-001,0.00000E+000,0.00000E+000,0.00000E+000,1.00000E+002,3.00000E+000
9.11563E-001,-3.0963E-002,9.70417E-002,8.24840E+000,1.00000E+002,1.50000E+000
-7.2610E-002,9.65815E-002,-1.2265E-002,9.72800E+001,1.00000E+002,2.00000E+000
-1.3534E-002,6.63392E-002,1.32347E-002,4.62088E+002,1.00000E+002,1.00000E+001
8.14365E+002,-6.6799E-001,6.57698E-001,0.00000E+000,0.00000E+000,0.00000E+000
8.58881E-002,2.15213E-001,-1.8507E-001,6.23883E+001,8.00000E+000,5.00000E+000
3.71979E-002,3.13453E-001,8.25056E-002,3.75361E+004,1.00000E+002,8.00000E+000
1.82478E+001,-3.0820E+001,3.73277E+001,2.19241E+002,1.00000E+002,1.50000E+000
-2.7497E-003,1.24943E-002,1.45979E-003,4.41360E+003,1.00000E+002,4.00000E+000
1.45349E-003,-6.0199E-003,-4.1028E-003,6.85435E+002,1.00000E+002,2.25000E+000
3.61136E-003,-1.2593E-002,9.10666E-003,1.12793E+002,1.00000E+002,4.00000E+000
-1.3893E-002,1.28809E-002,4.03312E-003,1.40638E+003,1.00000E+002,6.00000E+000
6.79946E+002,6.46334E+002,-1.0404E+002,1.88045E+001,1.00000E+002,1.50000E+000
-4.7324E+000,2.05127E+000,4.96160E+001,9.03430E+003,2.50000E+001,5.00000E+000
-8.0418E+000,1.16379E+002,-2.5998E+001,2.80811E+003,1.00000E+002,3.00000E+001
2.75281E-003,5.03620E-002,-1.8050E-002,3.94831E+002,1.00000E+002,4.00000E+000
1.41981E+000,5.87905E-001,2.46860E-001,2.05311E+001,1.00000E+002,1.50000E+000
-5.1335E-002,1.78455E-001,2.93264E-002,8.66617E+004,1.00000E+002,2.50000E+000
2.83850E-002,1.56124E-001,9.59408E-003,2.76731E+002,1.00000E+002,1.75000E+000
4.50000E-002,2.70000E+001,5.00000E+000
```

REFERENCE

(1) B. J. Sheu, D. L. Scharfetter, and H. C. Poon "Compact Short-Channel IGFET Model", University of California, Berkeley, ERL memo. UCB/ERL M84/20.

