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ABSTRACT

The MOSFET LEVEL II model in SPICE is analyzed to investigate the interrelationship of parameters, and to obtain equations for important non-capacitive quantities like the effective mobility, threshold voltage, saturation voltage, drain current, transconductance etc. An attempt is made to relate the equations implemented in the model to the user defined parameters and physical constants. Debugging was not one of the objectives of this project but some bugs in the program were discovered, their effects on computations are explained and corrections for most of them are suggested. This report is primarily for the user but it will also be helpful for those interested in looking at the program.

ACKNOWLEDGMENTS

I would like to thank my adviser professor Paul R. Gray for supervising this project and for providing the necessary research facilitites. Many other people helped me bring this project to completion as well. First of all, professor Richard Newton helped me begin by identifying the SPICE subroutines pertinent to this project. Many discussions with Resve Saleh were very helpful in understanding some internal SPICE parameters and data storage mechanisms. Professor David A. Hodges provided financial support during the summer of 1984 enabling me to continue working on this project. Last but not the least, Joey Doernberg reviewed the earlier drafts of this report and provided some valuable suggestions for improvements. I am very grateful to all these individuals for their help and support.

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INTRODUCTION

The purpose of this project is to produce a document by analyzing the code in order to help the users of MOSFET LEVEL II model in SPICE, understand the implementation of the model.

This report deals primarily with the non-capacitive calculations. That includes the computations for drain current, transconductance, output conductance and body effect conductance along with the quantities necessary for forming these quantities such as threshold voltage, drain-source saturation voltage etc. It is hoped that some other project will take up the calculations concerning capacitances.

During the course of this project some bugs were encountered. This report is kept free of code related details for the most part but it was still intented to report the errors which were found. These errors are reported in appendix C along with some suggestions for solutions. Needless to say that this appendix will make little or no sense without some knowledge of the SPICE code. A casual user is therefore advised to neglect this appendix. The effect of these errors on computations will be mentioned in appropriate contexts throughout this report.

The primary objective of this project is to present the implementation of MOS II model in SPICE. It is not the objective of the project to justify or criticize the model. The explanation of the code based on device physics as given in the report is only to make the report readable.

Without it the report would have been a collection of scrambled symbols and numbers with little or no meaning to any reader.

We have adhered to some conventions in the presentation of results in this report. First of all the names of user defined parameters have been left unchanged wherever they appear in the equations. Other variable names used in the code have been changed to their commonly accepted counterparts; for example, variable name XNI has been altered to n_i. Secondly, the equations presented are for n-channel device unless stated otherwise. Literally the same lines of code are executed for a p-channel device with appropriate sign alterations in equations. This is accomplished through the use of a variable called TYPE. TYPE has a value of +1 for n-channel device and a value of -1 for p-channel device.

All the constants which are used frequently are tabulated in appendix A. During the course of this project, some discoveries were made which may be useful for the user but they are not directly related to the model. they are listed in appendix B.

CHAPTER 1
ORGANIZATION OF THIS REPORT

This report involves explaining computations carried out in a complex piece of code, therefore it is necessary to give careful thought to the organization of the report. Probably a good way to begin is by examining a SPICE output file for a circuit containing a MOSFET. This will allow us to identify various parts of the output file and to establish some terminology, which will be used in the rest of the report.

The SPICE output file begins after the next page. Some of the blank lines in the original file have been erased for compactness. All of the remaining lines in the file have been numbered so that parts of the file can be referred easily. Lines 9 through 21 contain the echo print of the input file. We are interested particularly in line 11 and lines 14 through 16. Line 11 is the MOSFET device description. The parameters on this line will be called **device parameters**. Not all the device parameters have to be user defined and line 11 does not contain all of the device parameters.

Lines 14 through 16 contain the MOSFET model description for the device described in line 11. The same model description can be used for more than one device. The parameters in these lines will be called **model parameters**. Just like in the case of device parameters, not all the model parameters need to be defined by the user. Lines 14 through 16 don't contain all of them. It is however essential that LEVEL=2 be explicitly

specified by the user otherwise the LEVEL I model will be used.

Parameters will be used to refer to model parameters and device parameters collectively.

The calculations carried out by SPICE for a MOSFET can conceptually be broken down into several steps as shown in the flow chart of figure 1.1. Consequently this report can probably be best presented by breaking it down into several chapters each describing one of the steps in the flow chart.

The first step in the flow chart has to do with reading all of the device and model descriptions. SPICE has some sophisticated subroutines to read and store input data in a memory efficient manner but the user is not likely to be interested in the details of programming. Some of the information in appendix C was obtained during the analysis of these subroutines.

The second step is to decide what parameter values will be used for further computations. This also includes assigning values to those parameters which have not been defined by the user. Lines 22 through 45 contain a partial print out of the final values of the model parameters. Since no change is made to these values after this point, they will be referred to as the **finalized parameter values** or **finalized parameters.** All the model parameter values are not printed. The parameters LEVEL, VTO and KP will always be printed. The other parameters printed are those which are calculated or user defined for at least one MOSFET model description. It is safe to assume that the parameters not printed have been set to the

```
1 1********11/21/84 ******** SPICE 2G.6   3/15/83 ********21:59:16*****
2
3         A SPICE INPUT FILE WITH MOSFET LEVEL II
4
5  ****    INPUT LISTING                TEMPERATURE =   27.000 DEG C
6
7  ******************************************************************************
8
9  VDD 1 0 5V
10 RL  1 2 1K
11 M1  2 3 0 0 NMOD L=5U W=5U AD=30P AS=30P PD=17U PS=17U
12 VIN 3 0 1.5V
13 *
14 .MODEL NMOD NMOS LEVEL=2 VTO=.9 NSUB=1.0E15 UO=700 CGSO=.35N
15 +CGDO=.35N  CJ=80U MJ=.5 CJSW=.5N MJSW=.5 TOX=40N TPG=+1 XJ=.6U
16 +KP=60.4U GAMMA=.211 LD=.3U VMAX=5.0E4 NEFF=30 PHI=.576 NSS=1.0E11
17 *
18 .OPTIONS NOPAGE
19 .TEMP 50
20 .OP
21 .END
22 ****    MOSFET MODEL PARAMETERS        TEMPERATURE =   27.000 DEG C
23
24            NMOD
25 TYPE        NMOS
26 LEVEL        2.000
27 VTO          0.900
28 KP       6.04d-05
29 GAMMA         0.211
30 PHI          0.576
31 CGSO      3.50d-10
32 CGDO      3.50d-10
33 CJ        8.00d-05
34 MJ           0.500
35 CJSW      5.00d-10
36 MJSW         0.500
37 TOX       4.00d-08
38 NSUB      1.00d+15
39 NSS       1.00d+11
40 TPG          1.000
41 XJ        6.00d-07
42 LD        3.00d-07
43 UO         700.000
44 VMAX      5.00d+04
45 NEFF         30.000
```

```
46  ****    TEMPERATURE-ADJUSTED VALUES     TEMPERATURE =   50.000 DEG C
47
48  **** MOSFET MODEL PARAMETERS
49  NAME       VTO       PHI        PB      IS(JS)      KP        UO
50
51
52  NMOD     8.686d-01 5.222d-01 7.634d-01 2.698d-13 5.407d-05 6.266d-02
53  ****    SMALL SIGNAL BIAS SOLUTION      TEMPERATURE =   50.000 DEG C
54
55   NODE  VOLTAGE    NODE  VOLTAGE    NODE  VOLTAGE
56
57  ( 1)   5.0000   ( 2)   4.9865   ( 3)   1.5000
58
59
60
61     VOLTAGE SOURCE CURRENTS
62
63     NAME      CURRENT
64
65     VDD     -1.350d-05
66
67     VIN      0.  d+00
68
69
70     TOTAL POWER DISSIPATION  6.75d-05  WATTS
71  ****    OPERATING POINT INFORMATION     TEMPERATURE =   50.000 DEG C
72
73
74  **** MOSFETS
75
76
77           M1
78  MODEL     NMOD
79  ID       1.35e-05
80  VGS         1.500
81  VDS         4.987
82  VBS         0.
83  VTH         0.837
84  VDSAT       0.554
85  GM       4.05e-05
86  GDS      2.29e-07
87  GMB      3.39e-06
88  CBD      4.08e-15
89  CBS      1.12e-14
90  CGSOVL   1.75e-15
```

```
91   CGDOVL   1.75e-15
92   CGBOVL   0. e+00
93   CGS      1.27e-14
94   CGD      0. e+00
95   CGB      0. e+00
96
97         JOB CONCLUDED
98          TOTAL JOB TIME          0.98
```

default values.

If analysis is desired at a temperature other than the nominal temperature, the next step will involve adjusting the values of those parameters which have some temperature dependence. The list of adjusted parameters is printed from line 48 to 52. This list is not complete either.

