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IC process optimization and modeling: a dedicated computer tool.

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1. Summary

Semiconductor device and process simulation programs make a wide use of analytical models with parameters extracted from experimental data fitting. It is quite obvious that process designer have to characterize these models to fit their own environment. Moreover it is a major task of process engineers to find process parameters which optimize designer and customer requirements.
Both these problems are substantially non linear, multi-dimensional regression problems. We have developed a computer tool which solves this kind of problems; it is based on the Levemberg-Marquardt algorithm, which is an efficient solver of non-linear, multi-dimensional constrained least square problems (Doganis,1981 and Ward, 1982). This algorithm has been enhanced by introducing several original features, to try to escape from local minimum when possible, and some statistical facilities which helps user in finding outliers and in monitoring the quality of the regression. The program will be able to drive various kind of simulators by forcing their inputs and reading their outputs with the appropriate interface. The present release is linked via a Remote Procedure Calls package with ST-SPICE 1.0-A, (Nagel,1975 and Profumo,1988) and ST-SUPREM-III (Hansen,1985). In this way it is possible to consider these simulators as "external" models to be characterized or optimized. Each variable that may appear in a simulator file can be optimized over a certain user-specified target; moreover the program can optimize parameters that appear in more than one simulator file. Referring to process optimization it is possible to vary any SUPREM-III variable or parameter (times, temperatures, fluxes, diffusivities, mobilities and so on) to fit one of these targets:

- Junction depths and sheet resistance of each layer,
- V-threshold as function of the V-substrate,
- Active and/or chemical concentration of any impurity at any depth,
- Net charge at any depth.

2. Software structure and simulation interface

The program SOBS 2.3-B is an optimizer builted on the well known Levemberg-Marquardt algorithm as implemented in SUXES-IV, (Doganis,1985). The first release of SOBS has been linked with SGS-SPICE and was used since 1984 to extract model parameters for BJT, MOS device and other macro-models (Saporito,1984).

It is composed of the following modules :

- a compiler, that reads all files needed for the optimization, checks input syntax and compiles the optmization problem in an internal format that will be read by the algorithm module,
- the algorithm of minimization, the original Levemberg-Marquardt with an extension to search an optimal variation for each parameter to compute the gradient, that is to use a specific h_j^k for each parameter x_k to estimate the Jacobian $J_{i,j}$, (see Algorithm section),
- the simulation interface that is cumbersed by a specific module, one for each external tool and a general module for every present or future linked tool,
- the external tools that has been modified with the needed RPC package for the communication, plus other routines to write output binary files of a format compatible with SOBS.

2.1 Simulation Interface

The algorithm and the external tool are two different executables linked via an RPC (Remote Procedure Calls) package that sincronizes them. Sincronous message is sent when the algorithm needs a new computation of data for the current value of parameters. An asincronous mailbox is used to trap every event as the unpredicted crash of one of the two executable.

The actions performed by the Simulation Interface (SI) can be summarized in a preliminary phase in which the capabilities to produce all needed output is verified. When the optimization loop starts the SI performs the following actions :

- current value of the parameters is written in the SUPREM-III input binary files as produced from GENII, the SUPREM-III preprocessor,
- SUPREM-III runs and produces binary output in SOBS format,
- output files are read, post-processed and associated with target.

Then SI stops and the algorithm computes the current value of the parameters. The Algorithm can call the SI with new values and this loop continues until one termination criteria is reached.

3. Algorithm

Here x is the vector of parameters to be optimized, the vector $f(x)$ consists of the error evaluated at each data point. The quantity to be minimized (the objective function) is the norm of the error vector, given by :

$$||f(x)||^2 = \sum_k f_k(x)^2 \equiv \sum_k \left(\frac{O_k(x) - T_k}{T_k} \right)$$

where O_k is the calculated function value, for example the concentration at the $k-th$ point, that is the $k-th$ depth and T_k is the desidered value of concentration.

The program extracts the parameters in a user specified constrained region of operation. At each iteration of the algorithm, the model is evaluated at each data point and the error vector $f(x)$ is calculated, the parameter vector x is then adjusted to reduce the sum of the squares of the errors. The process converges when a termination criteria is reached. The heart of the method is the adjustment of x to minimize the error. Basically the Levemberg-Marquardt algorithm is used as implemented in SUXES-IV. The Jacobian (the matrix of partial derivatives of the errors with respect to the parameter values) is calculated numerically.