(2) B. J. Sheu, D. L. Scharfetter, and P. K. Ko, "SPICE2 Implementation of BSIM", Unversity of California, Berkeley, ERL memo. UCB/ERL M85/42.

(3) B. S. Messenger, "A Fully Automated MOS Device Characterization System for Process-Oriented Integrated Circuit Design", University of Califronia, Berkeley, ERL memo, UCB/ERL M84/18, Jan. 1984.

(4) A. H.-C. Fung "A Subthreshold Conduction Model for BSIM", University of California, Berkeley, ERL memo. UCB/ERL M85/22.

(5) J. R. Pierret, "A MOS Parameter Extraction Program for The BSIM Model", University of California, Berkeley, ERL memo. UCB/ERL M84/99.

Figure Captions:

Fig. 1 The parameter extraction system.

Fig. 2 The measured and calculated $I_{DS}-V_{GS}$ results of an N-channel and a P-channel device. The solid lines are calculated values. "x"'s are measured data.

Fig. 3 The flowchart of BSIM extraction program.

Fig. 4 The flowchart of the extraction routine.

Fig. 5 Quadratic interpolation of β_0 to the drain bias.

Fig. 6 (a). The bias-setup for an N-channel device in the Device-Type Test. For a P-channel device, the polarity of all biases are reversed. (b). A sample of the display on the HP4145 screen for this test.

Fig. 7 (a). The bias-setup for an N-channel device in the Device-Functionality Test. For a P-channel device, the polarity of all biases are reversed. (b). A sample of the display on the HP4145 screen for this test.

Fig. 8 A typical display on the HP4145 screen during measurement. The six curves are corresponding to six substrate biases.

Fig. 9 Subthreshold swing calculation.

