A SUBTHRESHOLD CONDUCTION MODEL FOR BSIM

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ABSTRACT

A model for the subthreshold conduction of a MOSFET has been developed and incorporated into the BSIM (Berkeley Short Channel IGFET) model. This subthreshold region model requires three additional electrical parameters in the BSIM process file. The BSIM parameter extraction program has been modified to include the subthreshold region measurements and extractions. The graphics part of the extraction program has also been modified to provide log I_D vs. V_G curves. Good agreements between measured data and calculated results using this subthreshold model have been observed.

ACKNOWLEDGEMENTS

I would like to thank my research advisor, Professor Ping K. Ko, for his support and technical advice throughout the course of my research. I would also like to extend my sincere appreciation to Bing J. Sheu who had provided valuable assistances in many ways. His technical knowledge and encouragement had helped me greatly in completing this work.

I am thankful to Joe Pierret who is now with the Signetics Corp.. His experience with the BSIM extraction program and patience had cleared, for me, many obstacles during the early part of this work. I also thank Min-chie Jeng for his help at the final stage of the project.

I would like to thank my parents, Chang-heng and Hsiu-ching, my brother Danny and my sister Peggy. Their encouragements and support over the past years are greatly acknowledged and deeply appreciated.

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I. INTRODUCTION

With the ever so rapid development of today's integrated circuit technology, a transistor model that is accurate and computationally efficient is of great importance in achieving fast and accurate circuit simulations. A process-oriented short channel MOS transistor model has been developed in Berkeley to meet this need. This BSIM model (Berkeley Short-channel IGFET Model) is physically meaningful and mathematically compact. Thus, while maintaining the accuracy, it requires less execution time of SPICE than prior models. With the capability to extract automatically, from physical devices, all necessary parameters for the model, the model further ensures accurate MOS circuit designs.

The capability of automatic parameter extraction is made possible through an integrated parameter extraction system. This system consists of an HP 9836 controller, an HP 4145A semiconductor parameter analyzer and either an automatic prober such as an Electroglas 2001X or a manual prober such as an Electroglas 1034X. A software program written in HP Pascal serves to control the automatic measurements of device characteristics and the extraction of model parameters. Size independent process files used as SPICE simulation input are created after successful characterization of each die on the wafer being characterized. The original extraction program developed by Brian Scott Messenger extracts, from each physical device, 17 electrical parameters for the BSIM (strong inversion region) model, and provides graphics capability for displaying I-V curves. The program was later enhanced by Joe Pierret who improved the program capability to include manual prober operation control, graphics displaying BSIM parameter vs. W or L, I-V playback with the size independent process file and continuous error checking.

As the world is pushing for an ever denser circuit, a good circuit simulation model has to behave well not only for circuits operating in the strong inversion region, but also for circuits operating in the weak-inversion subthreshold region. Although the BSIM model has been shown to suit well the purpose of simulating process-oriented MOS circuit designs operating in the strong inversion region, no attempt has been made to model the subthreshold conduction until now. To make the BSIM model more complete in simulating today's high density circuits, a model for the subthreshold region conduction has been developed and carefully evaluated. In order to evaluate the subthreshold model and later generate a complete process file for the BSIM model incorporating the subthreshold conduction, work has been done to modify the extraction program for inclusions of the subthreshold parameters extraction and the subthreshold region I-V playback.

This report describes the BSIM subthreshold model and its associated parameters in the BSIM process file. This subthreshold model requires three more electrical parameters in addition to the seventeen parameters used to model operations in the strong inversion region. A major part of the report describes the works done in the parameter extraction program: how it is implemented to measure subthreshold data, to extract the additional parameters and to playback the current (on a logarithmic scale) vs. voltage (on a linear scale) graph. However, sections are also devoted to explanation of the theoretical basis of the model, and both the measurement and simulation results. In the Appendices, a detail user's guide is provided to assist users of the extraction program on booting up the hardware system, loading the program, compiling the program and executing the program to its completion. Differences between this and the previous version of the extraction program are also addressed from both the user's and the program maintainer's point of view.

This report is meant mainly to present the BSIM subthreshold model. Readers are referred to Berkeley ERL memorandum titled A FULLY AUTOMATED MOS DEVICE CHARACTERIZATION SYSTEM FOR PROCESS-ORIENTED INTEGRATED CIRCUIT DESIGN by Brian Scott Messenger [1] and ERL memorandum titled A MOS PARAMETER EXTRACTION PROGRAM FOR THE BSIM MODEL by Joseph R. Pierret [3] for detail descriptions of the BSIM parameter extraction program and ERL memorandum titled COMPACT SHORT-CHANNEL IGFET MODEL (CSIM) by B. J. Sheu et al. [2] for the BSIM strong inversion region model.

II. OVERVIEW OF SUBTHRESHOLD CONDUCTION THEORY

2.1. Introduction

As many applications of MOS devices today, such as high density dynamic circuits, require low leakage specifications, a knowledge of the subthreshold conduction mechanism is critically important in both circuit design considerations and arriving at a good subthreshold conduction model that represents well the behavior of a device operating in this region. Theories and models have long been established to explain and model the subthreshold region. Although researchers have proposed various models for the subthreshold conduction [6]-[8], the underlying theories of these models are all very similar. This chapter briefs on the basic subthreshold conduction theory behind all these models.

2.2. Weak Inversion Region Current Behavior

As most of the early works on insulated gate field-effect transistor emphasizing on its operation in the strong inversion region, conduction below the threshold voltage at which the minority carrier concentration at the channel surface is equal to the impurity concentration in the semiconductor bulk is often ignored. Simple models for the linear and saturation regions present great discrepancies between experimental curves and theoretical results for gate to source voltage near the threshold. As it is observed, the current level in the channel of a device diminishes exponentially with decreasing gate voltage in the weak inversion region instead of dropping abruptly to zero below threshold like most strong inversion region models assumed. Because of the markedly different dependence of carrier density on gate voltage in the subthreshold region, works have been carried out to theorize and model the device behavior in this region.

Unlike the conduction mechanism of a MOS device operating in the strong inversion region where drift current dominates the conduction, the subthreshold region conduction is dominated by diffusion current. Although some authors have formulated the channel current in the subthreshold region as a drift current due to a lateral field [13], the diffusion current dominance in this region is widely accepted as the correct explanation for the exponential behavior of the subthreshold current.

2.3. Some Subthreshold Models

Based on a general one-dimensional model proposed by Sah and Pao for the strong inversion region, researchers have arrived at models that are simple and physically meaningful for the subthreshold region conduction. Expanding on Sah and Pao's model [12] and noting that "the surface concentration is the most informative physical parameter for the subthreshold region", Troutman has derived an expression for the subthreshold current of a long channel device [6].

$$I_{st} = \frac{WqD_{eff}N_o}{L}(1-e^{-U_{DS}}) \qquad (2.1)$$

where N_o is the equilibrium surface concentration, D_{eff} is the effective diffusion coefficient, and $U_{DS} = \frac{V_{DS}q}{kT}$.

With much of the same approach (also based on Sah and Pao's one dimensional model), Barron has also arrived at a similar expression for the subthreshold current of a p-channel device [7]

$$I = \frac{qWD_p n_i L_D e^{\frac{3U_F}{2}}}{L\sqrt{-(U_S+1)}} e^{-U_S}(1-e^{\frac{qV_D}{kT}}) \tag{2.2}$$

where D_p is the hole diffusion coefficient, L_D is the intrinsic Debye length, U_F is the equilibrium Fermi potential (normalized to units of kT/q), n_i is the intrinsic carrier density, and U_S is the surface potential near the source (normalized to units of kT/q).

Taylor, claiming a derivation that "relates more directly to the physics of the conduction mechanism and indicates more clearly the physical limitations of the approximations", has proposed

$$I = \frac{qWD}{L-y_d-y_s}\sqrt{\frac{\epsilon kT}{2q^2 n_i(\frac{q\Phi_S}{kT}+1)}}\, n_i e^{\frac{-q3\phi_F}{2}} e^{\frac{q\phi_S}{kT}}(1-e^{\frac{-qV_{DS}}{kT}}) \tag{2.3}$$

where D is the electron diffusion constant, y_d is the width of drain depletion region at the surface, y_s is the width of source depletion region at the surface, n_i is the intrinsic concentration, ϕ_S is the surface potential (referred to the substrate), kT/q is the thermal voltage, Φ_S is the surface potential (referred to the equilibrium bulk conduction band edge), and ϕ_F is the bulk Fermi potential. The derivation, again, is based on the one-dimensional model [8].

These models, although derived differently, have quite similar expressions. This has presented no surprise since all of them have been derived from the same Sah and Pao's one dimensional model. By imposing reasonable approximations on the otherwise rather complex integral equations, these models have correctly simulated the current behaviors in the subthreshold region and have been shown in good agreements with experimental data.

2.4. Subthreshold Current Dependence

Two important conclusions can be drawn about the subthreshold conduction from these models. First, the subthreshold current increases exponentially with the surface potential. Second, the current is exponentially dependent of the drain voltage; however, this drain voltage dependence ceases for V_{DS} greater than 3 to 5 kT/q. These dependences of subthreshold current on bias voltages are very important in developing the CAD models for the subthreshold region discussed in a later chapter. What is also interesting to note is the similarity between these equations and the equation of the diffusion current in a pn junction or a bipolar transistor in its "on" state. Since the conduction mechanism in a pn junction and a bipolar transistor is well understood to be diffusion dominant, the channel current of a MOSFET flowing in the subthreshold region is further accepted as being correctly theorized to be diffusion dominant.

2.5. Subthreshold Slope

Before going on to the next section, one other thing worth mentioning about the subthreshold region is the subthreshold slope or the gate-voltage swing. It is a convenient measure of the turn-off characteristic of a MOSFET and an important means of extracting parameters for the BSIM subthreshold conduction model described in the following chapter. The subthreshold slope is defined as the derivative of the gate voltage with respect to the log of the subthreshold current. It is often used for seeking influences of surface band-bending, gate insulator thickness, substrate doping, substrate bias and temperature on the subthreshold current behavior [10]. In the derivation of the BSIM subthreshold model, this subthreshold slope is used to calculate the coeffient n. Since n is a critically important parameter in the BSIM subthreshold model, the significance of the subthreshold slope cannot be overlooked.

2.6. Chapter Summary

The above discussions summarized the basic theories on subthreshold region conduction. The BSIM subthreshold model and a couple of other subthreshold models used for CAD purposes are presented in the following chapter.

III. SUBTHRESHOLD CONDUCTION MODELS

3.1. Introduction

In Chapter 2, we have briefed on the subthreshold conduction mechanism. Models derived from the device physics point of view were also briefly summarized. These models which simulate accurately the device behavior in the subthreshold region, however, become inadequate when used in CAD applications, such as a circuit simulation program. In order for a model to be well suited for the purpose of circuit simulation, it must be simple enough for the sake of computational efficiency and memory requirements, yet accurate enough to be able to arrive at a simulation that is at an acceptable level of accuracy. Detailed numerical models, such as those presented in Chapter 2, give excellent simulation results. However, when it comes to the computer execution time, these models which require complicated numerical analysis to arrive at the result are simply not practical enough to be implemented in a circuit simulator such as SPICE2.

Efforts have been devoted in developing accurate and efficient models for CAD applications. Models that are mathematically compact and physically meaningful have been reported [4]-[5]. These models, though still based their derivations on the physics of the device behavior, have been derived with one more requirement in mind that is to be mathematically efficient. As a result, some empirical parameters are employed in these models to simplify complex equations for easier computation.

In this chapter, we first would like to investigate two models that have successfully modeled the subthreshold region and been implemented in SPICE. Then, based on these models, we will present the BSIM subthreshold model.

3.2. Yang and Chatterjee's Model [5]

Realizing the restrictions of the computational efficiency and memory availability, Yang and Chatterjee have proposed a "quasi-physical" model with a parameter vector optimally extracted from physical devices. Its derivation is based on the modified Shichman-Hodges model used in SPICE2. Due to the presence of a significant lateral electric field, a multiplier is incorporated in the channel-charge equation for a long channel device in the strong inversion region

$$q_c = -C_{ox}(V_{GS}-V_{TH}-V_Y) \tag{3.1}$$

This incorporation of a multiplier α_s which is $\alpha+\gamma(V_{GS}-V_{TH})$ results in a modified Shichman-Hodges drain current equation for various regions of MOS operation above threshold.

$$\alpha_s\beta_n\left[2(V_{GS}-V_{TH})V_{DS}-\alpha_s V_{DS}^2\right] \qquad V_{GS}>V_{G\,sat}$$

$$\beta_n(V_{GS}-V_{TH})^2\left|1+\lambda\left(\frac{\alpha}{\alpha_s}\right)^2(V_{DS}-V_{D\,sat})\right| \qquad V_{G\,sat}\geqslant V_{GS}>V_{TH}$$

$$0 \qquad V_{GS}\leqslant V_{TH} \tag{3.2}$$

In order to model the subthreshold current, the subthreshold mobile charge density is derived by solving Poisson's equation with Q_s equals zero. With some approximations in the derivation, Yang and Chatterjee arrived at

$$q_{c,sub} = -\frac{\sqrt{2}\epsilon_s A_o}{\beta L_D} e^{N_G \beta (V_{BY} - 2\phi_f)} (e^{N_G \beta \psi_s} - 1) \tag{3.3}$$

where $A_o \approx 0.3$, $N_G \approx 1.0$ and $\beta = \frac{q}{kT}$. In Eq.3.3, A_o is an empirical parameter, N_G represents the uncertainty of the exact device temperature, ϕ_f is the bulk Fermi potential and ψ_s is the surface potential. And this leads to the subthreshold current equation,

$$I_{D,sub} = \beta_s e^{N_G \beta (V_{BS} + \phi_s - 2\phi_f)} (1 - e^{-N_G \beta V_{DS}}) \tag{3.4}$$

With 3 parameters N_G, ϕ_f and β_s extracted directly from physical device, this model seems to agree quite well with experimental results.

3.3. Antognetti et al.'s Model [4]

Aimed at improving the subthreshold model presently implemented in SPICE2, Antognetti et al. have also derived a subthreshold model that is fast in execution and reasonably accurate at simulating device characteristics in the weak inversion region. Starting with the diffusion current expression for an n-channel device

$$I_{diff} = -qD_n W x_d \frac{dn(y)}{dy} \bigg|_{y=y'} \tag{3.5}$$

Antognetti et al. have arrived at

$$I_{diff} = \frac{qD_n \eta \bar{x}_d n_{ch} W}{L_n \tanh(\frac{L_{eff}}{L_n})} \left[1 - e^{-\frac{V_{DS}}{V_T}} \right] \tag{3.6}$$

with some assumptions on the drain voltage and channel charge concentration.

From the observation that the channel charge concentration increases very slowly at higher gate voltage, Antognetti et al. concluded that the subthreshold diffusion current may be written as

$$I_{diff} = \frac{qD_n \eta \bar{x}_d W}{L_n \tanh(\frac{L_{eff}}{L_n})} \left[1-e^{-\frac{V_{DS}}{V_T}}\right] \frac{n_s n_x}{n_s + n_x} \tag{3.7}$$

where n_x is the limiting channel charge concentration and

$$n_s = N_{AS} e^{\alpha_1 \frac{V_{GS}-V_{TH}}{(1+\frac{C_x}{C_{ox}})V_T}} \tag{3.8}$$

In Eq.3.8, N_{AS} is the doping concentration in the channel, V_T is the thermal voltage, C_x accounts for the surface state charge and the depletion charge and α_1 accounts for the voltage dependence of the depletion charge. This model is also claimed to be in good agreement with experimental data. Yet, several parameters still need to be pre-evaluated for the utilization of this model.

3.4. The BSIM Subthreshold Model

The BSIM subthreshold conduction model has a lot in similarity with the two models described above. Aimed at meeting the requirements of being accurate and CPU-time effective, the BSIM subthreshold model combines Yang and Chatterjee's model with Antognetti et al's model to arrive at a model that is easily integrated into the original BSIM model and agrees well with the measured subthreshold I-V characteristics.

The BSIM subthreshold model was first proposed by Bing J. Sheu of the University of California at Berkeley. Realizing that continuity has to be assured at the transition between the subthreshold region and the strong inversion region in both the current and the first derivative of the current to enable easier convergence in circuit simulation, the complete drain current of the BSIM model is proposed as

$$I_{DS,complete} = I_{DS,strong-inversion} + I_{DS,subthreshold} \qquad (3.9)$$

In the strong inversion region version of the BSIM model, the drain currents for the linear region and saturation region are [2]

$$I_{DS,linear} = \frac{\beta_o}{\left[1+U_o(V_{GS}-V_{TH})\right](1+U_1 V_{DS})}$$

$$\left[(V_{GS}-V_{TH})V_{DS}-\frac{a}{2}V_{DS}^2\right] \qquad V_{GS} \geqslant V_{TH}, 0<V_{DS}<V_{D,sat} \qquad (3.10)$$

$$I_{DS,saturation} = \frac{\beta_o}{\left[1+U_o(V_{GS}-V_{TH})\right]2aK}(V_{GS}-V_{TH})^2$$

$$V_{GS} \geqslant V_{TH}, V_{DS} > V_{D,sat} \qquad (3.11)$$

where $\beta_o = \mu_o C_{ox} \frac{W}{L}$ and the current below threshold is simply zero. In order to model the strong inversion region current, 17 size-dependent electrical parameters are extracted automatically from physical devices and are developed into a process file that contains size-independent parameters. The I-V playback from the size independent process file parameters have proven that the model works well for the region above threshold.

The incorporation of subthreshold region in the BSIM model has added three more electrical parameters to the parameter extraction of each physical device. The diffusion current model proposed assumes the general form of the models reported by Yang and Antognetti

$$I_{\exp} = I_{pf}\, e^{\frac{V_{GS}-V_{TH}}{nV_{tm}}} \left[1-e^{-\frac{V_{DS}}{V_{tm}}} \right] \tag{3.12}$$

where I_{pf} is a pre-factor term, V_{tm} is kT/q and n is the coefficient to be modeled by 3 extracted electrical parameters for the subthreshold region. As the gate voltage is increased above the threshold voltage, the subthreshold current approaches a constant. This results in an upper limit being imposed on the subthreshold current. In our model, this limiting current level is experimentally determined to be the current when the gate voltage is 3kT/q above the threshold voltage. Thus,

$$I_{sub,lim} = \beta_o \frac{(3V_{tm})^2}{2} \tag{3.13}$$

since at $V_{GS} = \frac{3kT}{q} + V_{TH}$, the device is operating in the saturation region where the drain current is in the form of Eq. 3.11. In order to give a more constant limiting current and a simpler first derivative, the denominator of

Eq. 3.11 is stripped off in Eq. 3.13. For this denominator is only significant in the strong inversion region model, it is never included in the subthreshold current calculations.

With a similar derivation as Yang's to arrive at his model, the pre-factor term in Eq. 3.12 can be written as

$$I_{pf} = \beta_o n (V_{tm})^2 \qquad (3.14)$$

However, as later experiments showed, this pre-factor does not quite give an accurate subthreshold current. In order to compensate the discrepancy between measured and calculated data, the pre-factor employed in the BSIM model is determined to be

$$I_{pf} = \beta_o (V_{tm})^2 e^{1.8} \qquad (3.15)$$

This pre-factor gives not only a much better agreement between measured and calculated data, but also a much simpler first derivative of the current which is rather important in SPICE implementation consideration.

Having obtained both the limiting current and the diffusion current in the subthreshold region, the final subthreshold current is modeled as

$$I_{subthreshold} = \frac{I_{exp} I_{sub\,lim}}{I_{exp} + I_{sub\,lim}}, \qquad (3.16)$$

This equation correctly models the asymptotical nature of the subthreshold current as shown in Fig.3.1.

The coefficient n in the diffusion current equation is modeled by three parameters extracted from physical devices: n0, X2nb, X3nd. Linear dependences on both the drain voltage and the substrate bias has been experimentally proven to be adequate for modeling n. The equation used is as follow

$$n = n0 + X2nbV_{BS} + X3ndV_{DS} \tag{3.17}$$

and n0, X2nb, X3nd are determined using linear least square fit over combinations of six values of V_{BS} and four values of V_{DS}. As Fig.3.2 to Fig.3.8 show, though the dependence on V_{DS} is quite linear, the V_{BS} dependence seems not. However, we have conducted various experiments to determine the V_{BS} dependence of n and none of them seemed to be significantly better than the linear dependence. Among the dependences experimented are negative exponential V_{BS} depencence, linear reciprocal V_{BS} dependence and V_{BS} square dependence. Therefore, the dependences of n on both V_{DS} and V_{BS} are modeled as linear functions in the BSIM subthreshold region model.

The way n is calculated at each specific V_{BS} and V_{DS} bias is by first obtaining the subthreshold slope S from the measured log I_D vs. V_G curve. This slope is then multiplied to a constant that relates S to n. Since the subthreshold slope (gate-voltage swing) is defined as

$$S = \ln(10)\frac{dV_{GS}}{d(lnI_{DS})} \tag{3.18}$$

if we assume that, in the region well below the threshold voltage where the subthreshold slope is taken, the subthreshold current is approximately equal to Eq. 3.12, i.e. the limiting current has very little contribution in Eq. 3.16, it is easy to show that

$$n = \frac{1}{V_{tm}\ln(10)}S \tag{3.19}$$

The above assumption is experimentally confirmed to be valid as experimental curves and theoretical curves displaying good agreements as shown in Chapter 5.

3.5. Chapter Summary

In this chapter, we have presented the theoretical aspect of the BSIM subthreshold model. In the following chapters, we will see how the subthreshold parameter extraction is integrated into the BSIM parameter extraction program and how the simulated results compare with measurement data.