The next step is to resolve the inconsistencies and compute the secondary quantities. Sometimes the two processes go hand in hand. An example will help clarify it. The model parameters IS and JS specify bulk junction *saturation current* and bulk junction *saturation current density* respectively. The device parameters AD and AS specify the drain area and source area respectively. It is possible that the product of AD and JS is not the same as IS for a given device. This inconsistency is resolved by forming a secondary quantity called CDSAT which is the saturation current for the drain bulk junction. If CDSAT is assigned the value held by IS then IS overwrites JS. On the other hand if CDSAT is calculated by multiplying JS and AD then JS overwrites IS. A similar inconsistency about the saturation current of source bulk junction is resolved by forming CSSAT. IS and JS are dropped at this point and CSSAT and CDSAT are used

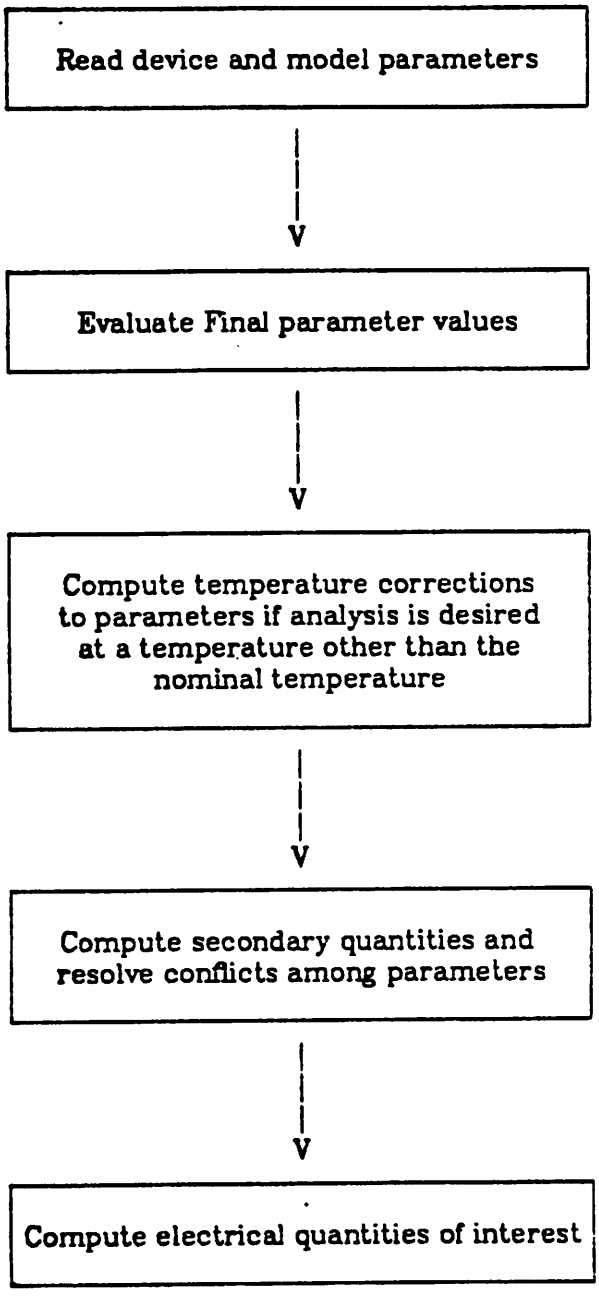

Figure 1.1: Flow Chart

for further computations.

The final step is to compute the useful electrical quantities like the drain current, transconductance etc. These quantities are printed in lines 77 through 95. SPICE uses the Newton-Raphson algorithm to obtain the operating point, which requires evaluating the derivatives of drain current with respect to various port voltages at each iteration. Obviously these derivatives are various conductances. In the final iteration these conductances provide the values at the operating point, which can be used in a later AC analysis.

CHAPTER 2

EVALUATION OF FINAL PARAMETER VALUES

The parameter values used for further computations are those provided by the user, computed from constants or the default values. We will call them **final parameter values** or **final parameters**. These final values are considered to be at the nominal temperature, 27^0 *C* by default. This temperature can be changed to any desired temperature value x by appending "TNOM=x" to the .OPTIONS card (without quotes). One incident where this may be necessary is when experimentally extracted model parameters are input on the .MODEL card and the temperature at which they were extracted is different from 27^0 *C*. To clarify how the final value of each parameter is obtained, the priority list will be used. A priority list starts with the definition of the parameter followed by a list of two to five statements. The definitions are taken from the SPICE User's Guide except where something useful could be added. Most of the statements in the priority list are conditional statements. Each statement tells a way the final value of the parameter is obtained. The list is to be read from statement one. The first conditional statement to become true or the first unconditional statement encountered tells the way the final value for the parameter is obtained. We call such a list a priority list because the statements occurring earlier in the list have priority over those occurring later.

For an example; consider the priority list for VTO shown after two pages. The first statement tells that the user input value is used if there is one. If a user input value exists there is no need to read any further. However, if no user defined value exists then the model parameter value will be calculated using the equations shown in statement two; provided model parameter NSUB has been input by the user. If NSUB has not been input then the VTO is set to zero as suggested by the third statement. The third statement is an unconditional statement.

The example priority list uses final values of two other model parameters in the calculations in statement 2, NSS and TPG. The priority lists below are arranged in such a way that a given priority list uses only those model parameters whose priority lists have occurred before. The equations shown in the priority list occasionally use some constants. These constants are tabulated at the end of the report if no further explanation appears for them within the priority list.

PRIORITY LISTS FOR MODEL PARAMETERS

NSUB: Substrate doping.

1. User defined value if greater than n_i (intrinsic carrier concentration) . A user defined value of less than n_i is considered an error and will cause the SPICE job to terminate with an error message.
2. *NSUB*=0.0 if not defined by the user. This value is used just as a flag.

TOX: Oxide thickness under the gate.

1. User defined value if any.
2. $TOX = 10^{-7}$ m.

UO: Surface mobility at low gate voltage.

1. User defined value if any.
2. $UO = 600\ cm^2/V\text{-sec}$.

KP: Intrinsic transconductance parameter.

1. User defined value if any.
2. $$KP = UO \times COX \tag{2.1}$$

   where COX is the oxide capacitance and is given by:

   $$COX = \frac{\varepsilon_{ox}}{TOX} \tag{2.2}$$

PHI: Surface potential in strong inversion.

1. User defined value if any.
2. $PHI = 0.0$ if NSUB is not defined by the user.
3. Calculated as shown below in equation (2.3) if this gives PHI > 0.1.

$$PHI = 2V_T \ln\left[\frac{NSUB}{n_i}\right] \tag{2.3}$$

4. PHI=0.1

TPG: Type of the gate:

+1 for gate type opposite to substrate.

-1 for gate type same as substrate.

0 for Aluminum gate.

1. User defined value if any.
2. $TPG=1$

GAMMA: Body effect coefficient.

1. User defined value if any.
2. Computed as shown below if NSUB is user defined.

$$GAMMA = \frac{\sqrt{2\varepsilon_{si} q NSUB}}{COX} \tag{2.4}$$

where COX is the gate oxide capacitance and is given by equation (2.2).

3. $GAMMA=0.0$

NSS: Surface state density.

1. User defined value if any.

2. $NSS=0.0$

VTO: Zero body-bias threshold voltage of a long and wide channel device in the same technology as that of the device using this VTO.

1. User defined value if any.
2. Computed as follows provided NSUB is user defined.

$$VTO=\Phi_{ms}+PHI+GAMMA\sqrt{PHI}-\frac{q\times NSS}{COX} \tag{2.5}$$

Where COX is the gate oxide capacitance and is given by equation (2.2).

Φ_{ms} is the difference in work function between metal and silicon and depends on TPG. Its value for the three possible values of TPG is given below.

$$\Phi_{ms}=-0.5-0.5E_g-0.5PHI \quad \text{for } TPG=0 \tag{2.6a}$$

$$\Phi_{ms}=-0.5E_g-0.5PHI \quad \text{for } TPG=1 \tag{2.6b}$$

$$\Phi_{ms}=0.5E_g-0.5PHI \quad \text{for } TPG=-1 \tag{2.6c}$$

E_g is the energy gap for silicon. The equation for energy gap is given below:

$$E_g=1.16-\frac{7.02\times10^{-4}\times T^2}{T+1108.0} \tag{2.7}$$

where T is the nominal temperature in K.

Equation (2.5) is similar to equation (2.8) below which is used by most people for hand calculation.

$$VTO=\Phi_{ms}+2\Phi_p+\frac{Q_b}{COX}-\frac{Q_{ss}}{COX} \qquad (2.8)$$

Comparing equations (2.5) and (2.8), the first term is the same in both. The second, third and fourth terms of equation (2.5) correspond to those of equation (2.8). In equation (2.8) Φ_p is the substrate potential in strong inversion. Q_b is the charge stored in substrate and Q_{ss} is the oxide charge.

3. VTO=0.0

AF: Flicker noise exponent.

1. User defined value if greater than or equal to 0.1.
2. AF=0.1 if user defined value is less than 0.1.
3. AF=1.0

FC: Coefficient for forward-bias depletion capacitance formula.

1. User defined value if less than or equal to 0.95.
2. If user defined value is greater than 0.95 than FC=0.95.
3. FC=0.5 if not defined by the user.

PB: Bulk junction potential.

1. User defined value if any.
2. PB=0.8V

CJ: Zero bias bulk junction capacitance $/m^2$ of the junction area.

1. User defined value if any.
2. $$CJ = \sqrt{\frac{q\,\varepsilon_{si}\,NSUB}{2PB}} \qquad (2.9)$$

   If NSUB is user defined.
3. $CJ = 0.0$

IS: Bulk junction saturation current.

1. User defined value if it is positive
2. User defined value if the source area parameter AS is input by the user and is positive for all the devices that use the model.
3. $IS = 4\times10^{-14}\,A$

   It seems from above that all the devices using the same model may be affected by a single device for which AS is not specified. This is really not the problem here. It will be shown in chapter 4 that the value of IS doesn't matter for those devices for which drain area, AD and source area, AS are specified. The problem here is that AD is not treated the same as AS. This is due to a bug. If the bug is fixed, statement 2 in the priority list will read:

2 User defined value if the source area parameter AS and the drain area parameter AD are input by the user and are positive .....