Fig. 10 The calculation of initial values for the threshold voltage and the conductance coefficient used in Newton-Raphson's algorithm.

Fig. 11 Determination of the effective channel length from beta0 parameter.

Fig. 12 Determination of the effective channel width from beta0 parameter.

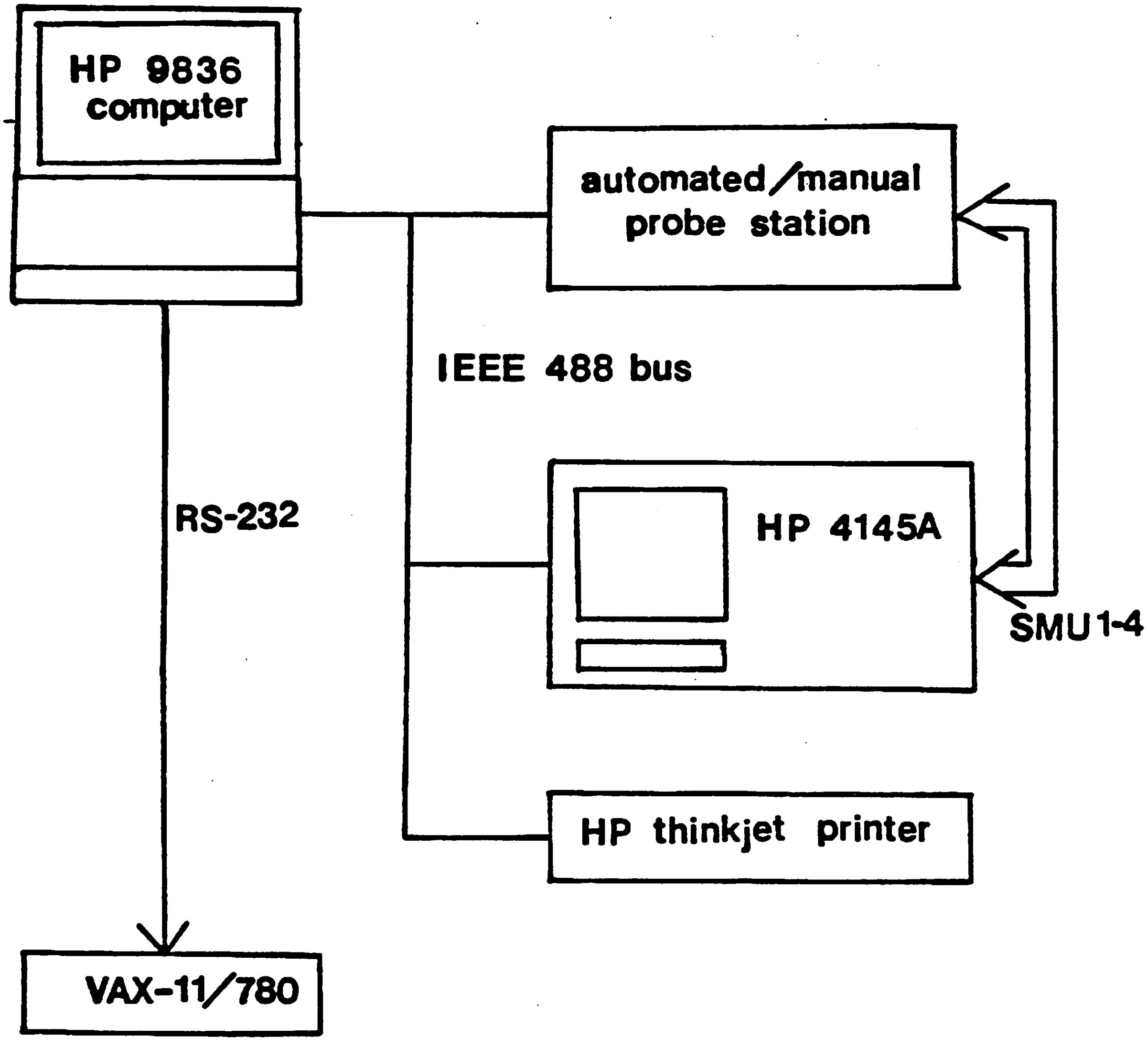

HP 9836 computer
automated/manual probe station
IEEE 488 bus
RS-232
HP 4145A
SMU1-4
HP thinkjet printer
VAX-11/780

FIG.1

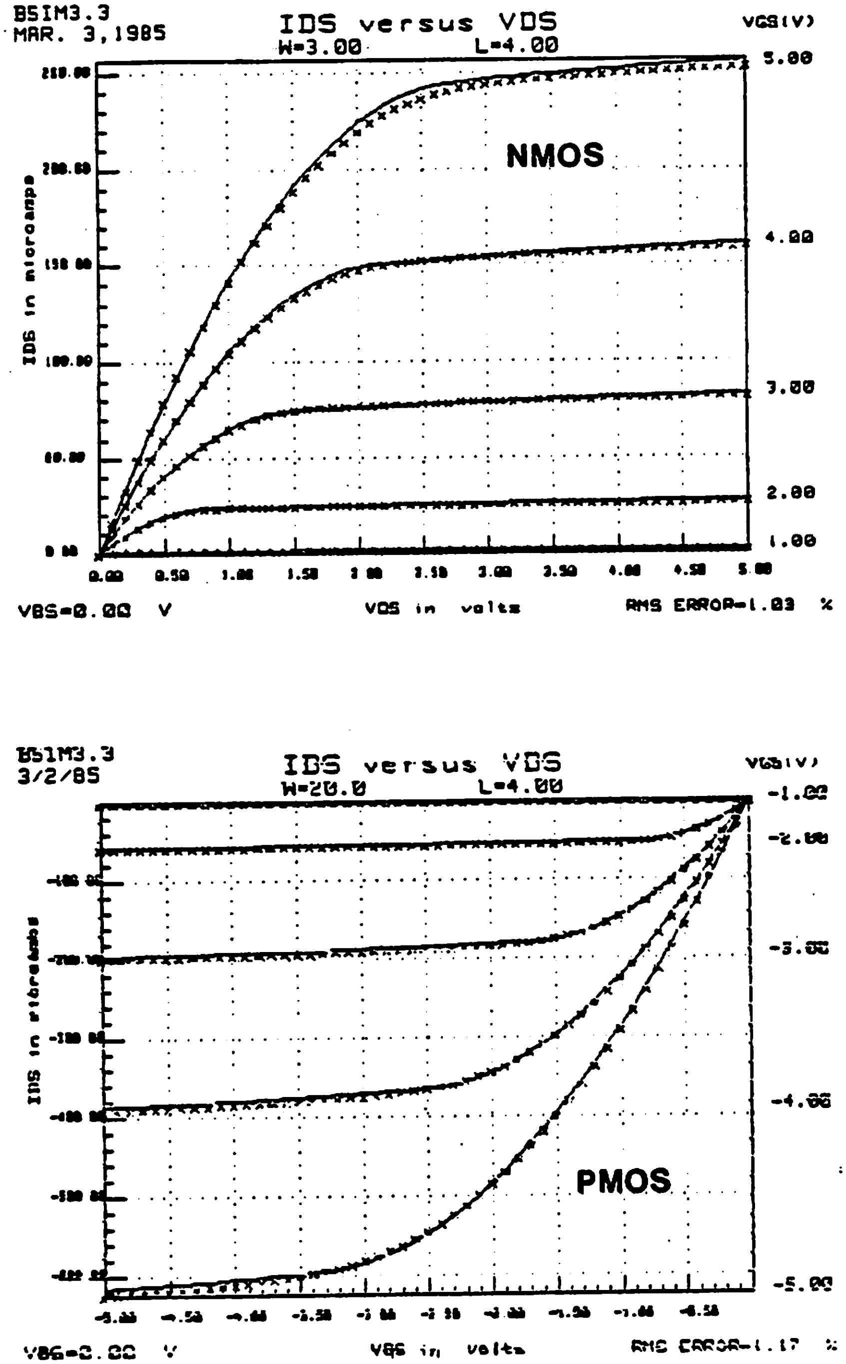

BSIM3.3
MAR. 3,1985
IDS versus VDS
W=3.00
L=4.00
VGS(V)
5.00
4.00
3.00
2.00
1.00
NMOS
IDS in microamps
250.00
200.00
150.00
100.00
50.00
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
VBS=0.00 V
VDS in volts
RMS ERROR=1.03 %
BSIM3.3
3/2/85
IDS versus VDS
W=20.0
L=4.00
VGS(V)
-1.00
-2.00
-3.00
-4.00
-5.00
PMOS
IDS in microamps
-100.00
-200.00
-300.00
-400.00
-500.00
-600.00
-5.00
-4.50
-4.00
-3.50
-3.00
-2.50
-2.00
-1.50
-1.00
-0.50
VBS=0.00 V
VDS in volts
RMS ERROR=1.17 %

FIG.2

BSIM EXTRACTION PROGRAM FLOWCHART

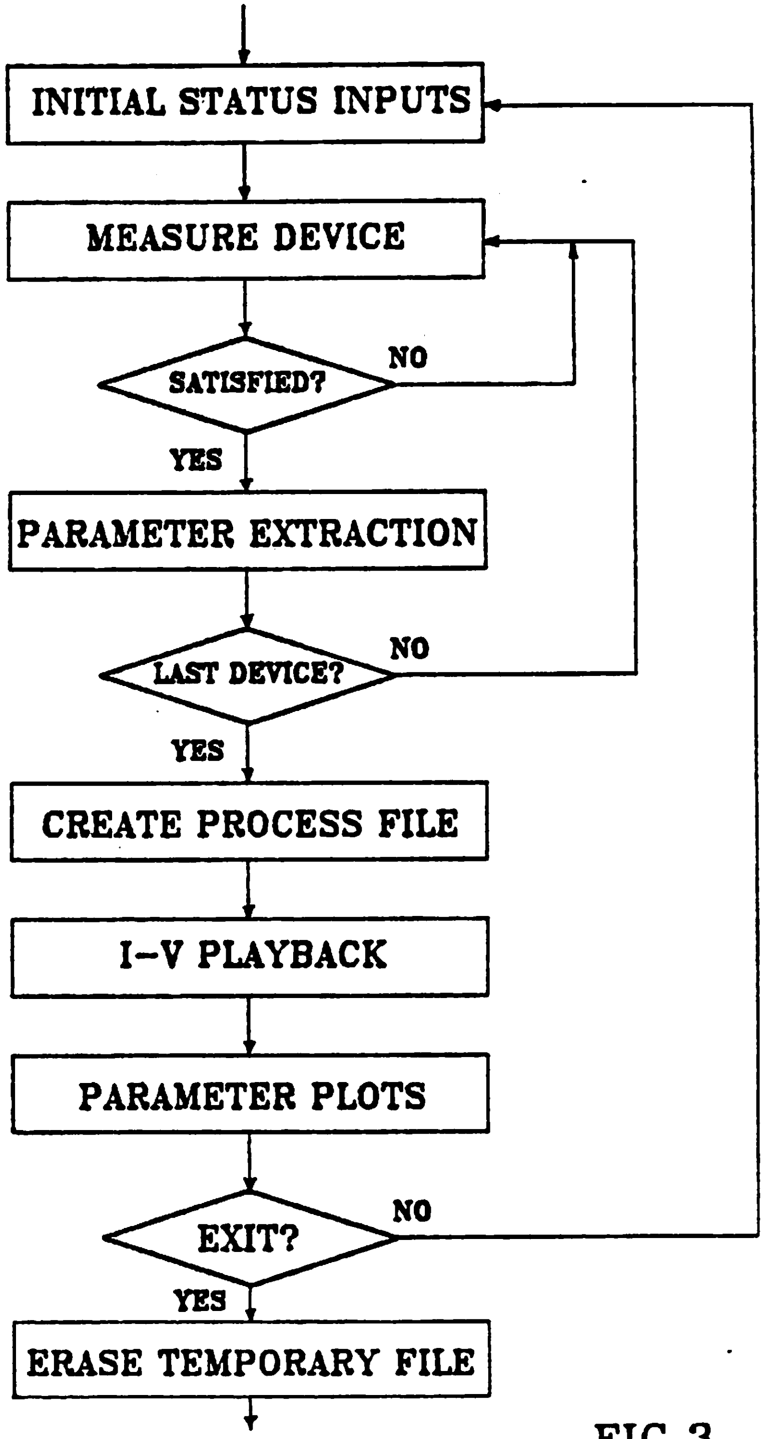


FIG.3

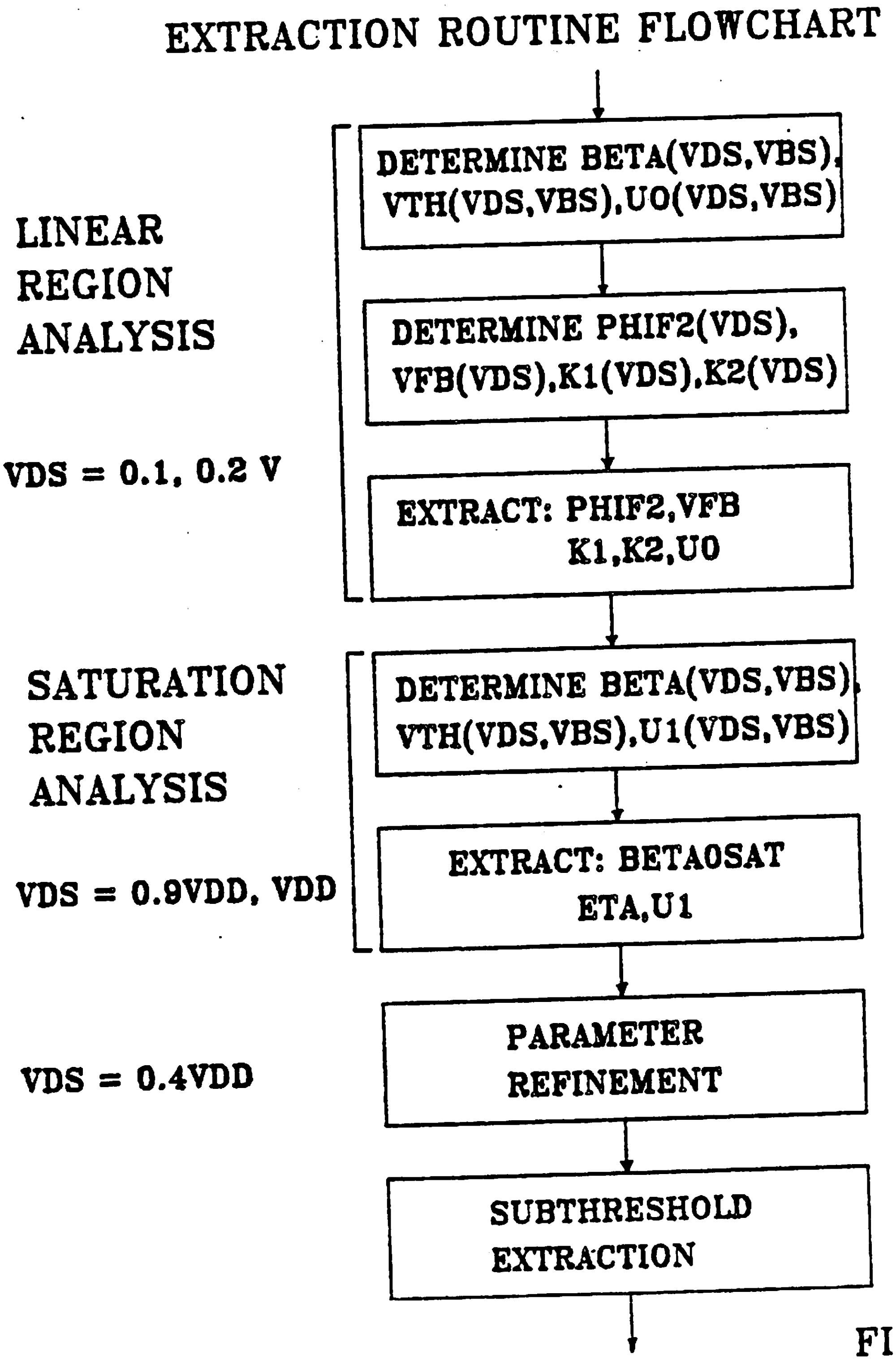

EXTRACTION ROUTINE FLOWCHART
LINEAR REGION ANALYSIS
VDS = 0.1, 0.2 V
DETERMINE BETA(VDS,VBS), VTH(VDS,VBS),U0(VDS,VBS)
DETERMINE PHIF2(VDS), VFB(VDS),K1(VDS),K2(VDS)
EXTRACT: PHIF2,VFB K1,K2,U0
SATURATION REGION ANALYSIS
VDS = 0.9VDD, VDD
DETERMINE BETA(VDS,VBS), VTH(VDS,VBS),U1(VDS,VBS)
EXTRACT: BETA0SAT ETA,U1
VDS = 0.4VDD
PARAMETER REFINEMENT
SUBTHRESHOLD EXTRACTION

FIG.4

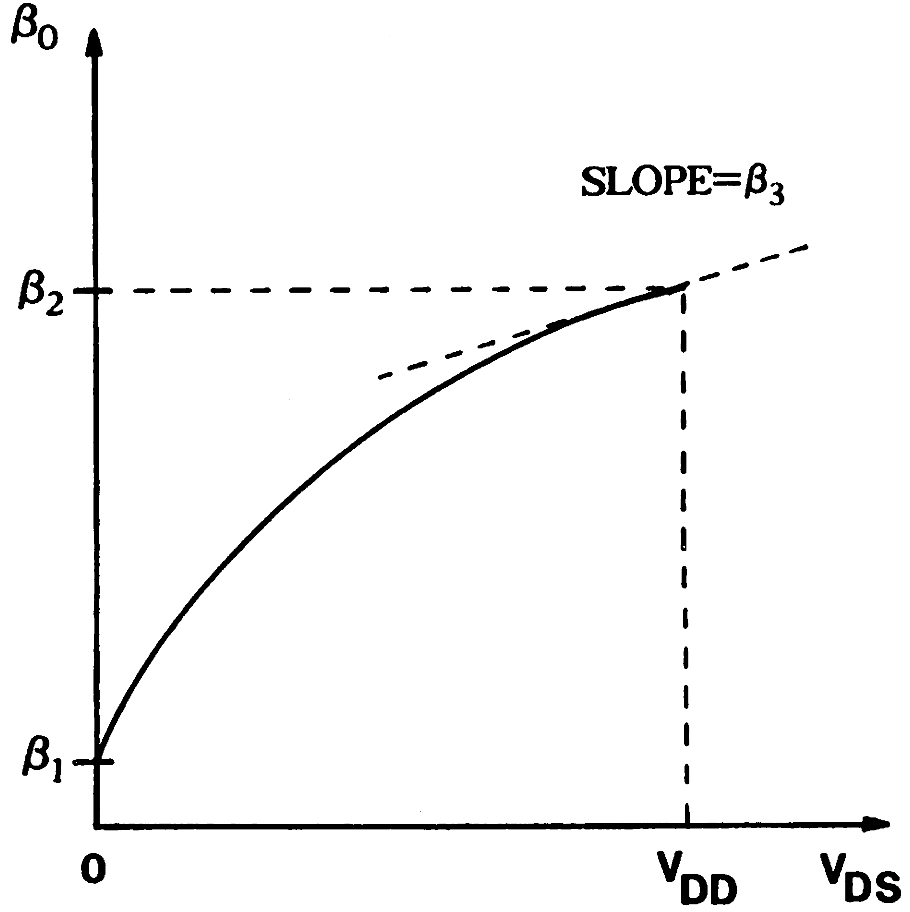


FIG.5

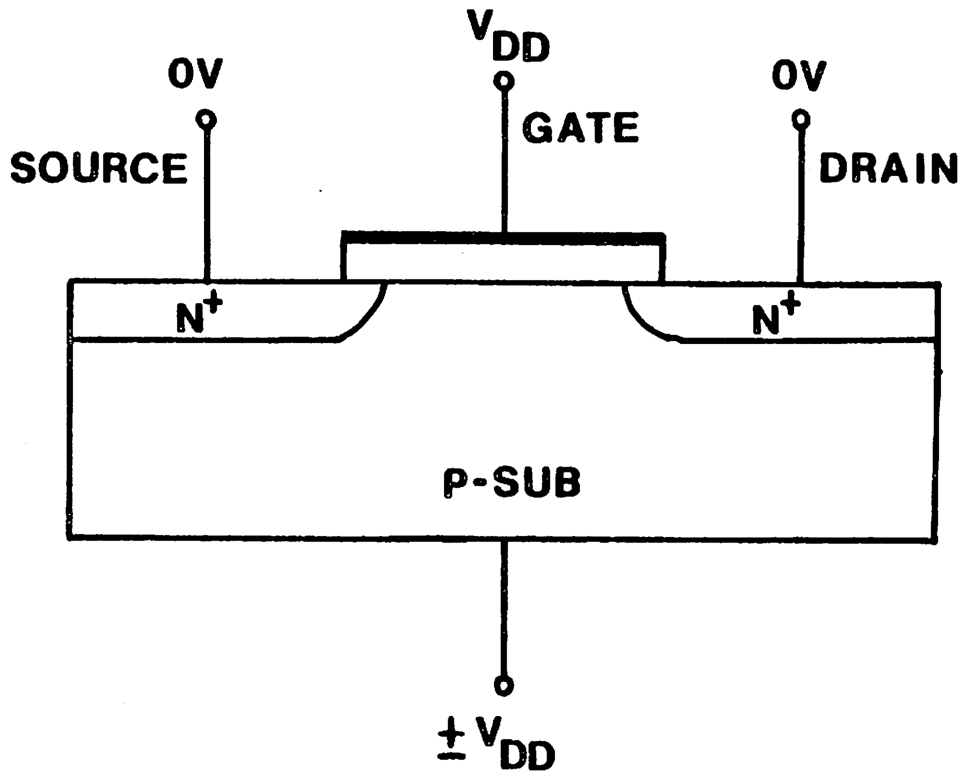
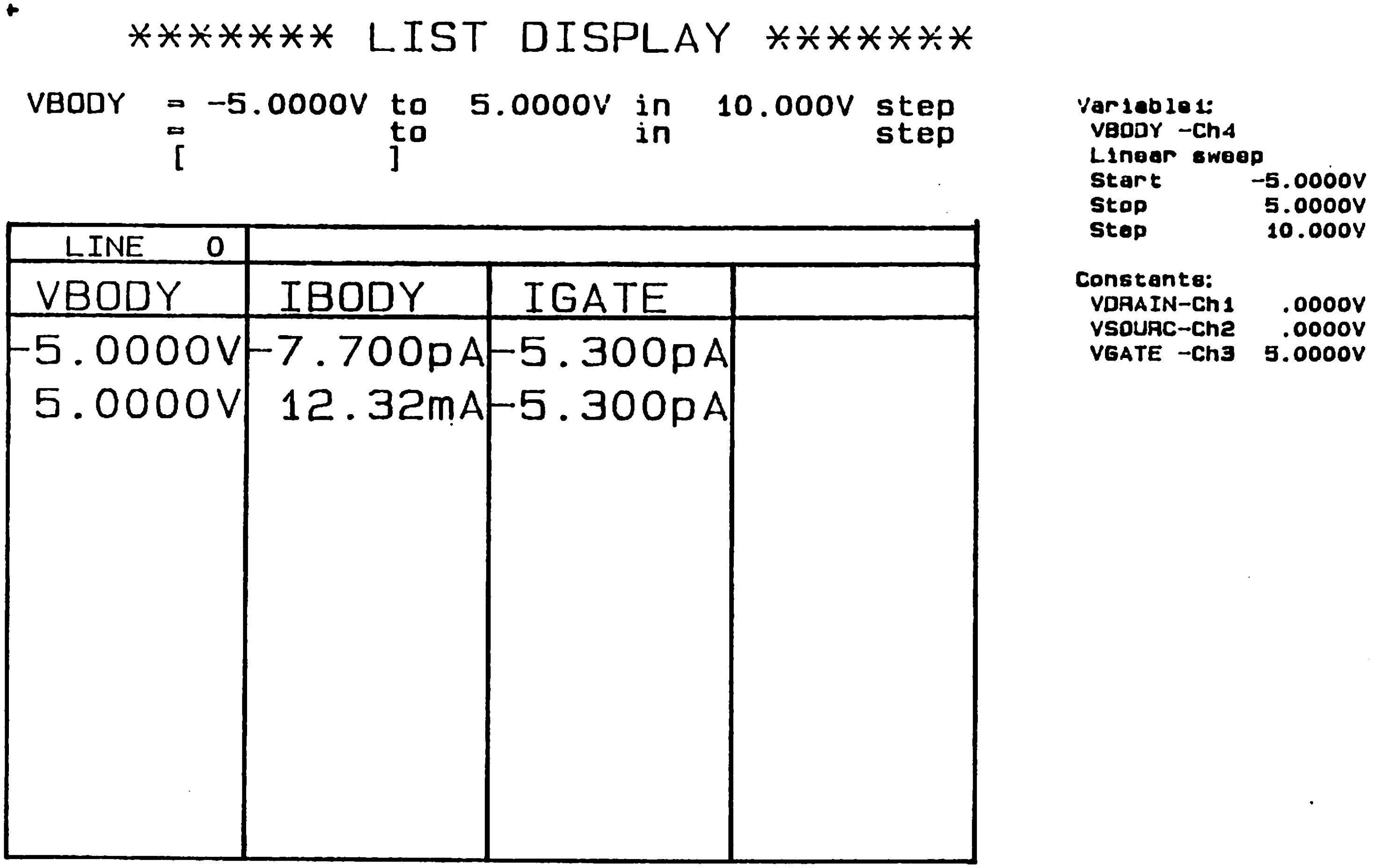


FIG.6(a)