To minimize the objective function :

$$F(x) = f^T f = \sum_{i=1}^{m} [f_i(x)]^2 x \in R^n, f : R^n \rightarrow R^m$$

it is necessary to find an x^* such that the gradient g of F equal zero :

$$g = 2J^T(x^*)f(x^*) = 0$$

where :

$$J_{ij} = \frac{\partial f_i(x)}{\partial x_i}$$

is the Jacobian of f. The Newton step x for improving an approximate solution x is obtained by solving the normal equations :

$$\left[J^T J + \sum_{i=1}^{m} f_i(x) \aleph^{(i)} \right] \triangle x = -J^T f(x)$$

where the term in brackets represent the Hessian matrix, and :

$$\aleph_{kj}^{(i)} = \partial^2 f_i(x) / \partial x_k \partial x_j$$

for $i = 1, ..., m$ and $k, j = 1, ..., n$.

The Levemberg-Marquardt (L-M) method approximates the second term into the square bracket with : $\lambda_k (J^T J)_{ii}$, where λ_k is a "weighting" parameter between the steepest descent and Gauss-Newton methods, and requires evaluation of the Jacobian of the residual vector $f(x)$ and solution of normal equations at each iteration step. The Jacobian J_{ij} is estimated numerically by means of either a forward difference approximation :

$$J_{ij}(x_k) \simeq \frac{f(x_k + h_j^k u_j) - f(x_k)}{h_j^k}$$

or a central difference approximation :

$$J_{ij}(x_k) \simeq \frac{f(x_k + h_j^k u_j) - f(x_k - h_j^k u_j)}{h_j^k}$$

where u_j is the j unit column vector and h_j^k is a small increment in the x_k direction.

4. Optimizable parameters, data and targets

Four types of files are required to run SOBS :

- input file with an initial estimate of the parameters to be optimized.
- data files with the targets.
- Suprem files that must be able to produce output consistent with the target.
- command files with the list of the previous files, and of the parameters to be optimized.

4.1 Optimizable parameters and input file

The parameters that can be optimized are process parameters as Time, Temperature, Implanted Dose, Energy, etc. or fitting parameters for new physical model for diffusion, deposition, oxidation etc. Every input variable in a Suprem file can be optimized; it is considered to be an optimizable parameter if it is present in the input file, with the syntax :

```
<prefix \ parameter> <initial value> <lower bound> <upper bound>
```

and in the Suprem file with the sintax :

```
# prefix # parameter
```

A parameter can be present in more than one suprem file and different parameters must have the same values :

```
<prefix1 \ parameter1> <prefix2 \ parameter2> ... <prefixn \ parametern>
<initial> <lower> <upper>
```

Example of input file and suprem file :

```
* input file
&parameter              initial  lower   upper
time1\time time2\time     100      90      120
time3\time                200     180      240

* suprem file 1
.diffusion  temp = 950  #time1# time = 100
.diffusion  temp = 900  #time2# time = 100

* suprem file 2
.diffusion  temp = 850  #time1# time = 100
.diffusion  temp = 950  #time3# time = 200
```

4.2 Data files and targets

To associate each data files to the related suprem files the command file must have the following two lines :

```
.datafiles    data1   data2   data3
.supremfiles  suprem1 suprem2 suprem2
```

The outputs of suprem1 will be associated to the targets if the file data1. The suprem2 file will be forced to produce two differents type of outputs to be associated with data2 and data3, because the same suprem file can be associated to several data files.

Each data file must have in the heading the field *model* followed by an integer. Each model number is associated with a different type of Suprem output.

Each data file has one column that is the target, and one column that is the independent variable. An additional column is present to specify the sub-type of the target.

Example of data file to optimize active concentrations of Boron and Phosporus.

```
model = 2
depth    trgtyp    target
0.2000     5         1.0e17
0.3000     5         2.0e17
0.2000     6         1.7e17
0.3000     6         2.7e17
```

The available models are :

- model = 1, the threshold voltage as computed from SUPREM-III is the target, the indipendent variable is the base-substrate voltage,
- model = 2, every active and/or chemical concentration, as well as the total net concentration can be the target. The target types are : BO-Active, BO-chemical, PH-A, PH-C, SB-A, SB-C, AS-A, AS-C, NET-chemical.
- model = 3, sheet resistance and/or junction depth of each layer,

Several models can be present and optimized at the same time.

4.3 Command file

The command file is composed of control cards as in that example :

```
.inputfile  initial
.iteration  time1\time time2\time
.datafile   data1    data2
.supremfile suprem1  suprem2
.outputfile file=output
```

The meaning of inputfile, datafile, supremfile is known, the iteration card asks for the extraction only of :

```
time1\time   time2\time
```

and the optimized value of parameters will be written in file output.dat.