FOR THE REMAINING MODEL PARAMETERS:

1. User defined value if any.
2. set to default values.

The definitions of the remining parameters along with their default values are given below. This is a reproduction from the SPICE User's Guide. Since we are only interested in LEVEL II model, those parameters which are not used in the LEVEL II model are not included.

Parameter	Definition	Units	Default
LAMBDA	channel-length modulation	1/V	0.0
RD	drain ohmic resistance	Ohm	0.0
RS	source ohmic resistance	Ohm	0.0
CBD	zero-bias B-D junction capacitance	F	0.0
CBS	zero-bias B-S junction capacitance	F	0.0
CGSO	gate-source overlap capacitance per meter channel width	F/m	0.0
CGDO	gate-drain overlap capacitance per meter channel width	F/m	0.0
CGBO	gate-bulk overlap capacitance per meter channel width	F/m	0.0
RSH	drain and source diffusion sheet resistance	Ohm/sq.	0.0

MJ	bulk junction bottom grading coefficient (to be used along with CJ)	-	0.5
CJSW	zero-bias bulk junction sidewall capacitance per meter of junction perimeter	F/m	0.0
MJSW	bulk junction sidewall grading coefficient	-	0.33
JS	bulk junction saturation current per sq-meter of junction area	A/m**2	0.0
NFS	fast surface state density	1/cm**2	0.0
XJ	metallurgical junction depth	m	0.0
LD	lateral diffusion	m	0.0
UCRIT	critical field for mobility degradation	V/cm	1.0E4
UEXP	critical field exponent in mobility degradation	-	0.0
VMAX	maximum drift velocity of carriers	m/s	0.0
NEFF	total channel charge (fixed and mobile) coefficient	-	1.0
XQC	thin-oxide capacitance model flag and coefficient of channel charge share attributed to drain (0-0.5)	-	1.0
KF	flicker noise coefficient	-	0.0
DELTA	width effect on threshold voltage	-	0.0

The above description does not address the question of negative user defined parameter values. With the exception of VTO, TPG, NSS and PHI, SPICE sets all those parameters to the default values for which negative values are input by the user. The default values are given in the table

above for most of the parameters. For others, last statement in the priority list always sets the parameter to default. This method does not seem to be foolproof. Very often the SPICE job will crash if some negative values are input by the user. A better solution would have been to treat the parameters with negative user defined values the same way as parameters with no user defined values are treated.

The user may avoid problems with negative model parameter values by remembering that the only model parameters for which negative values can be used are VTO, TPG, and NSS. The negative value for PHI is currently allowed which constitutes a bug because in some cases this will cause the job to terminate ungracefully. Another pitfall is trying to make PB=0.0. This will cause trouble because the right hand side of equation (2.9) is evaluated in any case, even if the value is not assigned to CJ. This will apparently result in a divide by zero and subsequently in a run time error.

Before concluding the discussion on model parameters the following points of interest will be mentioned.

1) In almost all cases the user defined values have the top priority so long as they are reasonable. This is obvious from the priority lists shown above.

2) Finalization of most model parameters is affected by whether or not NSUB is input by the user. As a general rule if NSUB is user defined

some parameters which are not defined by the user will be *computed*, otherwise they will be *set to their default values*. Because of this role of NSUB, the model description with a value of NSUB is often referred to as process oriented model. Note from the priority list for NSUB that it is set to the 0.0 if not defined by the user. This seems like an unreasonable value but as will be shown later, the value of zero is merely used as a flag to decide whether or not to carry out certain computations. This is a continuation of the role of NSUB as an indicator of *process oriented model*.

3) Many parameters were set to zero by default. A value of zero is only to be used as a flag as will be shown in chapter 5. Some examples of such parameters are LAMBDA, VMAX etc.

EVALUATION OF FINAL DEVICE PARAMETERS

Compared to model parameters, the computation of final device parameters is much simpler. All the device parameters will be defined first, they will be divided into two groups later. Final values for all device parameters in a given group are obtained in the same way and hence a single priority list is required. Following is the definition of all device parameters:

Parameter	Definition
L	channel length
W	channel width
AD	drain diffusion area
AS	source diffusion area
PD	perimeter of drain-bulk junction
PS	perimeter of source-bulk junction
NRD	equivalent number of squares of drain diffusion
NRS	equivalent number of squares of source diffusion

The priority lists for the two groups are given below:

L, W, AD and AS:

1. User defined value if any.
2. Initialized to DEFL, DEFW, DEFAD and DEFAS respectively. The values of DEFL, DEFW, DEFAD and DEFAS can be altered using the .OPTIONS card. If none of them appears on the .OPTIONS card, their default values are 100μ, 100μ, 0.0 and 0.0 respectively.

PD, PS, NRD, NRS:

1. User defined value if any.

2. Default value is assigned to the parameter. Default for PD and PS is 0.0 while the default value for NRD and NRS is 1.0.

All of the user defined values for device parameters must be *positive* otherwise an error message will be printed and the job will be aborted.

Finally, the user is warned about a bug which may give wrong results if the nominal temperature is not 27^0 *C*. n_i is the intrinsic carrier concentration and has a strong temperature dependence but the value of n_i used here is that for 27^0 *C*. Due to this bug, the value of PHI will be computed wrong and as a result, the value for VTO will not be correct either. Needless to say that this will introduce some error in the subsequent calculations. The way to get around this problem is to *input* a value of PHI rather than allowing SPICE to calculate it. Note from the priority list for PHI that the value input by the user has the top priority.

CHAPTER 3
TEMPERATURE ADJUSTMENTS TO PARAMETERS

In the last chapter the process of obtaining the final values for parameters at the nominal temperature was examined. In this chapter the adjustments made to these parameters will be investigated for the case when analysis is desired at a temperature other than the nominal temperature. A request for such an analysis can be made by using .TEMP card.

The purpose here is to give the user an opportunity to see what temperature dependencies are taken into account. This purpose will not be served well if only the equations used in the subroutine responsible for temperature adjustments are provided. This is because these equations make use of three temperatures- namely, the temperature at which the model parameters are presently available, the temperature at which the analysis is desired and a reference temperature. Hence these equations are rather complicated. Instead, we will give the expressions explicitly indicating temperature dependencies of the parameters. These expressions will involve one temperature for the most part and they have been derived from the equations that appear in the program.

The expressions given below will make use of constants $K_{Parameter}$. They are used to represent temperature independent parts of the parameters. We will once again group the parameters with each group

containing parameters that require similar temperature adjustments.

UO and KP:

$$UO = K_{UO}\, T^{-\frac{3}{2}} \tag{3.1}$$

$$KP = K_{KP}\, T^{-\frac{3}{2}} \tag{3.2}$$

This indicates that the mobility is considered limited by the lattice scattering and not by impurity scattering. Since KP is considered proportional to UO, the same temperature adjustment is applied to it.

PB and PHI:

$$PB = K_{PB}\, T - 2 V_T \ln\left[T^{\frac{3}{2}} \exp^{\frac{E_g(T)}{kT}}\right] \tag{3.3}$$

$$\Phi = K_\Phi T - 2 V_T \ln\left[T^{\frac{3}{2}} \exp^{\frac{E_g(T)}{kT}}\right] \tag{3.4}$$

Where $E_g(T)$ is the energy gap at temperature T.

If it is assumed that the abrupt junction approximation is used, PB is given by:

$$PB = V_T \ln\left[\frac{N_a N_d}{n_i^2}\right] \tag{3.5}$$

Then the expression in equation (3.3) can be obtained from the one in equation (3.5) with some algebraic manipulation. If this is done $K_{PB}\, T$ will turn out to be $\frac{kT}{q} \ln\left[N_a N_d\right]$. Similarly if PHI is assumed to be given by

$PHI = 2V_T \ln\left(\frac{NSUB}{n_i}\right)$ (see statement 3 in priority list for PHI in chapter 2), then $K_{PHI}T$ can be shown to be $V_T \ln\left(NSUB^2\right)$.

VTO: The adjustments to VTO are made as if it was calculated in statement 2 of the priority list for VTO. The temperature dependencies come about due to E_g and PHI. Because of a bug in the program, the temperature correction due to E_g is erroneous for an n-channel device with TPG=-1 and for a p-channel device with TPG=1. The temperature dependence for E_g is also given in statement 2 of the priority list for VTO.

IS and JS:

$$IS = K_{IS} \exp\left(\frac{-E_g}{kT}\right) \tag{3.6}$$

$$JS = K_{JS} \exp\left(\frac{-E_g}{kT}\right) \tag{3.7}$$

Recall that the saturation current or saturation current density for an abrupt p-n junction is proportional to $qn_i^2 D$. The above expressions take into account the dependency on n_i but clearly the dependency on D (the diffusion constant) is neglected. Since UO earlier was assumed to be proportional to $T^{-\frac{3}{2}}$, D should be proportional to $T^{-\frac{1}{2}}$ according to the Einstein relation ($D = V_T \mu$).

CJ, CBD, CBS and CJSW: These capacitances use some expressions which

don't have any obvious connection with the device physics:

$$C_j = \frac{K_{c_j}}{1 + M_j(0.0004(T - T_{ref}) - \frac{PB(T) - PB(T_{ref})}{PB(T_{ref})})} \tag{3.8}$$

Where C_j is one of the four model parameters, PB(T) is the value of model parameter PB at temperature T, and T_{ref} is 27^0C. It is used as the reference temperature. CJ, CBD and CBS use model parameter MJ in place of M_j and CJSW uses model parameter MJSW in place of M_j

No modifications are made to any of the device parameters.