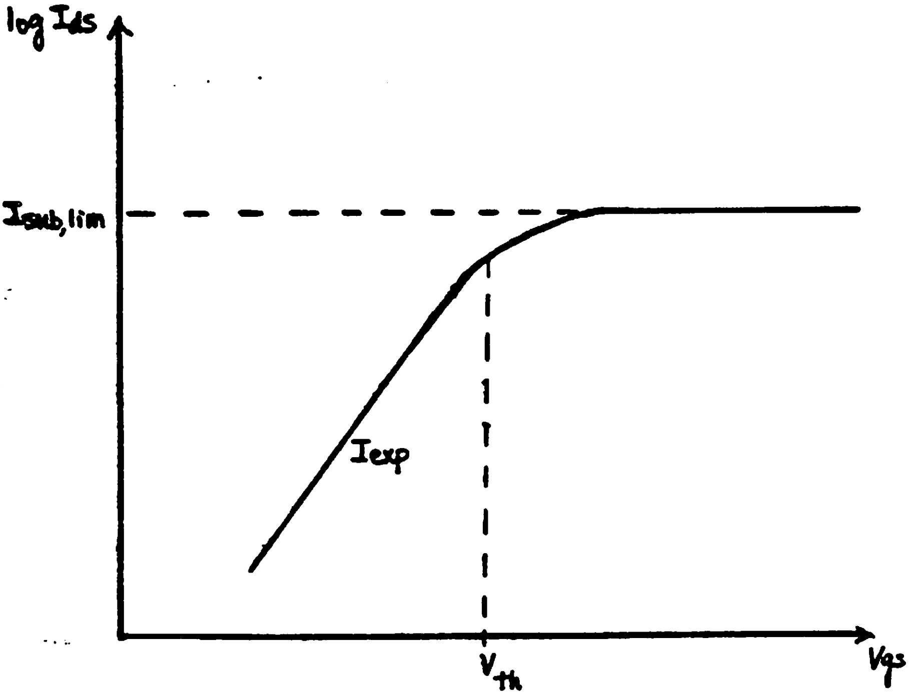


Fig. 3.1 Subthreshold drain current behavior

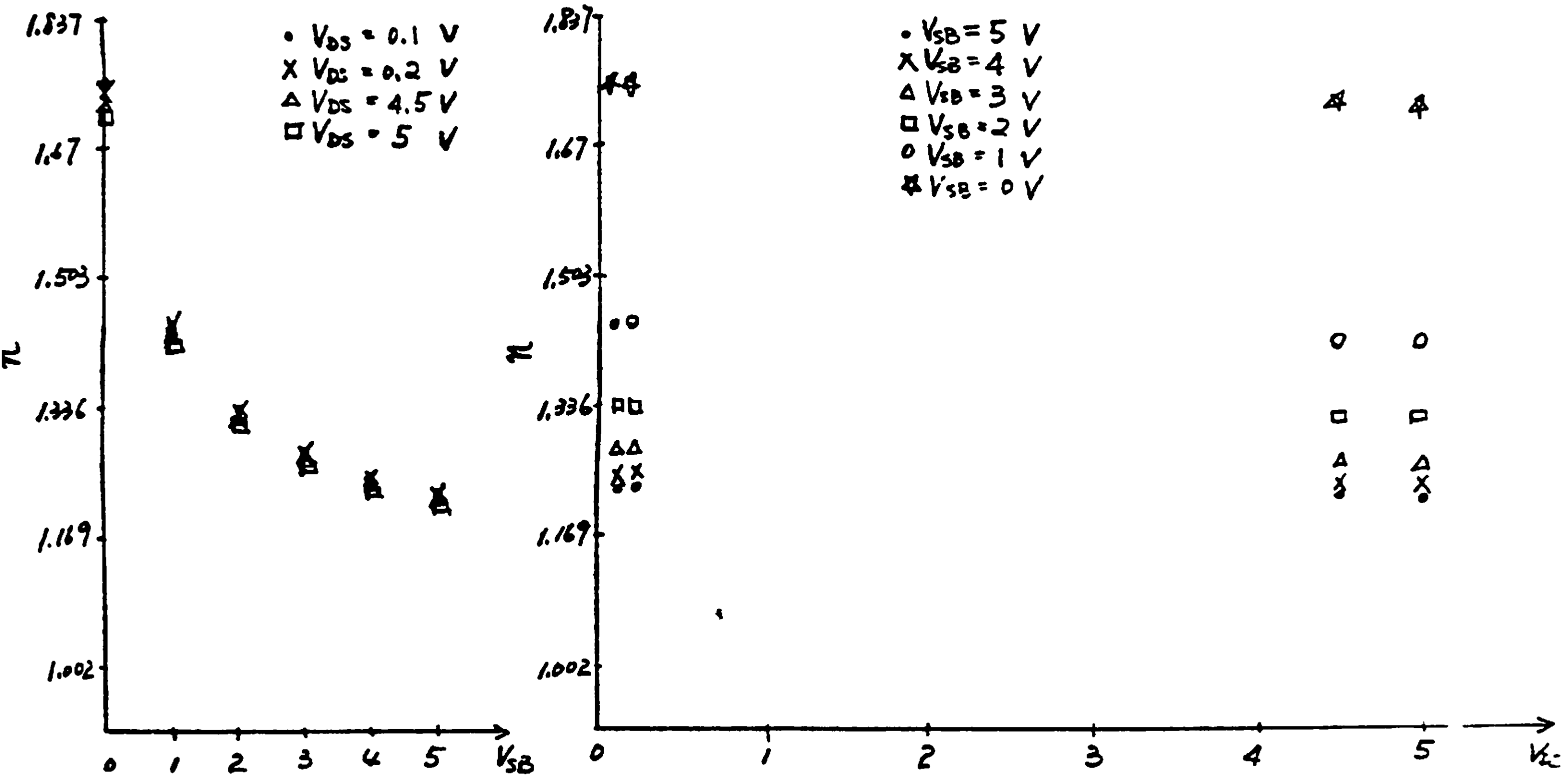


Fig. 3.2 Vbs and Vds dependences of coefficient n
W=2um L=4um

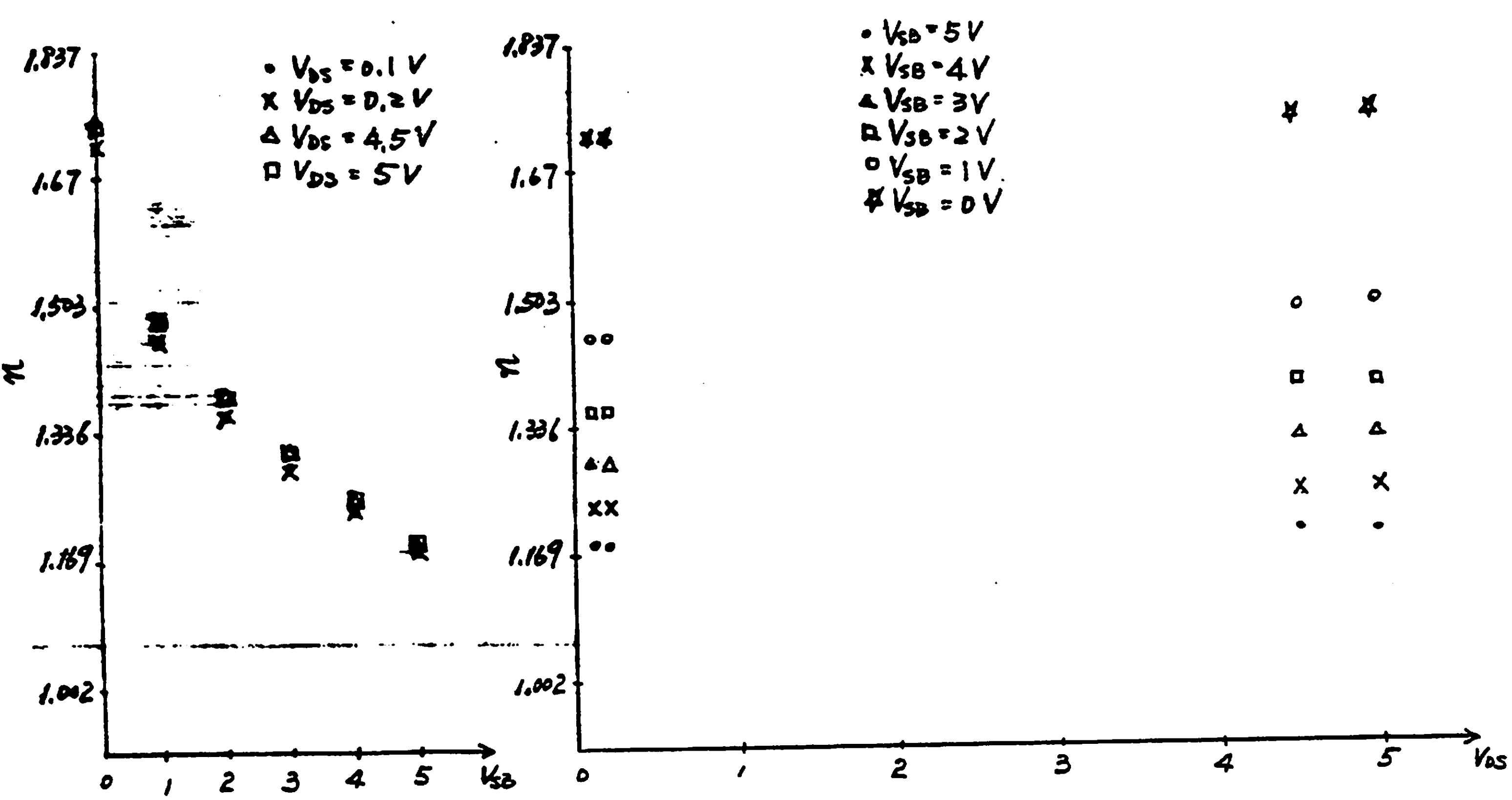


Fig. 3.3 Vbs and Vds dependences of coefficient n
W=20um L=20um

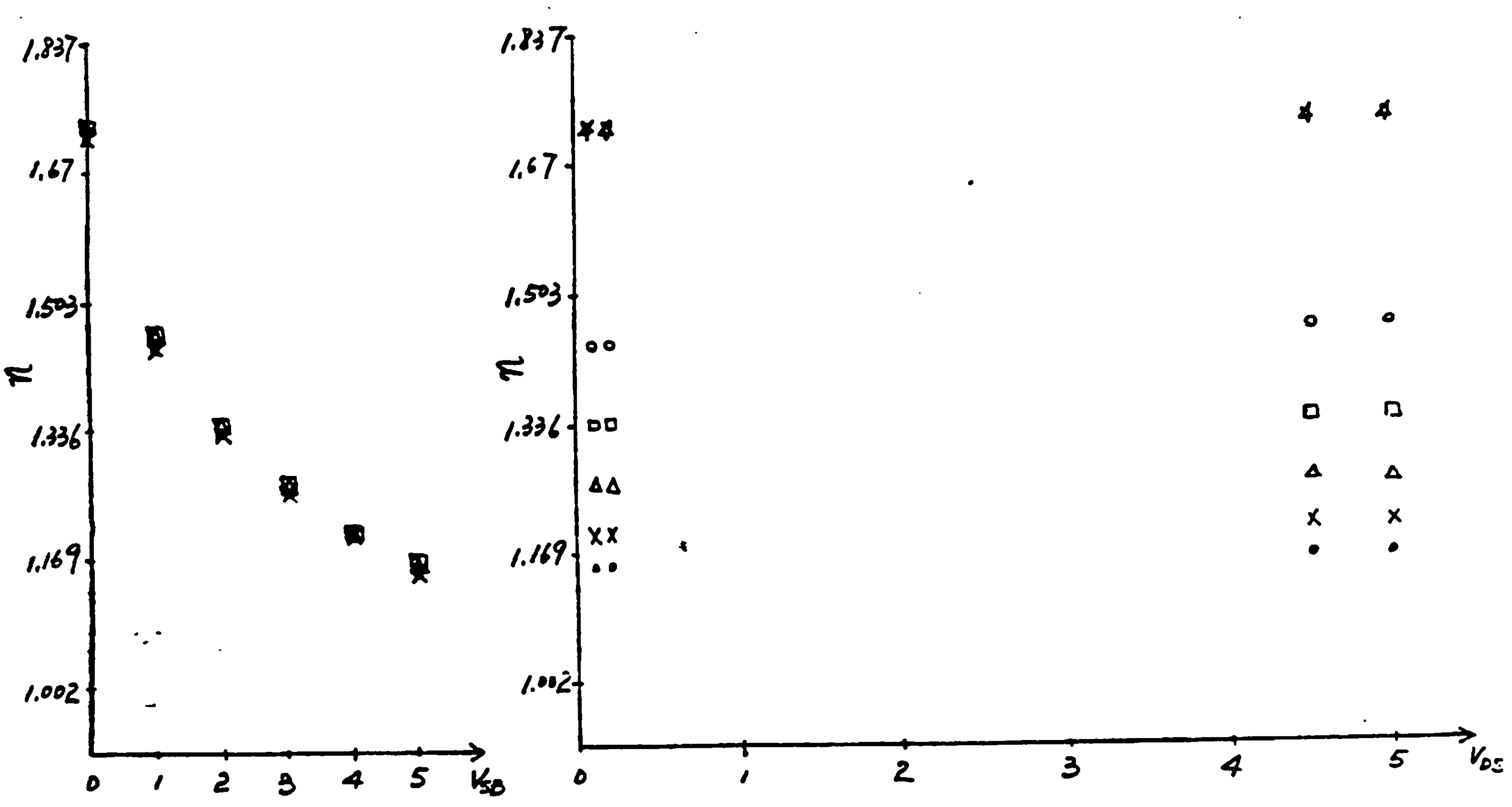


Fig. 3.4 Vbs and Vds dependences of coefficient n
W=20um L=4um

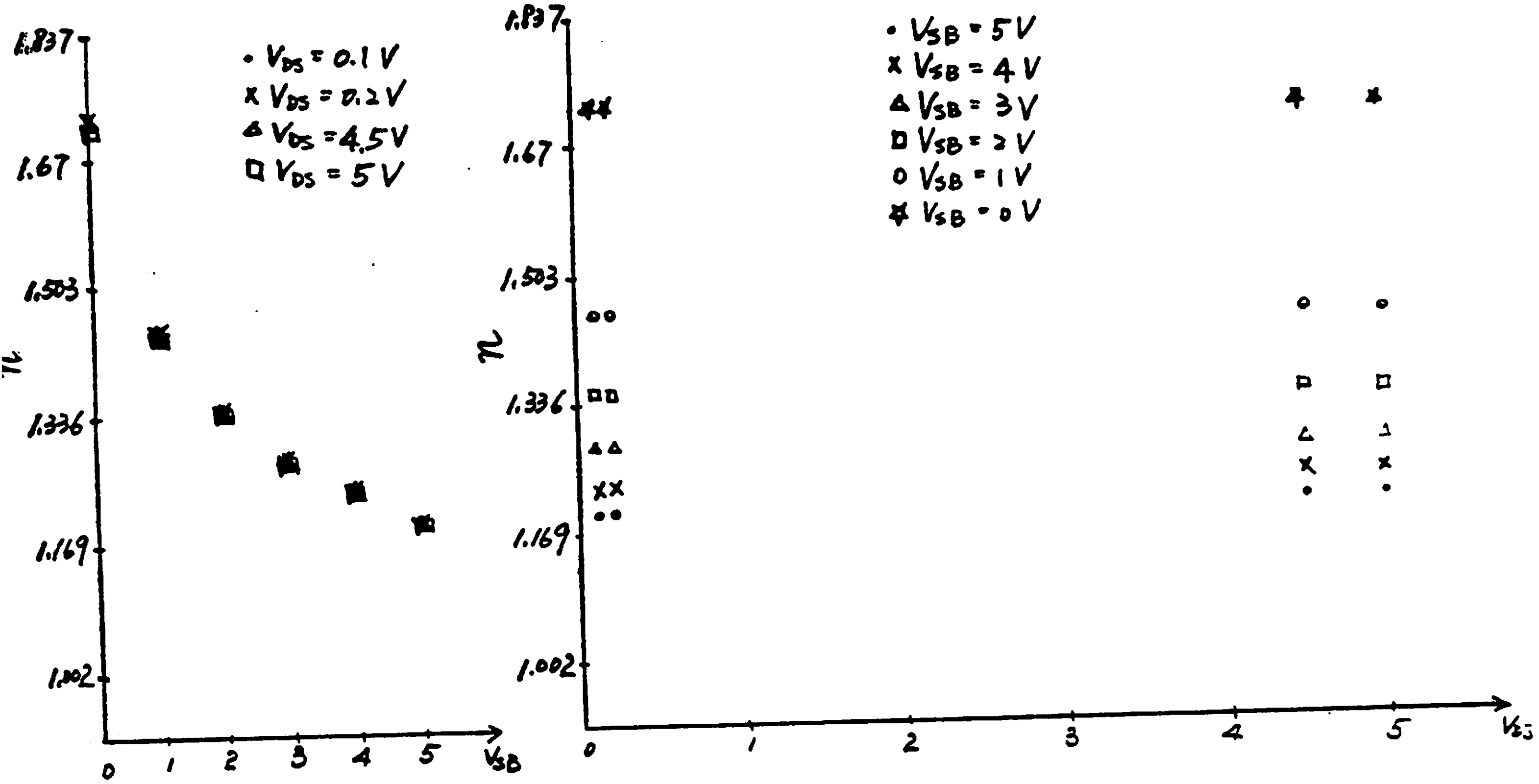


Fig. 3.5 Vbs and Vds dependences of coefficient n
W=4um L=4um

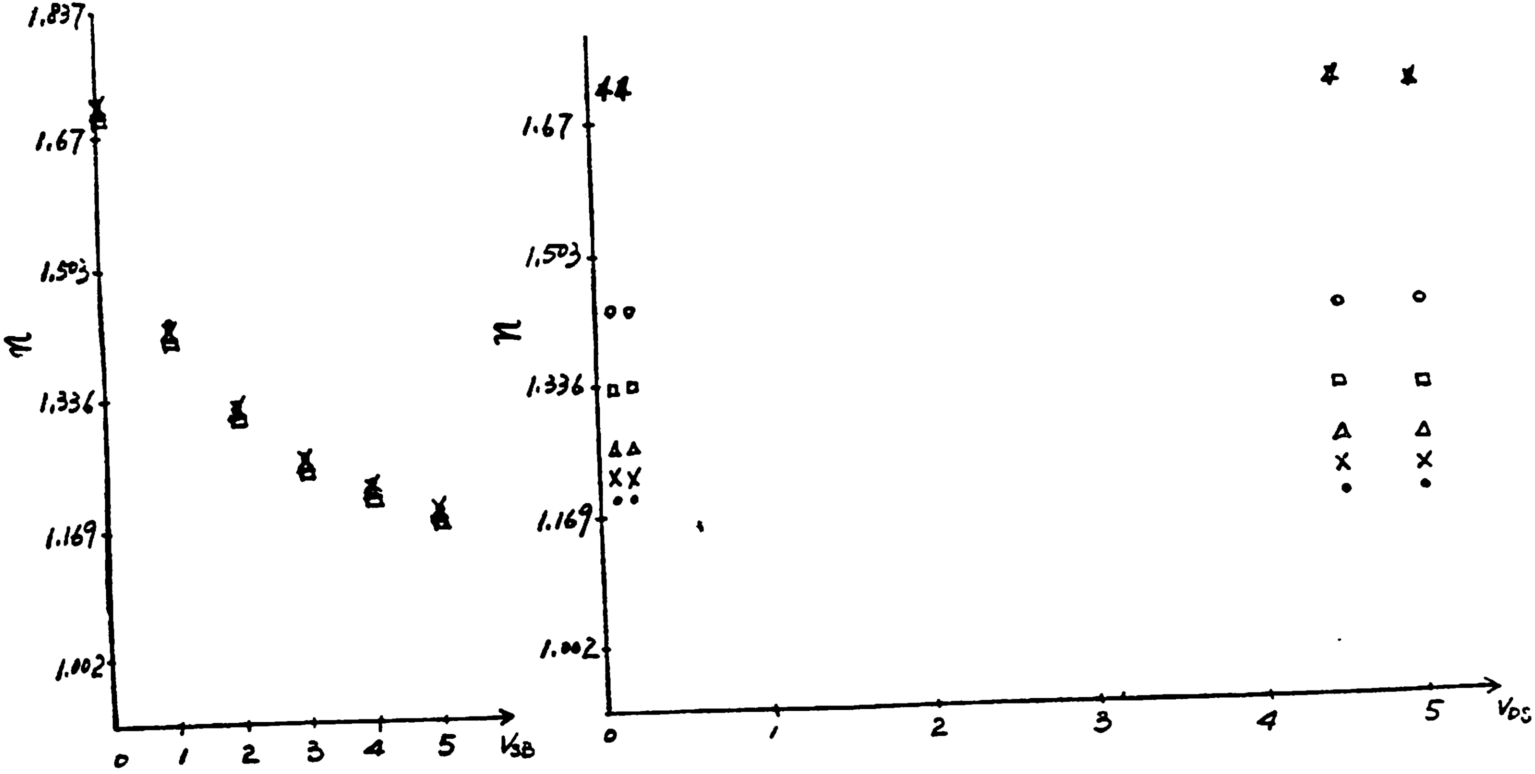


Fig. 3.6 Vbs and Vds dependences of coefficient n
W=3um L=4um

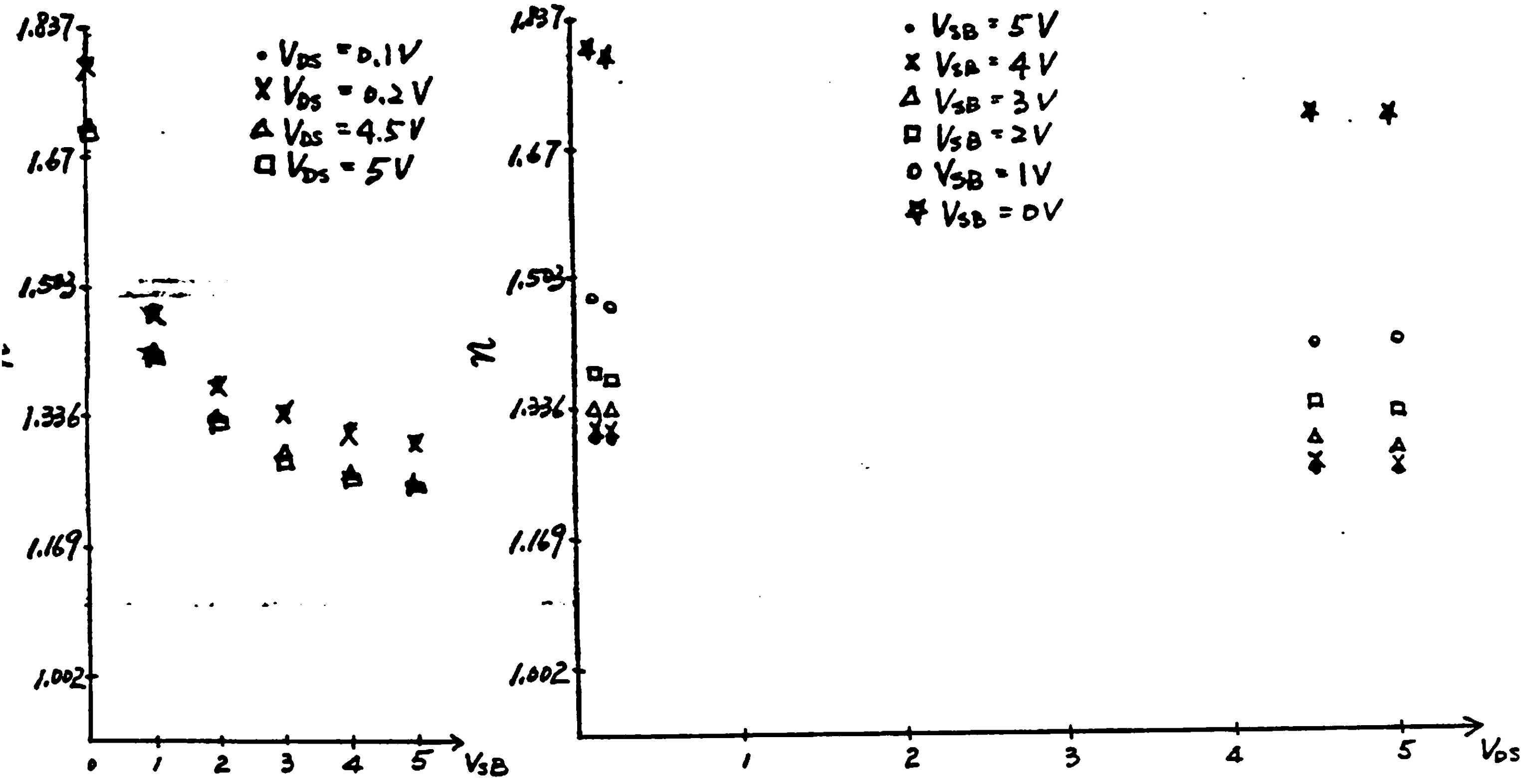
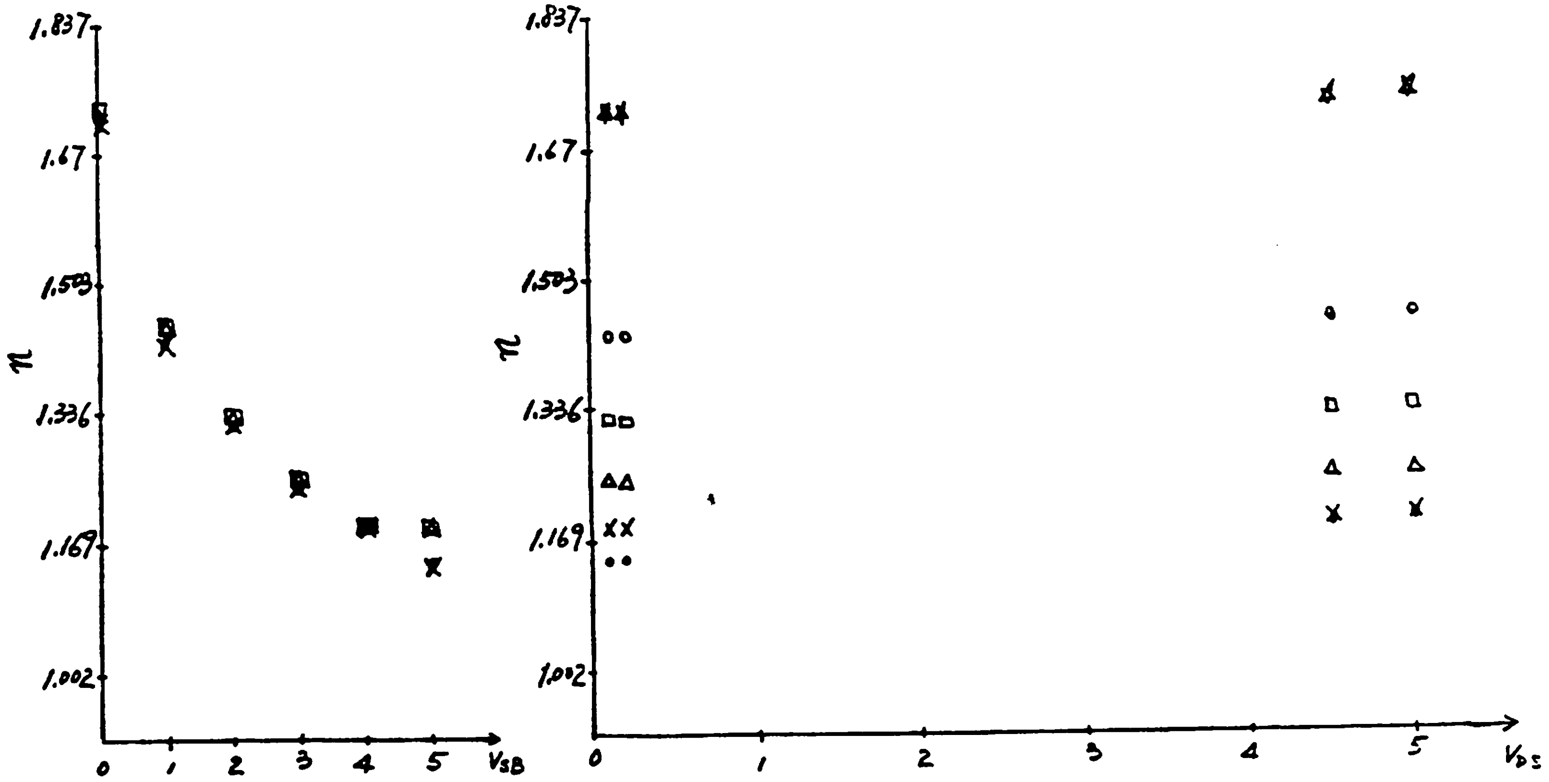


Fig. 3.7 Vbs and Vds dependences of coefficient n
W=1.5um L=4um



2 or 3.5

Fig. 3.8 Vbs and Vds dependences of coefficient n
W=20um L=3um

IV. IMPLEMENTATION IN BSIM PARAMETER EXTRACTION PROGRAM

4.1. Introduction

The BSIM parameter extraction program, before the subthreshold part is added, contains measurement routines, 17 electrical parameter extraction routines, graphics routines and process file creation routines [1], [3]. The measurement routines control the HP 4145A parameter analyzer to obtain data for extraction routines to generate electrical parameters by least square fitting the measurement data. The graphics routines display, at user's will, various I-V curves (I_D vs. V_D, I_D vs. V_G, ln I_D vs. V_D) and curves showing the dependence of each BSIM parameter on W or L. The process file generation routines create a process file containing size-independent parameters. This process file is then used as input for SPICE simulations utilizing the BSIM model.

In order to extract the parameters needed to model the subthreshold conduction, measurement routines are modified to obtain more data points in the subthreshold region. Graphics routines are also modified to display more meaningful I-V curves (log I_D vs. V_G) for the subthreshold region. Number of parameters that may be plotted against W or L is increased from 17 to 20 with the addition of 3 subthreshold parameters. And most important of all, the process file now contains size-independent parameters for modeling the subthreshold region, and SPICE simulations may be done accurately with the BSIM model for circuits with devices operating in the subthreshold region.

4.2. Modifications in Measurement Routines

Since only a small V_{GS} sweep region below threshold is needed to obtain the subthreshold slope and the original strong inversion data measurements cover the entire range of gate voltage sweeping from 0 to V_{DD}, modifications are necessary to define the range of each subthreshold data measurements. Due to the data buffer limits of the HP 4145A, meaningful data for the subthreshold region cannot be obtained with measurements that sweep V_G from 0 to V_{DD}. Thus, a gate voltage sweep range is defined solely for subthreshold measurements. The reason for defining a subthreshold measurement range is that in doing so, smaller V_{GS} stepping may be used. Because the subthreshold region is only a very small portion of the entire I_D vs. V_G curve, smaller V_{GS} stepping will give more data points in any given V_{GS} sweep range. For measurements used to extract those 17 strong inversion region parameters, data points are taken every 0.1 volt of the gate voltage. This means that there are only 3 or 4 points taken in the subthreshold region. It is certainly not very reliable to extract parameters from 3 or 4 data points.

As it is now implemented in the extraction program, data points are taken every 0.04 volt of the gate voltage which sweeps from (V_{TH}-0.5) to (V_{TH}-3kT/q) for the subthreshold measurements. This range of the subthreshold region ensures that data taken fall in the linear part of the log I_D vs. V_G curve so that the subthreshold slope may be calculated. The V_{GS} stepping of 0.04 volt guarantees that there will be at least 10 data points in the range defined above. Two points in the linear portion are then optimally selected to obtain S as follows,

$$S = \left| \frac{\ln(I_{DS,data1}) - \ln(I_{DS,data2})}{V_{GS,data1} - V_{GS,data2}} \right| \ln(10) \qquad (4.1)$$

Once S is calculated, n follows right through.

In order to obtain subthreshold data as described above, V_{TH} has to be defined. The threshold voltage derived for the BSIM model takes the form of [2]

$$V_{TH} = V_{FB} + 2Phif + K1 * \sqrt{2Phif - V_{BS}} - K2 * (2Phif - V_{BS}) - \mathrm{ETA} * V_{DS} \quad (4.2)$$

where V_{FB}, 2Phif, K1, K2 and ETA are all extracted parameters. Thus, it is apparent that subthreshold measurements can only be done after the original 17 parameters have been extracted. This is exactly how we have implemented the subthreshold region measurements.

Once the measurements are completed and n is calculated for every V_{BS} and V_{DS} values, the 3-variable least square routine is called to extract the 3 subthreshold electrical parameters, n0, X2nb and X3nd.

4.3. Modifications in Graphics Routines

The major modification made in the graphics routine is changing the ln I_D vs. V_D routine to log I_D vs. V_G. This new graphics routine shows clearly the current behavior in the subthreshold region. A low current limit is set at 1 pico amp. For measured current data values below this limit, they are all set equal to 1 pico amp. The upper bound of the graph is, as implemented before, autoscaled to show a most complete display possible.

As for the abscissa, the gate voltage is swept from 0 to V_{DD}-2V_{DD}/5. Thus, if V_{DD} is equal to 5 volts, the curves are plotted with V_{GS} varying from 0 to 3 volts for n-channel device. The reason for not displaying the complete graph with V_{GS} varying from 0 to V_{DD} is again due to the limitation of the HP 4145A buffer capacity. Since the HP 4145A buffer can only store 512 data points, stepping V_{GS} at 0.04 volt for 6 different V_{BS} biases over the entire 0 to V_{DD} range will exceed the limit of data points that HP 4145A is capable of measuring. Because this graph is selected mainly for viewing the subthreshold current behavior, current measurements at V_{GS} higher than 3 volts (if V_{DD} is 5 volts) are relatively unimportant. The other two graph selections (I_D vs. V_G ; I_D vs. V_D) are much meaningful for viewing the strong inversion region current behavior.

4.4. More Modifications in The Parameter Extraction Program

Other modifications of the extraction program include expanding the size of the arrays for process file parameter storage, plotting 3 subthreshold parameters vs. W or L and updating the BSIM simulation function. The BSIM simulation function is called to calculate the current for comparison with measured data using the BSIM model. Zero current level was implemented in the function for V_{GS} less than the threshold voltage. With the incorporation of the subthreshold model, currents are calculated in the weak inversion region and the limiting subthreshold current is added to the strong inversion region current to give a complete drain current characteristics as described in Chapter 3. Modifications have also been made to provide users with more freedom in selecting devices to be included in the process file generation. At the end of each device measurement, user has a chance to discard or remeasure the device characteristics if the measurements were not satisfactory enough. In granting user an opportunity to save the whole measurement process while generating a process file that requires data being taken from multiple devices, time may be saved considerably in many cases when bad measurements unpredictably strike.

4.5. Chapter Summary

Discussions presented in this Chapter summarize how the subthreshold model is integrated into the BSIM parameter extraction program. For more information on changes made to the extraction program, readers are referred to Appendix 2.

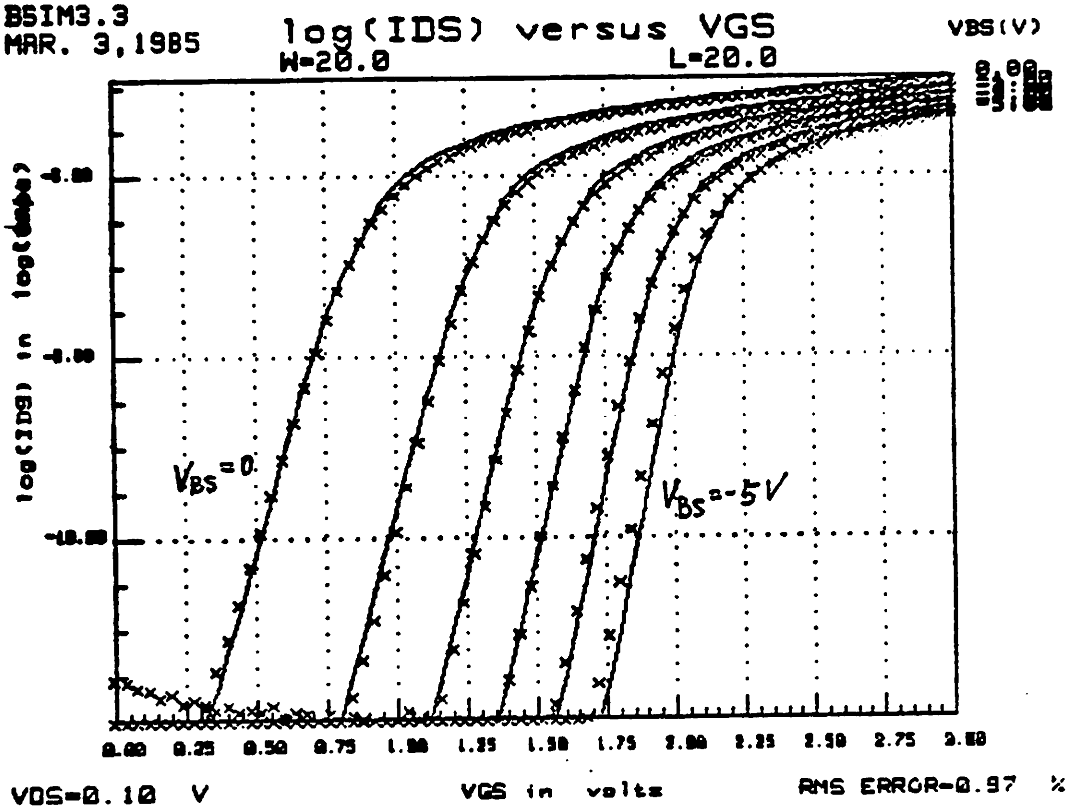
V. EXPERIMENTAL RESULTS

This chapter is devoted to experimental results obtained from various devices. Both measurement curves and simulated curves are shown for each device characterized. Two groups of curves are shown in this chapter. Log I_D vs. V_G curves give a clear picture of the subthreshold current behavior, and I_D vs. V_G curves show the traces of the strong inversion region currents.