```
******* LIST DISPLAY *******

VBODY   = -5.0000V to  5.0000V in  10.000V step
        =          to          in          step
        [          ]
```

LINE 0			
VBODY	IBODY	IGATE	
-5.0000V	-7.700pA	-5.300pA	
5.0000V	12.32mA	-5.300pA	

```
Variable1:
 VBODY -Ch4
 Linear sweep
 Start          -5.0000V
 Stop            5.0000V
 Step            10.000V

Constants:
 VDRAIN-Ch1       .0000V
 VSOURC-Ch2       .0000V
 VGATE -Ch3      5.0000V
```

FIG.6(b)

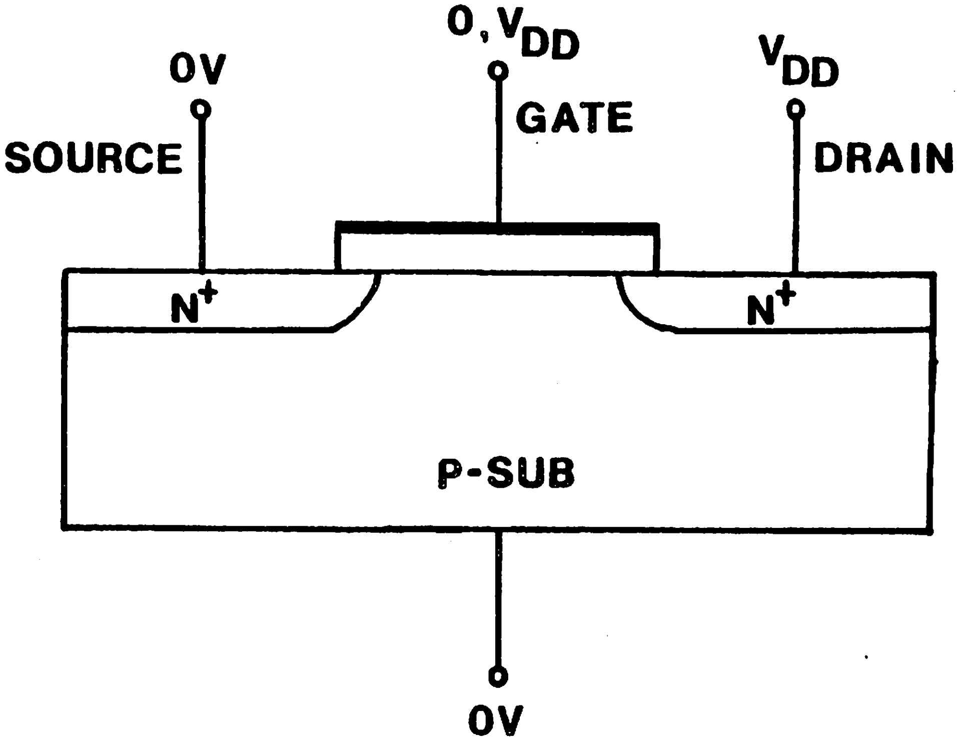
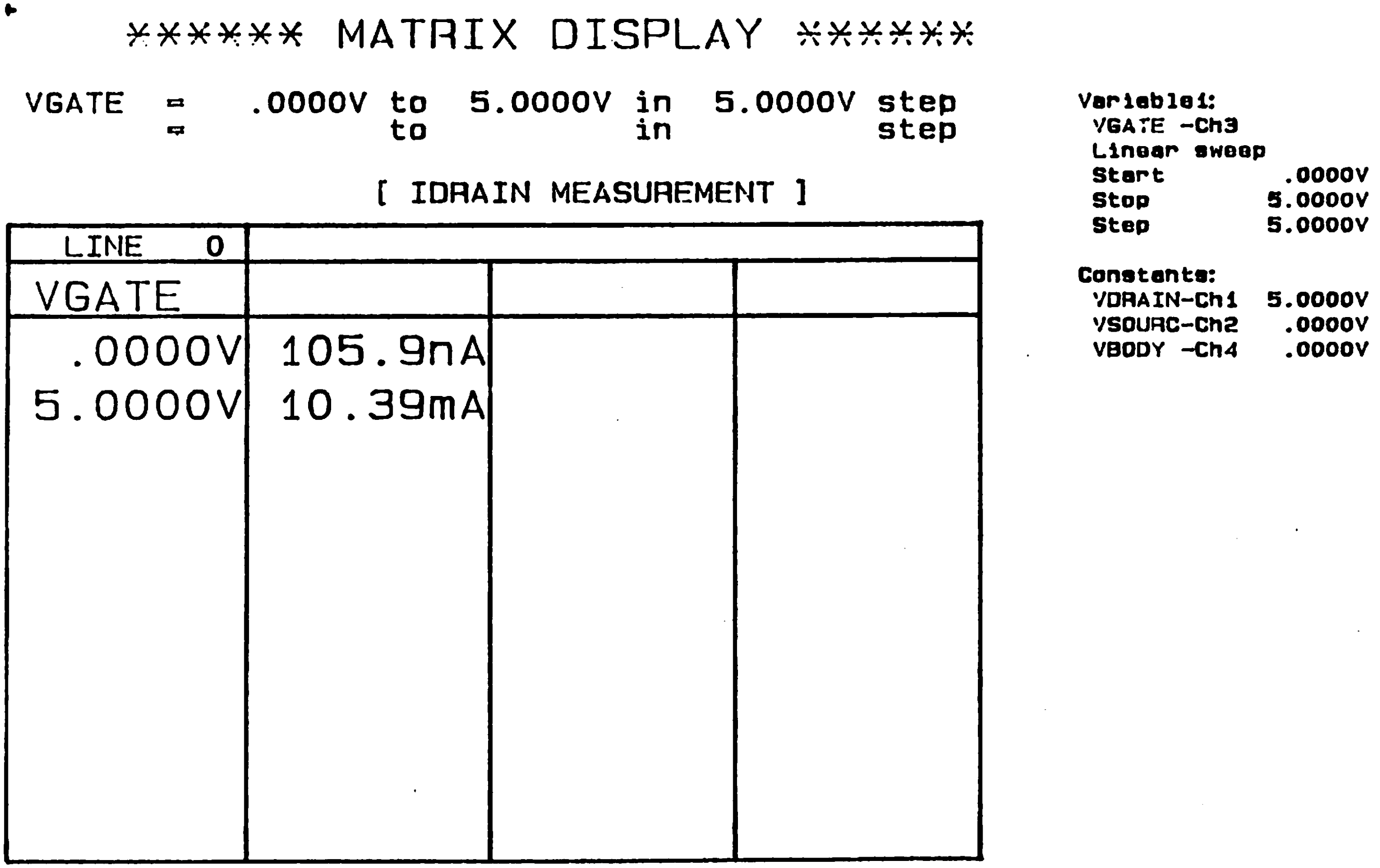


FIG.7(a)

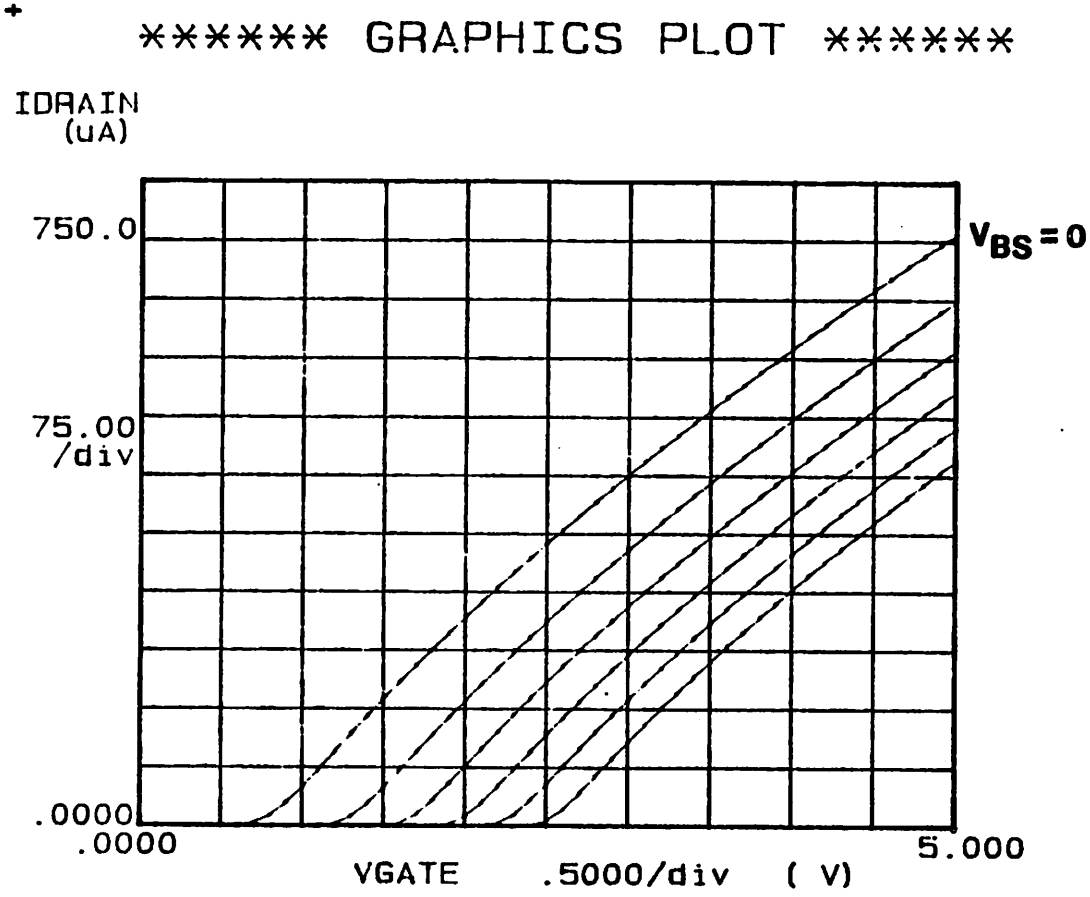


```
****** MATRIX DISPLAY ******

VGATE   =   .0000V to  5.0000V in  5.0000V step
        =          to          in          step

              [ IDRAIN MEASUREMENT ]
```

LINE 0			
VGATE			
.0000V	105.9nA		
5.0000V	10.39mA		

```
Variable1:
 VGATE -Ch3
 Linear sweep
 Start           .0000V
 Stop           5.0000V
 Step           5.0000V

Constants:
 VDRAIN-Ch1     5.0000V
 VSOURC-Ch2      .0000V
 VBODY -Ch4      .0000V
```

FIG.7(b)