CHAPTER 4
FORMULATING SECONDARY QUANTITIES
and
RESOLVING CONFLICTS AMONG PARAMETERS

In this chapter the secondary quantities formulated from user defined parameters will be examined. These secondary quantities along with the model and device parameters will be used to form the electrical quantities of interest like threshold voltage, drain current, transconductance etc. The parameter values used in the equations here and later are the final values as obtained in chapter 2.

The names of these quantities will be kept the same as those commonly used in the literature or will be derived from those used in the literature except where such names are not common. The names appearing in the code are restricted to six alphanumeric characters because the code is written in FORTRAN, but most of them are very suggestive. Probably the major difference between commonly accepted nomenclature and that in the code is that the letter I is generally used for current in literature but in the program letter C is used for current, therefore CDSAT is the saturation current for the p-n junction between drain and bulk. It will however be changed to $I_{DB_{sat}}$.

Wherever there is a conflict to resolve the priority list scheme introduced in chapter 2 will be used to illustrate how the secondary quantity

in question is computed.

$I_{DB_{sat}}$ and $I_{SB_{sat}}$: Saturation current for drain bulk junction; and saturation current for source bulk junction.

1. If JS, AD and AS are all non-zero then

   $I_{DB_{sat}}=JS\times AD$ and

   $I_{SB_{sat}}=JS\times AS$

2. $I_{DB_{sat}}=IS$ and

   $I_{SB_{sat}}=IS$

Note that model parameter JS has priority over IS if the condition in statement 1 above is met.

G_d and G_s: Drain series conductance; and source series conductance

1. If RS is non-zero but RD is zero then $G_s=\frac{1}{RS}$ and the resistance in series with the drain is zero.
2. If RD is non-zero but RS is zero then $G_d=\frac{1}{RD}$ and the resistance in series with the source is zero.
3. If RD and RS both are non-zero then $G_d=\frac{1}{RD}$ and $G_s=\frac{1}{RS}$
4. If both RD and RS are zero then $G_d=\frac{1}{RSH\times NRS}$ and $G_s=\frac{1}{RSH\times NRD}$ provided RSH is non- zero.

5. If all three of RD, RS and RSH are zero then the resistances in series with both drain and source are zero.

Whenever the resistance in series with drain and source is non-zero, one or two new node(s) is (are) defined for the device.

XL: Channel length at zero drain-source voltage.

$$XL = L - 2LD \tag{4.1}$$

L is the device parameter and LD is the model parameter.

β: Channel conductance factor.

$$\beta = KP\frac{W}{XL} \tag{4.2}$$

This is the same β as appears in the first order drain current equation for a MOSFET in most texts on the subject. Some standard text books use k instead of β.

V_T: Thermal voltage.

It is given by:

(4.3)

where k is Boltzman constant, T is the temperature and q is the charge on an electron.

C_{ox}:Oxide capacitance per unit of gate area.

$$C_{ox} = \frac{\varepsilon_{ox}}{TOX} \tag{4.4}$$

X_d:Voltage independent part of depletion width.

$$X_d = \sqrt{\frac{2\varepsilon_{si}}{qNSUB}} \tag{4.5}$$

We know from device physics that the depletion width of a pn junction with one side much lightly doped compared to the other has the depletion width of $\sqrt{\frac{2\varepsilon_{si}\Phi_i}{qN}}$ with zero bias where N is the doping concentration of the lightly doped side and Φ_i is the built-in potential of the junction. The depletion width under the oxide of a MOSFET with zero substrate bias and a small drain to source voltage in strong inversion is given by $\sqrt{\frac{2\varepsilon_{si}\Phi_s}{qN}}$ where N is the substrate doping and Φ_s is the surface potential in strong inversion. Note that both of these have the same temperature independent part which is the same as X_d defined above.

VBI: There is no commonly accepted name for this quantity in device physics, this is just VTO with the contribution due to depletion charge subtracted off. It is given by:

$$VBI = VTO - GAMMA\sqrt{PHI} \tag{4.6}$$

SARG: Once again there is no commonly accepted name for this quantity. It is defined below:

$$SARG=\sqrt{PHI-VBS} \tag{4.7a}$$

for VBS ≥ 0.0.

$$SARG=\frac{\sqrt{PHI}}{1+\frac{0.5VBS}{PHI}} \tag{4.7b}$$

for VBS < 0.0.

The quantity $\sqrt{PHI-VBS}$ is widely used in equations for second order effects. This quantity however will be troublesome if VBS > PHI. This will happen if the source bulk junction is forward-biased which is very unlikely to be the case at the operating point. However, SPICE uses an iterative method of solution for the DC operating point called the Newton-Raphson algorithm and it is possible for VBS to be greater than PHI during some iterations. The idea here is to define an empirical expression which replaces $\sqrt{PHI-VBS}$ under such circumstances and prevents a job crash which would have resulted from trying to take square root of a negative number. The expression chosen for VBS < 0.0 is such that SARG and its first derivative with respect to VBS are continuous at VBS=0.0. This is necessary for Newton-Raphson algorithm to converge.

BARG: This is similar to SARG defined above.

$$BARG=\sqrt{PHI+VDS-VBS} \tag{4.8a}$$

for VDS ≥ VBS.

$$BARG=\frac{\sqrt{PHI}}{1+0.5\frac{VBS-VDS}{PHI}} \tag{4.8b}$$

for VDS < VBS.

Again, the negative expression is chosen such that BARG and it's first derivative are continuous at VDS=VBS.

Many of the equations to be presented in the next chapter use SARG and BARG as they appear in the code but SARG and BARG will be replaced by their corresponding expressions for VBS > 0.0 and VDS > VBS before they are presented. As for the other secondary quantities explained in this chapter, It will be assumed that the reader is already familiar with them and they will be used with little or no explanation.

CHAPTER 5
COMPUTED ELECTRICAL QUANTITIES

This chapter builds upon the previously defined parameters and uses them to compute the desired electrical quantities. Even though justification or criticism of these equations is beyond the scope of this report, an effort will still be made to explain them in the light of device physics. The theoretical explanation given here is primarily based on " The Simulation Of MOS Integrated Circuits Using SPICE 2 " by Anderi Vladimirescu and Sally Liu.

By now the reader should be familiar with model parameters, device parameters, secondary quantities and some physical constants. The user defined parameters were defined in chapter 2, and the secondary quantities in chapter 3. The constants will be given in appendix B. Whenever a quantity is used that belongs to any one of these categories, just the identify of the category is identified. If a quantity is not one of the three types, we will show equations relating it to these three types and to the three port voltages VBS, VGS and VDS.

Once again an attempt will be made to use the commonly accepted names rather than the variable names used in the program but due to a large number of variables used in the particular subroutine that will be analyzed here, it will not always be possible. The names of electrical quantities printed by SPICE will be left unaltered. For example, GDS (

drain-source conductance) will be used instead of the commonly used name g_o (output conductance).

1. VTH: Threshold voltage of the device at the operating point.

$$VTH = VBI + \gamma_{SD}\sqrt{PHI - VBS} + FACTOR(PHI - VBS) + V_T \times XN \tag{1.1}$$

There are four terms in this equation, the first term VBI is a secondary quantity, the second, third and the fourth terms each have a second order correction. They will be discussed one at a time.

1.1. Short channel effect

A part of the depletion charge under the channel can be attributed to drain-bulk and source-bulk junctions. In short channel devices this charge forms a significant fraction of the total depletion charge in the substrate. Consequently the the threshold voltage is decreased. This is taken into account in the formulation of γ_{SD} in accordance with Yau's model.

$$\gamma_{SD} = GAMMA(1 - ARGSS - ARGSD) \tag{1.1.1}$$

where:

$$ARGSS = 0.5\frac{XJ}{XL}\left(\sqrt{1+2\frac{X_d\sqrt{PHI - VBS}}{XJ}} - 1\right) \tag{1.1.2}$$

$$ARGSD = 0.5\frac{XJ}{XL}\left(\sqrt{1+2\frac{X_d\sqrt{PHI + VDS - VBS}}{XJ}} - 1\right) \tag{1.1.3}$$

Here GAMMA, PHI and XJ are parameters; and X_d and XL are secondary quantities.

If XJ=0.0, NSUB=0.0 or GAMMA =0.0, the above correction is skipped and γ_{SD}=GAMMA. In addition to that, if VBS=0.0, the first two terms in equation 1.1 give VTH=VTO as should be the case.

1.2. Narrow channel effect

The depletion charge under the channel extends slightly beyond the width of the channel. In wide devices this is only a small fraction of the total charge in the substrate but in narrow devices the effect can be significant. Such a charge reduces the mobile charge in the channel because the channel charge and the depletion charge must add up to the charge on the gate. As a result more gate charge is needed to bring about channel inversion. Hence the threshold voltage is increased. The third term in equation 1.1 accounts for this effect. FACTOR in the third term is given by:

$$FACTOR = 0.125 \frac{2\pi\varepsilon_{si}\, DELTA}{C_{ox}} \qquad (1.2.1)$$

Here DELTA is a model parameter. ε_{si} is a constant and C_{ox} is a secondary quantity.

If DELTA=0.0, the narrow channel effect is neglected and VTH is given by the remaining terms in equation 1.1.

1.3. Effect due to fast surface states

The last term in equation 1.1 takes into account the effect on threshold voltage due to fast surface states. V_T in this term is a secondary quantity and XN is given by:

$$XN=1+\frac{CFS}{C_{ox}}+\frac{C_D}{C_{ox}} \tag{1.3.1}$$

where:

$$CFS=qNFS \tag{1.3.2}$$

$$C_D=\frac{\partial Q_D}{\partial V_{BS}} \tag{1.3.3}$$

Q_D is the depletion charge under the channel. NFS is a curve fitting model parameter and is not dimensionless therefore equation 1.3.2 does not have any dimensional inconsistency. C_{ox} is secondary quantity and q is a constant.