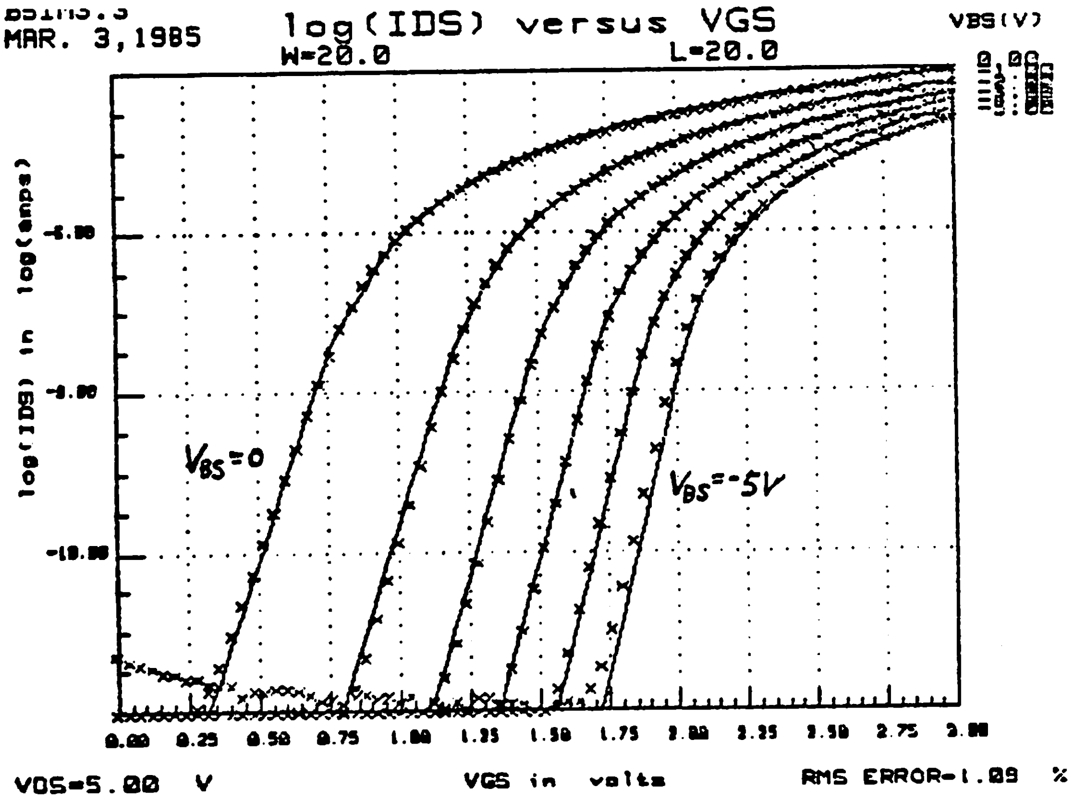
A 2um CMOS process with 300 angstrom oxide thickness wafer from XEROX PARC is characterized. Measurement curves are directly obtained from the HP 4145A, and simulation curves are play-backs from process file generated with devices of various sizes. Devices used to generate this process file are W=20um L=20um, W=20um L=4um, W=20um L=3um. W=3um L=4um, W=4um L=4um, W=20um L=2.5um. and W=2um L=4um for both N-channel and P-channel devices. N channel devices, as well as P channel devices are characterized and all device sizes are indicated on the figures.

As can be seen from the log I_D vs. V_G graphs. the subthreshold model works well in simulating the measured subthreshold current. Since the BSIM model has already been proven to work rather well for strong inversion region, it is vitally important that the subthreshold region model should not, in any way, affect the original model. As one can see from I_D vs. V_G curves. the incorporation of the subthreshold current in the BSIM model is shown to have virtually no effect on the strong inversion region current simulation.

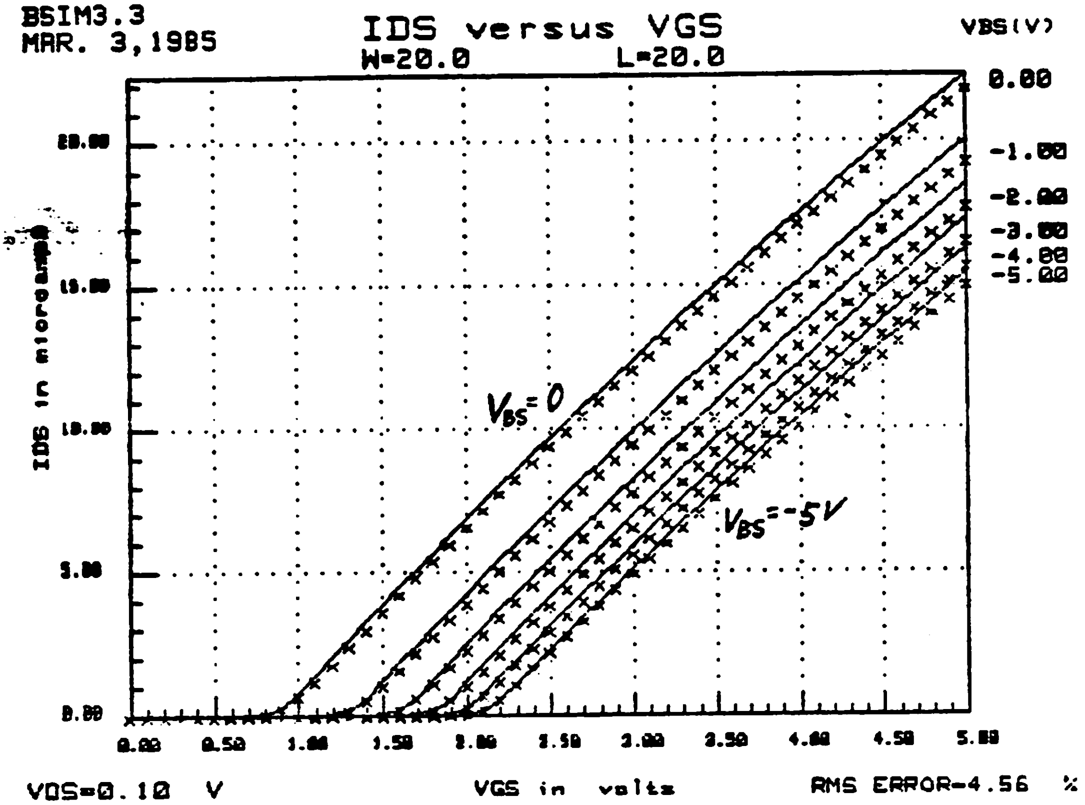
These results have experimentally confirmed the correctness of the proposed subthreshold model. Along with the theoretical basis of this model dicussed previously, the BSIM subthreshold model is proven to be a well acceptable model for simulating circuits with devices operating in the subthreshold region.



N-channel device W=20um L=20um Vds=0.1V



N-channel device W=20um L=20um Vds=5.0V



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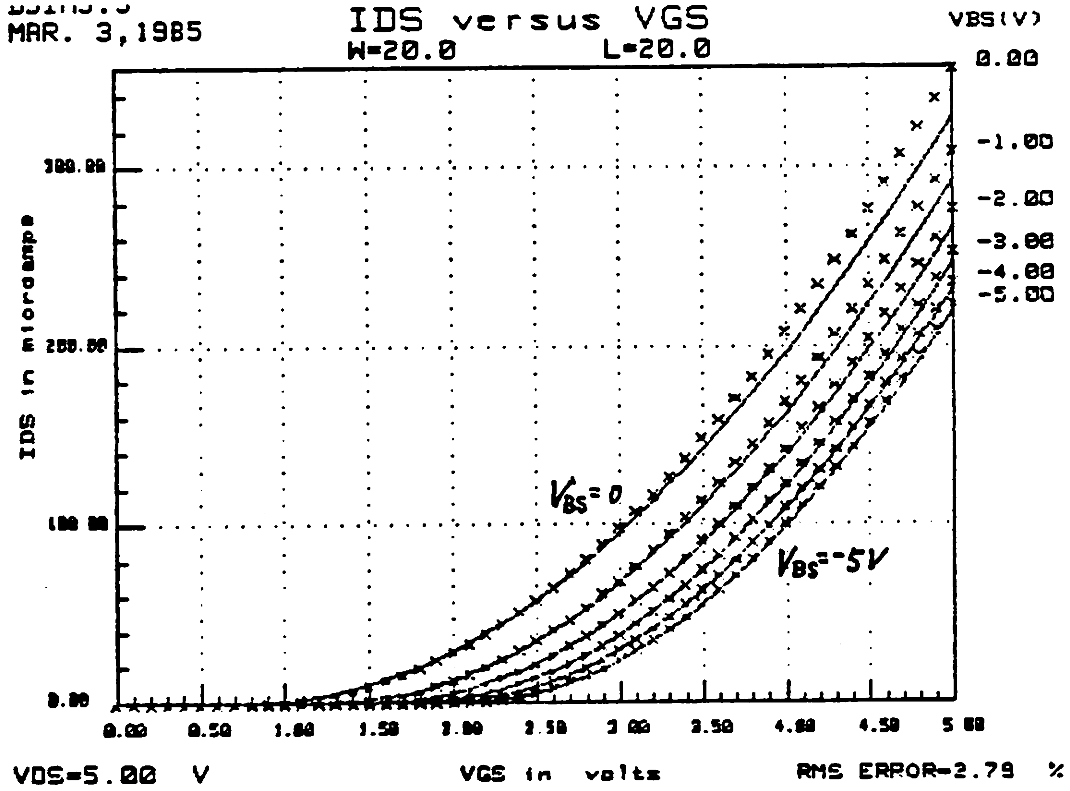

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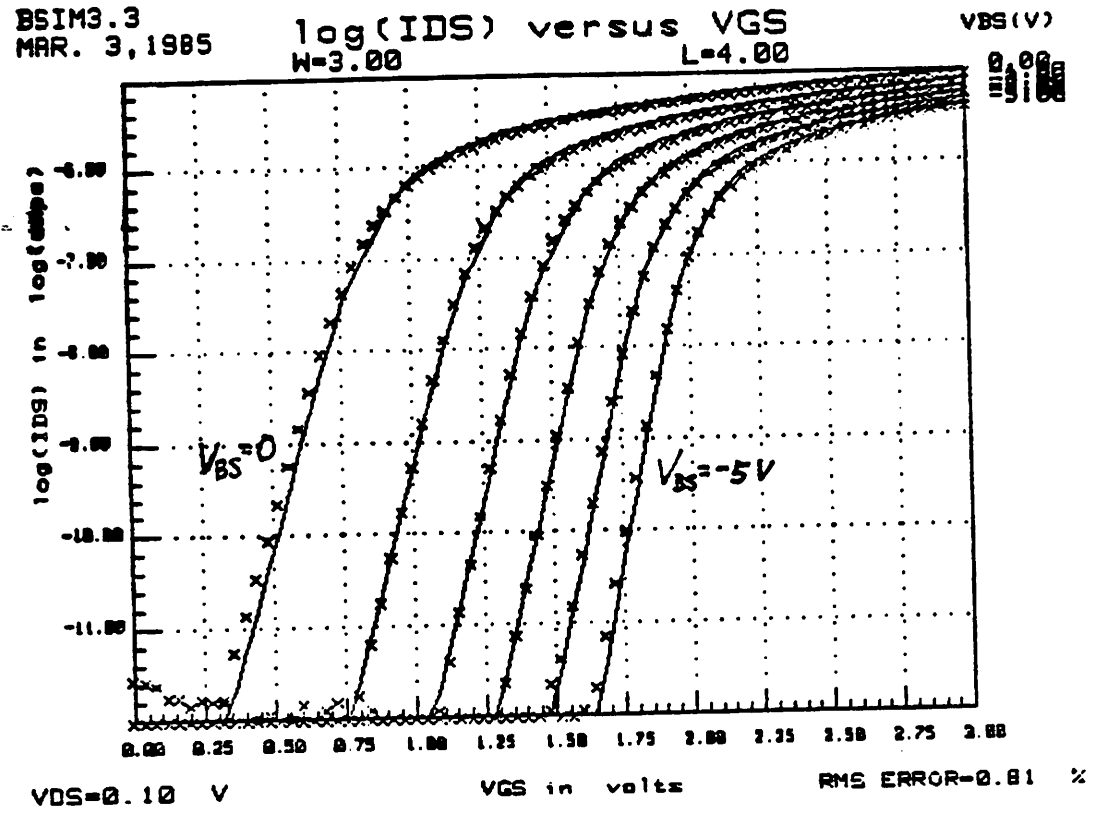

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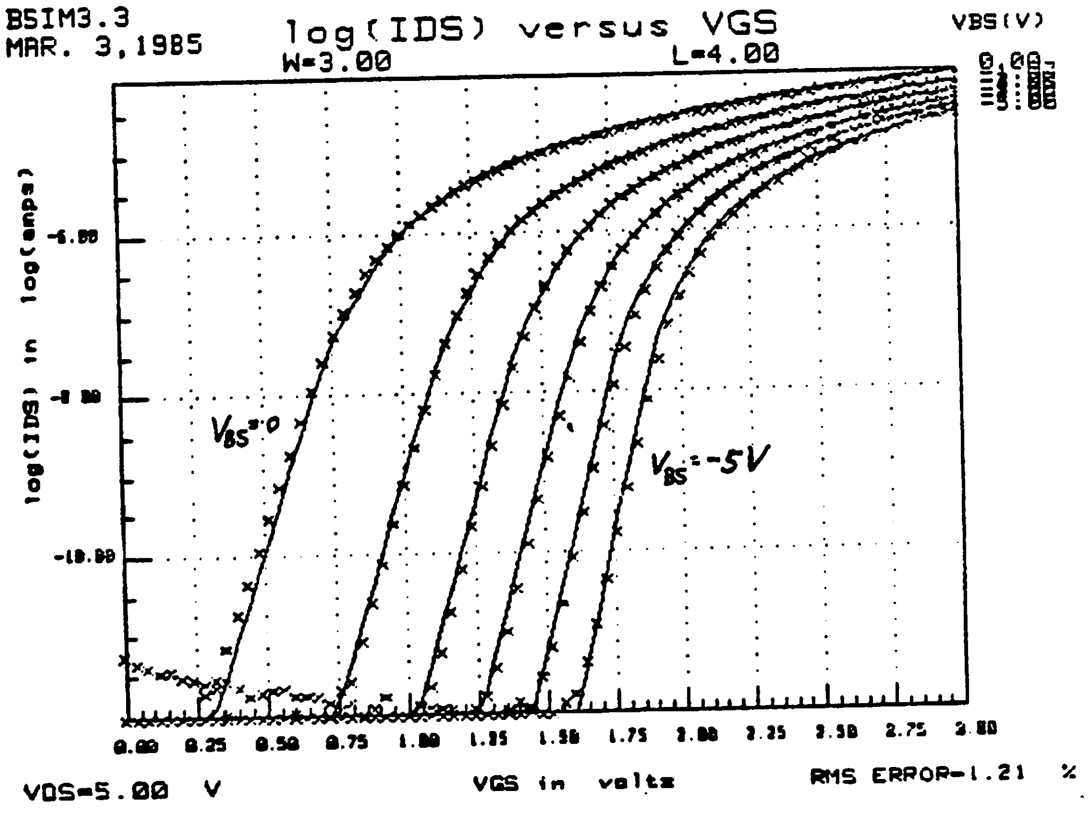

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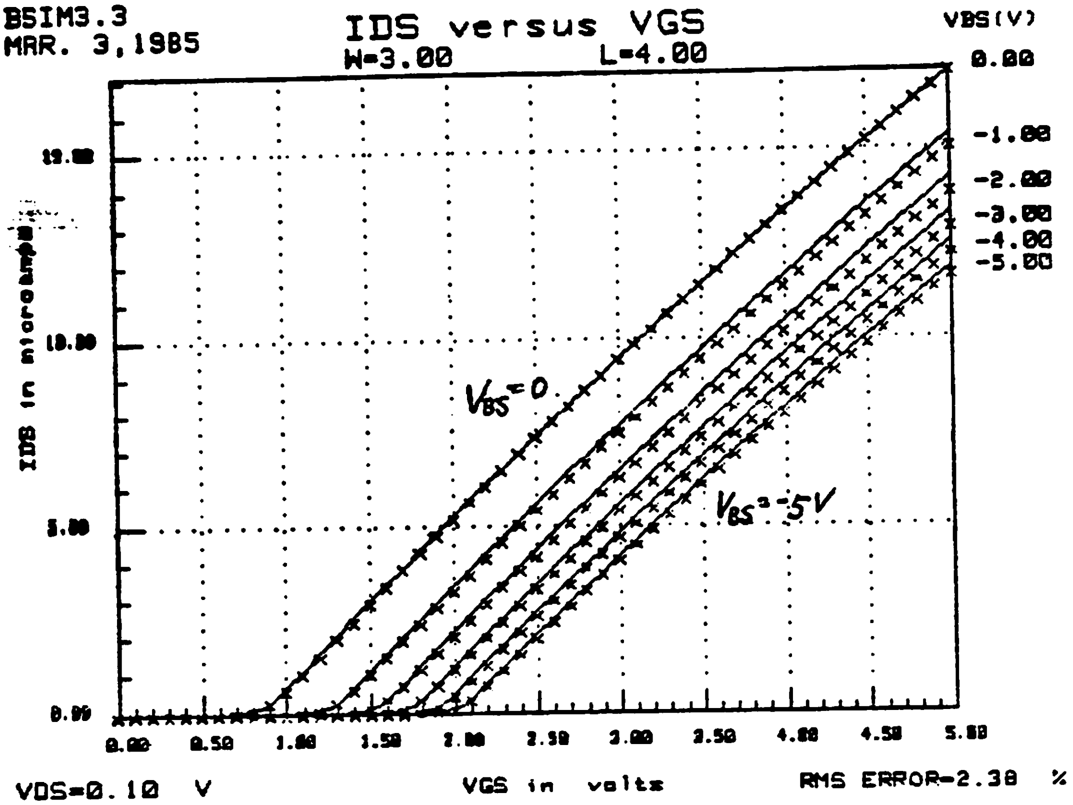

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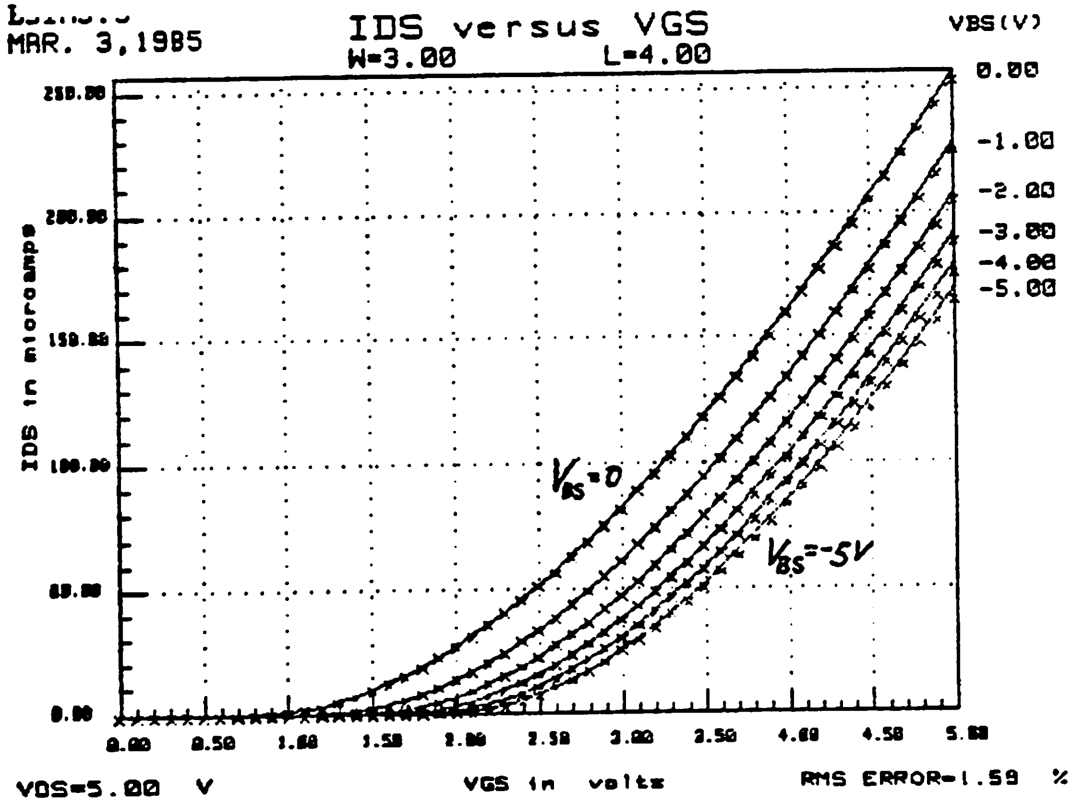
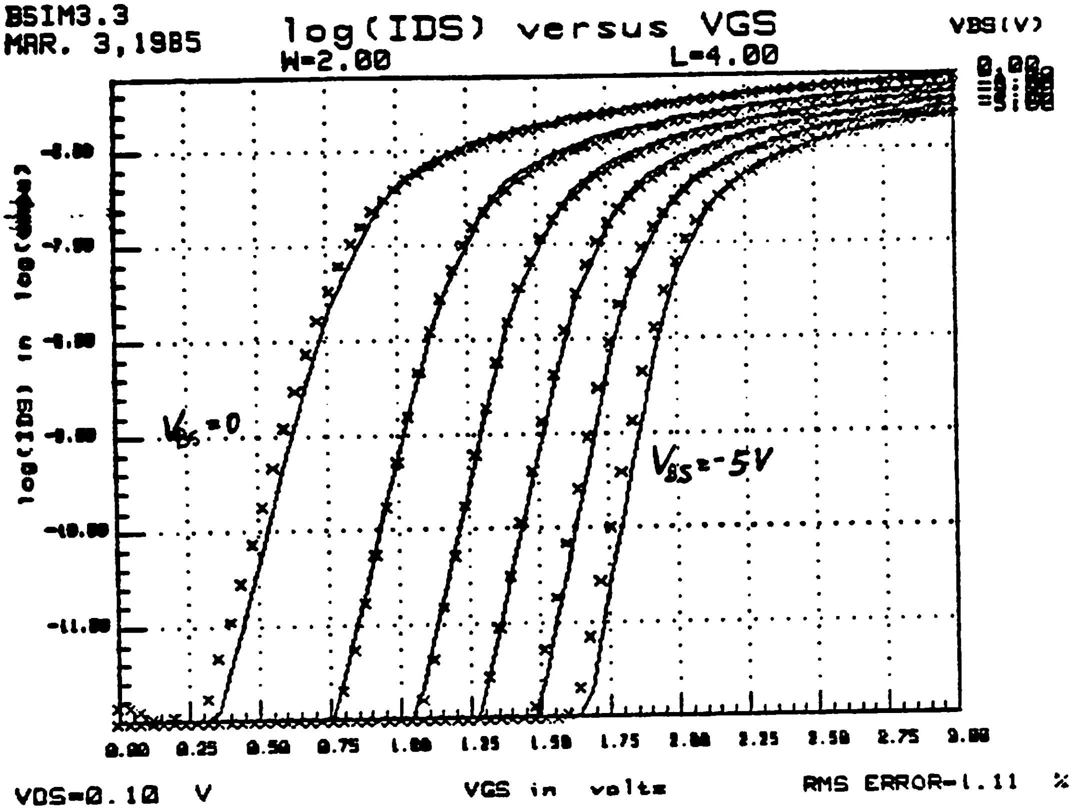
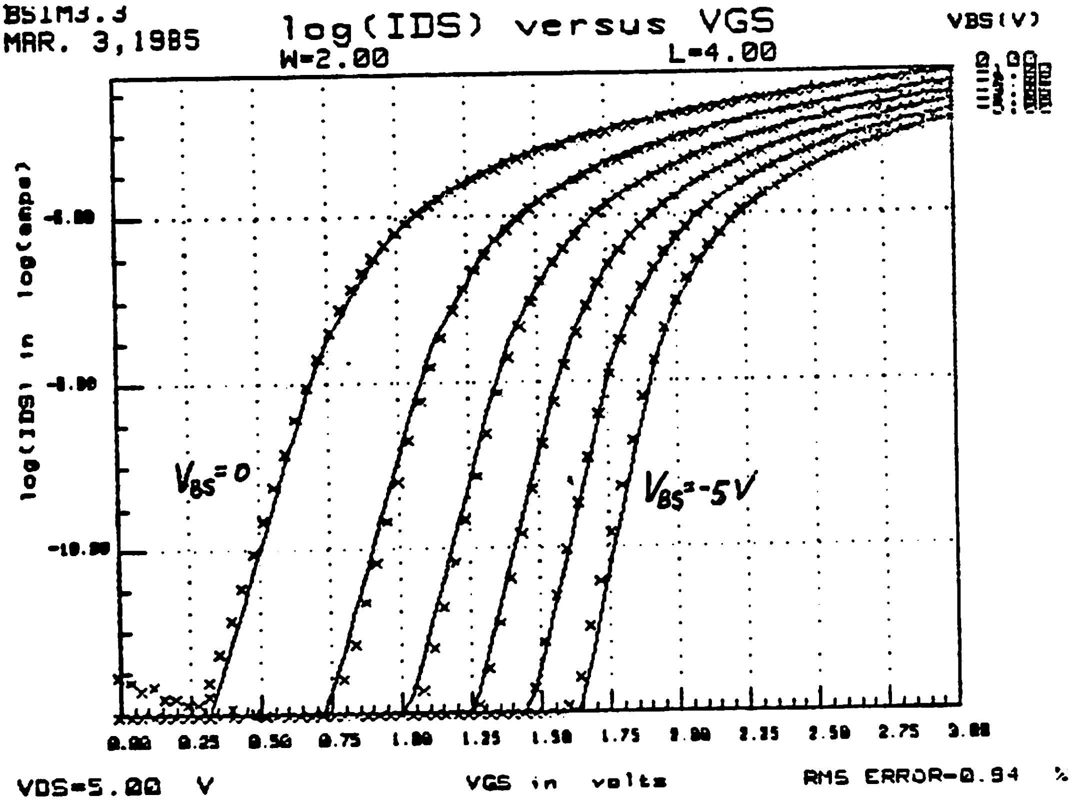