```
Variable1:
 VGATE -Ch3
 Linear sweep
 Start          .0000V
 Stop          5.0000V
 Step           .1000V

Variable2:
 VBODY -Ch4
 Start        -5.0000V
 Stop           .0000V
 Step          1.0000V

Constants:
 VDRAIN-Ch1    .1000V
 VSOURC-Ch2    .0000V
```

FIG.8

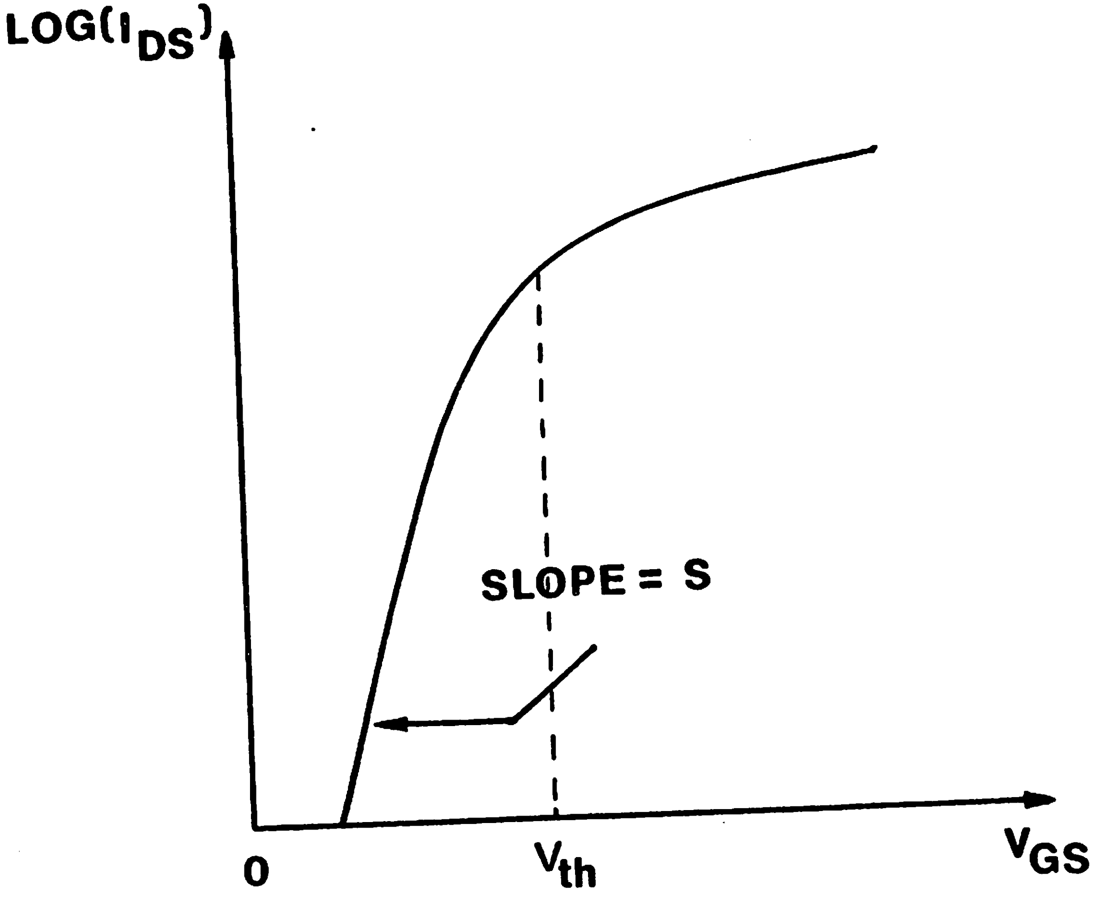


FIG.9

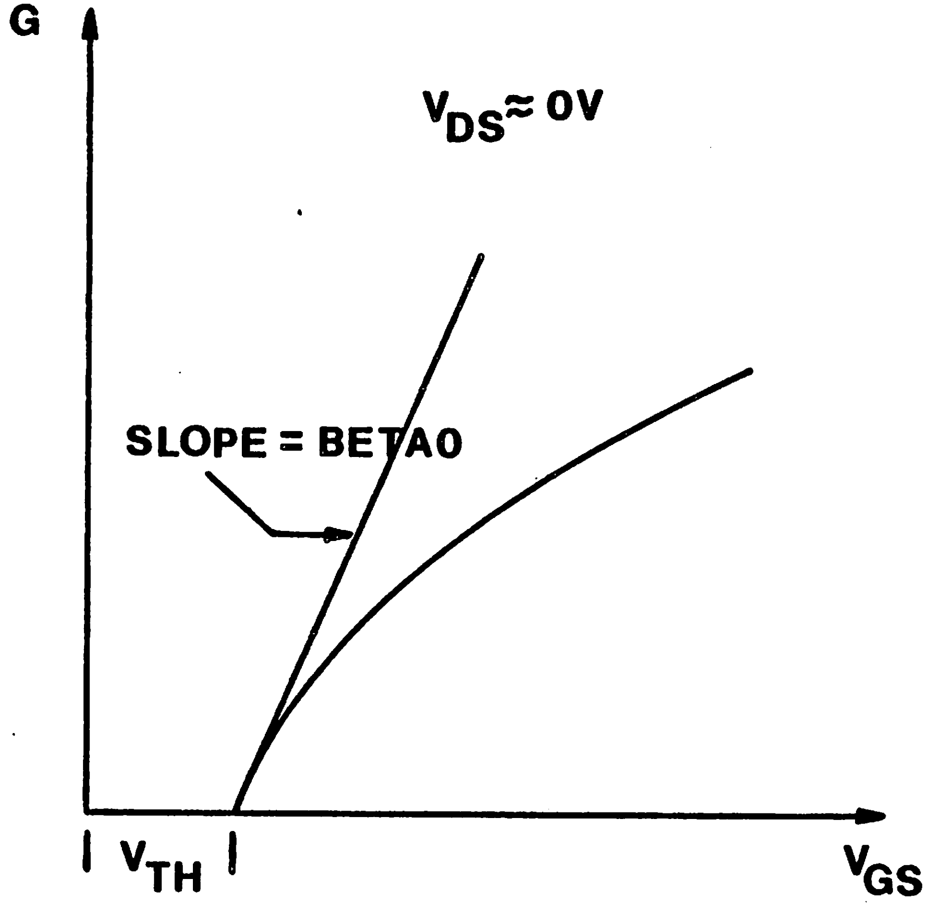


FIG.10

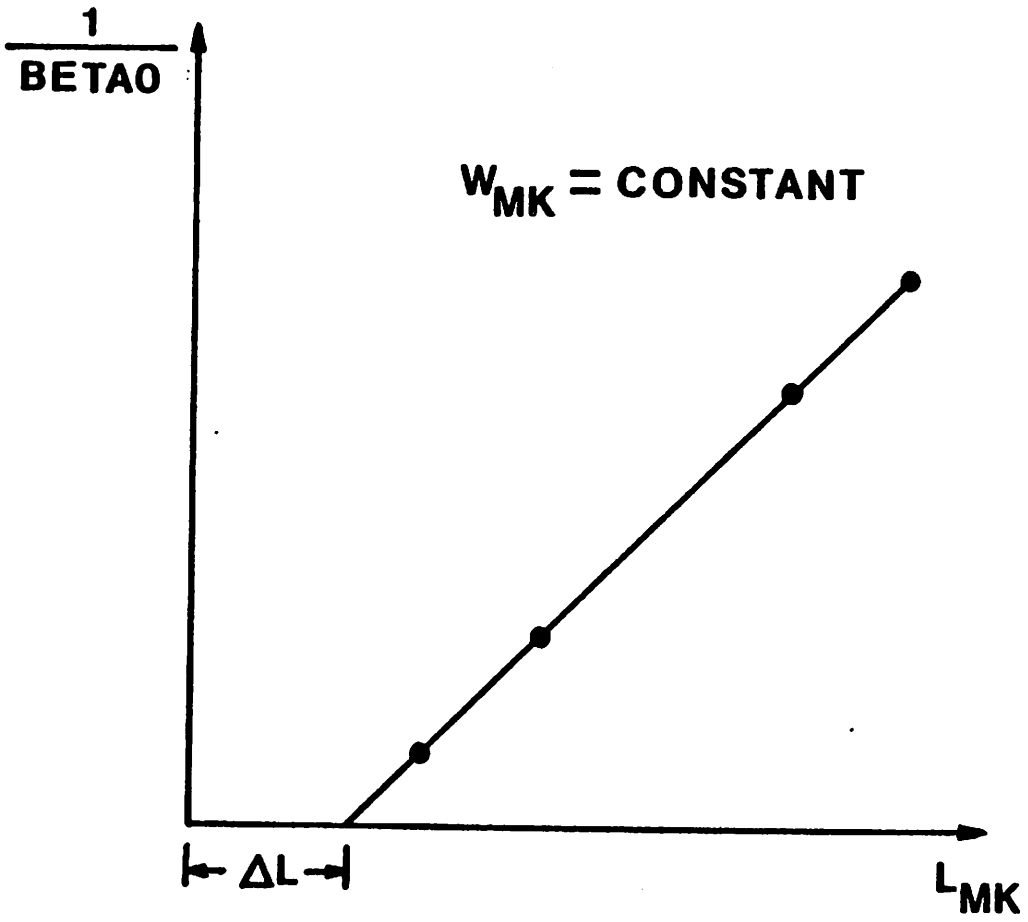


FIG.11

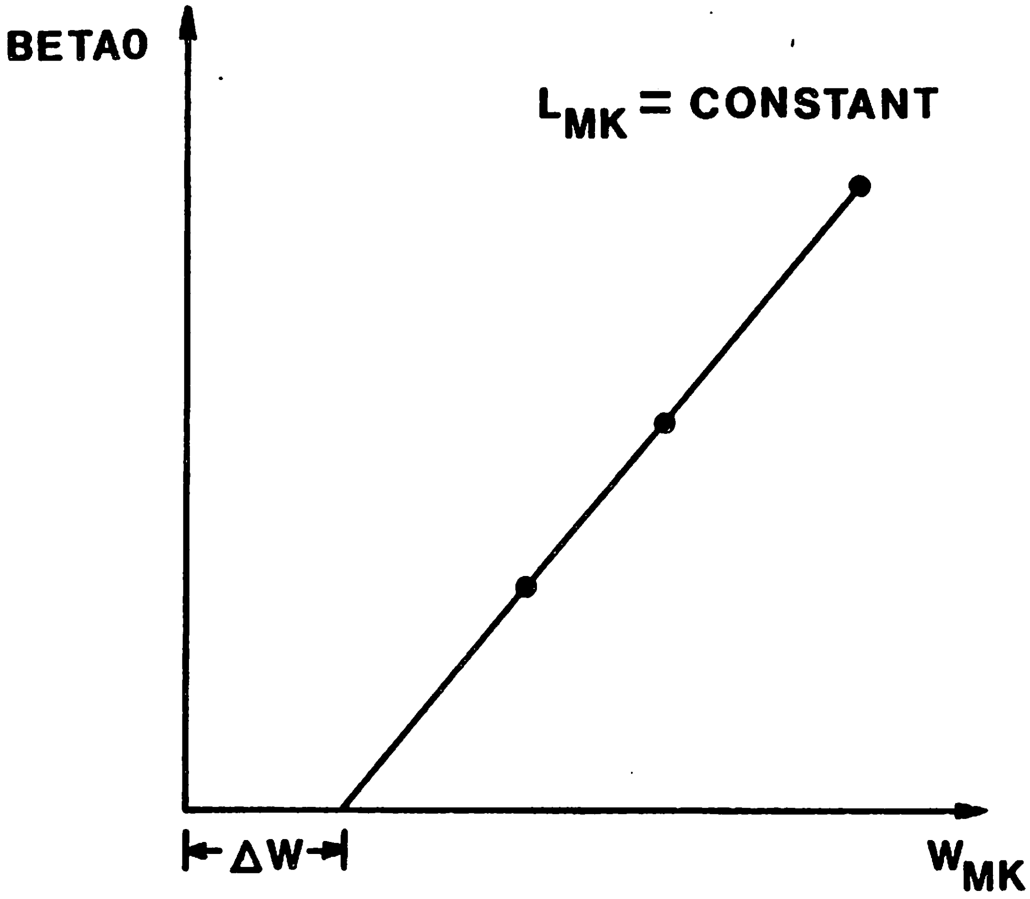