If NFS is zero, XN is forced to be zero and this correction is neglected.

2. U_{eff}: The effective mobility

The effective mobility of carriers in the channel decreases as the carriers approach their scattering limited velocity. This degradation in mobility is modeled by equation (2.1) shown below:

$$U_{eff} = UO\left\{\frac{UCRIT\,\varepsilon_{si} / C_{ox}}{VGS - VTH}\right\}^{VEXP} \qquad (2.1)$$

This computation is done only if $UCRIT\,\varepsilon_{si} / C_{ox}$ < VGS - VTH otherwise U_{eff} is set to UO. This insures that $U_{eff} < UO$ provided UEXP is greater than 1.0.

In equation (2.1) VTH is the threshold voltage and is discussed in section 1 above; UO, UCRIT and UEXP are model parameters; ε_{si} is a constant and C_{ox} is a secondary quantity.

3. VDSAT: The saturation voltage

The saturation voltage is calculated one of the two ways. It is calculated using a pinch-off model if VMAX is zero, otherwise it is calculated using the velocity saturation model.

3.1. Calculation of VDSAT using the pinch-off model

The equation used for VDSAT is given below:

$$VDSAT = \frac{VGSX - VBIN}{\eta} + \frac{1}{2}\left\{\frac{\gamma_{SD}}{\eta}\right\}^2 (1 - ARG) \qquad (3.1.1)$$

All the quantities used in equation (3.1.1) will now be presented:

VGSX:

Formation of this quantity is somewhat complicated and can be best presented using a priority list.

1. If NFS=0.0 then VGSX=VGS.
2. VGSX=VGS if VGS > VTH.
3. VGSX = VTH if VTH > VGS.

NFS is a parameter, and VTH is threshold voltage described in section 1 above.

VBIN:

$$VBIN = VBI + FACTOR(PHI - VBS) \tag{3.1.2}$$

where VBI is a secondary quantity and FACTOR is defined in equation (1.2.1)

η:

$$\eta = 1 + FACTOR \tag{3.1.3}$$

where FACTOR is given by equation (1.2.1).

γ_{SD}: γ_{SD} is given by equation (1.1.1).

ARG:

$$ARG = \left[1 + 4\left[\frac{\eta}{\gamma_{SD}}\right]^2\left[\frac{VGSX - VBIN}{\eta}\right] + PHI - VBS\right]^{\frac{1}{2}} \tag{3.1.4}$$

All of the quantities in equation (3.1.4) except PHI have been defined above. PHI is a parameter.

Equation (3.1.1) can be examined in more detail to see how it compares with the first order equation $VDSAT = VGS - VTH$. For an "ON" device VGS > VTH, Therefore VGSX=VGS from the priority list for VGSX. If the narrow channel effect is also neglected then FACTOR=0.0 and from equation (3.1.3) η=1.0. Also from equation (3.1.3) VBIN=VBI. Hence equation (3.1.1) reduces to:

$$VDSAT = VGS - VBI + \frac{1}{2}(\gamma_{SD})^2(1-ARG) \qquad (3.1.5)$$

VBI can be substituted in equation (3.1.5) from chapter 4 in terms of VTO:

$$VDSAT = VGS - VTO + GAMMA\sqrt{PHI} + \frac{1}{2}(\gamma_{SD})^2(1-ARG) \qquad (3.1.6)$$

Equation (3.1.6) is similar to the first order equation VDSAT = VGS - VTH if the third and fourth terms were some corrections for body effect and short channel effect.

3.2. Calculation of VDSAT using velocity saturation model

Before examining the code, the ideas involved here will be discussed as described in " The Simulation of MOS Integrated Circuits Using SPICE2" by Andrei Vladimirescu and Sally Liu.

The current in a conductor is given by:

$$I = (charge/unit\ volume) \times (cross\text{-}section\ area) \times (velocity\ of\ electrons) \qquad (3.2.1)$$

For a MOSFET with a non-zero but small VDS, this translates to:

$$I_D = Q_{CHAN} \times W \times V \qquad (3.2.2)$$

In equation (3.2.2) I_D is the drain current, Q_{CHAN} is the mobile charge in the channel per unit area, W is the width of the channel and V is the velocity of mobile charge carriers in the channel.

Clearly Q_{CHAN} is a function of distance from the source and decreases in moving from the source to the drain. To a first order approximation it can be considered as the charge per unit area stored across the oxide capacitance and is given at a point in the channel by $C_{ox}(VGS - VTH - V_{CHAN}(y))$. Where VTH is the threshold voltage and $V_{CHAN}(y)$ is the channel potential with respect to the source at the point of interest. This potential is a function of y, the distance from the source to the point. Since I_D is a constant at any cross-section of the channel, V must increase in moving from source to drain so that the right hand side of equation (3.2.2) also remains a constant at any cross-section of the channel.

If VDS is increased, the current I_D will increase and so will V. If VDS keeps on increasing, V will eventually reach a maximum possible value at the drain-end of the channel. This maximum value is called the **scattering limited velocity** of the carriers and will be designated by V_{MAX}. The value of VDS where V_{MAX} is reached is really the drain source saturation voltage VDSAT. A further increase in VDS will result in carriers reaching V_{MAX} before reaching the drain. The point where V_{MAX} is first reached will be called the **saturation point**. Once V_{MAX} is reached, the carriers will travel

travel the rest of the way to the drain at the velocity V_{MAX}. The effective channel length is between the source and the saturation point.

Equation (3.2.2) at the saturation point can be written as:

$$I_{D_{SAT}} = Q_{CHAN_{SAT}} \times W \times V_{MAX} \tag{3.2.3}$$

In equation (3.2.3), V_{MAX} is given by the user defined parameter VMAX, W is a device parameter, $I_{D_{SAT}}$ and $Q_{CHAN_{SAT}}$ are functions of VDSAT. These quantities are given by:

$$I_{D_{SAT}} = U_{eff}\, C_{ox} \frac{W}{L_{eff}} \left\{ \left(VGS - VBIN - \eta \frac{VDSAT}{2} \right) VDSAT - \frac{\gamma_{SD}}{1.5} \left[(VDSAT + PHI - VBS)^{\frac{3}{2}} - (PHI - VBS)^{\frac{3}{2}} \right] \right\} \tag{3.2.4}$$

$$Q_{CHAN_{SAT}} = C_{ox} \left[VGS - VBIN - \eta\, VDSAT - \gamma_{SD} \sqrt{VDSAT + PHI - VBS} \right] \tag{3.2.5}$$

In the above two equations C_{ox} is a secondary quantity, L_{eff} is the effective channel length, PHI is a model parameter U_{eff}, VBIN, η, and γ_{SD} are defined in equations (2.1), (3.1.2), (3.1.3),and (1 1.1) respectively.

The equation for $I_{D_{SAT}}$ will be discussed in more detail later. For now it should be enough to see that all the quantities in this equation are known except the effective channel length,L_{eff}. The equation for $Q_{CHAN_{SAT}}$ does not contain any unknown quantity. An approximation is made at this point to facilitate the computation for VDSAT. XL is used instead of L_{eff} in equation (3.2.4). XL is a secondary quantity. With this approximation, if equations (3.2.4) and equations (3.2.5) are substituted in equation

(3.2.3), the resulting equation will have only one unknown namely VDSAT. The equation thus obtained is given below:

$$VMAX = \frac{U_{eff}\left\{\left(VGS - VBIN - \eta\frac{VDSAT}{2}\right)VDSAT - \frac{\gamma_{SD}}{1.5}\left\{(VDSAT + PHI - VBS)^{\frac{3}{2}} - (PHI - VBS)^{\frac{3}{2}}\right\}\right\}}{XL\left\{VGS - VBIN - \eta\, VDSAT - \gamma_{SD}\sqrt{VDSAT + PHI - VBS}\right\}} \tag{3.2.6}$$

Equation (3.2.6) can be written in somewhat more manageable form if the following substitutions are made:

$$V1 = \frac{VGS - VBIN}{\eta} + PHI - VBS \tag{3.2.7a}$$

$$V2 = PHI - VBS \tag{3.2.7b}$$

$$XV = \frac{VMAX \times XL}{U_{eff}} \tag{3.2.7c}$$

$$X = \sqrt{VDSAT + PHI - VBS} \tag{3.2.7d}$$

With these substitutions, equation (3.2.6) becomes:

$$XV = \frac{(V1 - \frac{V2}{2} - \frac{X^2}{2})(X^2 - V2) - \frac{\gamma_{SD}}{1.5\eta}(X^3 - V2^{\frac{3}{2}})}{V1 - \frac{\gamma_{SD}}{\eta}X - X^2} \tag{3.2.8}$$

It is clear that the above equation can be written as a fourth order polynomial equation in X as:

$$X^4 + A X^3 + B X^2 + C X + D = 0 \tag{3.2.9}$$

The coefficients A, B, C and D are:

$$A=\frac{\gamma_{SD}}{0.75\eta} \tag{3.2.10a}$$

$$B=-2(V1+XV) \tag{3.2.10b}$$

$$C=-2\frac{\gamma_{SD}}{\eta}XV \tag{3.2.10c}$$

$$D=2V1(V2+XV)-V2^2-\frac{\gamma_{SD}}{0.75\eta}V2^{\frac{3}{2}} \tag{3.2.10d}$$

After the discussion of the ideas involved in the calculation of VDSAT using velocity saturation model, it is possible to talk about the code again. The calculation in the code starts with evaluation of the quantities on the left hand side of equations (3.2.7a) through (3.2.7c). Next, the coefficients of the fourth order polynomial equation are formed from equations (3.2.10). Finally a closed form method to solve such an equation is used to obtain the value of X. Once X is known it is a trivial matter to obtain VDSAT from equation (3.2.7d).