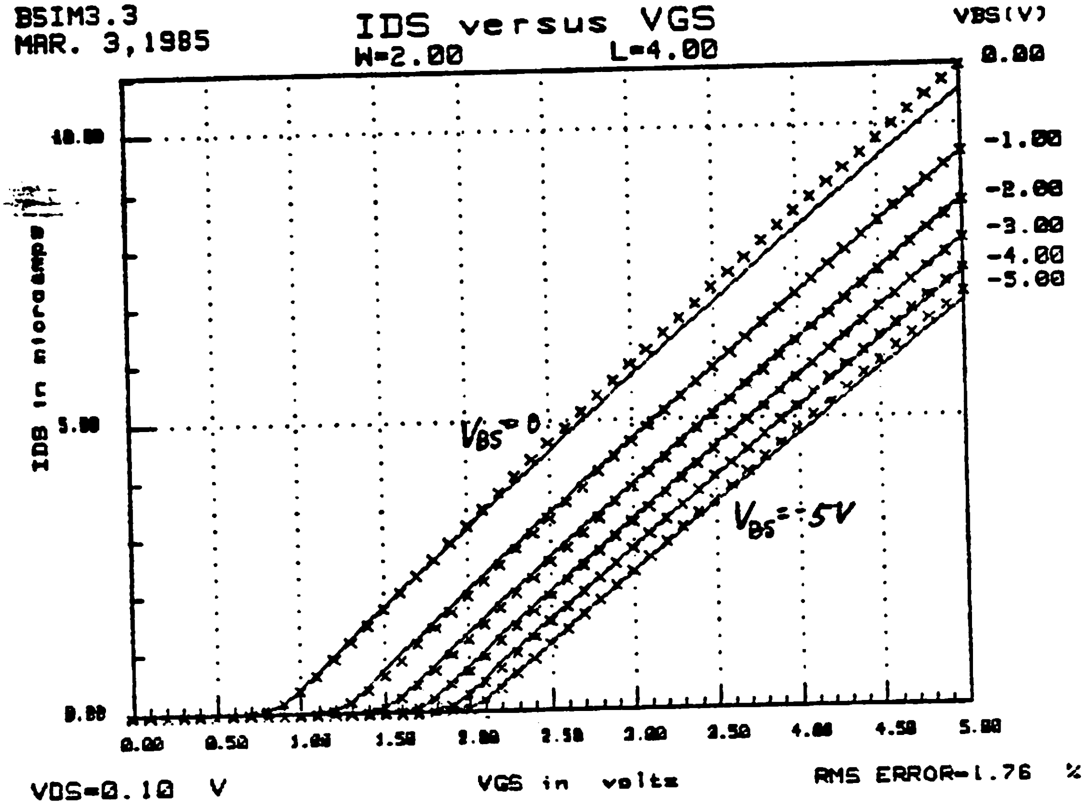
N-channel device W=3um L=4um Vds=5.0V



N-channel device W=2um L=4um Vds=0.1V



N-channel device W=2um L=4um Vds=5.0V



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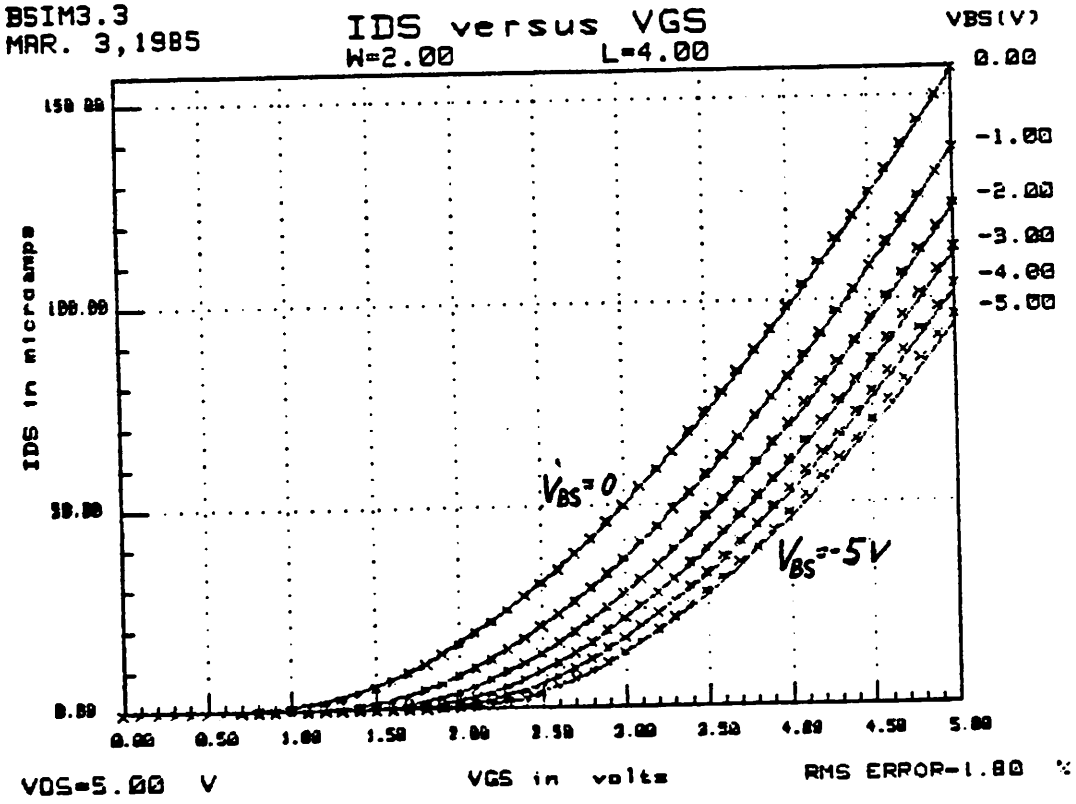

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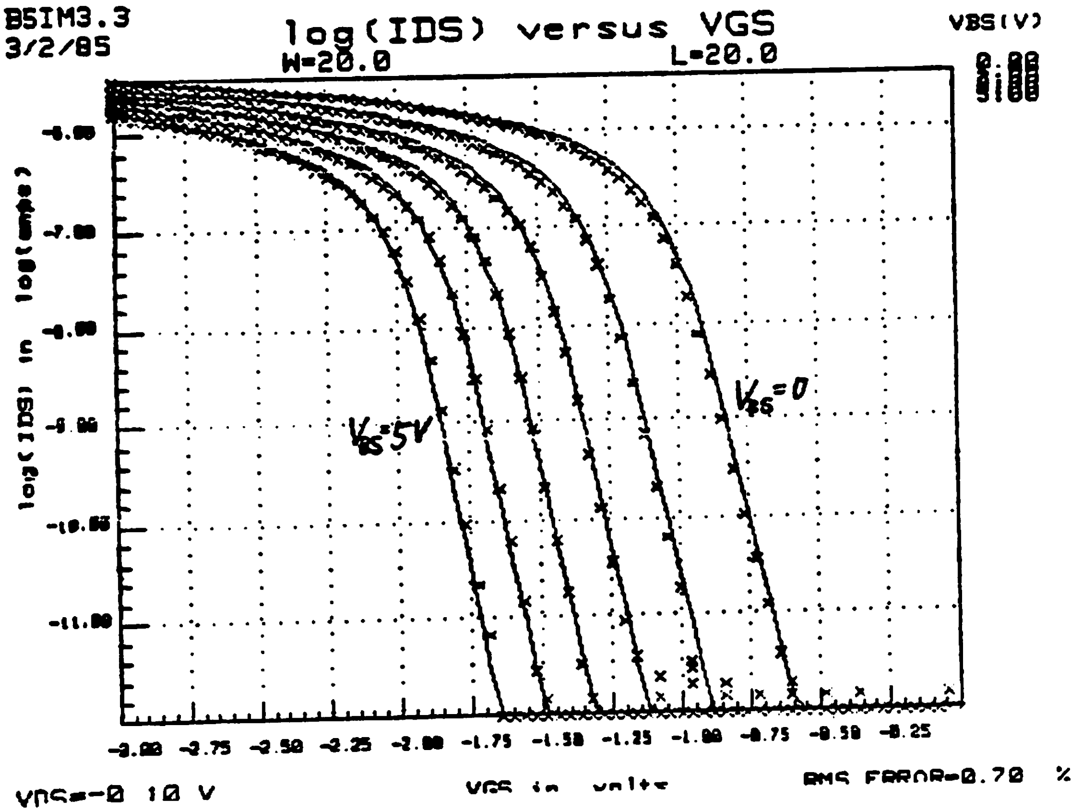
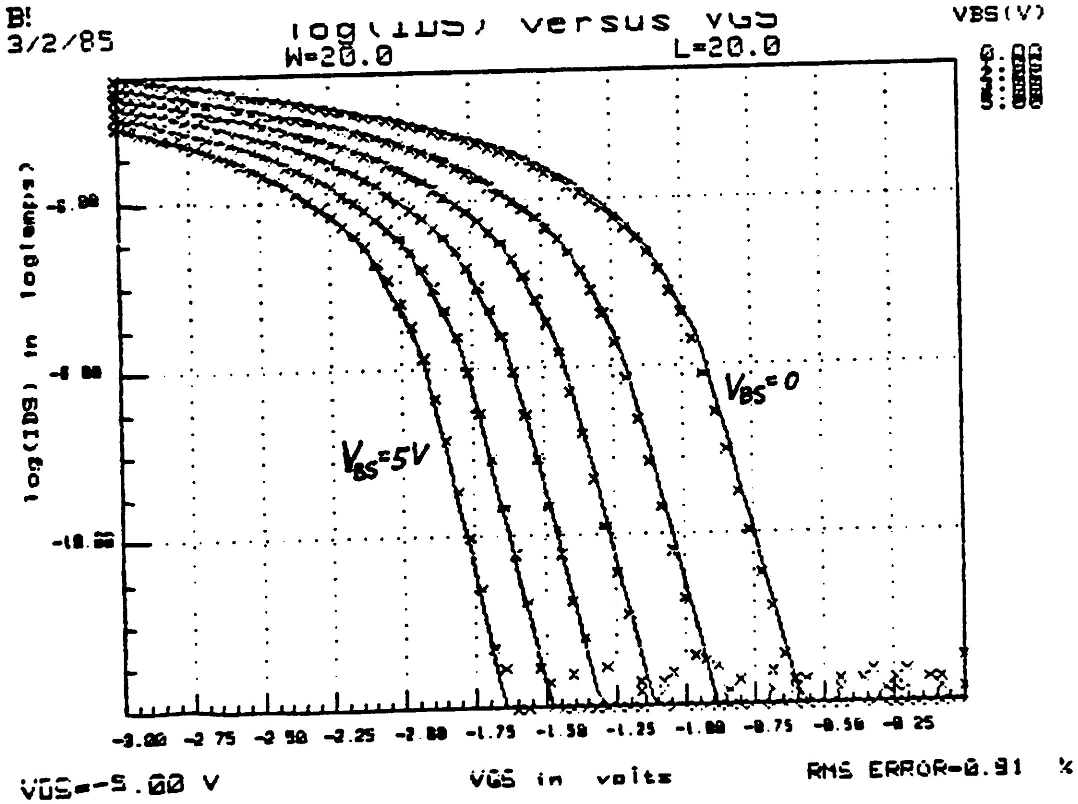


P-channel device W=20um L=20um Vds=0.1V



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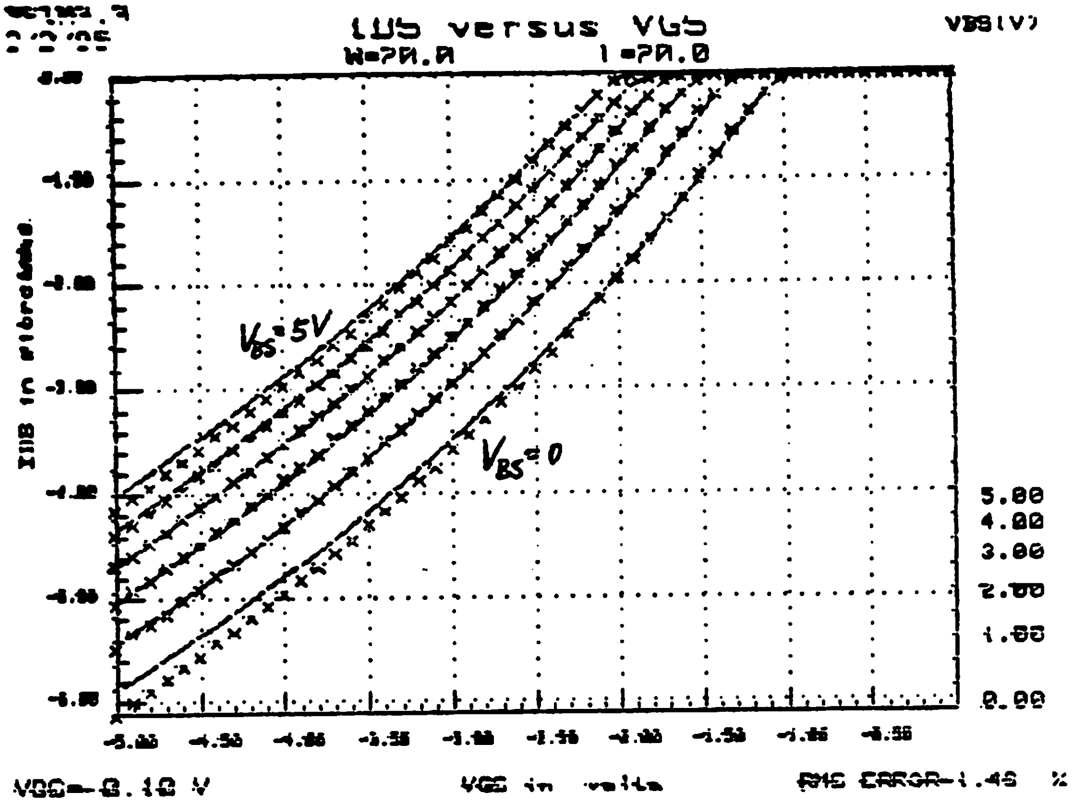

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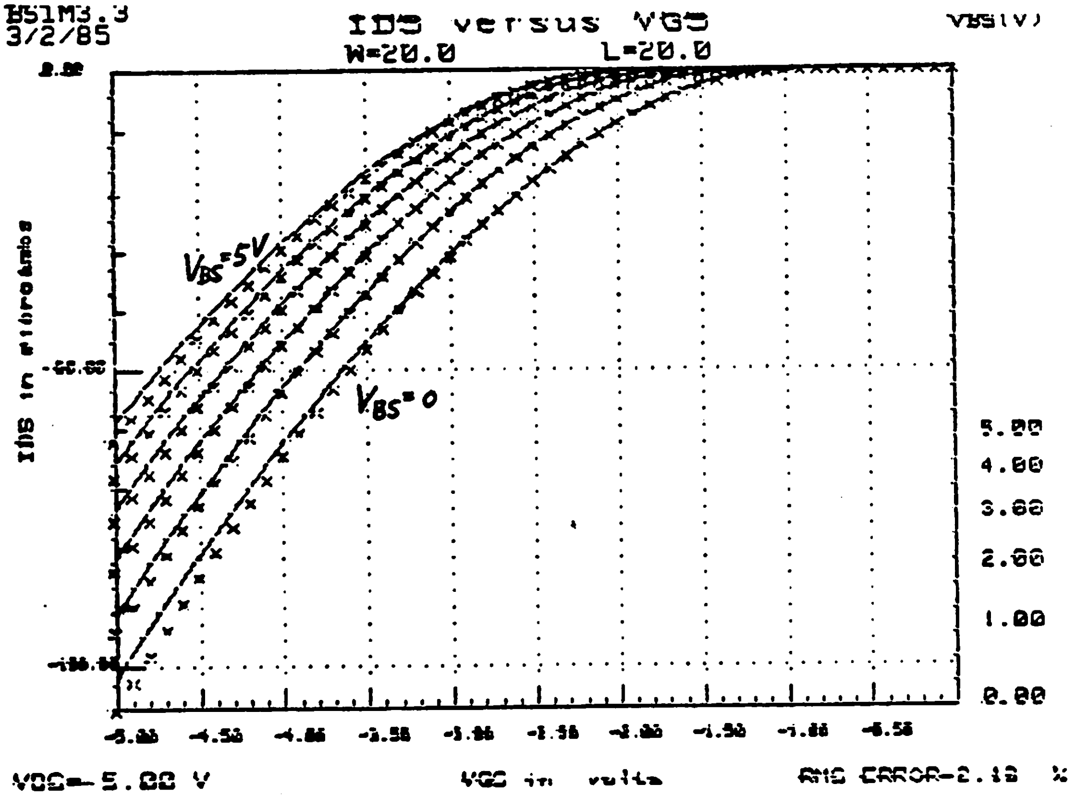

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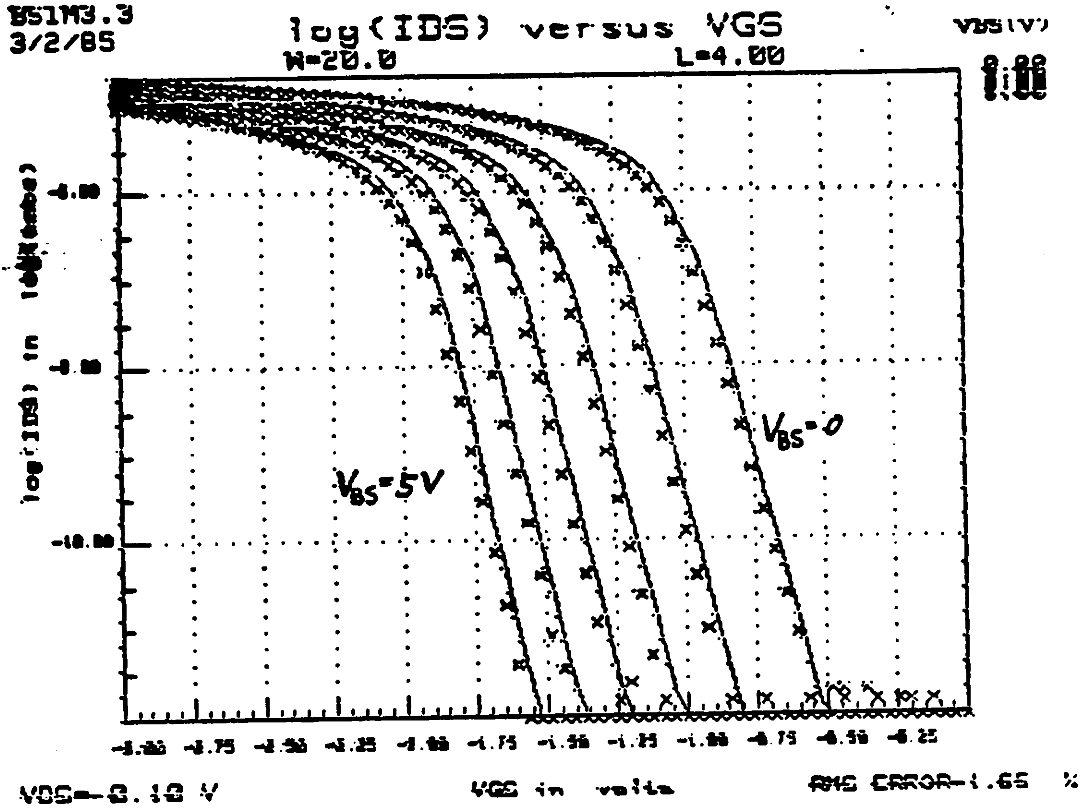

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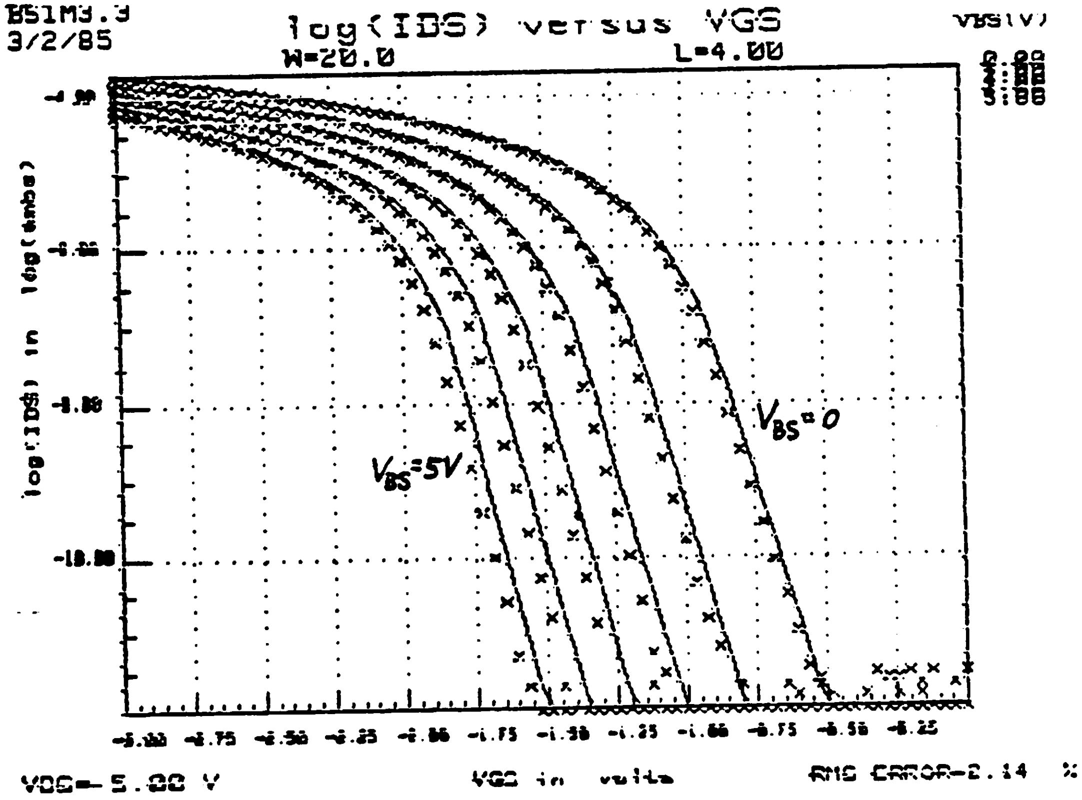

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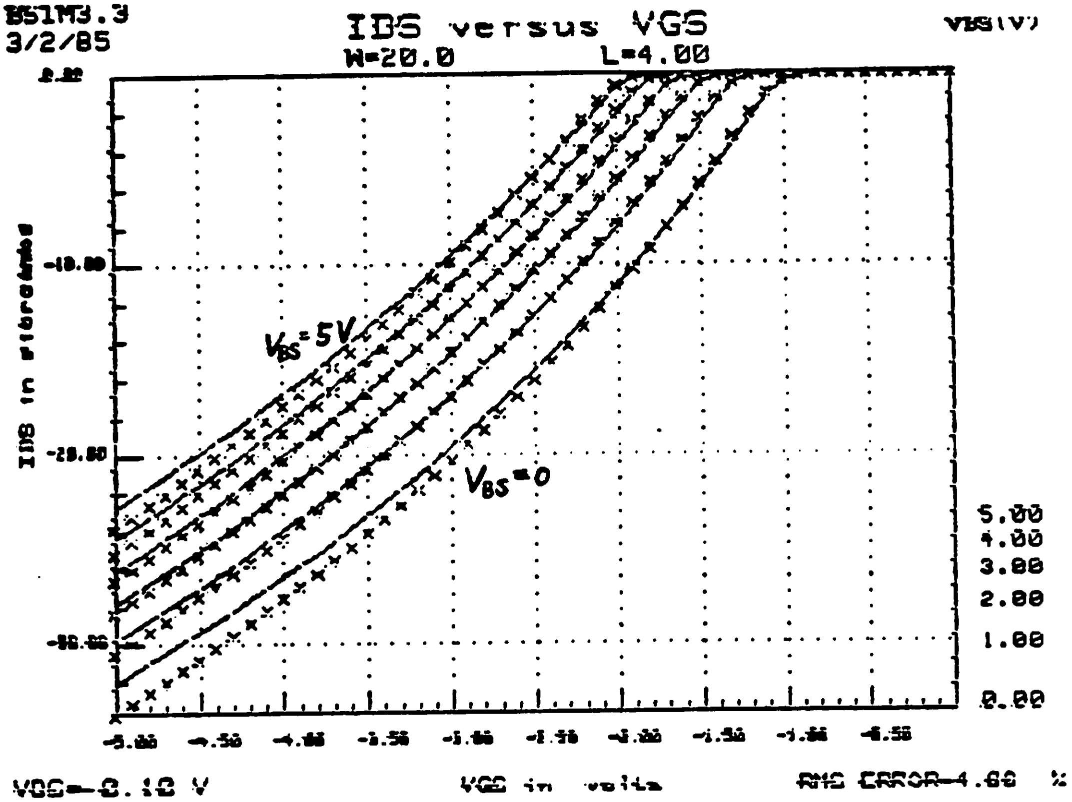

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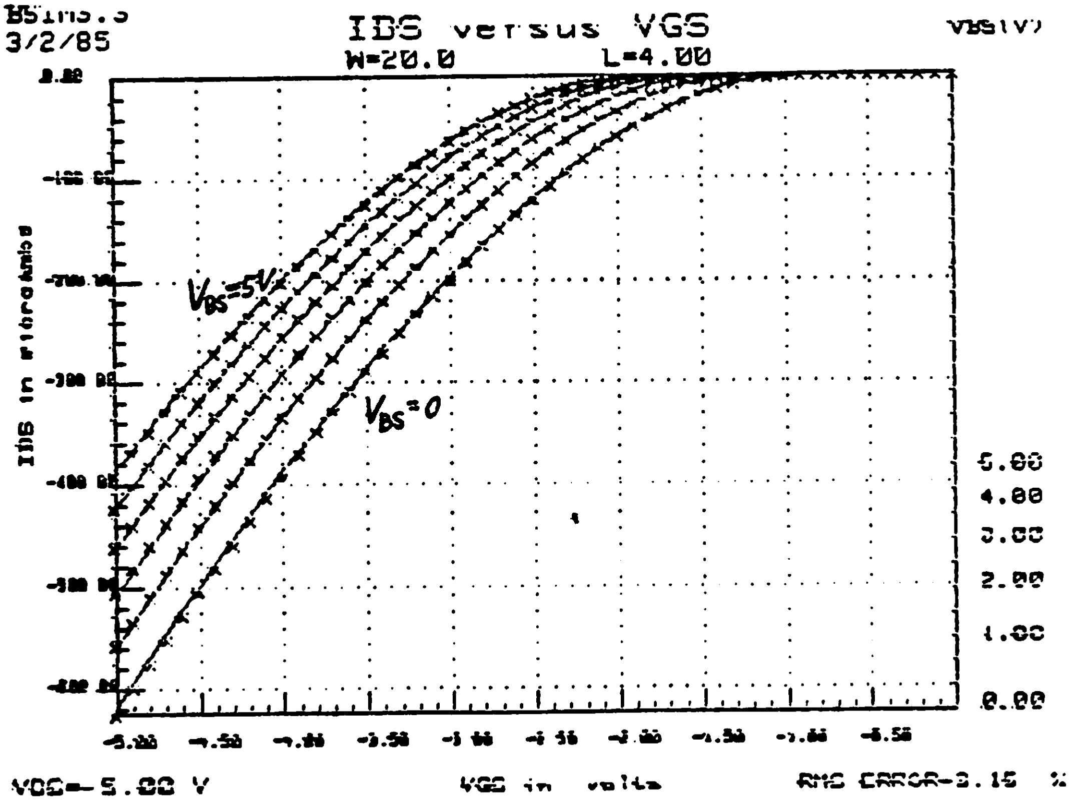

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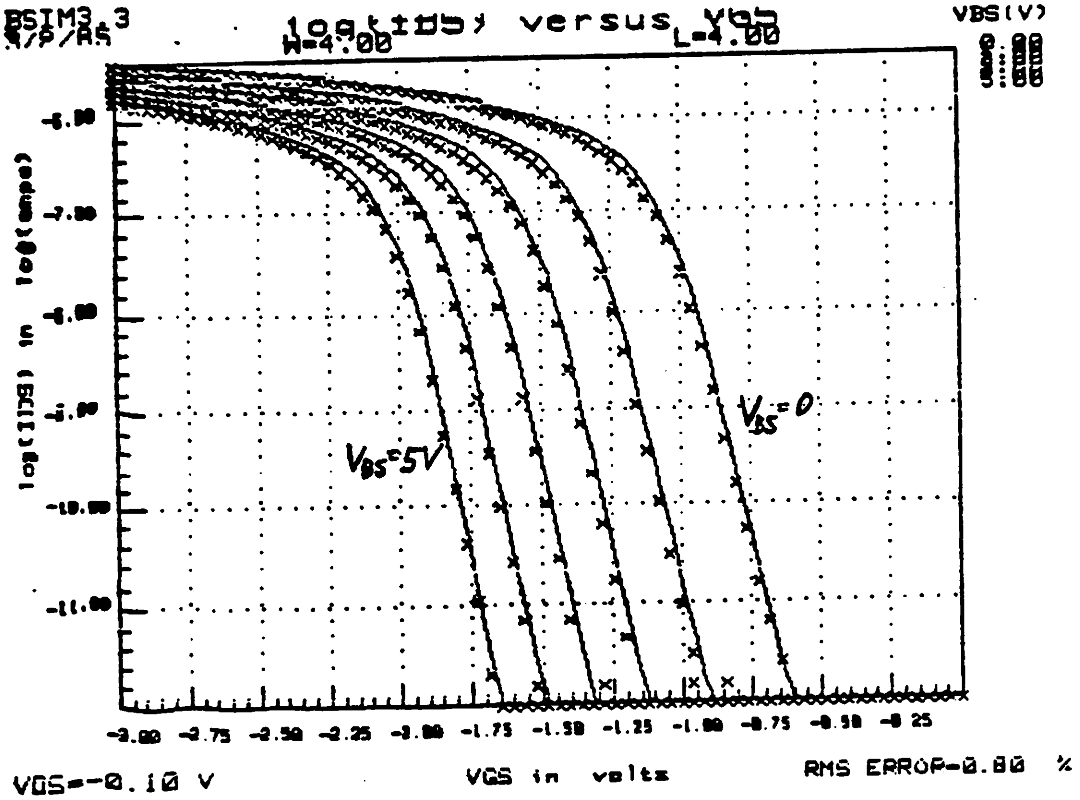