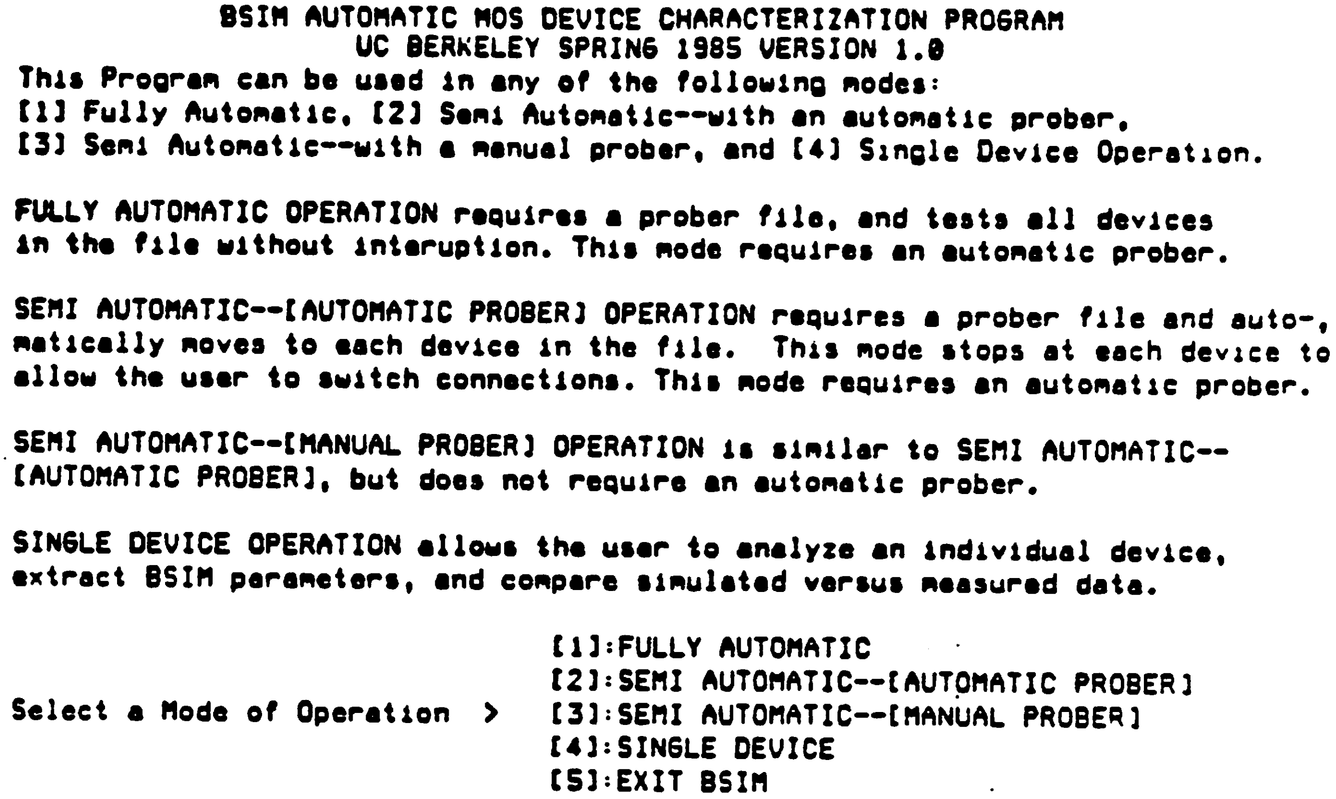
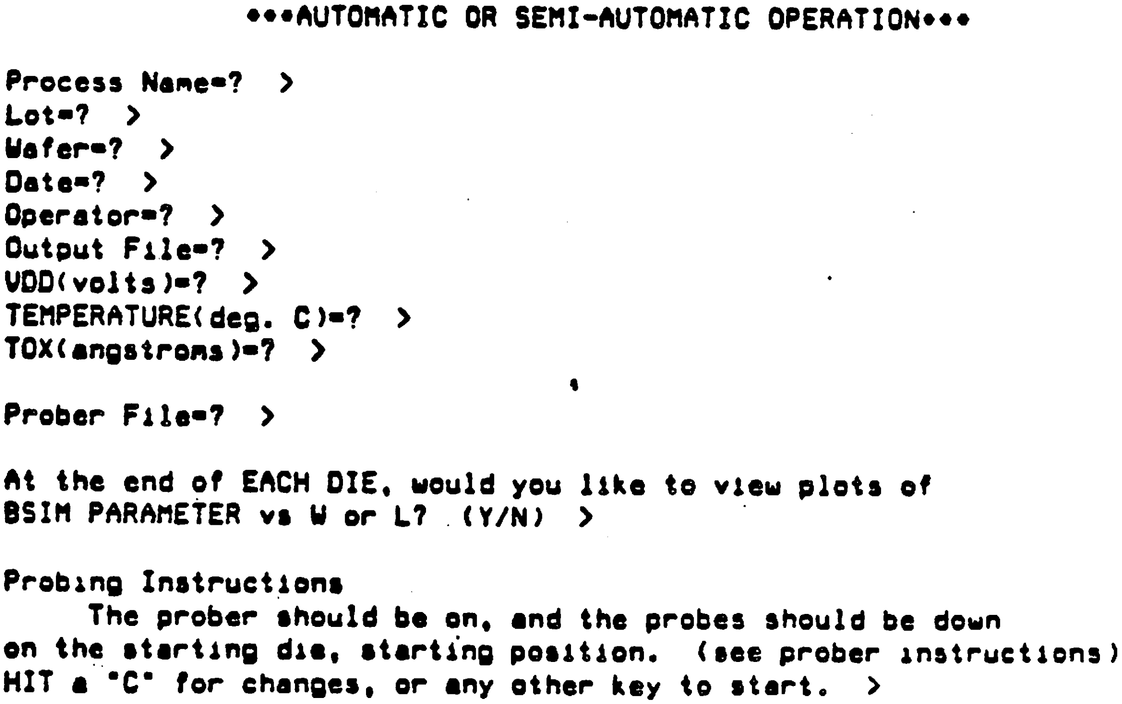


FIG.12



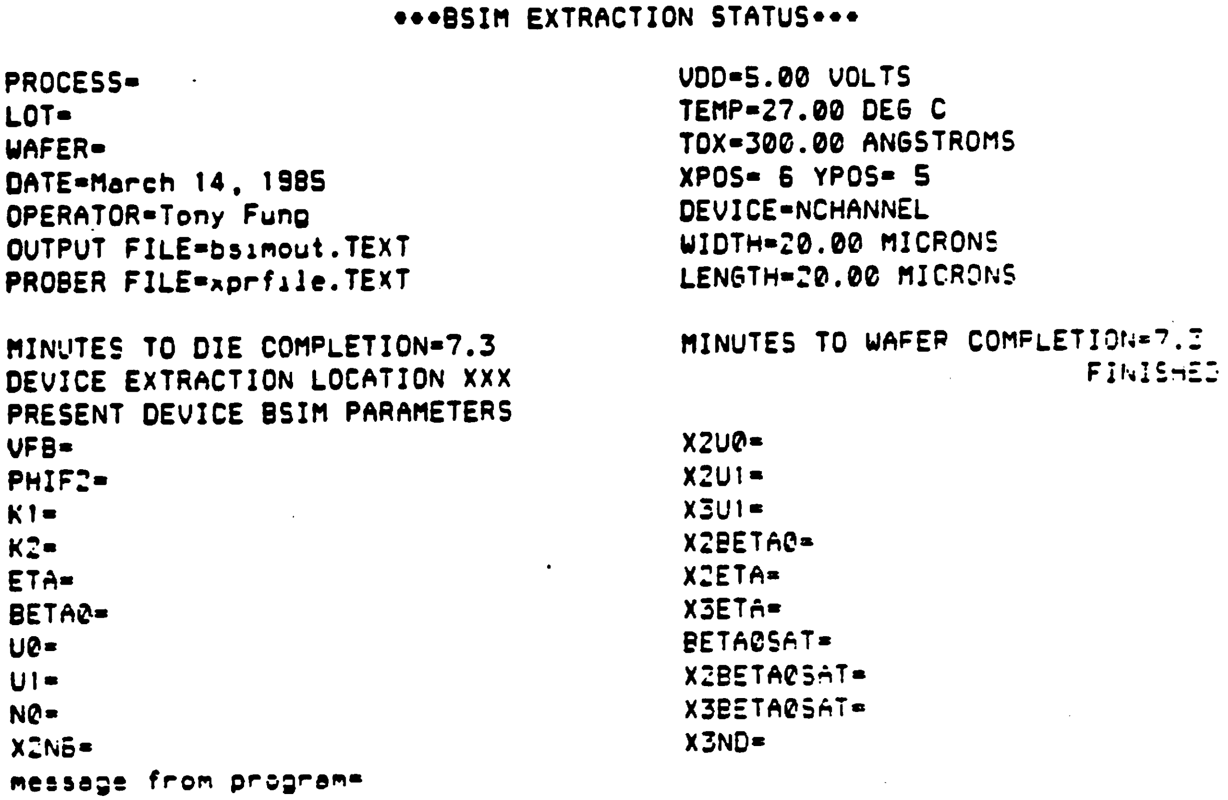
```
              BSIM AUTOMATIC MOS DEVICE CHARACTERIZATION PROGRAM
                     UC BERKELEY SPRING 1985 VERSION 1.0
This Program can be used in any of the following modes:
[1] Fully Automatic, [2] Semi Automatic--with an automatic prober,
[3] Semi Automatic--with a manual prober, and [4] Single Device Operation.