The closed form method used in the code is called Ferrari's method. It is fairly complex and not suitable for hand calculations. Therefore it will serve no purpose to present it here.

Since equation (3.2.9) is a fourth order polynomial equation, it has four possible solutions. The smallest positive solution is taken to be the valid solution. If no positive real root is obtained then VDSAT is evaluated using the pinch-off model as explained in section 3.1 previously.

4. L_{eff}: The effective channel length

The computation primarily depends on whether or not the model parameter LAMBDA is zero.

4.1. Effective channel length with LAMBDA equal to 0.0

In this case the effective channel length is given by:

$$L_{eff} = XL(1 - LAMBDA \times VDS) \tag{4.1.1}$$

4.2. Effective channel length with LAMBDA not equal to 0.0

Once again two possibilities exist depending on how VDSAT was calculated.

4.2.1. Effective channel length with VMAX equal to zero

If VMAX is zero then VDSAT was evaluated using the pinch-off model. Consistent with that the effective channel length is evaluated using the following equation:

$$L_{eff} = XL\left[1 - \frac{X_d}{XL}\left[\frac{VDS - VDSAT}{4} + \sqrt{1 + \left[\frac{VDS - VDSAT}{4}\right]^2}\right]^{\frac{1}{2}}\right] \tag{4.2.1.1}$$

where X_d and XL are secondary quantities.

4.2.2. Effective channel length with VMAX not equal to zero

In this case the effective channel length is given by:

$$L_{eff} = XL\left[1 - \frac{X_{dv}}{XL}\left[\sqrt{\left[\frac{VMAX \times X_{dv}}{2U_{eff}}\right]^2 + ARGV} - \frac{VMAX \times X_{dv}}{2U_{eff}}\right]\right] \qquad (4.2.1.2)$$

In the above equation VMAX is a model parameter; U_{eff} was explained in section 2. XL is a secondary quantity; ARGV is given by (VDS - VDSAT) provided it is positive, otherwise ARGV = 0.0; and X_{dv} is given by the equation below:

$$X_{dv} = \frac{X_D}{\sqrt{NEFF}} \qquad (4.2.1.3)$$

NEFF is a model parameter and X_d is a secondary quantity. The purpose of X_{dv} will become a little clearer if X_d is substituted from the chapter 4:

$$X_{dv} = \sqrt{\frac{2\varepsilon_{si}}{q\ NSUB \times NEFF}} \qquad (4.2.1.4)$$

Recall that X_d is the voltage independent part of the depletion width. From the above equation X_{dv} is also the voltage independent part of the depletion width with the tweaking parameter NEFF; which in effect modifies the value of NSUB, the substrate doping parameter.

A bug exists in the program which will now be explained. VMAX is used as the flag to decide which one of the two methods described above is to be used to calculate L_{eff}. As described in the end of section 4.2.2, there is a possibility for VDSAT to be calculated by the pinch-off model even if VMAX is non-zero. This happens if no real positive solution to

equation (3.2.9) exists. Therefore there is a possibility that VDSAT is actually evaluated using the pinch-off model but L_{eff} is evaluated as if VDSAT was evaluated using velocity saturation model.

5. Limiting channel shortening at punch through

It is conceivable that with very high values of VDS, the formulas given in section 4 give negative values for L_{eff}. This is a non-realistic situation because once L_{eff} becomes zero, punch through occurs and these equations no longer hold. Punch through is not modeled here but a correction to L_{eff} is made in order to prevent negative values to carry through to further computations because even for a circuit where there is no reason for such high values of VDS to occur, they may still occur during some Newton-Raphson iterations.

The correction is an empirical one and is applied if L_{eff} as obtained from the equations in section 4 is less than an arbitrarily chosen length XWB. XWB is the depletion width between source-bulk junction with VBS=0.0. It is given by:

$$XWB = X_d \times PB \tag{5.1}$$

PB is a model parameter and X_d is a secondary quantity.

In the equations presented here, L_{eff} calculated by equations in section 4 will be denoted by L'_{eff}. If the correction is to be made L_{eff} is obtained from L'_{eff} according to equation (5.2):

$$L_{eff} = \frac{XWB}{1 + \frac{XWB - L'_{eff}}{XWB}} \tag{5.2}$$

Note that L_{eff} as given by equation (5.2) will never become negative. In the limit that L'_{eff} goes to negative infinity, L_{eff} will approach zero. Furthermore, it is easy to see from equation (5.2) that for $L'_{eff}=XWB$, $L_{eff} = L'_{eff}$ and $\frac{\partial L_{eff}}{\partial VDS} = \frac{\partial L'_{eff}}{\partial VDS}$. Therefore the continuity of L_{eff} and its derivative is insured at the break point (i.e L_{eff} = XWB) which is essential for the Newton-Raphson algorithm to be efficient.

6. β_{eff} : The effective β

In chapter 4, the channel conduction factor β was introduced. In this chapter β is modified to form β_{eff} in order to account for mobility degradation and channel length shortening. β_{eff} is later used in expressions for drain current and various conductances.

$$\beta_{eff} = \beta \times \frac{U_{eff}}{UO} \times \frac{XL}{L_{eff}} \tag{6.1}$$

Where UO is a model parameter, XL is a secondary quantity, U_{eff} and L_{eff} are defined in section 2 and section 4.

7. I_D: Drain Current and its derivatives (i.e conductances) GM, GDS, GMB

One of the purposes of all the quantities that have been presented so far is to tie the equations in this section to the elementary quantities like the user defined parameters and constants. Once again, some explanation of the ideas involved is in order before we look at the equations. This is especially necessary because the equations to be presented here differ widely from the those used in the first order calculations of drain current and various conductances.

The fundamental equation for drain current used in the MOS LEVEL II model is the one for the linear region as given below:

$$I_D=\beta_{eff}\left[(VGS-VBIN-\eta\frac{VDS}{2})VDS-\frac{\gamma_{SD}}{1.5}\left\{(VDS+PHI-VBS)^{\frac{3}{2}}-(PHI-VBS)^{\frac{3}{2}}\right\}\right] \qquad (7.1)$$

Where PHI is a model parameter, VBIN, η, β_{eff} and γ_{SD} are defined in equations (3.1.2), (3.1.3),(7:1) and (1.1.1) respectively.

The equations which appear in the code for other regions of operations are merely adaptations of equation (7.1) under the conditions in the particular region. For instance the equation for $I_{D_{SAT}}$; the current in saturation region is simply equation (7.1) with VDS replaced by VDSAT. where VDSAT is the drain source saturation voltage and has already been treated in section 3 above. This is how equation (3.2.4) was obtained.

The various conductances in a given region of operation are the derivatives of the adapted form of equation (7.1) in that region. For instance the equation for GM of a device operating in the saturation is obtained by taking the derivative of equation (3.2.4) with respect to VGS. One important aspect of finding the conductances is to realize that many quantities in the equation for drain current indirectly depend on three port voltages; namely VDS, VGS and VBS. For instance, in equation (3.2.4), L_{eff}, U_{eff}, VBIN, η, and γ_{SD} are all voltage dependent. In the code whenever any voltage dependent quantity like these was evaluated, the expressions for its derivatives were formed as well for future use. We have thus far not included the expressions for the derivatives in order to maintain the readability of the report. Furthermore, the derivatives can be obtained from the equations that have been presented thus far with a possible exception of VDSAT when it is obtained using velocity saturation. Therefore these equations will be presented before moving on. First, the equations for DFUNDG; DFUNDB, and DFUNDS will be presented. These are the quantities whose ratios will give us the derivatives we want in equations (7.4):

$$DFUNDS = XL\ VMAX\left\{\gamma_{SD}\frac{\partial}{\partial VBS}\sqrt{PHI-VBS+VDSAT}\right\}-$$

$$U_{eff}\left\{\frac{VGSX-VBIN}{\eta}VDSAT-\gamma_{SD}\sqrt{PHI-VBS+VDSAT}\right\} \qquad (7.2a)$$

$$DFUNDG=\frac{XL\ VMAX-U_{eff}\ VDSAT}{\eta} \qquad (7.2b)$$

$$DFUNDB = -XL\ VMAX\left[\gamma_{SD}\frac{\partial}{\partial VBS}\sqrt{PHI-VBS+VDSAT}-\frac{FACTOR}{\eta}\right]$$

$$+\frac{U_{eff}}{\eta}\left[\frac{\partial BODYS}{\partial VBS}\frac{\partial \gamma_{SD}}{\partial VBS}\frac{BODYS}{1.5}\right] \qquad (7.2c)$$

In equations (7.2), PHI and VMAX are model parameters, XL is a secondary quantity, γ_{SD}, VBIN, η, and FACTOR are given by equations (1.1.1), (3.1.2), (3.1.3), and (1.2.1) respectively; U_{eff} is described in section 2; a priority list for VGSX is given in section 3.1, and BODYS is given by:

$$BODYS = \sqrt{PHI-VBS+VDSAT}-\sqrt{PHI-VBS} \qquad (7.3)$$

$$\frac{\partial VDSAT}{\partial VGS} = -\frac{DFUNDG}{DFUNDS} \qquad (7.4a)$$

$$\frac{\partial VDSAT}{\partial VBS} = -\frac{DFUNDB}{DFUNDS} \qquad (7.4b)$$

In presenting the equations for conductances, the purpose is to show what voltage dependencies are taken into account to obtain a given conductance.