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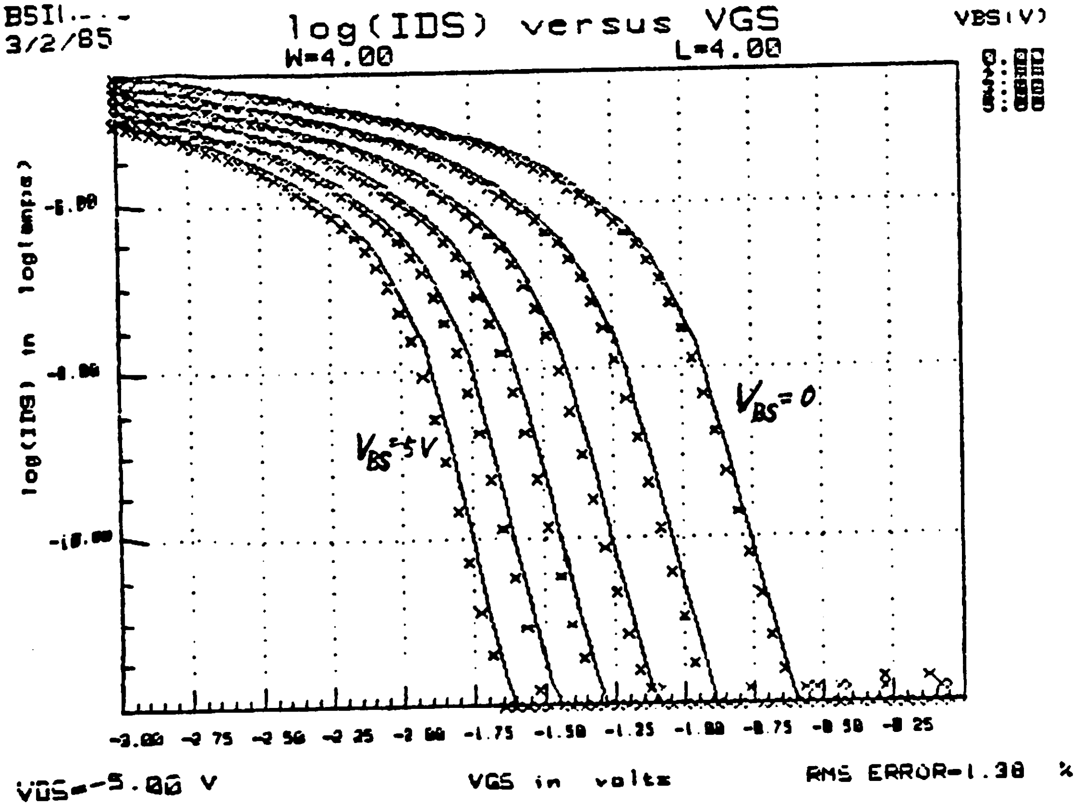

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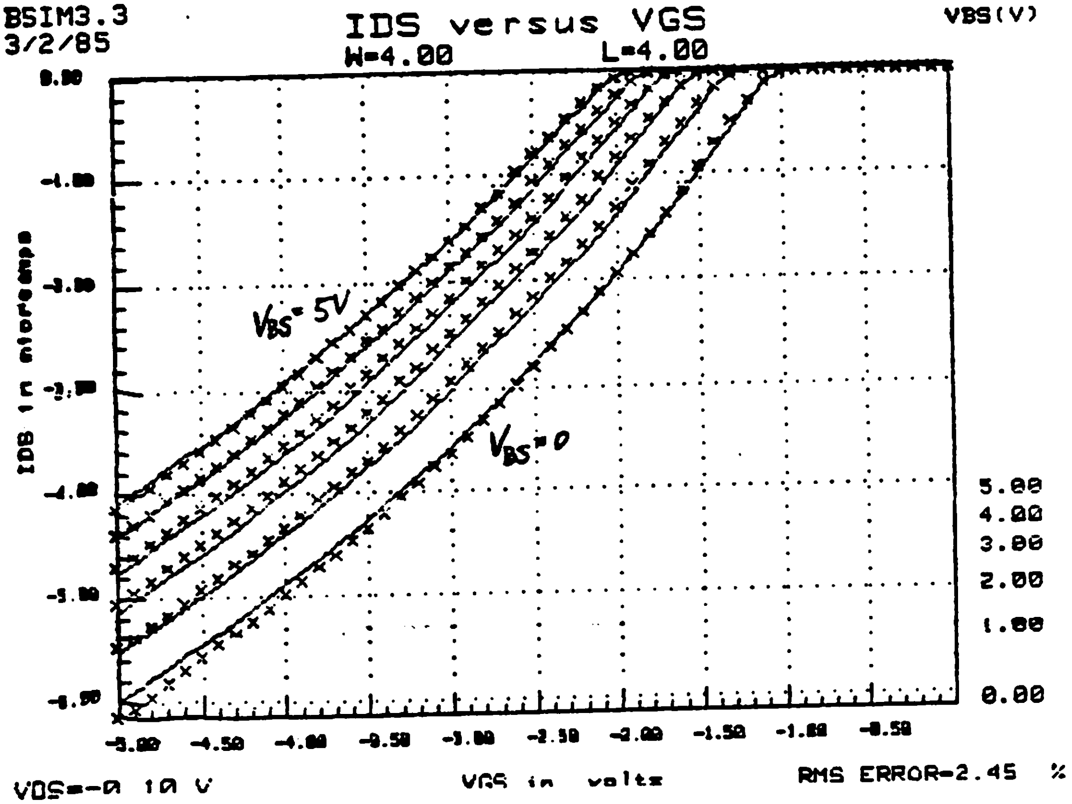

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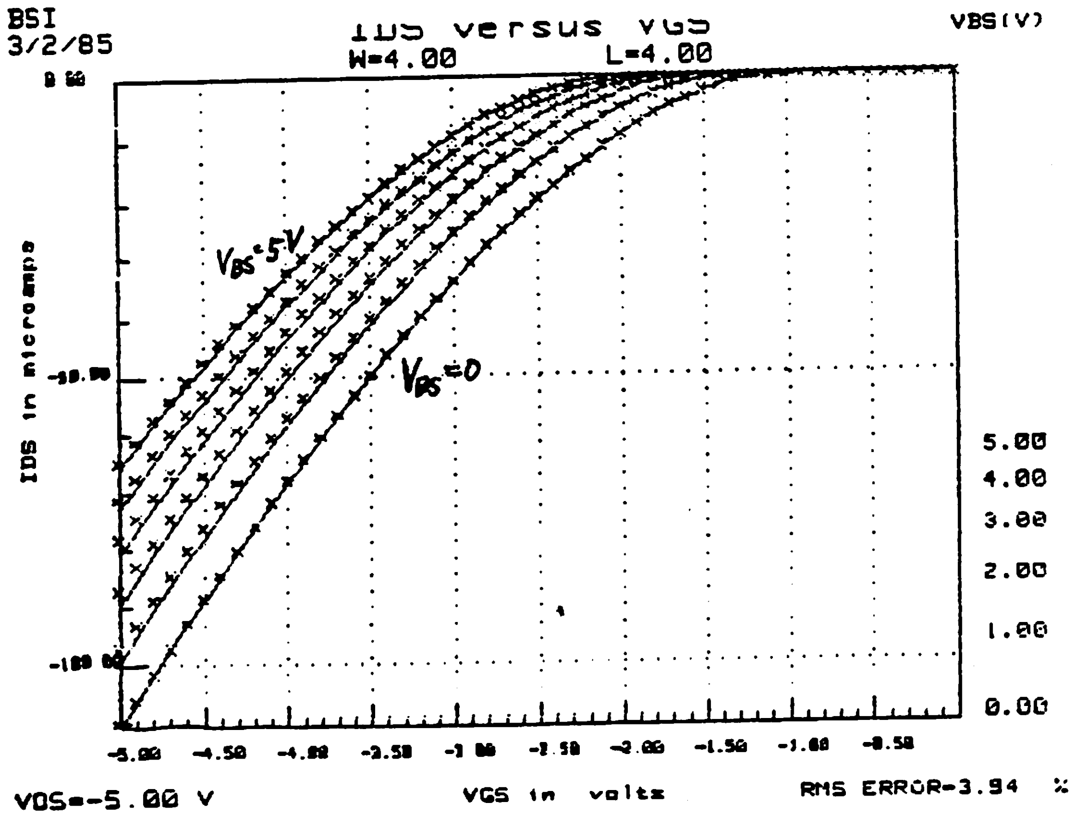

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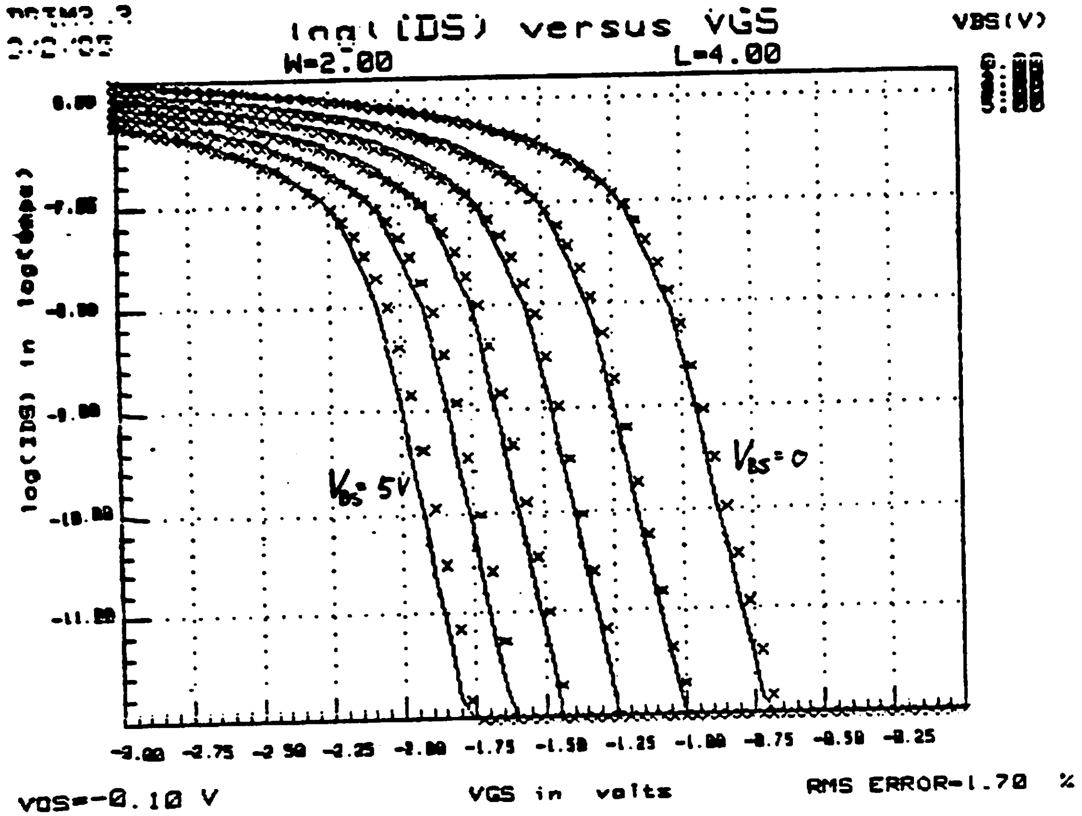

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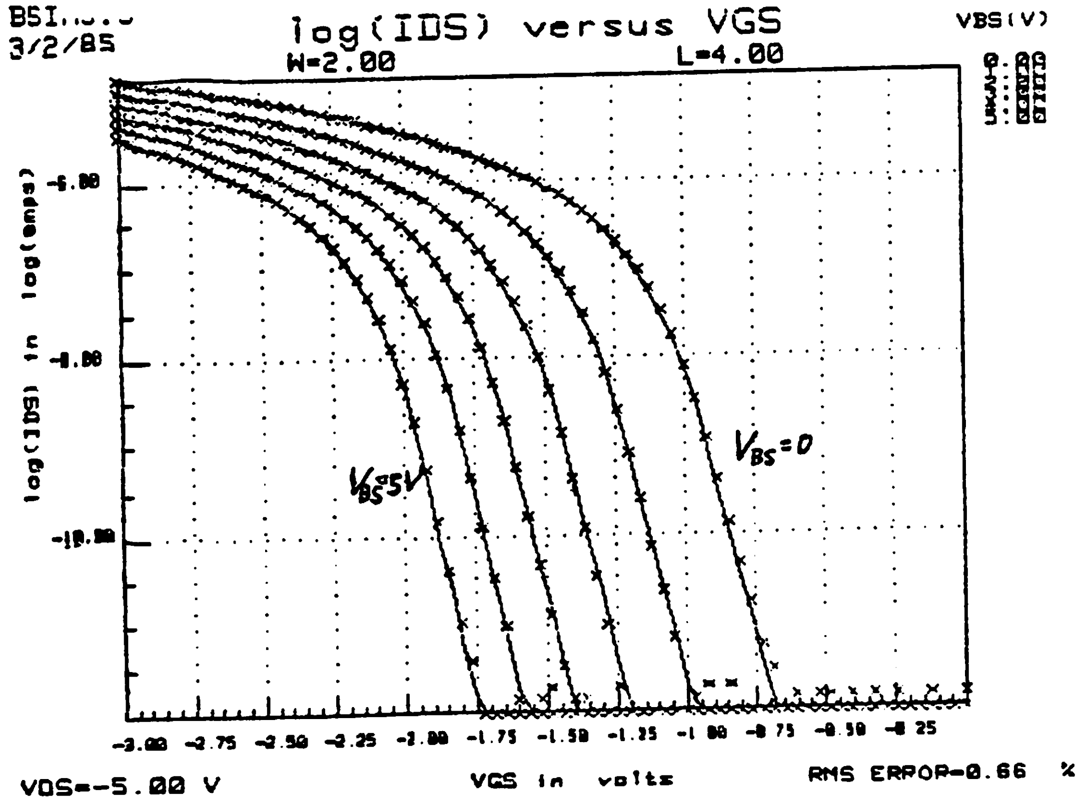

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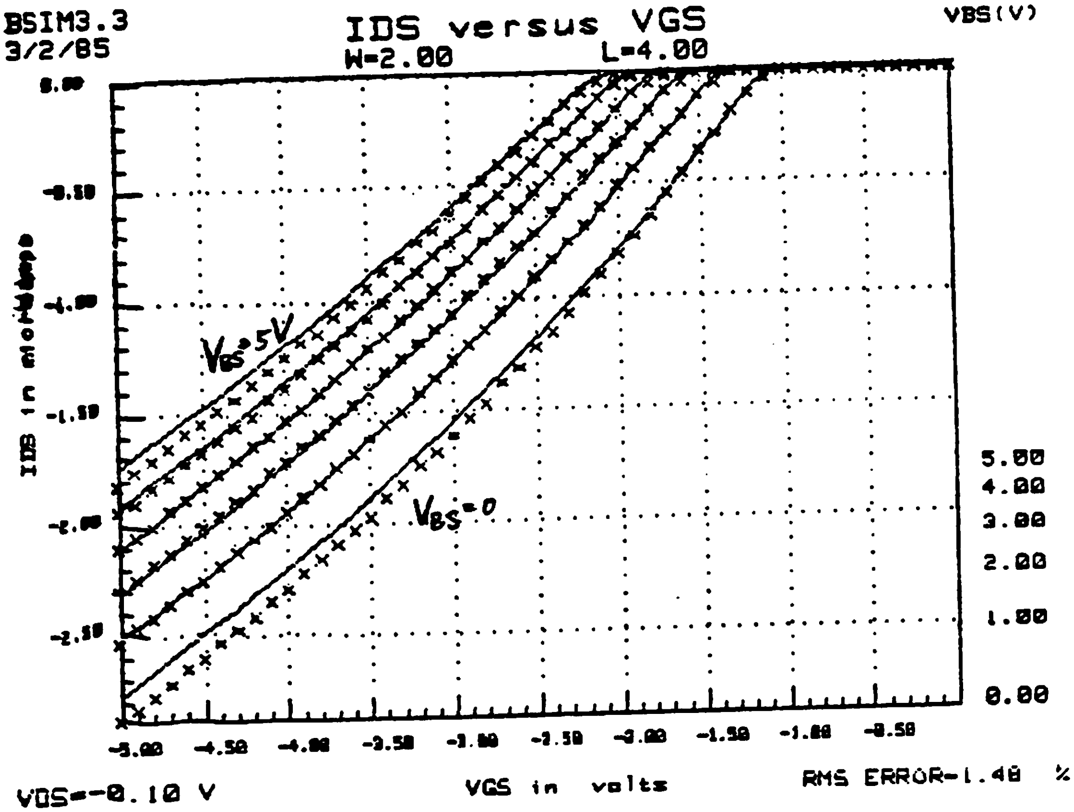
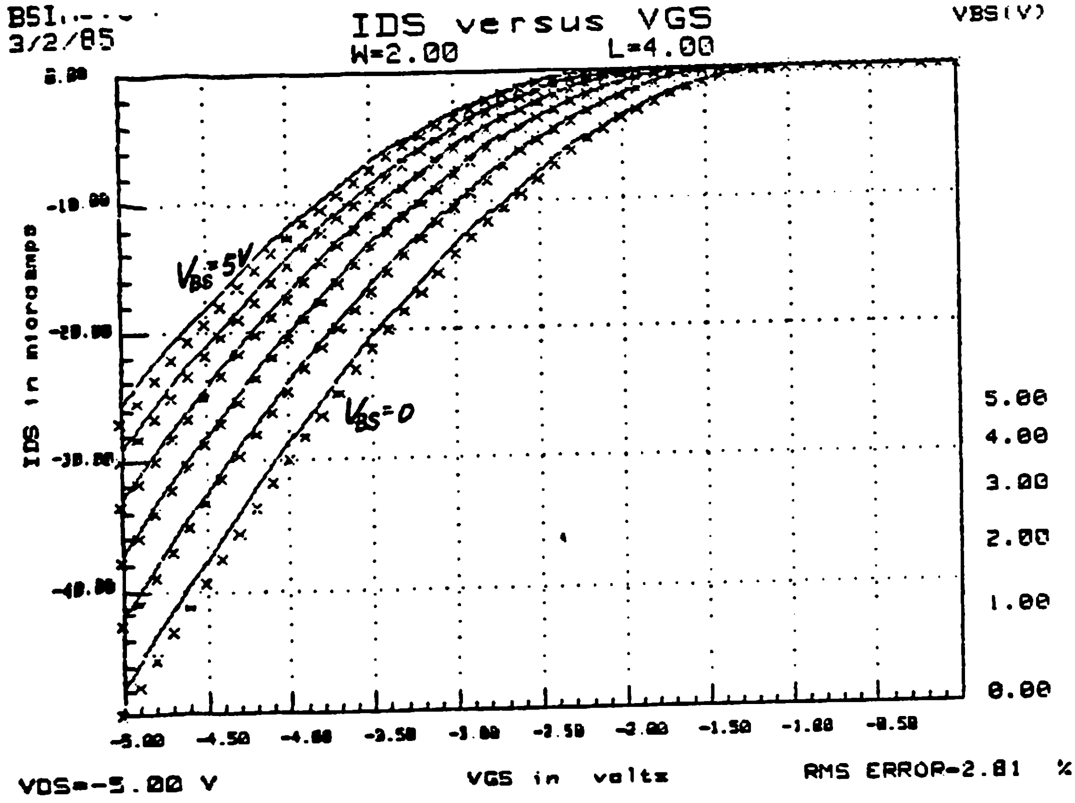


P-channel device W=2um L=4um Vds=0.1V



P-channel device W=2um L=4um Vds=5.0V

VI. CONCLUSION

A subthreshold model has been presented for the BSIM process-oriented model. This subthreshold model requires three electrical parameters to be extracted from physical devices. With the original 17 electrical parameters needed to model the strong inversion region, a total of 20 electrical parameters are now extracted by the BSIM extraction program.

The BSIM parameter extraction program has been modified to incorporate the extraction of the three subthreshold parameters. Measurements for the subthreshold region are carried out after the strong inversion region measurements, and the subthreshold slope is used to extract the parameters.

The graphics routine now displays log I_D vs. V_G curves for viewing the subthreshold region current behavior on a semi-log scale. A slight modification of the main procedure enables user to prepare a better process file by remeasuring or discarding devices that had bad measurement data.

This subthreshold model is physically meaningful and accurate. Calculated results are shown to be in good agreements with measured data (Chapter 5). It has now been well integrated into the original BSIM model. Since many circuit applications require operations not only in the strong inversion region, but also in the subthreshold region, a BSIM model incorporating the subthreshold region conduction is definitely more useful serving as a circuit simulation model.

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Appendix 1. BSIM PARAMETER EXTRACTION PROGRAM USER'S GUIDE

I. SYSTEM SETUP

The parameter extraction hardware system consists of an HP 9836 computer of one mega byte memory (possibly with the addition of HP 9888A Bus Expander), 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 **CAPITAL BOLD** face letters. Program prompts are in *italic* letters. Users are referred to Berkeley ERL memorandum titled A FULLY AUTOMATED MOS DEVICE CHARACTERIZATION SYSTEM FOR PROCESS-ORIENTED INTEGRATED CIRCUIT DESIGN by Brian S. Messenger for prober file creation and HP 9836 to VAX file transfer.

(1) HP 9836 SETUP INSTRUCTIONS

Four operating system disks are needed to setup 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). There is a different version of Pascal 2.0 SYSVOL used in Berkeley to make HP 9836 setup procedure easier to follow. Procedure using the modified HP Pascal 2.0 SYSVOL is described below.

(A) 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 Dlete Find Insert Jmp Rplace Quit Xchg Zap?
=A Press 'ENTER' to P-load EDITOR, FILER, VT2 & Put LIBRARY-
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).

(2) HP 4145A SETUP INSTRUCTIONS

(A) **INSERT** the HP 4145A SOFTWARE DISKETT REVISION A5 in the disc drive located on the lower left corner (below the 4145A screen).

(B) **CLOSE** the disc drive door.

(C) **PRESS** the 'ON' switch located to the left of the dics drive to turn on the HP 4145A.

(D) Lights on the machine should light up, an HP 4145A menu should be displayed shortly thereafter and the machine is ready.

II. 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 two disks. In order to run the program, contents on the two disks have to be combined to form one single text file. 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 first part of the program (bsim1.0.1.TEXT) in the right disc drive (unit#3).

INSERT second part of the program (bsim1.0.2.TEXT) in the left disc drive (unit#4).

CLOSE both disc drives' doors.

(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:bsim1.0.1.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 bsim1.0.1.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?
```

At this point, you have half of the extraction program stored in RAM.

HIT [E] key to invoke EDITOR.

(H) You should be prompted with the following page.

```
Editor [Rev. 2.0 19-Oct-82]

Copyright 1982 Hewlett-Packard Co.
        All rights reserved.