FULLY AUTOMATIC OPERATION requires a prober file, and tests all devices
in the file without interuption. This mode requires an automatic prober.

SEMI AUTOMATIC--[AUTOMATIC PROBER] OPERATION requires a prober file and auto-,
matically moves to each device in the file.  This mode stops at each device to
allow the user to switch connections. This mode requires an automatic prober.

SEMI AUTOMATIC--[MANUAL PROBER] OPERATION is similar to SEMI AUTOMATIC--
[AUTOMATIC PROBER], but does not require an automatic prober.

SINGLE DEVICE OPERATION allows the user to analyze an individual device,
extract BSIM parameters, and compare simulated versus measured data.

                                 [1]:FULLY AUTOMATIC
                                 [2]:SEMI AUTOMATIC--[AUTOMATIC PROBER]
Select a Mode of Operation  >    [3]:SEMI AUTOMATIC--[MANUAL PROBER]
                                 [4]:SINGLE DEVICE
                                 [5]:EXIT BSIM
```

Fig. A1



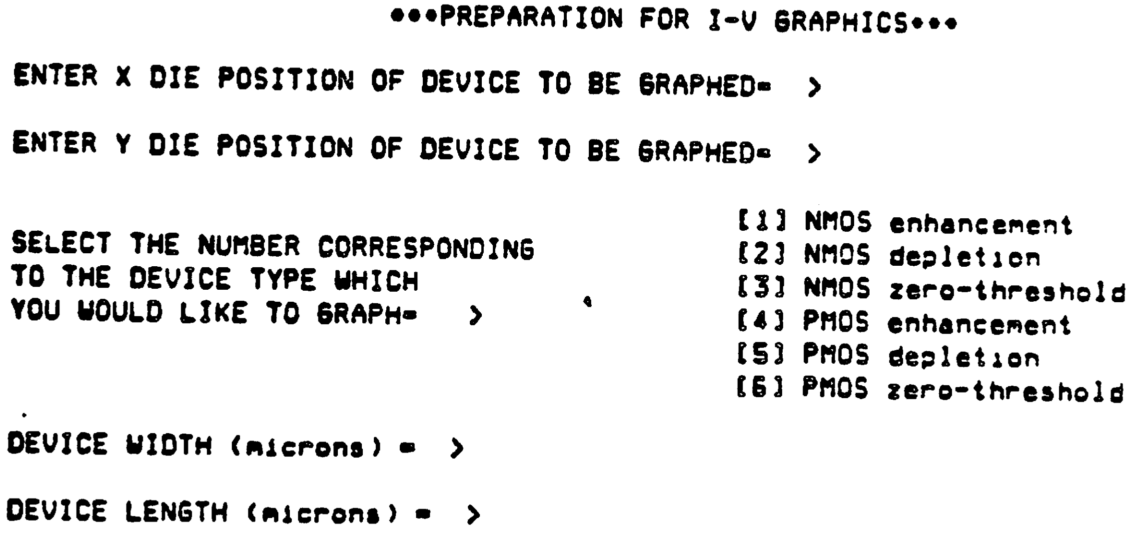
```
                 ***AUTOMATIC OR SEMI-AUTOMATIC OPERATION***

Process Name=?  >
Lot=?  >
Wafer=?  >
Date=?  >
Operator=?  >
Output File=?  >
VDD(volts)=?  >
TEMPERATURE(deg. C)=?  >
TOX(angstroms)=?  >

Prober File=?  >

At the end of EACH DIE, would you like to view plots of
BSIM PARAMETER vs W or L?  (Y/N)  >

Probing Instructions
     The prober should be on, and the probes should be down
on the starting die, starting position.  (see prober instructions)
HIT a "C" for changes, or any other key to start.  >
```

Fig. A2



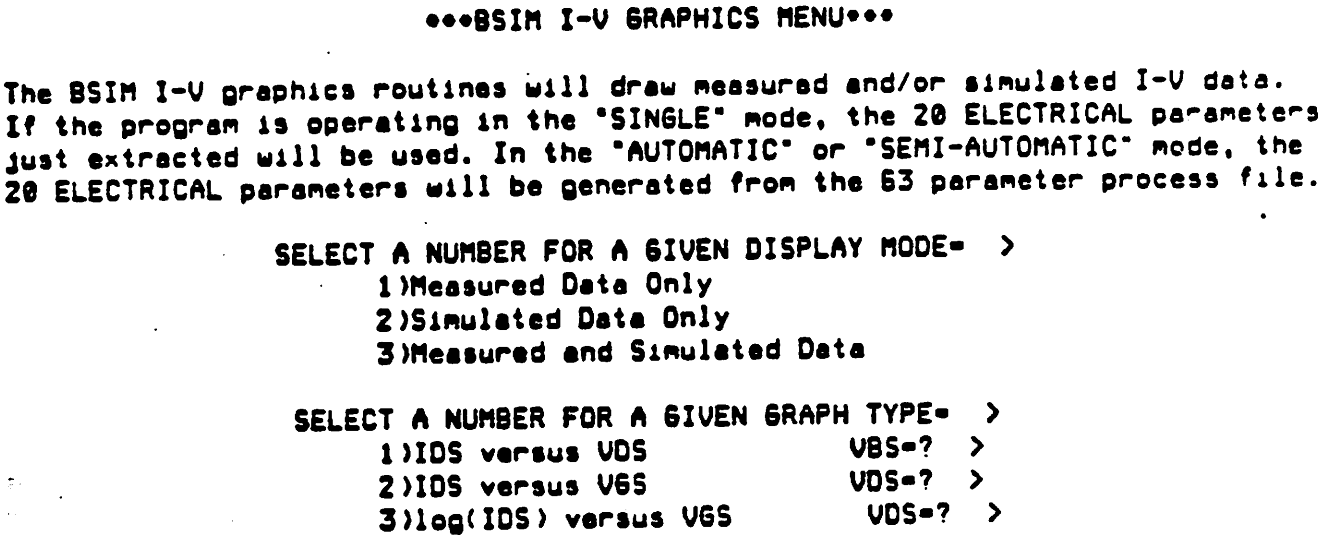
```
                          ***BSIM EXTRACTION STATUS***

PROCESS=                                  VDD=5.00 VOLTS
LOT=                                      TEMP=27.00 DEG C
WAFER=                                    TOX=300.00 ANGSTROMS
DATE=March 14, 1985                       XPOS= 6 YPOS= 5
OPERATOR=Tony Fung                        DEVICE=NCHANNEL
OUTPUT FILE=bsimout.TEXT                  WIDTH=20.00 MICRONS
PROBER FILE=xprfile.TEXT                  LENGTH=20.00 MICRONS

MINUTES TO DIE COMPLETION=7.3             MINUTES TO WAFER COMPLETION=7.3
DEVICE EXTRACTION LOCATION XXX                                   FINISHED
PRESENT DEVICE BSIM PARAMETERS
VFB=                                      X2U0=
PHIF2=                                    X2U1=
K1=                                       X3U1=
K2=                                       X2BETA0=
ETA=                                      X2ETA=
BETA0=                                    X3ETA=
U0=                                       BETA0SAT=
U1=                                       X2BETA0SAT=
N0=                                       X3BETA0SAT=
X2NB=                                     X3ND=
message from program=
```

Fig. A3



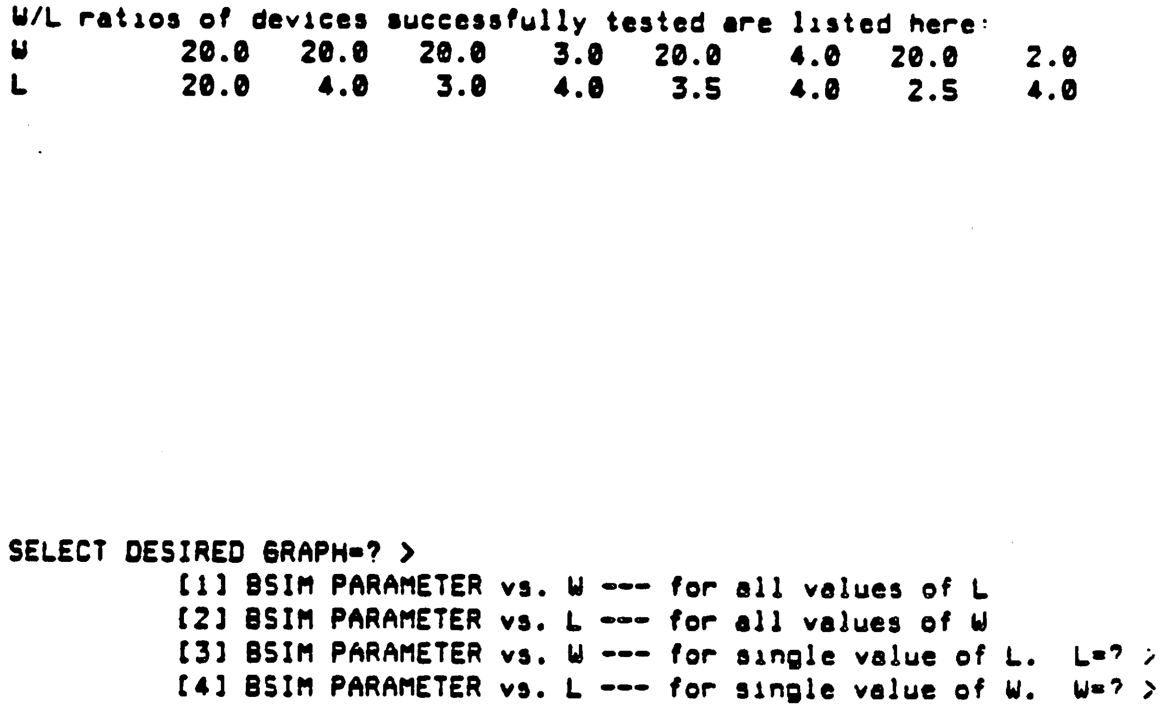
```
                         ***PREPARATION FOR I-V GRAPHICS***