Finally, continuing with our practice, all quantities that appear in an equation for drain current will be identified. These identifications should suffice to locate equations needed to obtain derivatives that appear in the equations for conductances in the same section. The equations for I_D in each region will be examined separately:

7.1. Cutoff region

A device is in the cutoff region if its I_D is zero. There are four possible ways that can happen which are covered in the code. In each case GM is different but in all cases the following equations hold:

$$I_D = 0.0 \tag{7.1.1}$$

$$GM = 0.0 \tag{7.1.2}$$

$$GMB = 0.0 \tag{7.1.3}$$

To avoid repetition, the quantities in the equations for GDS in the four cases will be identified after discussing all four cases.

7.1.1. NFS = 0.0, C_{ox} = 0.0, and VGS ≤ VTH

$$GDS = 0.0 \tag{7.1.1.1}$$

If NFS and C_{ox} are non-zero, then the sub-threshold current may exist depending upon VDS. The device is not considered to be in the cutoff region if it has a sub-threshold current. This possibility will be covered later in detail.

7.1.2. NFS and C_{ox} are non-zero, VDS ≤ 10^{-8}, and VGS > VTH

10^{-8} is chosen as an arbitrary number, the point is that VDS is so small that it doesn't cause any significant drain current. Here GM is given by:

$$GDS = \beta_{eff}\left[VGS - VBIN - \gamma_{SD}\sqrt{PHI - VBS}\right] \qquad (7.1.2.1)$$

This equation is obtained by taking the derivative of equation (7.1) and setting VDS = 0.0.

7.1.3. NFS and C_{ox} are non-zero, VDS = 10^{-8}, and VGS ≤ VTH

Once again, VDS is not large enough to cause any significant current

$$GDS = \beta_{eff}\left[VGS - VBIN - \gamma_{SD}\sqrt{PHI - VBS}\right]\exp\left[\frac{VGS - VTH}{VT\,XN}\right] \qquad (7.1.3.1)$$

This equation is obtained by taking the derivative of equation (7.1.3.1) and setting VDS = 0.0. Equation (7.1.3.1) is presented below in the discussion for subthreshold conduction.

7.1.4. NFS and C_{ox} are non-zero, VDS > 10^{-8}, VGS ≤ VTH, and VDSAT ≤ 0.0

The equation for GDS is given by

$$GDS = 0.0 \qquad (7.1.4.1)$$

In the equations above, NFS is a model parameter; V_T and C_{ox} are secondary quantities; β_{eff} and VTH is discussed in section 6 and 1 respectively; and VBIN, γ_{SD}, and XN are given by equations (3.1.2), (1.1.1) and (1.3.1) respectively.

7.2. Subthreshold conduction

This region of operation is characterized by NFS and C_{ox} being nonzero, VDS > 10^{-8}, VGS ≤ VTH, and VDSAT > 0.0. Two possibilities now exist: either VDS ≤ VDSAT or VDS > VDSAT.

7.2.1. VDS ≤ VDSAT:

The drain current in this case is given by:

$$I_D=\beta_{eff}\left\{\left(VTH-VBIN-\eta\frac{VDS}{2}\right)VDS-\frac{\gamma_{SD}}{1.5}\left[(VDS+PHI-VBS)^{\frac{3}{2}}-(PHI-VBS)^{\frac{3}{2}}\right]\right\}\exp\left[\frac{VGS-VTH}{V_T\,XN}\right] \tag{7.2.1.1}$$

$$GM=\frac{I_D}{V_T\,XN} \tag{7.2.1.2}$$

where PHI is a model parameter, V_T is a secondary quantity. VTH is discussed in section 1. VBIN, η, β_{eff}, XN and γ_{SD} are defined in equations (3.1.2), (3.1.3),(7.1),(1.3.1) and (1.1.1) respectively.

$$GDS=\frac{\partial I_D}{\partial VDS}+\frac{\partial I_D}{\partial L_{eff}}\frac{\partial L_{eff}}{\partial VDS}+\frac{\partial I_D}{\partial \gamma_{SD}}\frac{\partial \gamma_{SD}}{\partial VDS}+\frac{\partial I_D}{\partial VTH}\frac{\partial VTH}{\partial VDS}+\frac{\partial I_D}{\partial XN}\frac{\partial XN}{\partial VDS} \tag{7.2.1.3}$$

$\frac{\partial I_D}{\partial VTH}$ takes into account only VTH in the exponent.

$$GMB = \frac{\partial I_D}{\partial VBS} + \frac{\partial I_D}{\partial L_{eff}} \frac{\partial L_{eff}}{\partial VBS} + \frac{\partial I_D}{\partial \gamma_{SD}} \frac{\partial \gamma_{SD}}{\partial VBS} + \frac{\partial I_D}{\partial VTH} \frac{\partial VTH}{\partial VBS}$$

(7.2.1.4)

7.2.2. VDS > VDSAT:

The equation for I_D is obtained by evaluating equation (7.2.1.1) with VDS = VDSAT. Since that will make I_D a function of VDSAT and VDSAT in general is a function of VDS, VGS and VBS, the expressions for all the conductances will be affected.

$$I_D = \beta_{eff} \left[\left(VTH - VBIN - \eta \frac{VDSAT}{2} \right) VDSAT - \right.$$

$$\left. \frac{\gamma_{SD}}{1.5} \left\{ (VDSAT + PHI - VBS)^{\frac{3}{2}} - (PHI - VBS)^{\frac{3}{2}} \right\} \right] \exp\left[\frac{VGS - VTH}{V_T XN} \right]$$

(7.2.2.1)

where PHI is a model parameter, V_T is a secondary quantity. VTH and VDSAT are discussed in section 1 and 3. VBIN, η, β_{eff}, XN and γ_{SD} are defined in equations (3.1.2), (3.1.3),(7.1),(1.3.1) and (1.1.1) respectively.

$$GM = \frac{I_D}{V_T XN} + \frac{\partial I_D}{\partial VDSAT} \frac{\partial VDSAT}{\partial VGS} \qquad (7.2.2.2)$$

$$GDS = \frac{\partial I_D}{\partial L_{eff}} \frac{\partial L_{eff}}{\partial VDS} + \frac{\partial I_D}{\partial \gamma_{SD}} \frac{\partial \gamma_{SD}}{\partial VDS} + \frac{\partial I_D}{\partial VTH} \frac{\partial VTH}{\partial VDS} + \frac{\partial I_D}{\partial XN} \frac{\partial XN}{\partial VDS}$$

(7.2.2.3)

$$GMB=\frac{\partial I_D}{\partial VBS}+\frac{\partial I_D}{\partial L_{eff}}\frac{\partial L_{eff}}{\partial VBS}+\frac{\partial I_D}{\partial VBIN}\frac{\partial VBIN}{\partial VBS}+\frac{\partial I_D}{\partial \gamma_{SD}}\frac{\partial \gamma_{SD}}{\partial VBS}+$$

$$\frac{\partial I_D}{\partial VTH}\frac{\partial VTH}{\partial VBS}+\frac{\partial I_D}{\partial VDSAT}\frac{\partial VDSAT}{\partial VBS} \quad (7.2.2.4)$$

7.3. Linear or triode region

This region is characterized by VGS > VTH, VDS > 10^{-8}, VDS ≤ VDSAT. The equations for this region of operation of the device are given below:

$$I_D=\beta_{eff}\left[\left(VGS-VBIN-\eta\frac{VDS}{2}\right)VDS-\right.$$

$$\left.\frac{\gamma_{SD}}{1.5}\left\{(VDS+PHI-VBS)^{\frac{3}{2}}-(PHI-VBS)^{\frac{3}{2}}\right\}\right] \quad (7.3.1)$$

Where PHI is a model parameter, VBIN, η, β_{eff} and γ_{SD} are defined in equations (3.1.2), (3.1.3),(7.1) and (1.1.1) respectively.

$$GM=\frac{\partial I_D}{\partial VGS}+\frac{\partial I_D}{\partial U_{eff}}\frac{\partial U_{eff}}{\partial VGS}+\frac{\partial I_D}{\partial L_{eff}}\frac{\partial L_{eff}}{\partial VGS} \quad (7.3.2)$$

$$GDS=\frac{\partial I_D}{\partial VDS}+\frac{\partial I_D}{\partial U_{eff}}\frac{\partial U_{eff}}{\partial VDS}+\frac{\partial I_D}{\partial L_{eff}}\frac{\partial L_{eff}}{\partial VDS}+\frac{\partial I_D}{\partial \gamma_{SD}}\frac{\partial \gamma_{SD}}{\partial VDS} \quad (7.3.3)$$

$$GMB=\frac{\partial I_D}{\partial VBS}+\frac{\partial I_D}{\partial U_{eff}}\frac{\partial U_{eff}}{\partial VBS}+\frac{\partial I_D}{\partial L_{eff}}\frac{\partial L_{eff}}{\partial VBS}+$$

$$\frac{\partial I_D}{\partial VBIN}\frac{\partial VBIN}{\partial VBS}+\frac{\partial I_D}{\partial \gamma_{SD}}\frac{\partial \gamma_{SD}}{\partial VBS} \quad (7.3.4)$$