No workfile found.
File? (<ent> for new file, <stop> exits)
:
```

TYPE bsim.TEXT

HIT [ENTER] key.

(I) You will see, at this point, a message indicating the program called bsim.TEXT is being read from RAM.

Reading......

DO NOTHING until the screen is filled with text.

HIT [J] key.

HIT [E] key.

HIT [C] key.

(J) The following line should now appear at the top of the screen.

>Copy: Buffer File <sh-exc>

HIT [F] key.

(K) You should be prompted with this line on the top of the screen.

>Copy: File [marker,marker]?

TYPE #4:bsim1.0.2.TEXT

HIT [ENTER] key.

(L) The word "Copy" is now displayed at the top left corner of your screen followed by a series of dots '.' appearing one at a time. This indicates that the content stored on the bsim1.0.2.TEXT disc (the second half of the program) is being copied to the end of the now active file.

DO NOTHING until the copying is done. (i.e. more text shown on the screen after the end of the original text on the screen)

HIT [Q] key.

(M) The following page should appear.

>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 RAM:bsim.TEXT
Overwrite as file RAM:bsim.TEXT

HIT [O] key.

(N) **DO NOTHING** until you see this prompt

Exit from or Return to the editor?

HIT [E] key.

(O) Up to this point, you have combined two parts of the extraction program into one single complete file and stored it in the RAM under the name bsim.TEXT (or whatever name you originally chose in step E.). The main command line should appear on the top of the screen again.

(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.

[1]: Fully Automatic

(see below)

[2]: Semi Automatic -- [AUTOMATIC PROBER]

(see below)

[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 IV. describes how to load Prober File into RAM.

(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 (N0,X2NB,X3ND).

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

(f) Mode [1] skips this step.

For modes [2] and [3], you should be prompted with

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

[3] 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 die to be tested.

(h) If you have answered NO to

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

in step b, skip steps h through m.

If you have answered YES to the above question in step b, you will now be prompted with Fig.A4.

READ instructions.

HIT the number key corresponding to desired device type.

(i) Fig.A5 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.

(j) Fig.A6 should appear.

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

(k) You should be prompted with

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

HIT [C] key to change.

HIT [ENTER] key to continue.

(l) Requested graph is now displayed along with the selection menu shown in Fig.A7. Selections [1], [2] are explained when I-V Graphics is explained in SINGLE DEVICE operation. Selection [3] brings Fig.A4 back onto the screen and steps h through k are repeated.

(m) Mode [1] skips this step.

For modes [2] and [3], if there is no more die on the wafer to be characterized and parameter vs. W or L graphics are exited, skip this step. If there are still dies on the wafer to be characterized, you will be prompted with

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

[3] 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.

(n) 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.A8 will be displayed on the screen.

INPUT all information requested for your desired graph.

(o) Fig.A9 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.

(p) You should now be prompted with

Place probes on device and Press "ENTER"

PROBE the device you want to graph.

PRESS [ENTER] key.

(q) IV graphics actions are described in [4]:SINGLE DEVICE mode step h.

[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 N0, X2NB, X3ND 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.A9 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 [1]. A cross hair will appear at the middle of the screen. It 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.A9 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.A8 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.A8 about the device to be graphed. Steps [3]:Semi Automatic--[MANUAL PROBER] o, p, q are repeated to select desired graph.

(5)**Exit I-V Graphics Menu:** Activated by hitting the number key [5]. Graphics mode is exitted and the MAIN BSIM MENU PAGE is displayed.

III. 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.

IV. 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.

Appendix 2. BSIM EXTRACTION PROGRAM SOURCE CODE MODIFICATIONS

I. PROCEDURES MODIFIED

1. **Procedure initialize_17_bsim_parameters_to_zero**

   3 more parameters used to model the subthreshold region are initialized to zero.

2. **Procedure initial_status_display**

   3 subthreshold parameters are added for display with the original 17 parameters.

3. **Procedure measure_device_data**

   Statements calling procedures for subthreshold region measurements are added.

4. **Procedure channel_definition_for_IDSvsVGS_data**

   Body bias is set to be constant for each subthreshold measurement display on the HP 4145A

5. **Procedure source_setup_measure_IDSvsVGS**

   Body bias is set up as constant voltage source for each subthreshold measurement display on the HP 4145A

6. **Procedure linear_region_data_reduction**

   Because of the addition of 3 subthreshold parameters in the status display, positions of the original 17 parameters on the display page are changed. Positions where parameter values are to be placed are updated.

7. **Procedure saturation_region_data_reduction**

   Positions where parameter values are to be placed are updated.

8. **Procedure prepare_for_IV_graphics**

   3 subthreshold parameters are included for setting up play-back of I-V curves.

9. **Procedure iv_maxminxy**

   Method of determining maximum and minimum data values to be graphed is slightly changed to give optimum display.

10. **Procedure string_setup_measure_IDSvsVGS**

    Ranges for subthreshold measurement displays on HP 4145A are defined differently from strong inversion region measurements.

11. **Procedure measure_IDSvsVGS_data**

HP 4145A is setup differently to measure log Id vs. Vg curves.

12. **Function bsimsim**

    Subthreshold model equations are implemented.

13. **Procedure IDvsVD**

    Setup of HP 4145A for strong inversion region measurements is made sure.

14. **Procedure logIDvsVG**

    Previously lnIDvsVD. Subthreshold current is measured, simulated and displayed on a semi-log scale.

15. **Procedure IDvsVG**

    Setup of HP 4145A for strong inversion region measurements is made sure.

16. **Procedure draw_menu**

    lnIDvsVD changed to logIDvsVG.

17. **Procedure make_xyz_axis_labels**

    Labels for 3 subthreshold parameters.

18 **Procedure page3**

Choices of 3 subthreshold parameters are included for BSIM parameter vs. W, L graph.

19. **Procedure store_parameters_in_die_files**

3 more parameters are stored in process file.

20. **Procedure load_up_process_parameters**

Array sizes are increased to accomodate 3 more parameters.

21. **Procedure bsim1.0 (THE MAIN BSIM PROCEDURE)**

More prompts have been added for generation of better process files and process files including subthreshold parameters.

II. PROCEDURE ADDED

1. **Procedure string_setup_measure_subthIDSvsVGS**

Added after Procedure string_setup_measure_IDSvsVGS for setting up the HP 4145A for subthreshold region measurements.

2. **Procedure measure_and_reduce_subthIDSvsVGS**

Added after Procedure measure_and_reduce_IDSvsVGS_data for measuring subthreshold region data.

3. **Procedure subthreshold_parameter_extraction**

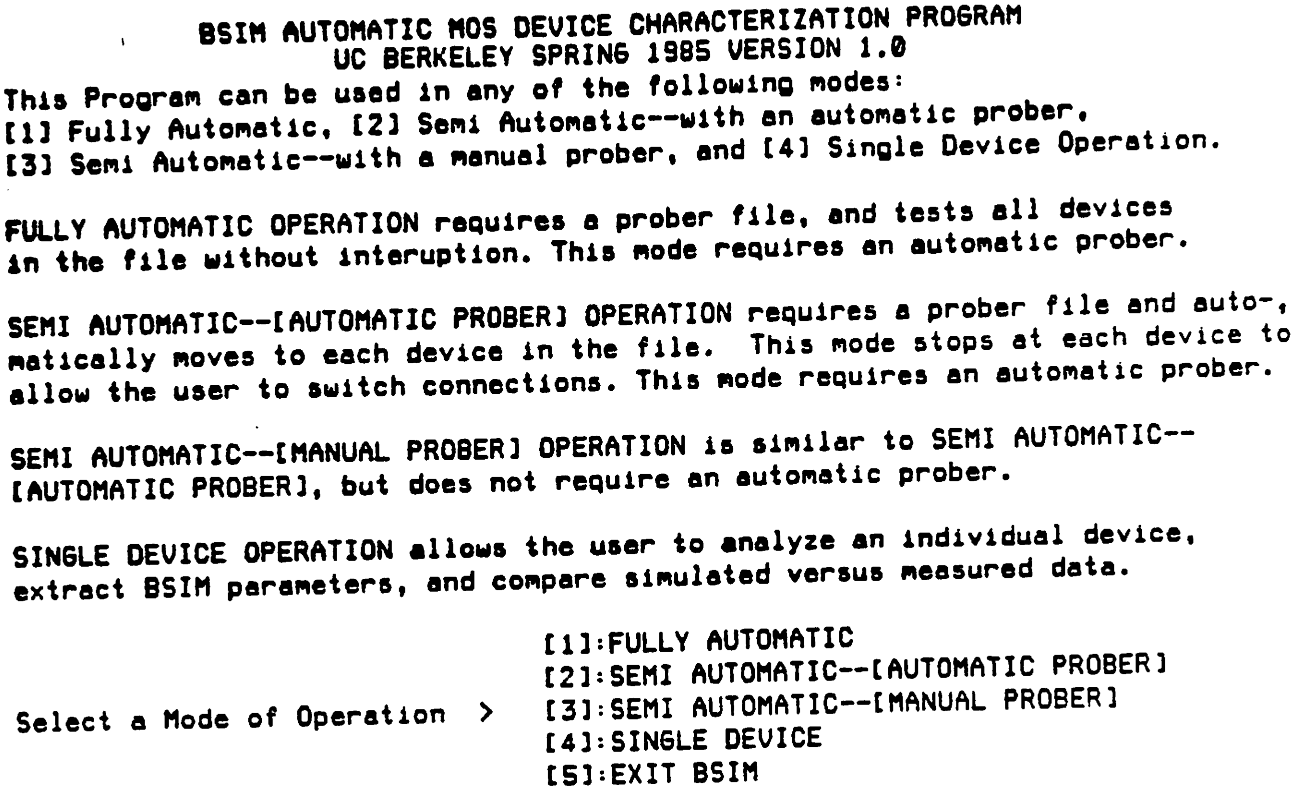
Added after Procedure extract_device_parameters for extracting 3 subthreshold parameters.

Appendix 3. BSIM MODEL BEHAVIOR ON SHORT CHANNEL DEVICES

Measurement and simulated results from a 1 um NMOS process wafer with oxide thickness of 200 angstroms and ΔL of 0.3 um are presented in this appendix. A process file was generated with devices of various lengths ranging from 4um to 1.25um. Specifically, the device sizes are W * L = 50um * 4um, 50um * 3um, 50um * 2.5um, 50um * 2um, 50um * 1.5um, and 50um * 1.25um. As it is observed from the I-V playback curves (Fig.A12-A35), agreements between measured data and calculated results are not as good for devices with channel lengths shorter than 3um as for devices with longer channel lengths. All calculated current levels seem to be higher than actually measured. This is especially apparent in the log I_D vs. V_G graphs of device lengths less than 3um.

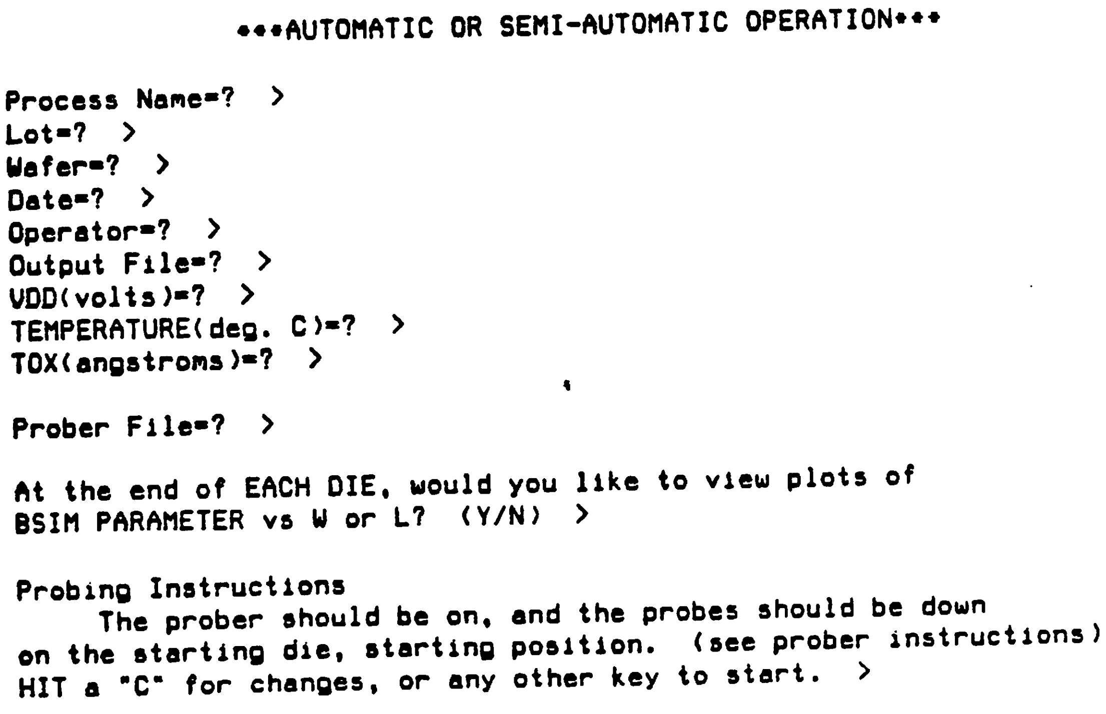
The discrepancy between simulated and measured results for short channel devices has been found possibly more to do with the strong inversion threshold voltage model than with the subthreshold model. From the log I_D vs. V_G graphs, we may note that the calculated curves are not predicting correct threshold voltages at the transition between strong inversion and subthreshold regions for substrate biases that are different than zero. Thus, it is our suspicion that the substrate bias dependence is not properly accounted for in the BSIM threshold voltage model. If we take a close look at the I_D vs. V_G graphs presented in this appendix, we can see that the BSIM model is predicting higher current level even in the strong inversion region. However, since a short channel device is much more sensitive to body bias, the discrepancy is, therefore, observed to be more severe for short channel devices. If the threshold voltage is correctly modeled, it is our belief that simulated curves will be shifted to match more closely with measured data in both the strong inversion and subthreshold regions.

The observation of the BSIM model behavior on short channel devices has exposed the inadequacy of the BSIM model in some cases. Further efforts are certainly needed to make the model more suitable in simulating correctly device behaviors in all regions of operations for all sizes of devices.



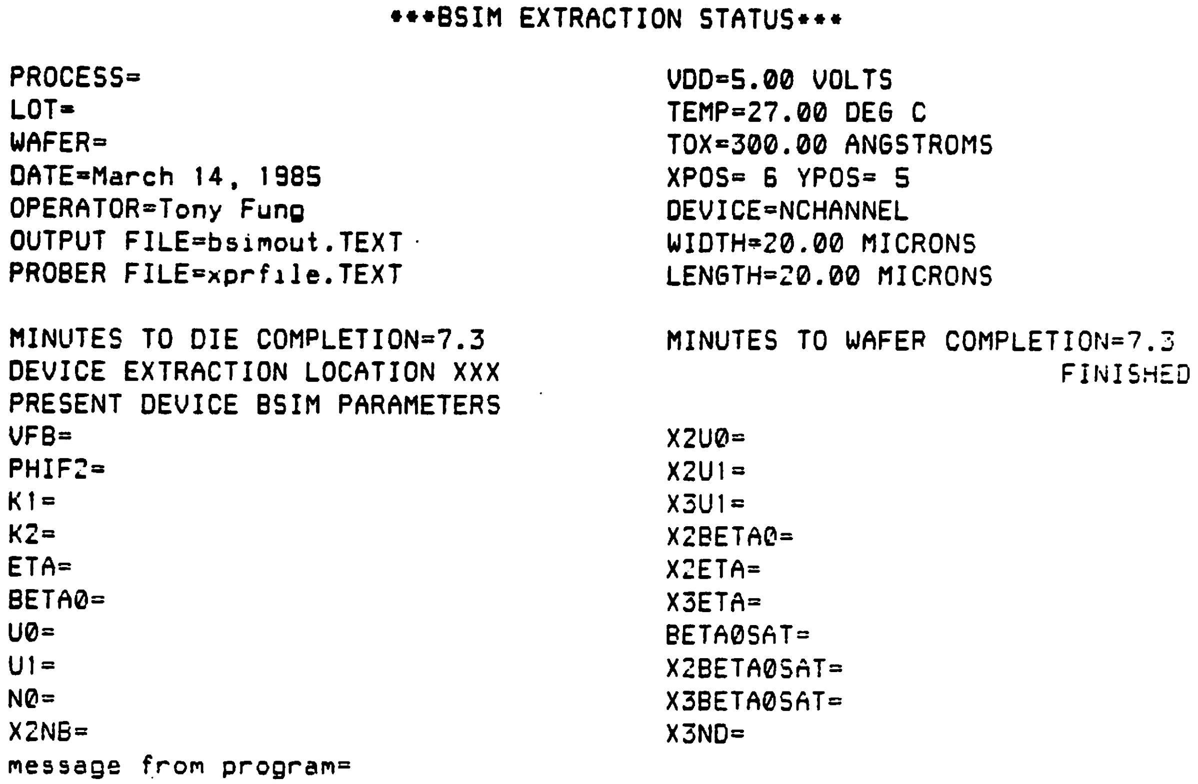
```
          BSIM AUTOMATIC MOS DEVICE CHARACTERIZATION PROGRAM
                 UC BERKELEY SPRING 1985 VERSION 1.0
This Program can be used in any of the following modes:
[1] Fully Automatic, [2] Semi Automatic--with an automatic prober,
[3] Semi Automatic--with a manual prober, and [4] Single Device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



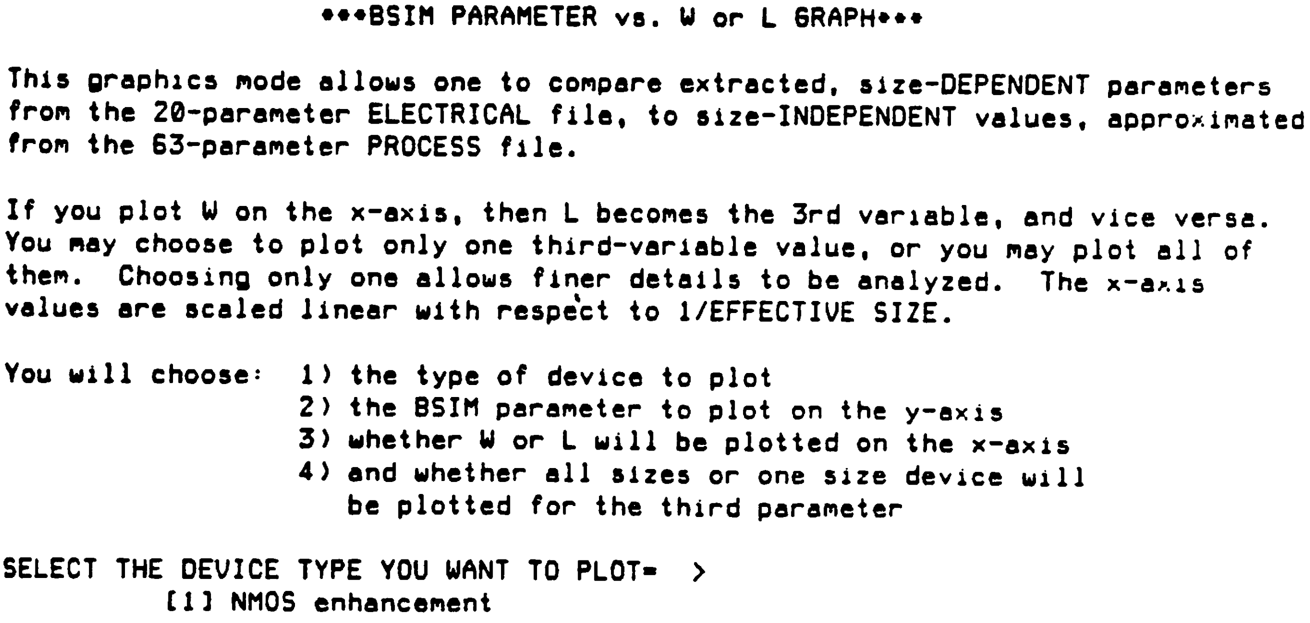
```
              ***AUTOMATIC OR SEMI-AUTOMATIC OPERATION***

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



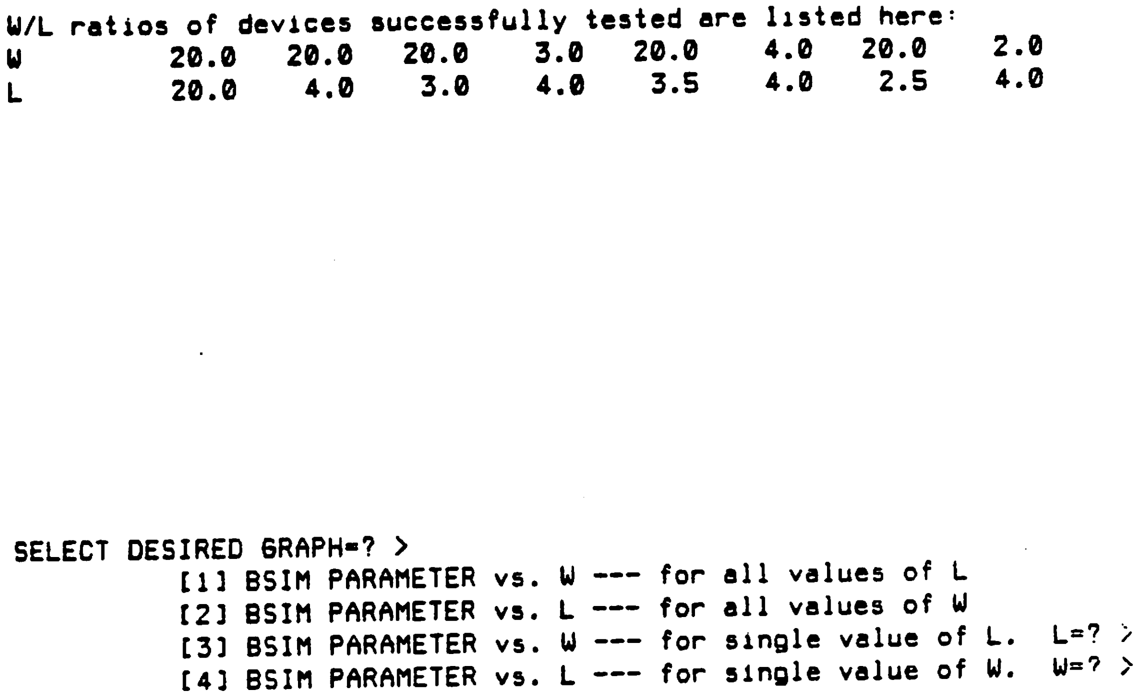
```
                            ***BSIM EXTRACTION STATUS***

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



```
                    ***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 versa.
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
```

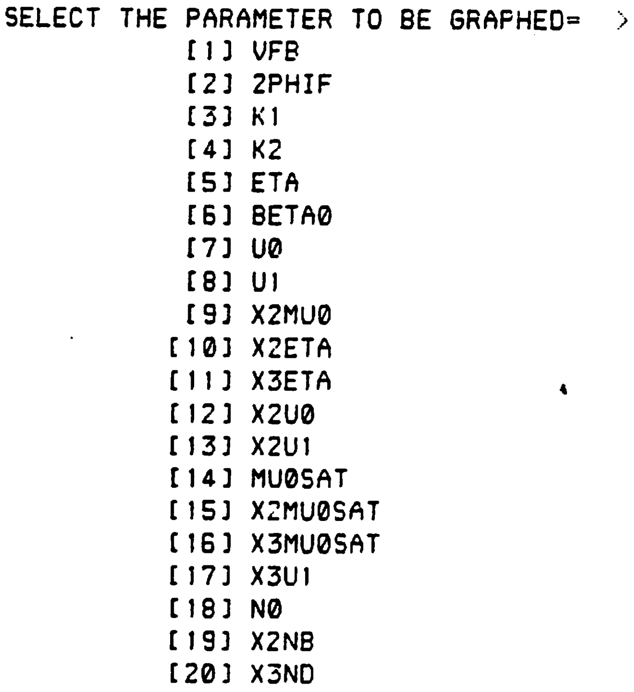
Fig. A4



```
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
```

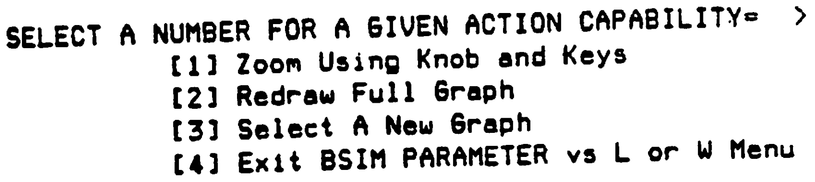
```
SELECT DESIRED GRAPH=? >
          [1] BSIM PARAMETER vs. W --- for all values of L
          [2] BSIM PARAMETER vs. L --- for all values of W
          [3] BSIM PARAMETER vs. W --- for single value of L.  L=? >
          [4] BSIM PARAMETER vs. L --- for single value of W.  W=? >
```

Fig. A5



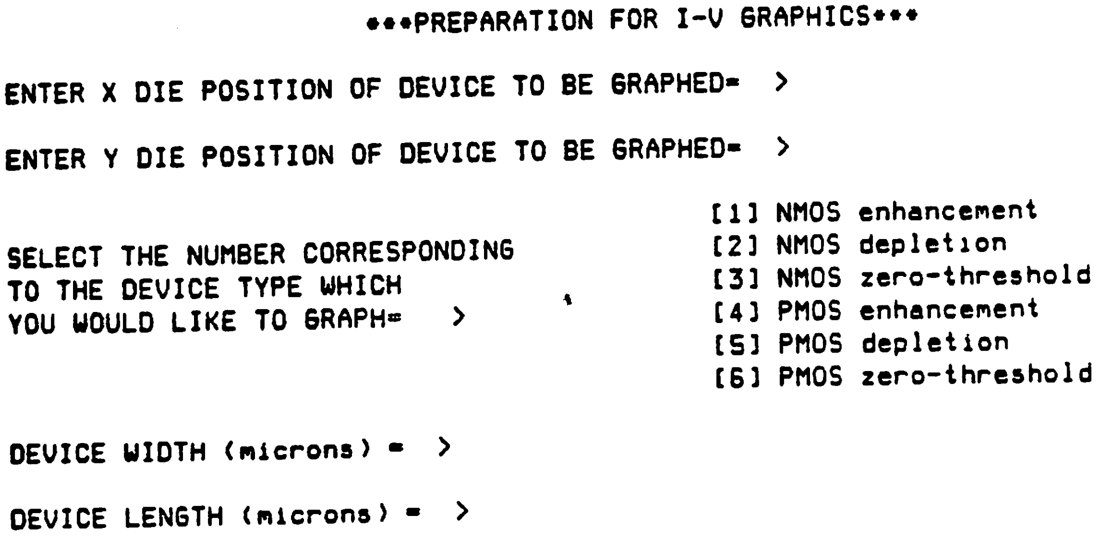
```
SELECT THE PARAMETER TO BE GRAPHED=  >
           [1] VFB
           [2] 2PHIF
           [3] K1
           [4] K2
           [5] ETA
           [6] BETA0
           [7] U0
           [8] U1
           [9] X2MU0
          [10] X2ETA
          [11] X3ETA
          [12] X2U0
          [13] X2U1
  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

Fig. A6



```
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. A7



```
                    ***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) =  >
```

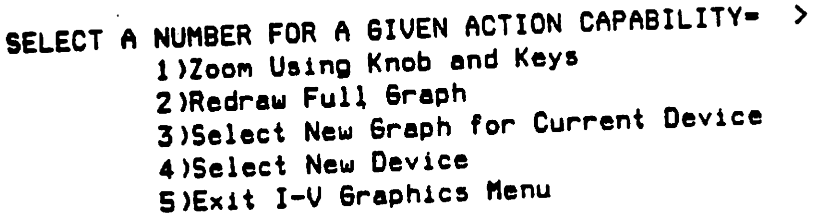
Fig. A8

```
                        ***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. A9

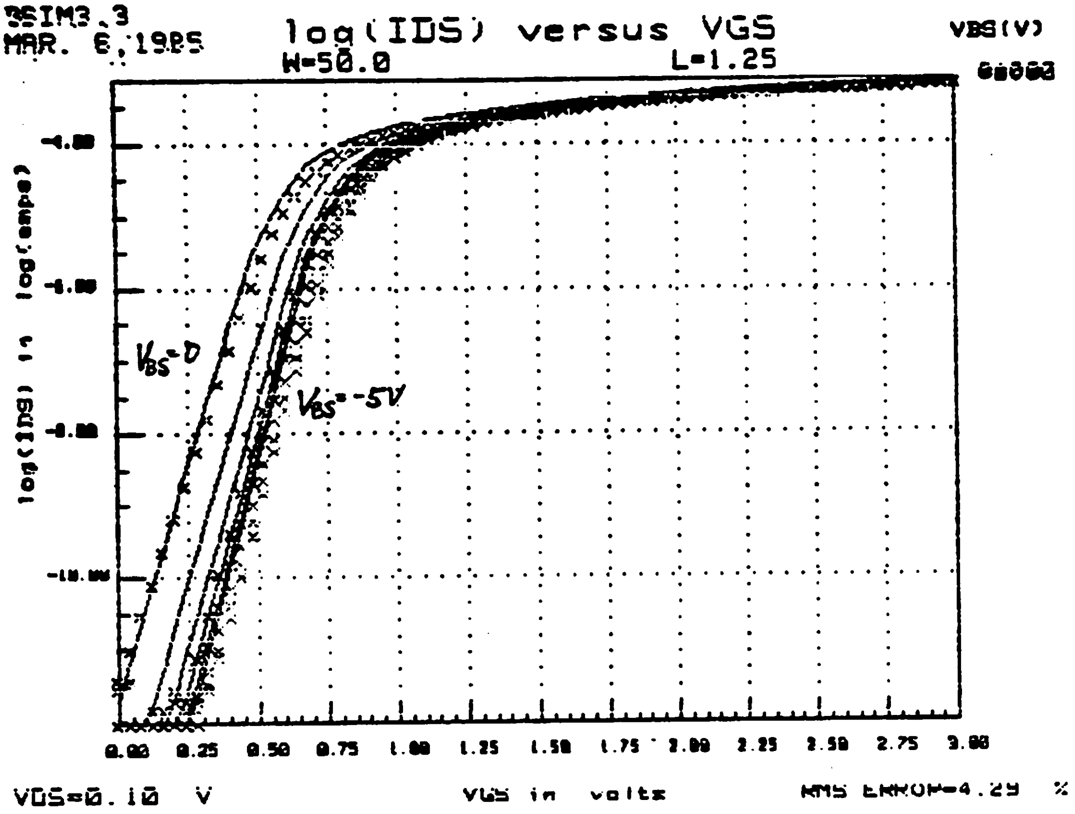
```
                        ***SINGLE DEVICE OPERATION***

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



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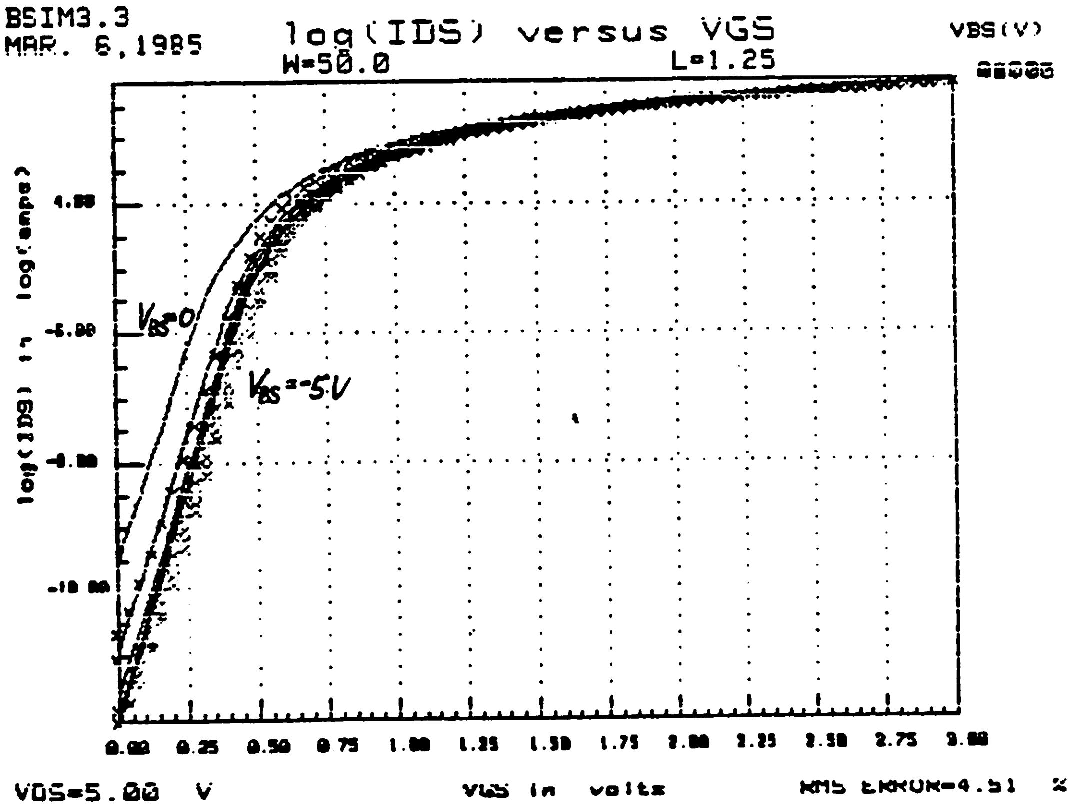
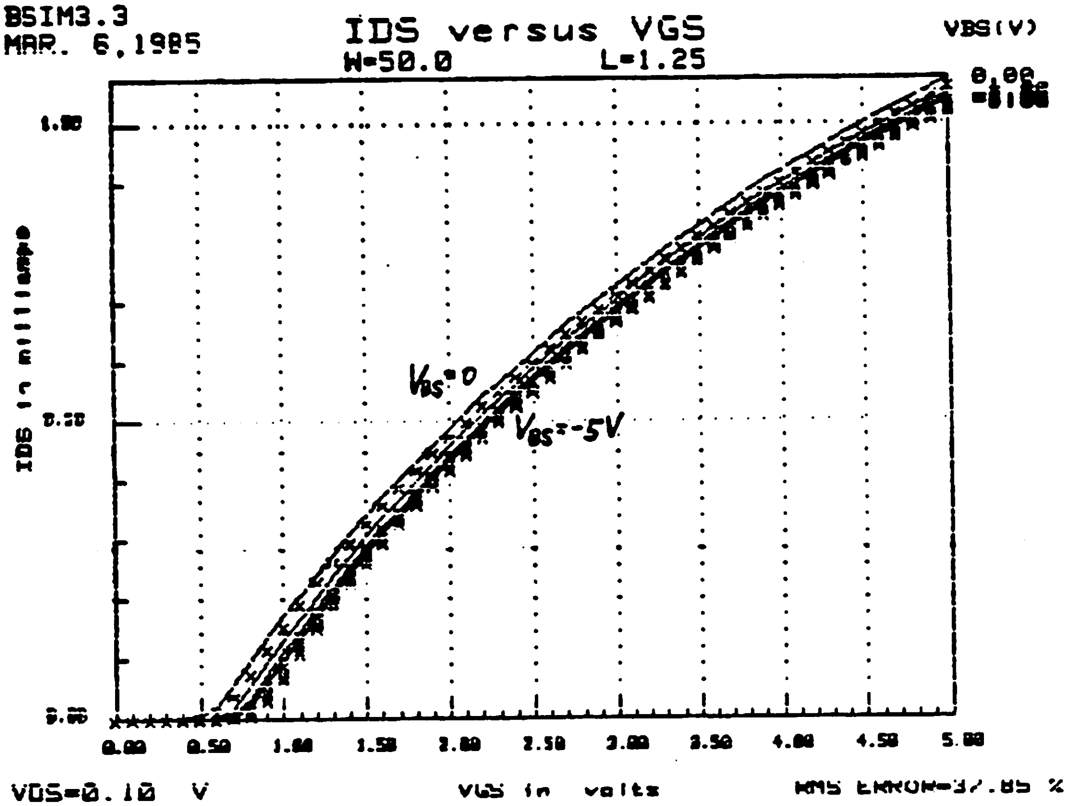