ENTER X DIE POSITION OF DEVICE TO BE GRAPHED=  >

ENTER Y DIE POSITION OF DEVICE TO BE GRAPHED=  >

                                                  [1] NMOS enhancement
SELECT THE NUMBER CORRESPONDING                   [2] NMOS depletion
TO THE DEVICE TYPE WHICH                          [3] NMOS zero-threshold
YOU WOULD LIKE TO GRAPH=   >                      [4] PMOS enhancement
                                                  [5] PMOS depletion
                                                  [6] PMOS zero-threshold

DEVICE WIDTH (microns) =  >

DEVICE LENGTH (microns) =  >
```

Fig. A4



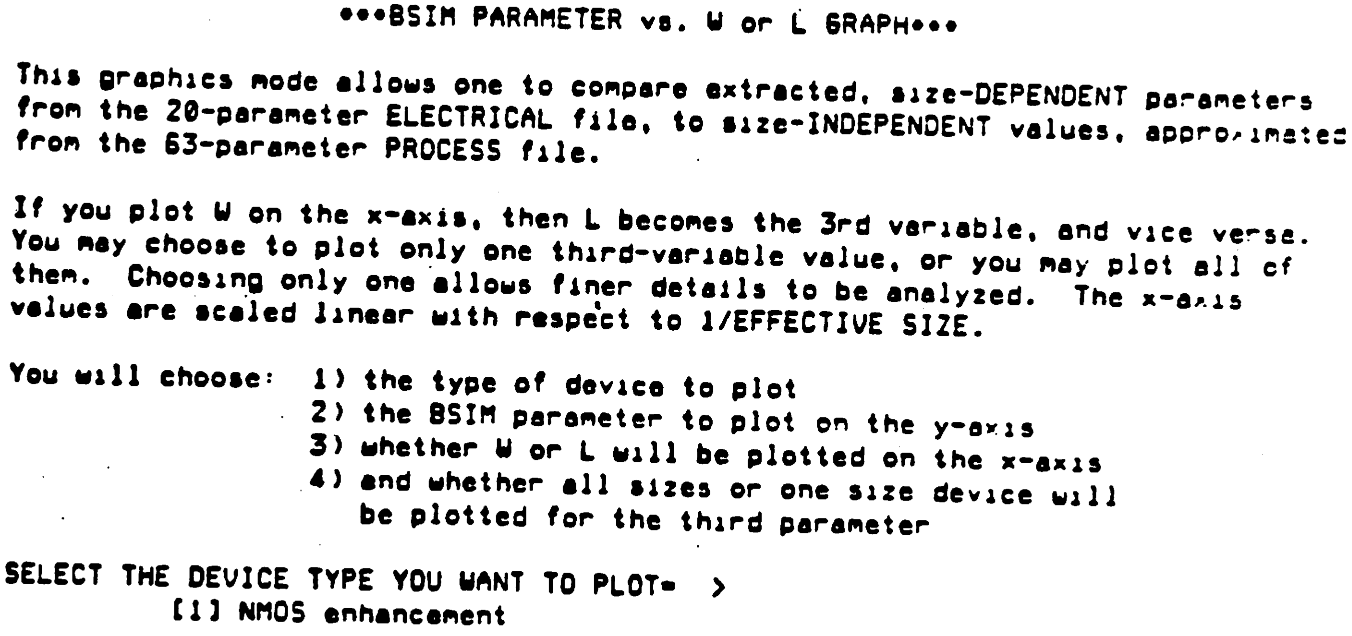
```
                            ***BSIM I-V GRAPHICS MENU***

The BSIM I-V graphics routines will draw measured and/or simulated I-V data.
If the program is operating in the "SINGLE" mode, the 20 ELECTRICAL parameters
just extracted will be used. In the "AUTOMATIC" or "SEMI-AUTOMATIC" mode, the
20 ELECTRICAL parameters will be generated from the 63 parameter process file.

                SELECT A NUMBER FOR A GIVEN DISPLAY MODE=  >
                     1)Measured Data Only
                     2)Simulated Data Only
                     3)Measured and Simulated Data

                 SELECT A NUMBER FOR A GIVEN GRAPH TYPE=  >
                     1)IDS versus VDS            VBS=?  >
                     2)IDS versus VGS            VDS=?  >
                     3)log(IDS) versus VGS        VDS=?  >
```

Fig. A5



```
W/L ratios of devices successfully tested are listed here:
W         20.0   20.0   20.0    3.0   20.0    4.0   20.0    2.0
L         20.0    4.0    3.0    4.0    3.5    4.0    2.5    4.0




SELECT DESIRED GRAPH=? >
          [1] BSIM PARAMETER vs. W --- for all values of L
          [2] BSIM PARAMETER vs. L --- for all values of W
          [3] BSIM PARAMETER vs. W --- for single value of L.  L=? >
          [4] BSIM PARAMETER vs. L --- for single value of W.  W=? >
```

Fig. A6

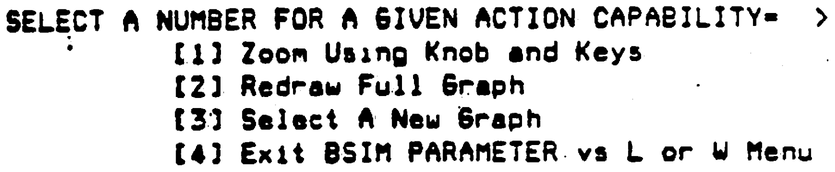


```
                        ***BSIM PARAMETER vs. W or L GRAPH***

This graphics mode allows one to compare extracted, size-DEPENDENT parameters
from the 20-parameter ELECTRICAL file, to size-INDEPENDENT values, approximated
from the 63-parameter PROCESS file.

If you plot W on the x-axis, then L becomes the 3rd variable, and vice verse.
You may choose to plot only one third-variable value, or you may plot all of
them.  Choosing only one allows finer details to be analyzed.  The x-axis
values are scaled linear with respect to 1/EFFECTIVE SIZE.

You will choose:  1) the type of device to plot
                  2) the BSIM parameter to plot on the y-axis
                  3) whether W or L will be plotted on the x-axis
                  4) and whether all sizes or one size device will
                     be plotted for the third parameter

SELECT THE DEVICE TYPE YOU WANT TO PLOT=  >
          [1] NMOS enhancement
```

Fig. A7

```
SELECT THE PARAMETER TO BE GRAPHED=   >
              [1] VFB
              [2] ZPHIF
              [3] K1
              [4] K2
              [5] ETA
              [6] BETA0
              [7] U0
              [8] U1
              [9] X2MU0
             [10] X2ETA
             [11] X3ETA
             [12] X2U0
             [13] X2U1
             [14] MU0SAT
             [15] X2MU0SAT
             [16] X3MU0SAT
             [17] X3U1
             [18] N0
             [19] X2NB
             [20] X3ND
```

Fig. A8

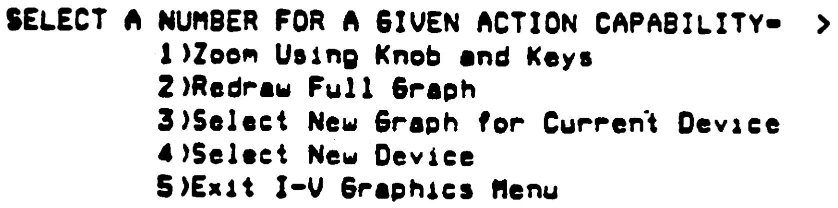


```
SELECT A NUMBER FOR A GIVEN ACTION CAPABILITY=  >
          [1] Zoom Using Knob and Keys
          [2] Redraw Full Graph
          [3] Select A New Graph
          [4] Exit BSIM PARAMETER vs L or W Menu
```

Fig. A9

```
                         ***SINGLE DEVICE OPERATION***

Process Name=?  >
Lot=?  >
Wafer=?  >          XPOSITION=?  >          YPOSITON=?  >
Date=?  >
Operator=?  >
Output File=?  >
VDD(volts)=?  >
TEMPERATURE(deg. C)=?  >
TOX(angstroms)=?  >
PHIF2 or NSUB=?  >
drawn width (microns)=?  >
drawn length (microns)=?  >
Device type=?  >    [1] enhancement, [2] zero-threshold, [3] depletion

SMU connected to DRAIN=?  >
SMU connected to GATE=?  >
SMU connected to SOURCE=?  >
SMU connected to BODY=?  >

Hit a "C" for changes or any other key to start.  >
```

Fig. A10



```
SELECT A NUMBER FOR A GIVEN ACTION CAPABILITY=  >
         1)Zoom Using Knob and Keys
         2)Redraw Full Graph
         3)Select New Graph for Current Device
         4)Select New Device
         5)Exit I-V Graphics Menu
```

Fig. A11