7.4. Saturation Region

This region of operation is characterized by VGS > 0.0 and VDS > VDSAT > 0.0. The equations for operation in this region are given below:

$$I_D=\beta_{eff}\left[\left(VGS-VBIN-\eta\frac{VDSAT}{2}\right)VDSAT-\right.$$

$$\left.\frac{\gamma_{SD}}{1.5}\left\{(VDSAT+PHI-VBS)^{\frac{3}{2}}-(PHI-VBS)^{\frac{3}{2}}\right\}\right] \qquad (7.4.1)$$

where PHI is a model parameter, VDSAT is discussed in section 3. VBIN, η, β_{eff} and γ_{SD} are defined in equations (3.1.2), (3.1.3),(7.1) and (1.1.1) respectively.

$$GM=\frac{\partial I_D}{\partial VGS}+\frac{\partial I_D}{\partial U_{eff}}\frac{\partial U_{eff}}{\partial VGS}+\frac{\partial I_D}{\partial L_{eff}}\frac{\partial L_{eff}}{\partial VGS}+\frac{\partial I_D}{\partial VDSAT}\frac{\partial VDSAT}{\partial VGS} \qquad (7.4.2)$$

$$GDS=\frac{\partial I_D}{\partial L_{eff}}\frac{\partial L_{eff}}{\partial VDS}+\frac{\partial I_D}{\partial \gamma_{SD}}\frac{\partial \gamma_{SD}}{\partial VDS} \qquad (7.4.3)$$

$$GMB=\frac{\partial I_D}{\partial VBS}+\frac{\partial I_D}{\partial U_{eff}}\frac{\partial U_{eff}}{\partial VBS}+\frac{\partial I_D}{\partial L_{eff}}\frac{\partial L_{eff}}{\partial VBS}+\frac{\partial I_D}{\partial VBIN}\frac{\partial VBIN}{\partial VBS}+$$

$$\frac{\partial I_D}{\partial VDSAT}\frac{\partial VDSAT}{\partial VBS}+\frac{\partial I_D}{\partial \gamma_{SD}}\frac{\partial \gamma_{SD}}{\partial VBS} \qquad (7.4.4)$$

APPENDIX A
PHYSICAL CONSTANTS

A table of physical constants is given below. The precision shown here is the same as used in SPICE. Some constants are shown as the product of a constant with another constant from the table. For instance, ε_{ox} is shown as formed by $3.9 \times \varepsilon_o$ that's exactly how it is evaluated in the code.

Constant	Definition	Value	Units
k	Boltzman's constant	1.3806226E-23	$J\,K^{-1}$
ε_o	permittivity of vacuum	8.85421487E-12	$F\,m^{-1}$
ε_{si}	permittivity of silicon	$11.7 \times \varepsilon_o$	$F\,m^{-1}$
ε_{ox}	permittivity of oxide	$3.9 \times \varepsilon_o$	$F\,m^{-1}$
q	charge on an electron	1.6021918E-19	C

APPENDIX B
USEFUL HINTS

As mentioned in the introduction, here are some interesting facts about SPICE that we encountered during the course of this project. These facts will hopefully be useful for the users but they couldn't appropriately be included in any of the chapters so far.

Sequencing of cards

The normal line length in SPICE is 80 columns. In other words SPICE tries to understand whatever it reads from columns 1 to 80 of an input line. The line length can be shortened to 72 columns by typing non-blank characters in columns 73 to 80 on the *title card*. This provision may be helpful for those who still have to use cards and would like to number their cards so that the SPICE input deck could be put together if it is dropped accidently. The following message is printed by SPICE when line length is shrunk.

WARNING: INPUT LINE-WIDTH SET TO 72 COLUMNS BECAUSE
POSSIBLE SEQUENCING APPEARS IN COLS 73-80

Illegal numbers

All the internal REAL parameters in SPICE are declared double precision. In spite of that SPICE expects an input number of the form xyzE±PW if the number has an exponential. where xyz is a fraction which may or may not have a decimal point and PW is an integer. If the + sign after E is dropped, there should be no space between E and PW. For example 1.3E 15 is an illegal number whereas 1.3E15 and 1.3E+15 are legal numbers. The reader is specially cautioned about numbers of the form 1.3E 15 or of the form 1.3D15 because in such cases no error message may be printed but SPICE will read only 1.3 rather than 1.3×10^{15}. In the case of other illegal numbers, the following error message will be printed:

0*ERROR*: ILLEGAL NUMBER -- SCAN STOPPED AT COLUMN i

where i is the column within or just after the illegal number.

Range of input numbers

All the numbers in the input file must be within the range of 1.0E-35 to 1.0E+35. If the number is not within this range, an error message is printed. The error message may be misleading because it is the same message which is printed when an illegal number is encountered as described above.

Entering MOSFET device parameters

The device parameters can be entered on the device definition card with their names as shown below:

```
M1  2 3 0 0 NMOD1 L=100U W=500U AD=1N AS=1N
+PD=2004P PS=2004P NRD=10 NRS=10
```

or equivalently they may be entered without their names as shown below:

```
M1  2 3 0 0 NMOD1 100U 500U 1N 1N 2004P 2004P 10 10
```

If the second approach is used then the parameter values must be in the order in which they appear in the first case. If named and unnamed parameters are input on a single device card then the values read will not always be assigned to the parameters for which they were intented. No error message will be printed in this case. It is possible to have some device of both types in a single SPICE input file.

APPENDIX C
BUGS AND THEIR SOLUTIONS

This appendix is for those who are familiar with SPICE code and would like to know the exact lines of codes where the bugs lie. Therefore a user with no interest in the code should neglect this. The bugs explained here have already been discussed in the report in the appropriate context and their effects on the computations have already been explained.

The line numbers appearing in front of the lines of code shown below are the serial line numbers. They are not a part of the source code.

1. Subroutine MODCHK is supposed to provide final values of model parameters at the nominal temperature, TNOM. In line 110 below, the energy gap EGFET is therefore evaluated at TNOM but the intrinsic carrier concentration XNI in line 109 does not show any temperature dependency. The value used here is 1.45D15 m^{-3} which is valid only at the temperature of 300 K.

```
106    TNOM=VALUE(ITEMPS+1)+CTOK
107    XKT=BOLTZ*TNOM
108    VT=XKT/CHARGE
109    XNI=1.45D16
110    EGFET=1.16D0-(7.02D-4*TNOM*TNOM)/(TNOM+1108.0D0)
```

This bug can easily be fixed by evaluating XNI after the evaluation of EGFET and by making XNI a function of TNOM and EGFET.

2. Shown below are some more lines of MODCHK. lines 160 and 161 are executed if the program needs to calculate the value of VTO. If VTO has been input by the user, lines 166 and 167 of the code are executed. In either case an attempt is made to take the square root of VALUE(LOCV+5) which is the model parameter PHI. Since a negative input value of PHI is allowed to go through by the subroutine READIN, a run time error results from the lines below:

```
160     VALUE(LOCV+2)=VALUE(LOCV+44)
161     1  +TYPE*(VALUE(LOCV+4)*DSQRT(VALUE(LOCV+5))+VALUE(LOCV+5))

166   20 VALUE(LOCV+44)=VALUE(LOCV+2)
167     1  -TYPE*(VALUE(LOCV+4)*DSQRT(VALUE(LOCV+5))+VALUE(LOCV+5))
```

This problem can be solved by initializing the value of PHI to default if the user inputs a negative value as is done for most other parameters in subroutine READIN.

3. In the lines of subroutine MODCHK below, VALUE(LOCV+23) is the model parameter PB. A user input value of zero for PB is allowed by subroutine READIN. This will result in a job crash because the following lines would attempt to divide by zero with PB=0.0.

```
267     CJ=DSQRT(EPSSIL*CHARGE*VALUE(LOCV+23)*1.0D6/
268    1  (2.0D0*VALUE(LOCV+12)))
```

The solution is obvious. A value of zero should not be allowed to remain, the parameter can be initialized to default in such a case.

4. In the following lines of subroutines MODCHK, It appears incorrect that a model parameter VALUE(LOCM+11) should be set to a certain value because something or the other is true about the device parameters VALUE(LOCV+3) and VALUE(LOCV+4) of a single device that uses the model:

```
609  950 AD=VALUE(LOCV+3)
610      AS=VALUE(LOCV+4)
611      IF ((AD.LE.0.0D0).OR.(AS.LE.0.0D0)
612     1  .AND.VALUE(LOCM+11).LE.0.0D0)
613     2  VALUE(LOCM+11)=1.0D-14
```

This really is not the problem as explained in the priority list for IS in chapter 2. The actual problem is that AD and AS should be treated equally because MOSFET is a symmetric device and source and drain are only related to the bias. This can be fixed by adding a parenthesis in line 611 to make it look like:

```
611      IF (((AD.LE.0.0D0).OR.(AS.LE.0.0D0))
```

5. As mentioned in chapter 5, an effort is made to obtain VDSAT using velocity saturation model if VMAX is input by the user and is non-

zero. If the effort fails VDSAT is evaluated using pinch-off model. A flag called IVMFLG is set in the program when that happens as shown in line 271 of subroutine MOSEQ2. Later in the program when a decision is to be made about how to calculate the effective channel length, only the value of VMAX is checked rather than both VMAX and IVMFLG. This leaves the possibility that no solution was obtained using the velocity saturation model. Therefore, VDSAT was calculated using pinch-off model but effective channel length is still calculated using velocity saturation model.

```
271  IVMFLG=IVMFLG+1
```

```
287  IF (VMAX.GT.0.0D0) GO TO 603
```

This problem can be fixed by altering line 287 to read:

```
287  IF (VMAX.GT.0.0D0).AND.(IVMFLG.LE.0.0D0) GO TO 603
```