Fig. A13



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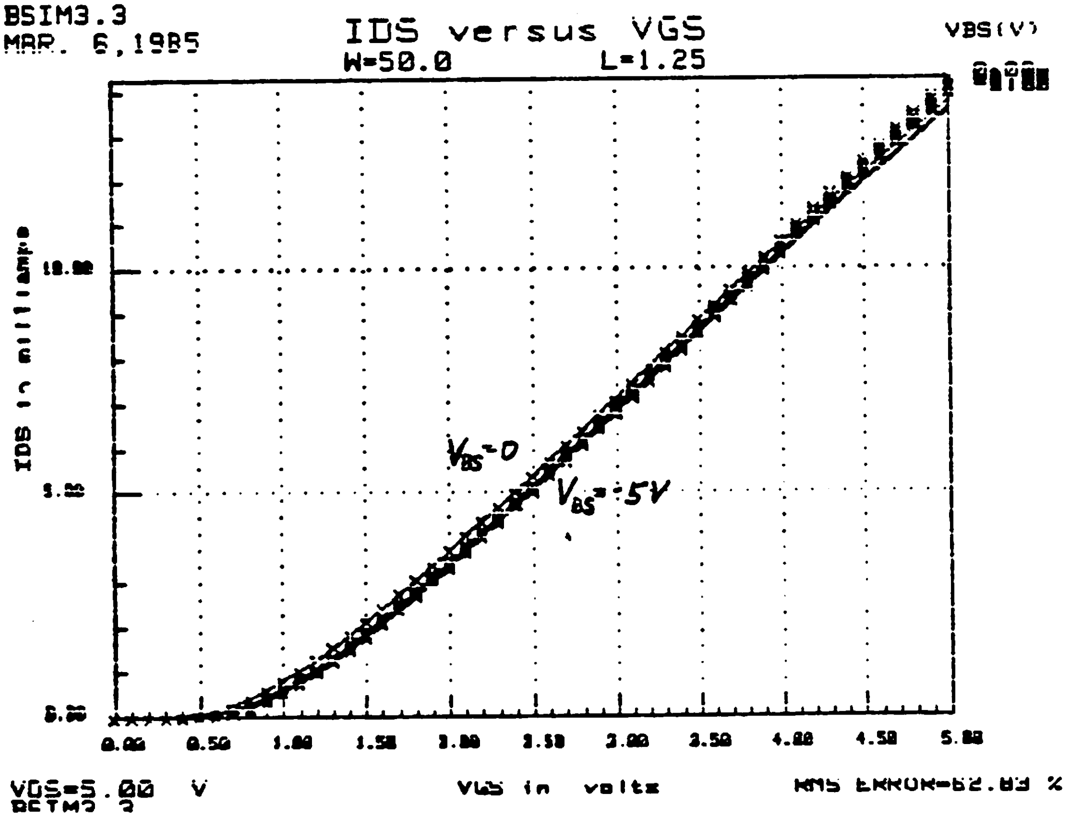

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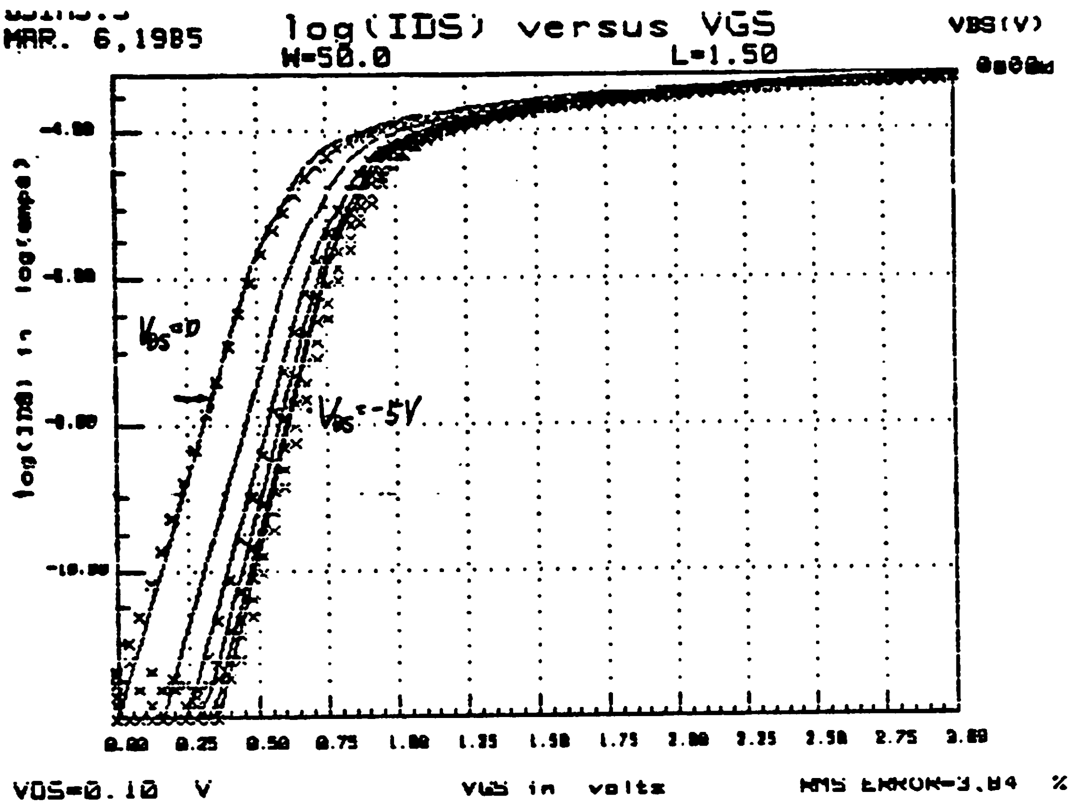

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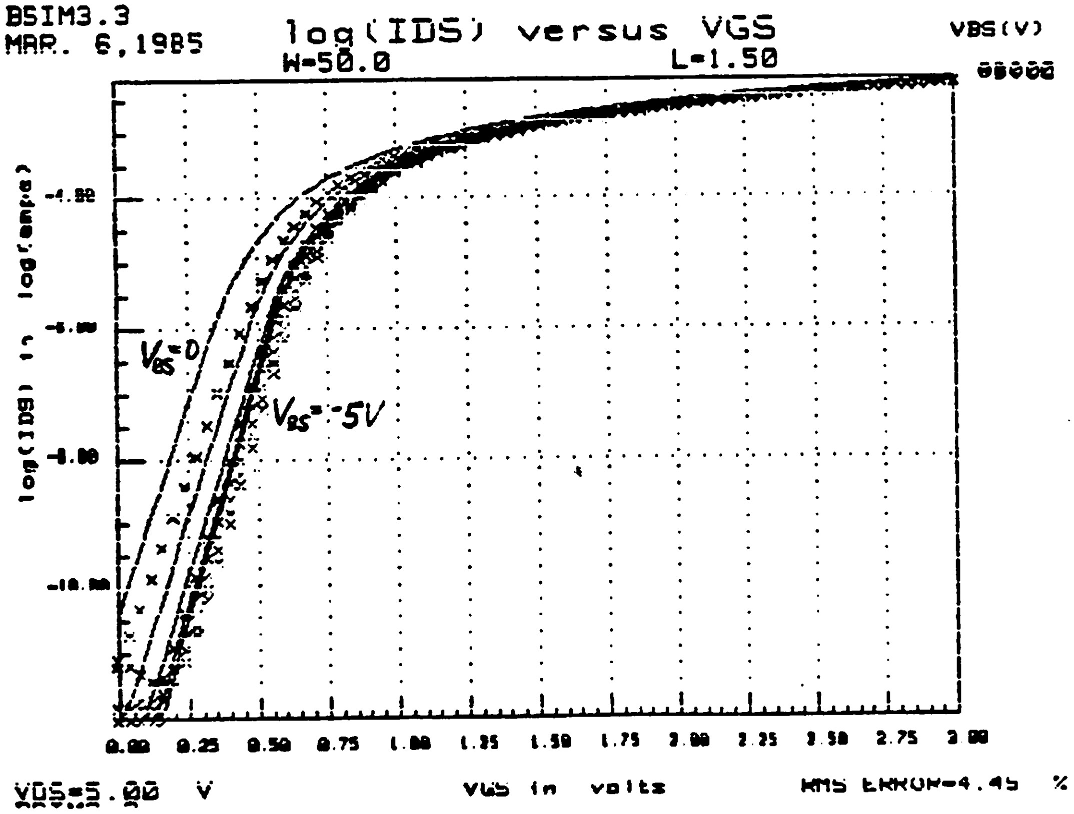

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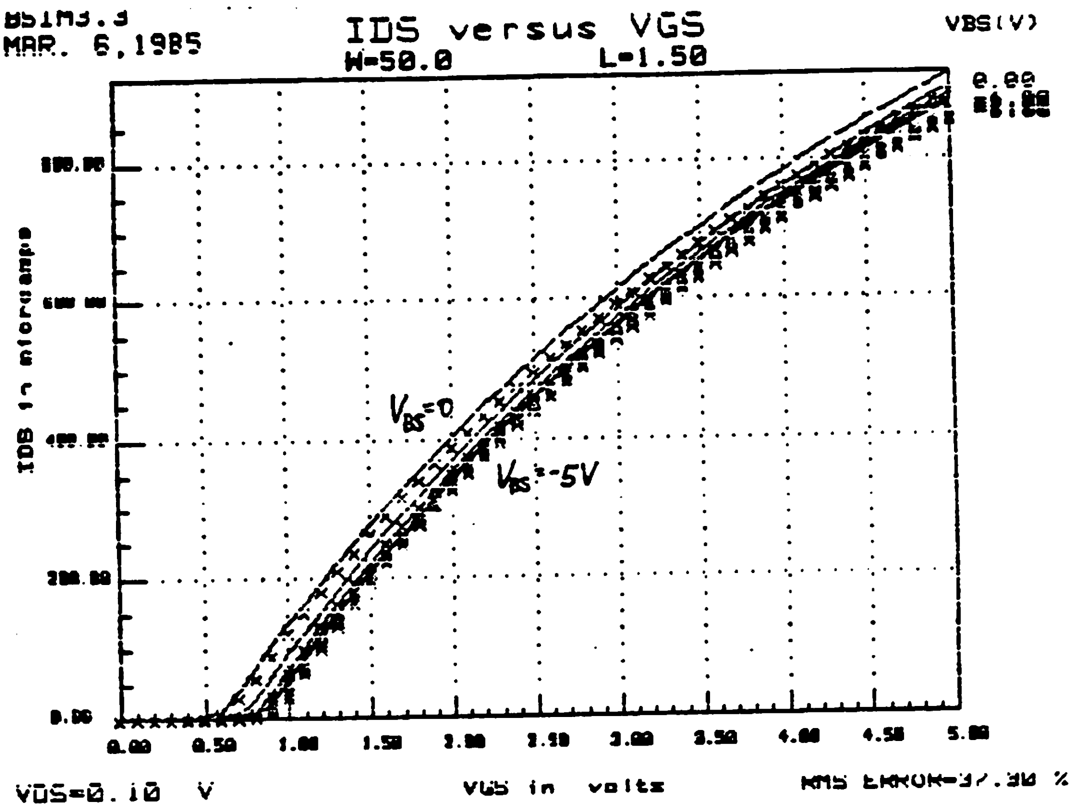

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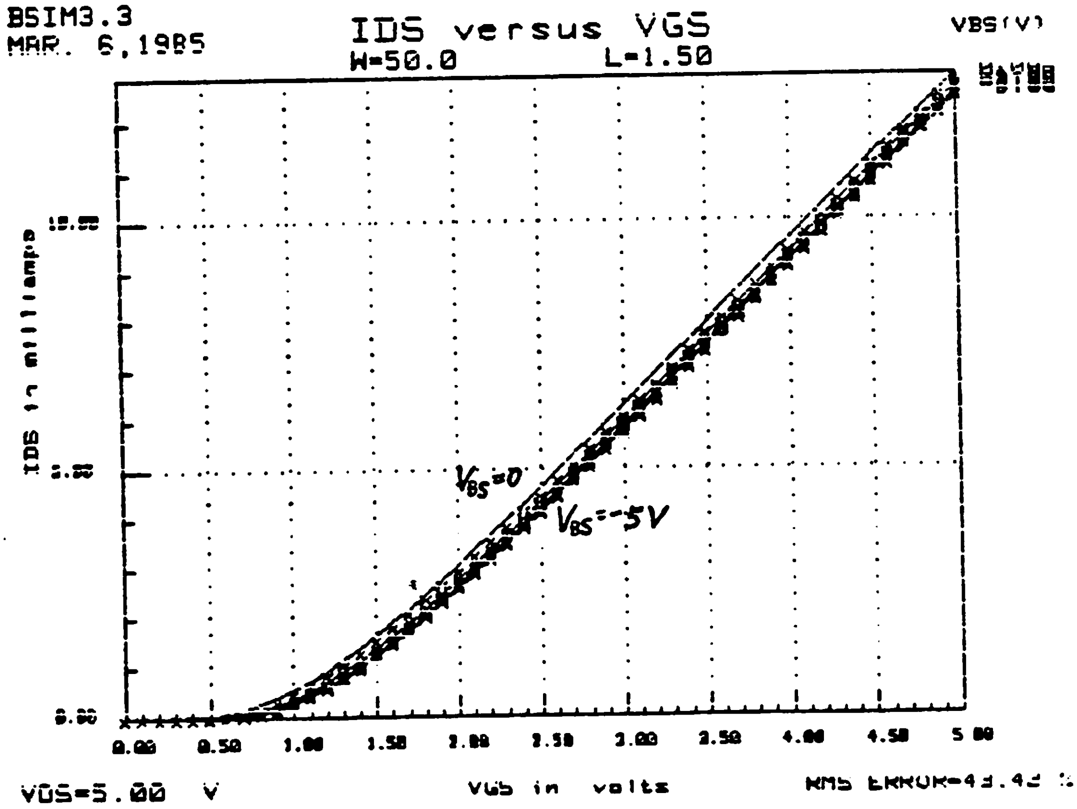

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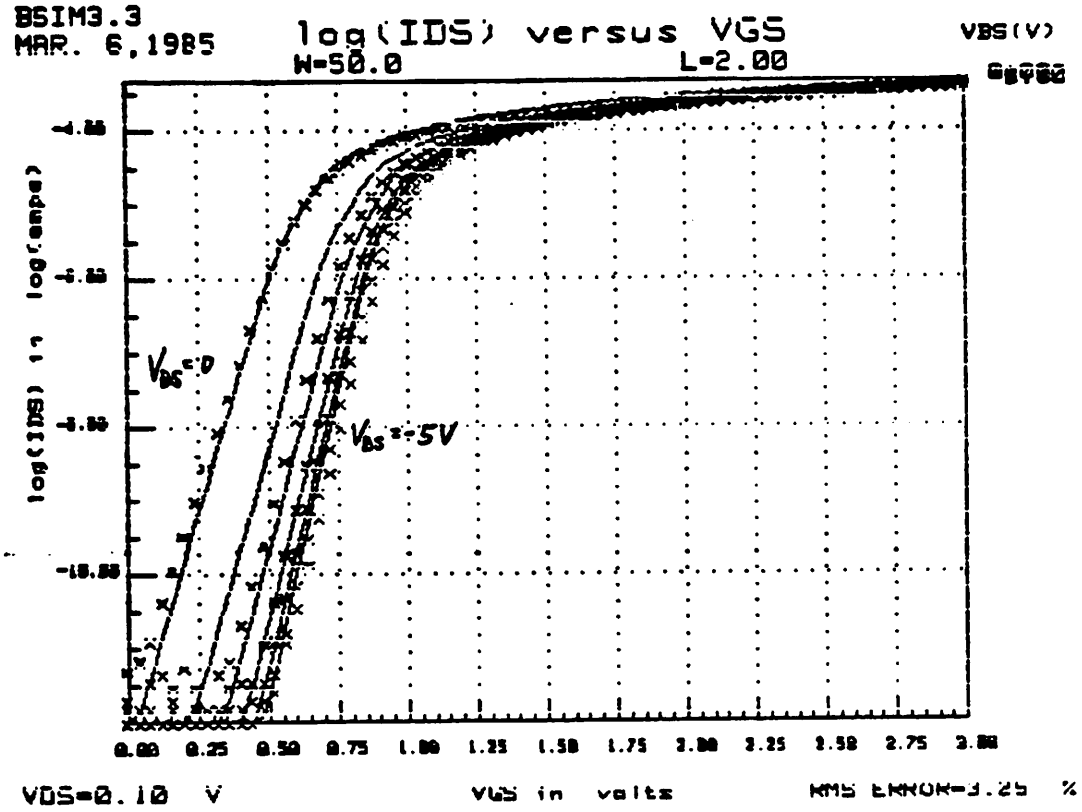
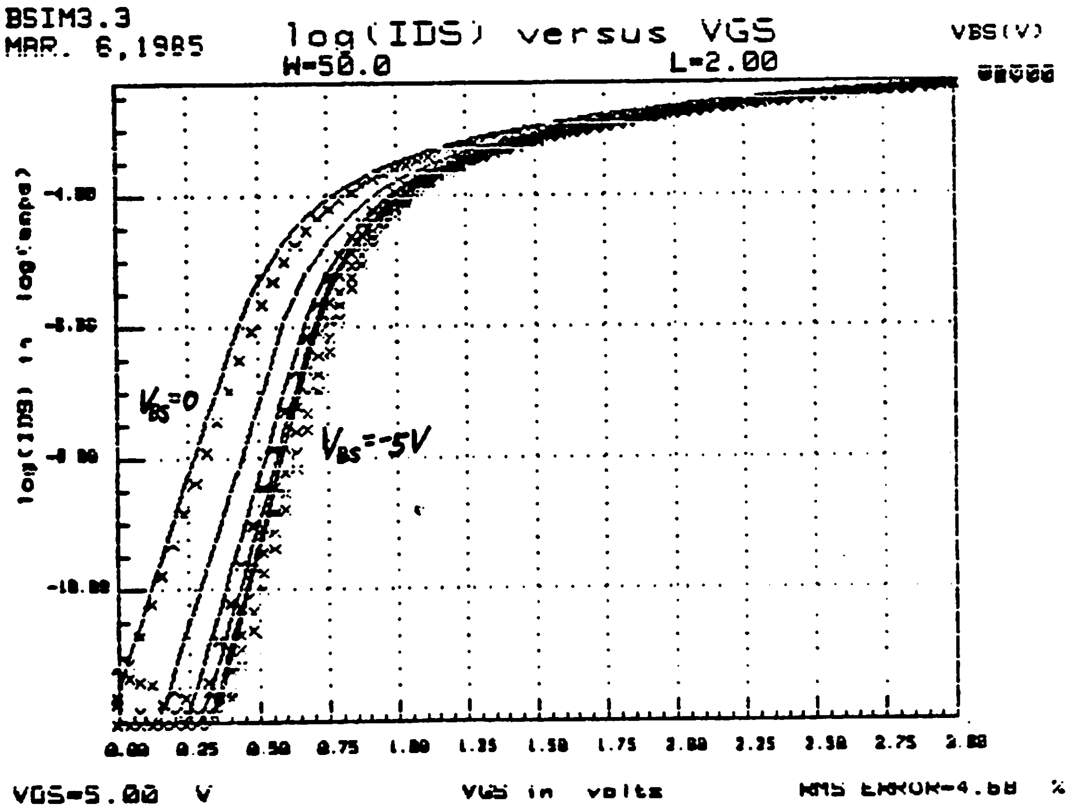


Fig. A20



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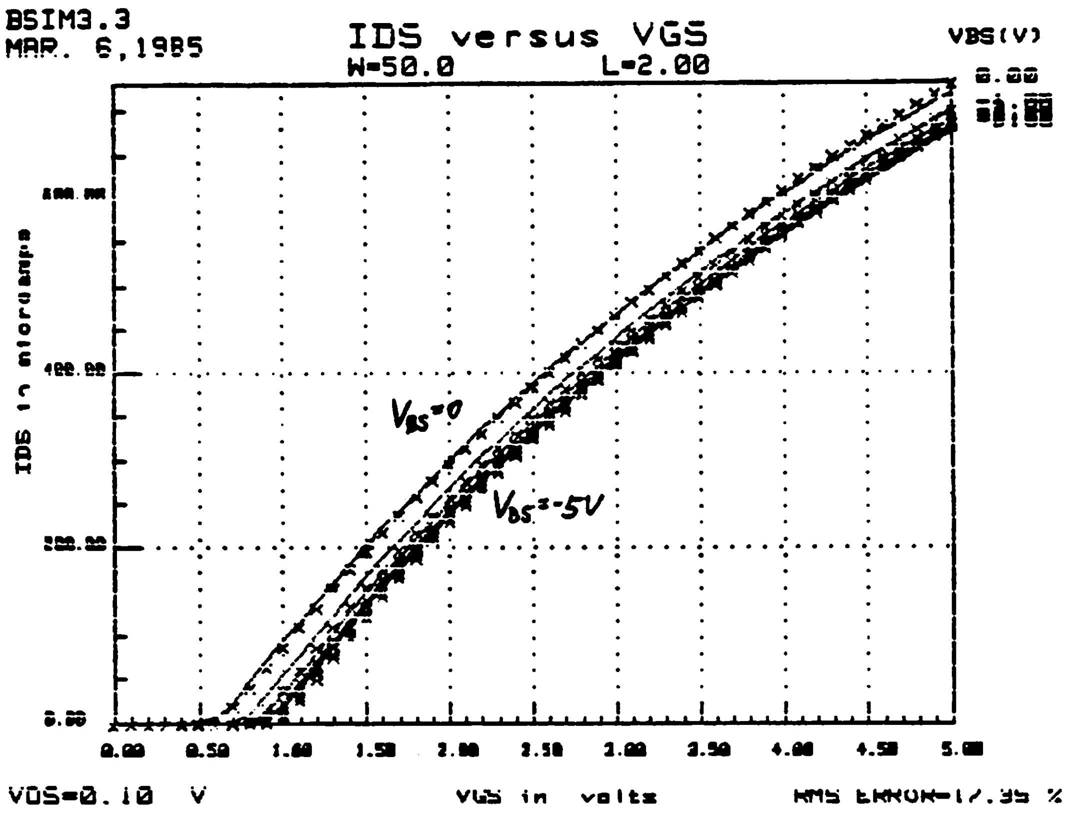

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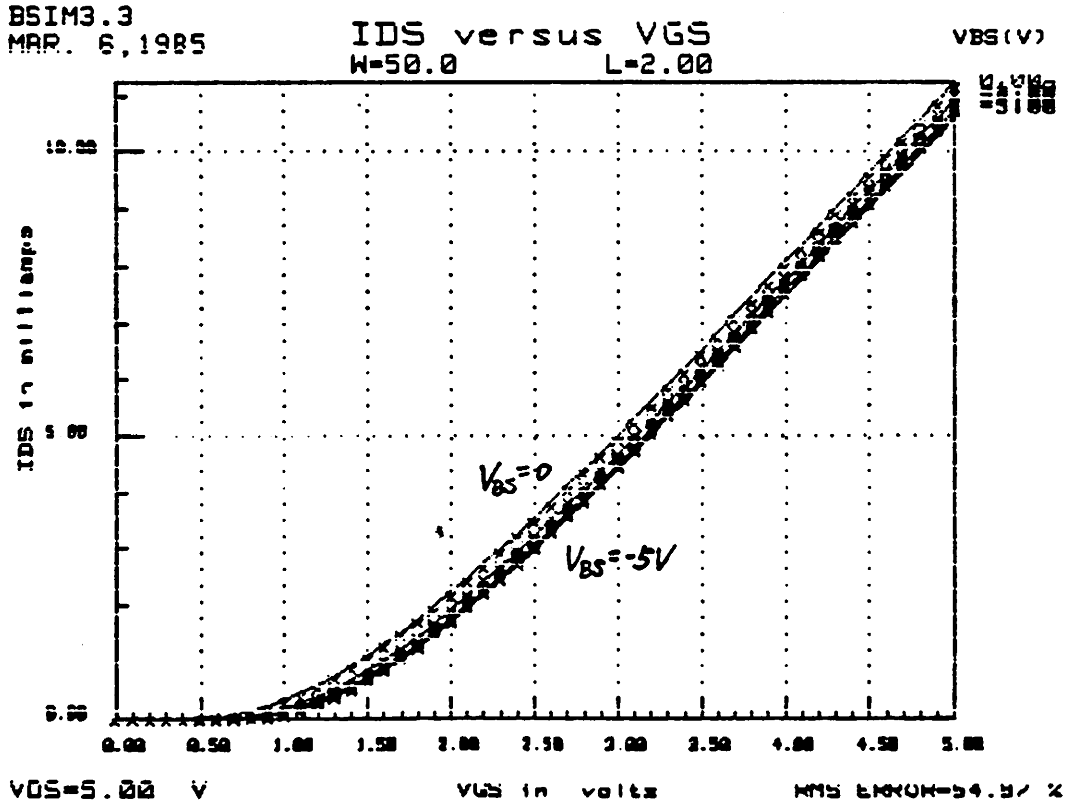

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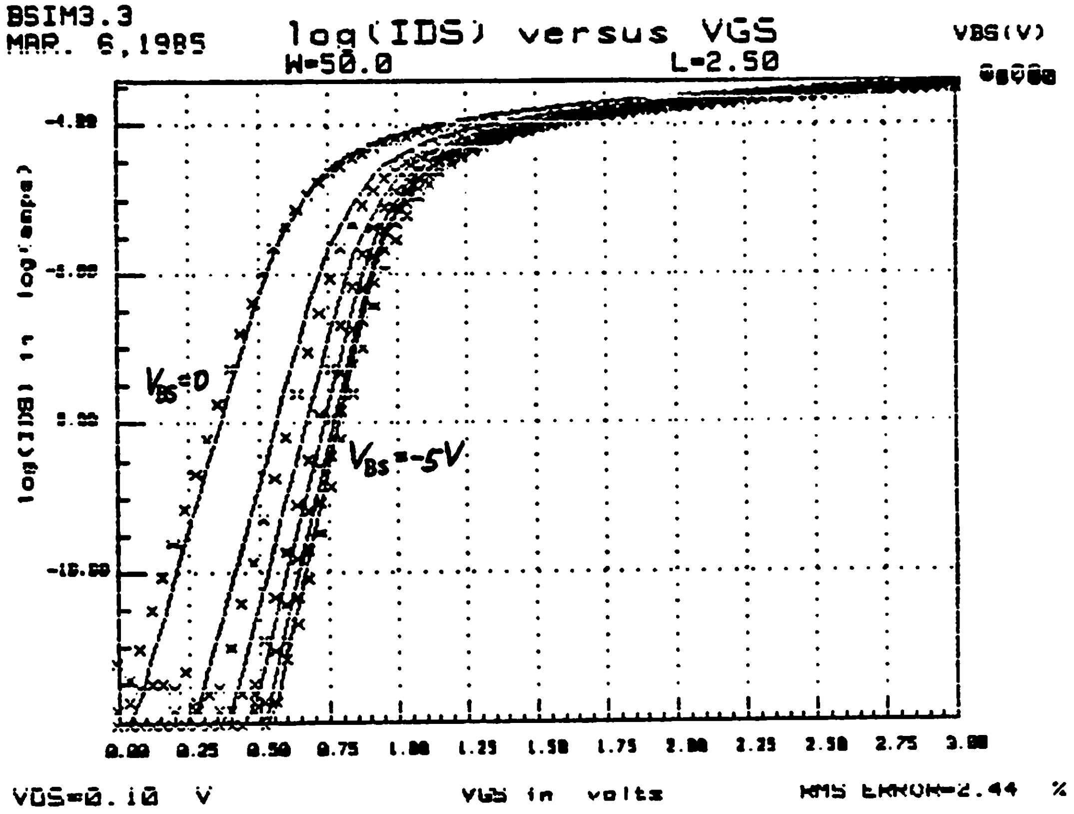
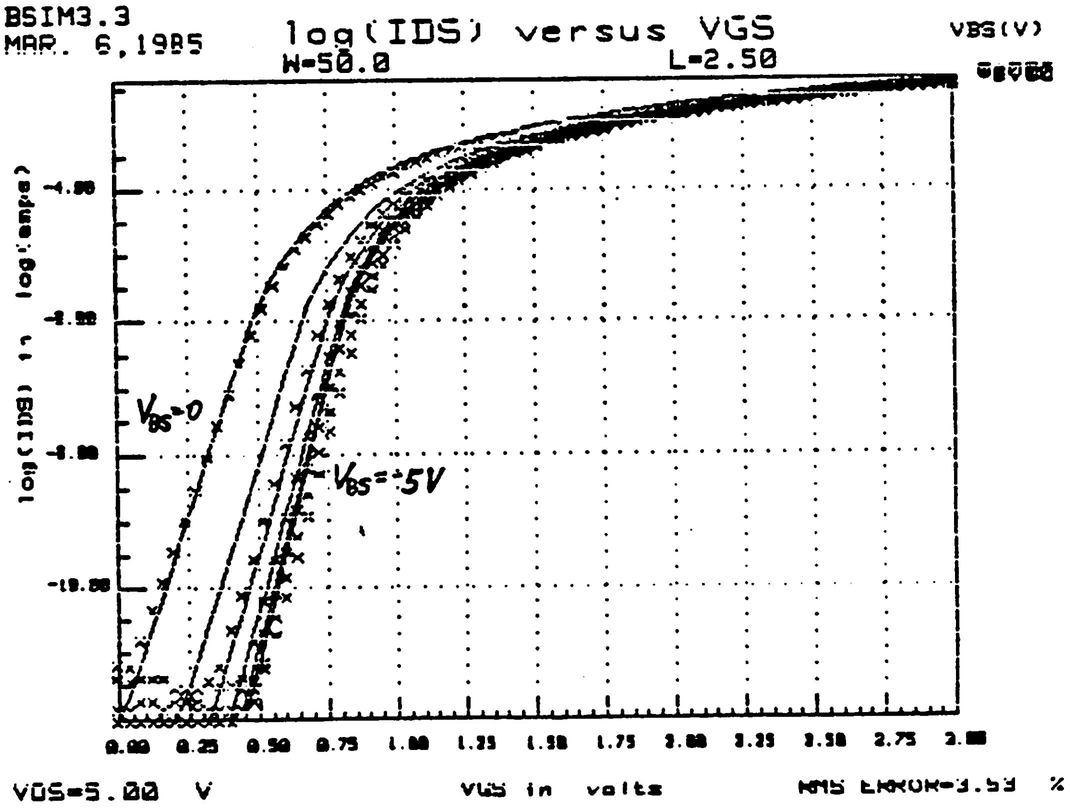


Fig. /24



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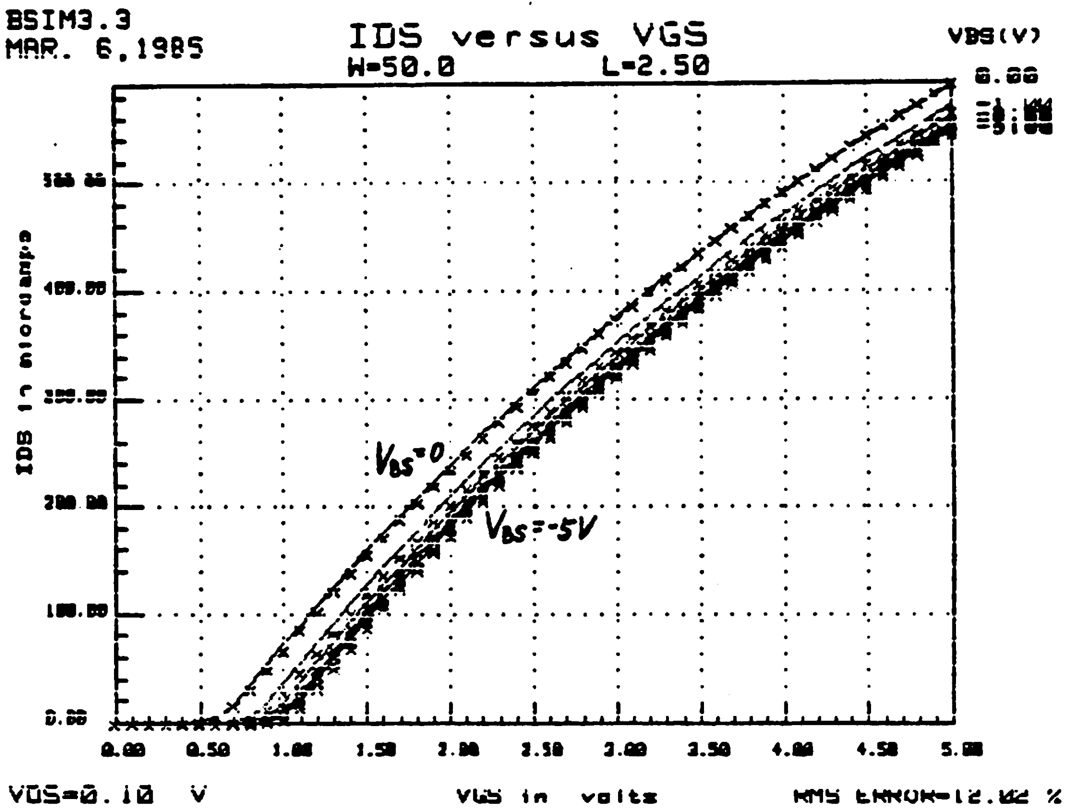

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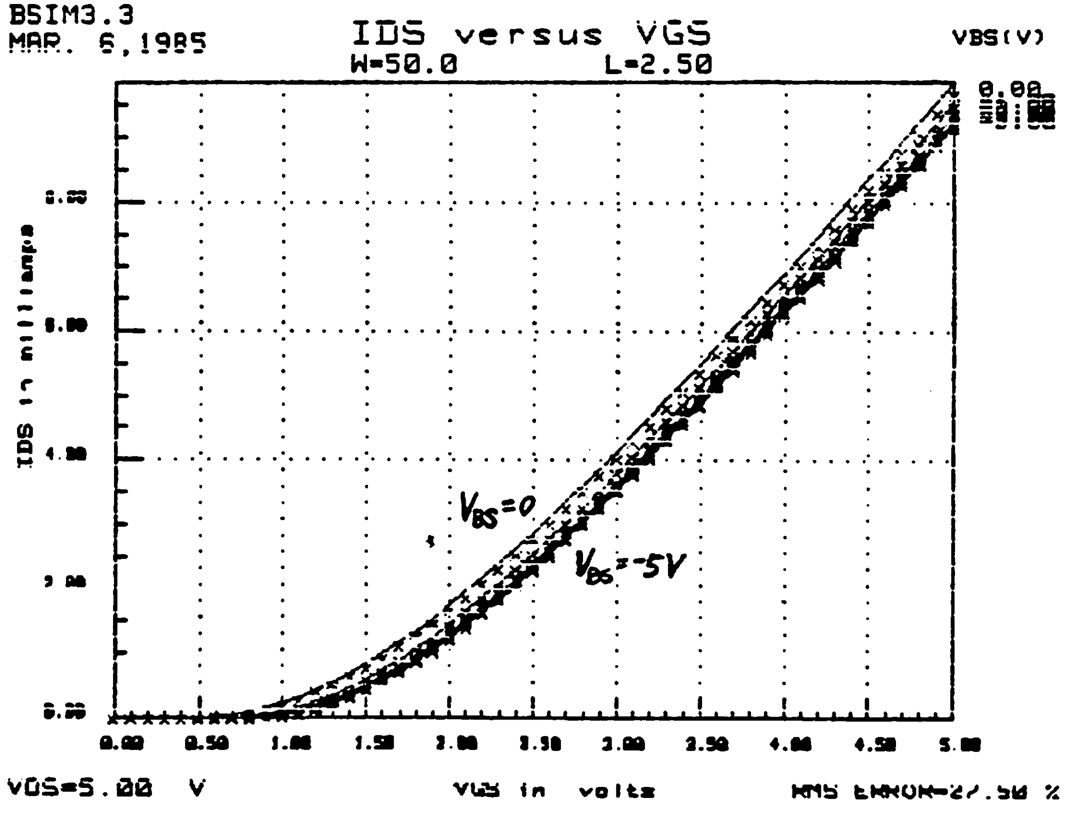

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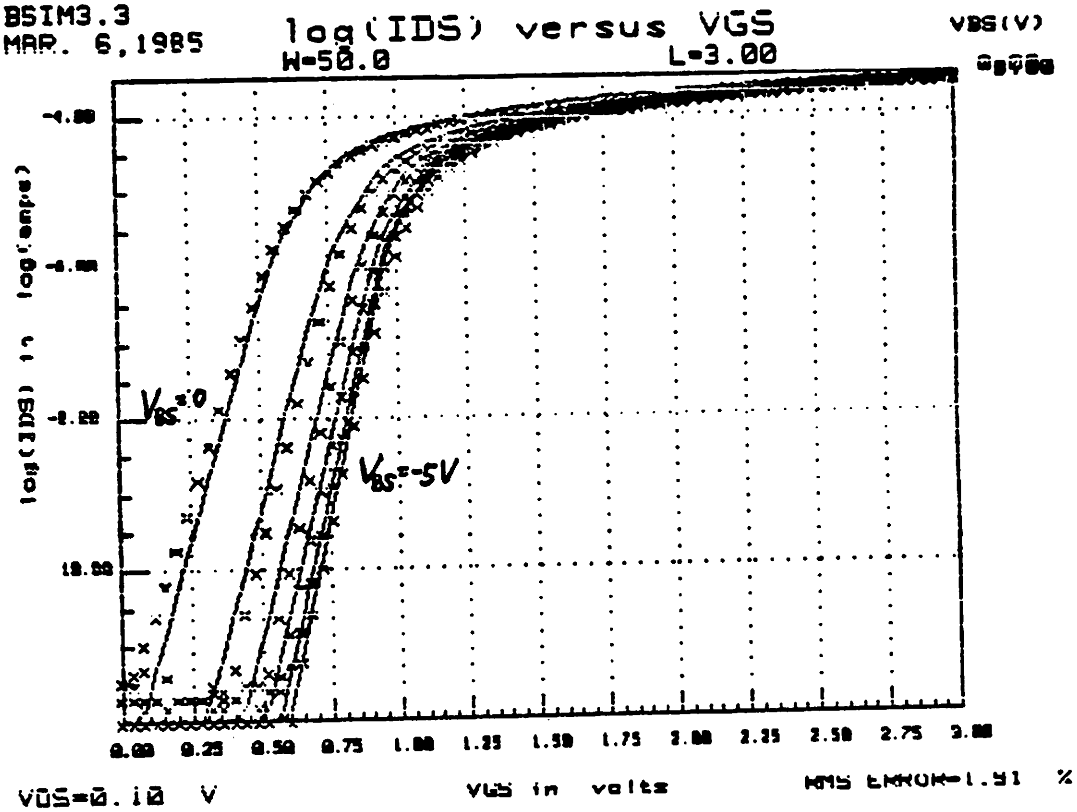

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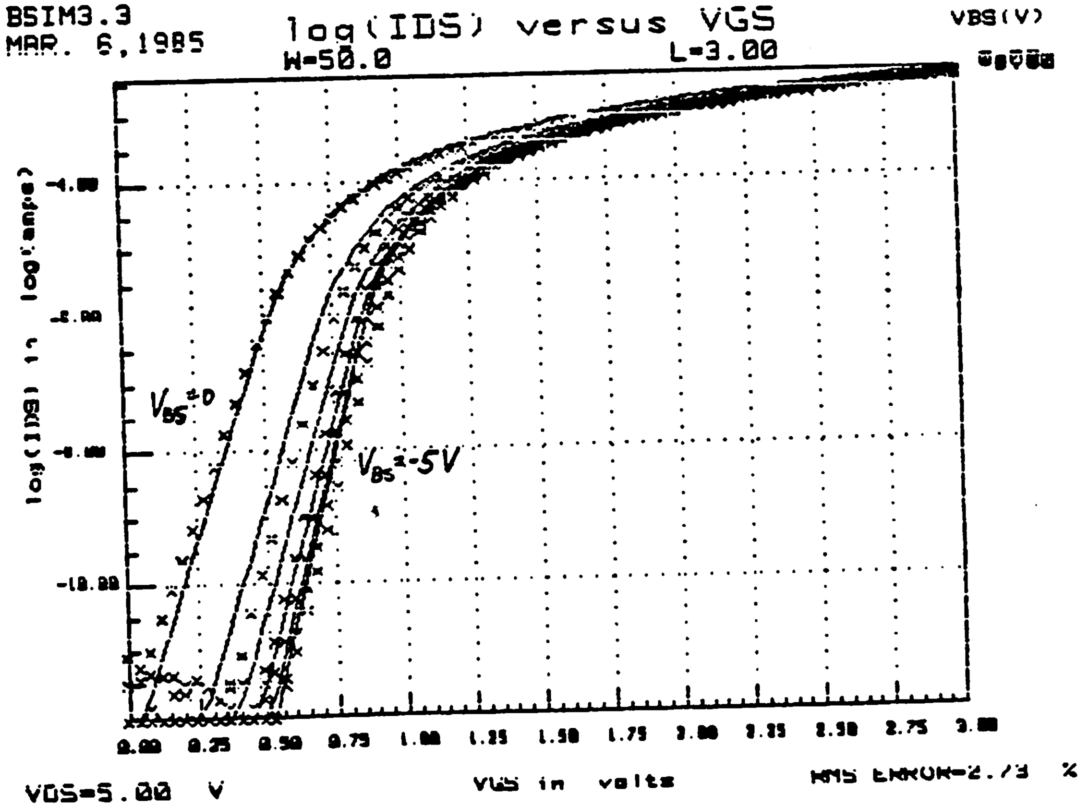

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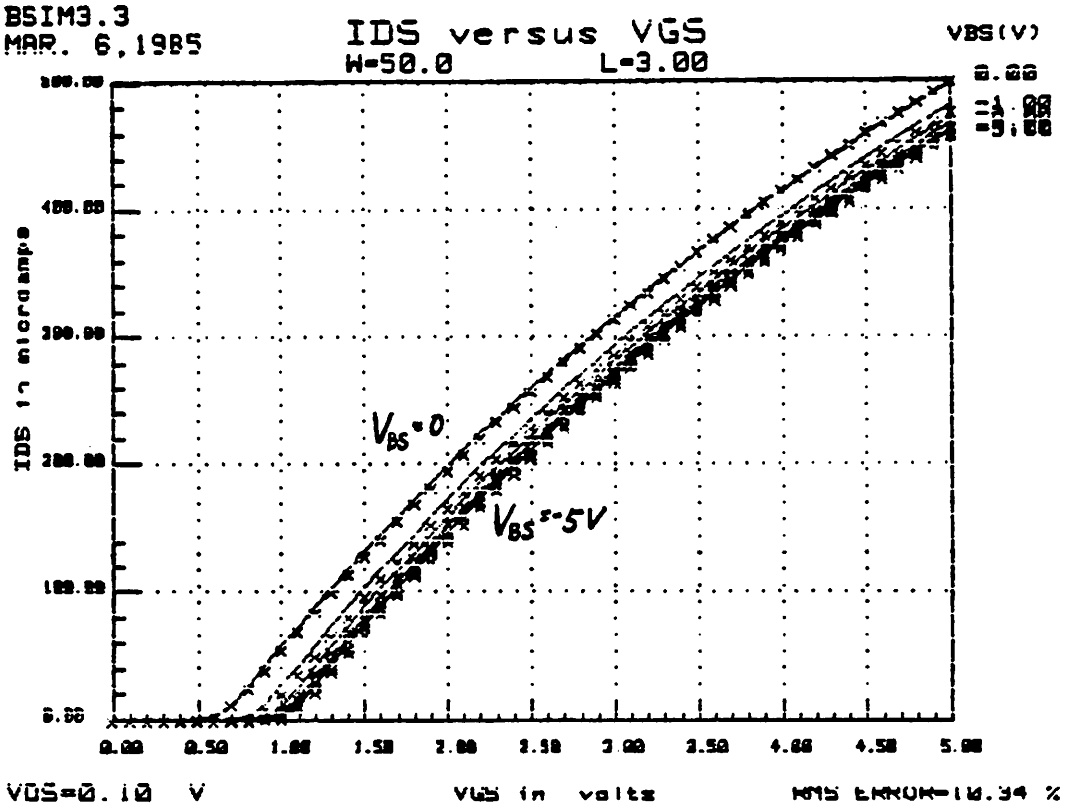


Fig. A30

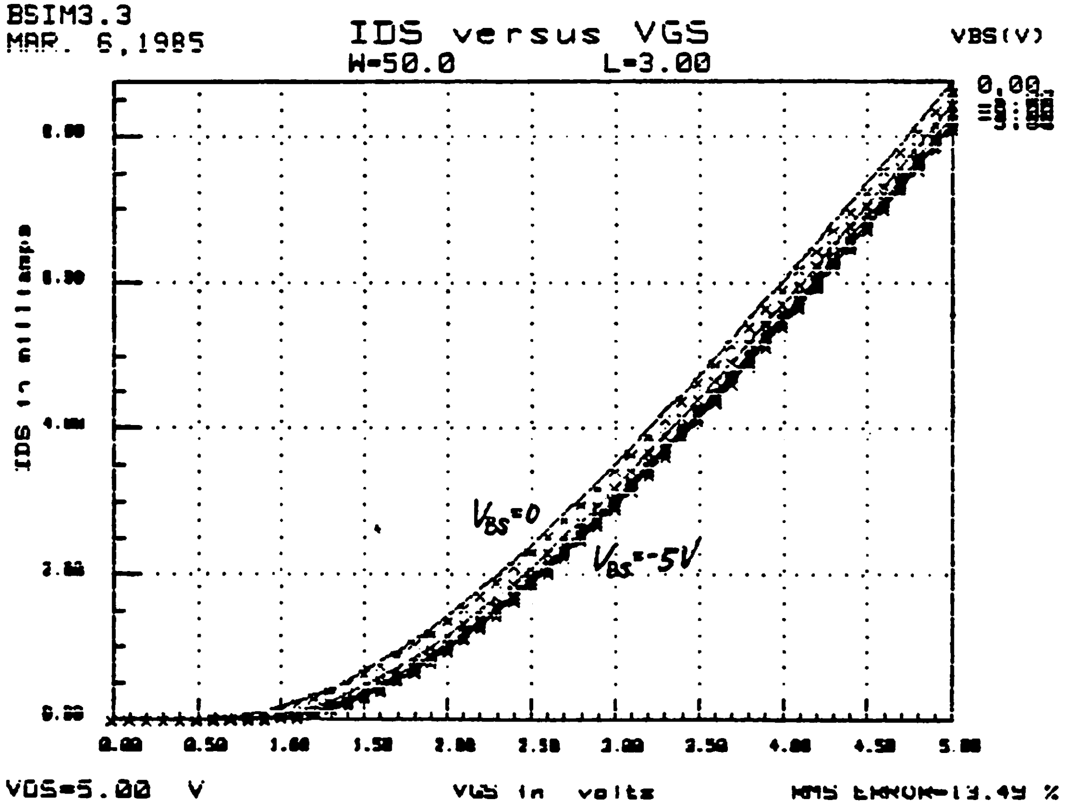
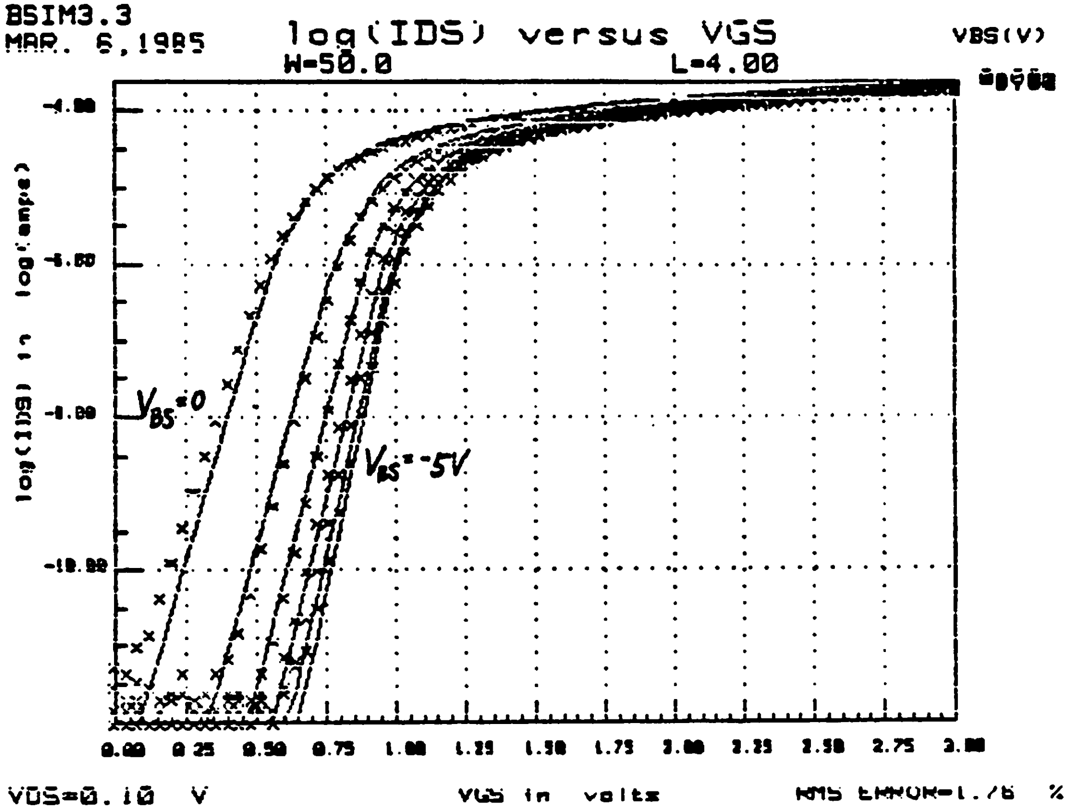


Fig. A31



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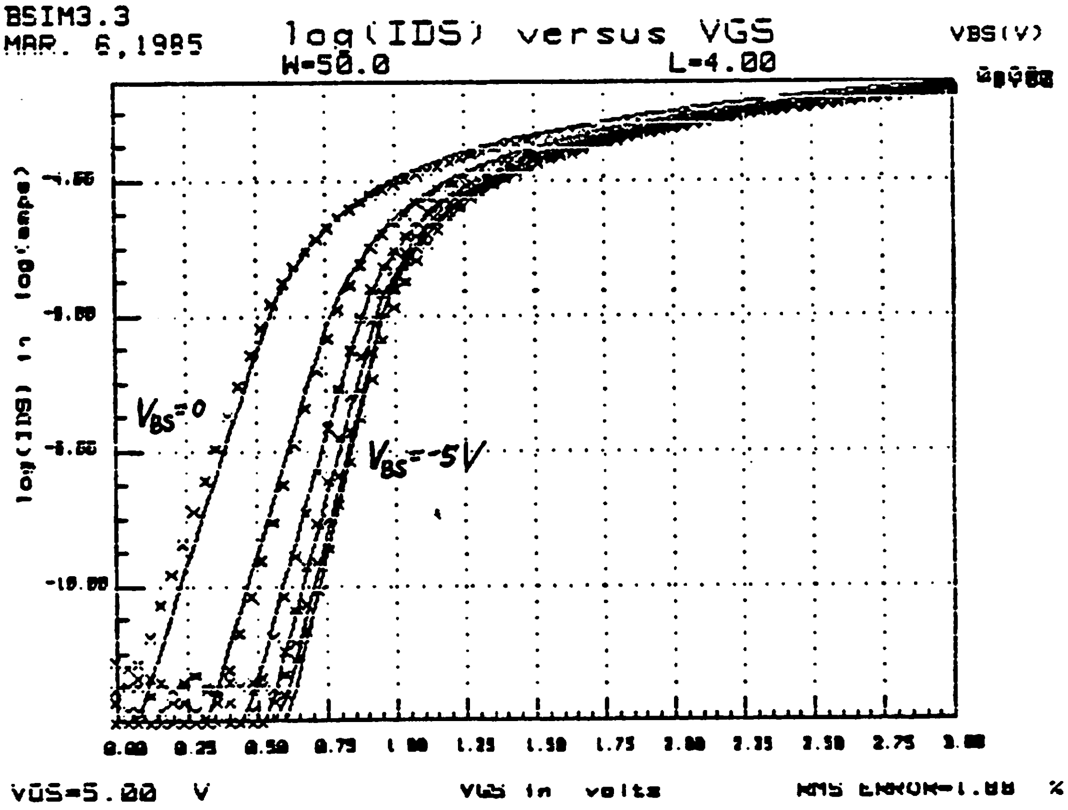

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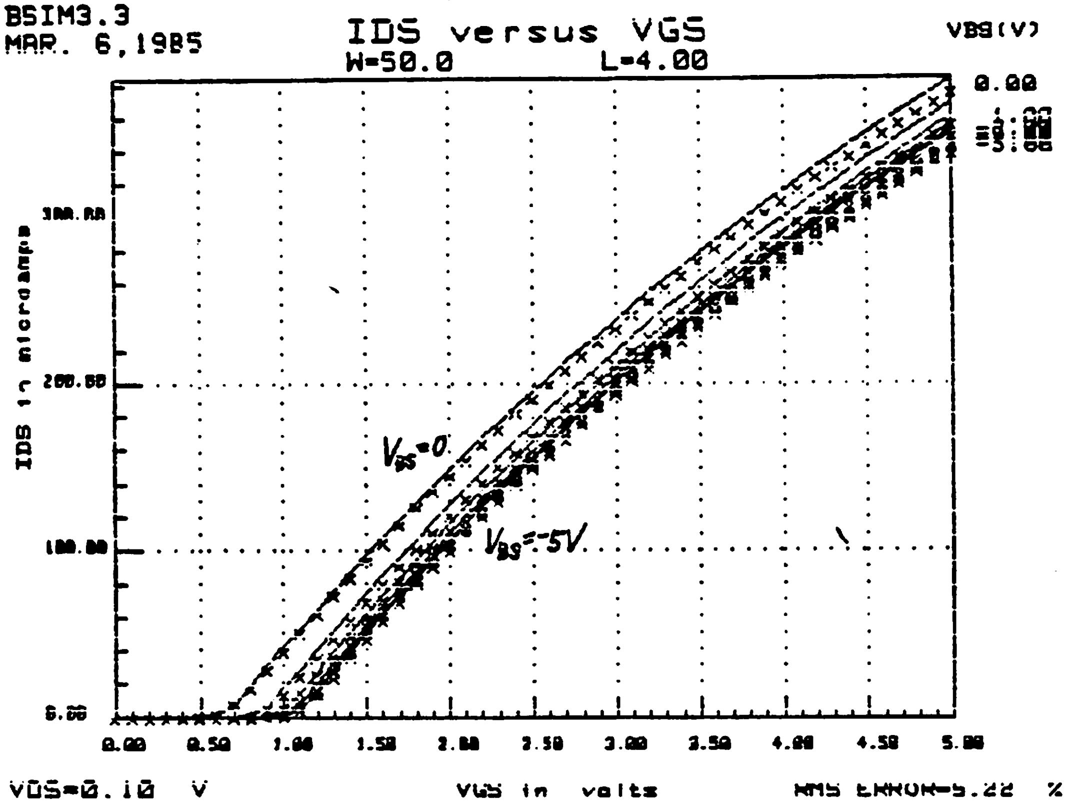

Fig. A34

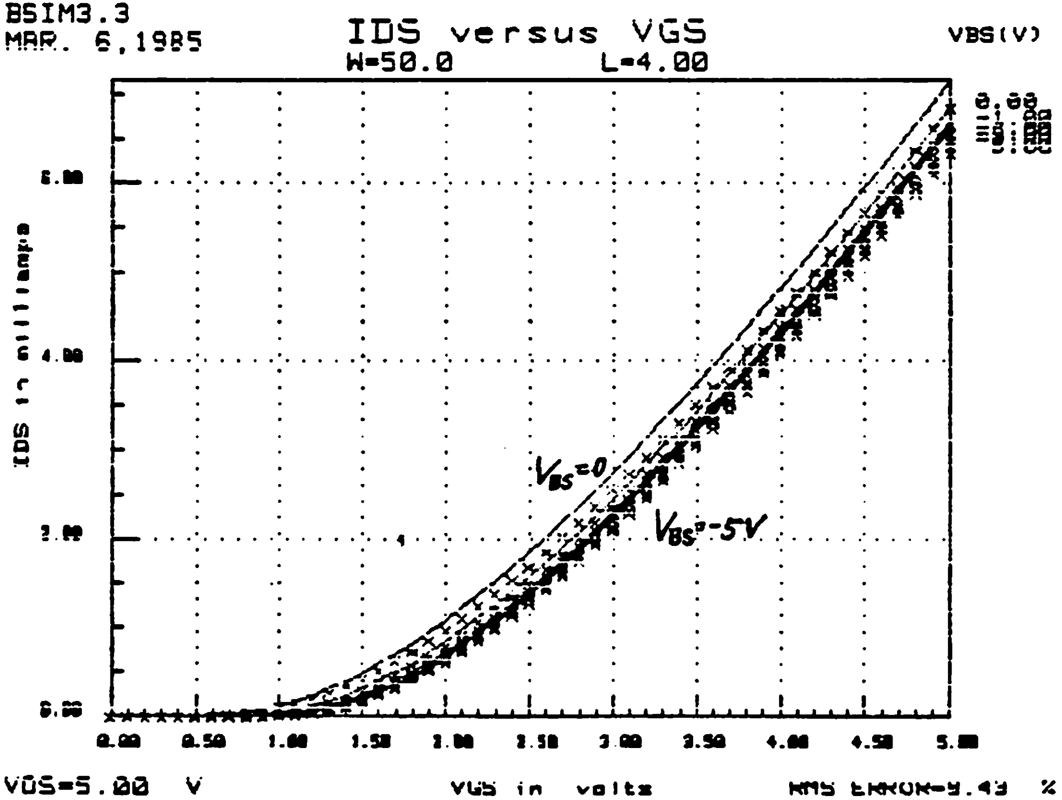

Fig. A35