5. Limits of the program and final consideration

The example showned is a fitting of the net concentration after seven steps. The optimizable parameter are three : thickness of the first deposition, temperature and time of the first diffusion. The target cannot be reached with greater accuracy, because the initial region, of 0.3 micron, is flat, and the output cannot be flattened with that parameters. The region deeper than 0.3 micron is very accurate. The initial mean error (131.204 %) has been reduced of ten times (11.614 %), in 7 minutes of elapsed time of a VAX 8650. The figure shows graphically the same information listed in the error file. The optimization flow is reported and it is possible to see the number of iterations performed.

The number of optimizable parameters, either of the data (or suprem) files and of the targets data has hardware and software limitation. The physical limits of the

system : page file quota, or working set of the main process (algorithm) and the detached one (SUPREM-III) must be taken into account before the compilation of the source code because the program is all written in Fortran and it needs a static definition of the work space.

The dimension of the problem that can be solved also depends from the good formulation of the minimization problem. The knowledge of the physical models implemented in SUPREM-III will avoid the formulation of unreacheable problems. If the User knows what are the parameters sensitive to solve the minimization problem then SOBS can help him to find the optimal value in less time then by hand.

In the following figure is shown the initial, the final and the target profile.

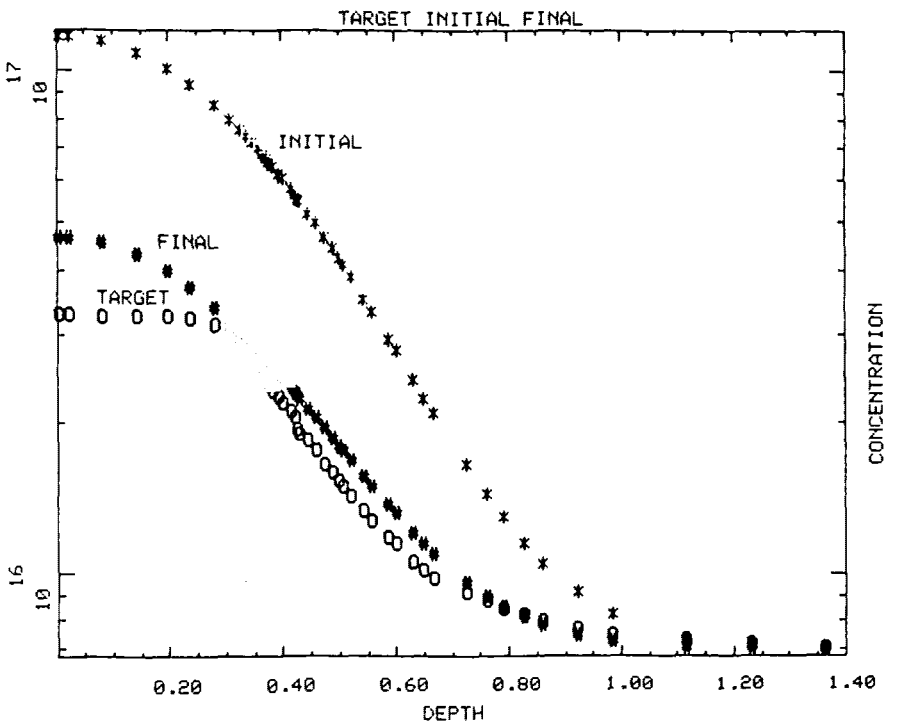

Fig 1. Final result compared with initial and target.

6. Example

example of input file with initial values of parameters, lower and upper bounds :

```
*
&PARAMETERS     INITIAL/EXTRACTED          LOWER              UPPER
THI1\THICKNESS          0.0050             0.0010             0.0100
TEM1\TEMPER          1000.000            950.000           1100.000
TIM1\TIME              90.000             10.000             100.000
*
```

example of supremfile in which to optimize :
#THI1#THICKNESS #TEM1#TEMPERATURE #TIM1#TIME

```
TITLE         BOXER ISOLATION
INITIALIZE    <100> SILICON BORON CONCENTRATION=7E15
+             THICKNESS=4 DX=0.02

$ Deposition of a thin oxide
DEPOSITIO     OXIDE #THI1# THICK=0.005

$ Deposition of a doped oxide
DEPOSITIO     OXIDE CONCEN=1.184E20 BORON THICK=0.20 TEMP=390
PRINT LAYERS

$ Diffusion for the impurities throught the thin oxide
DIFFUSION     #TEM1# TEMPERAT=1000 #TIM1# TIME=50
PRINT LAYERS

$ Etch oxide
ETCH          OXIDE ALL

$ Deposition oxide
DEPOSIT       OXIDE THIC=0.5

$ Diffusion for the impurities
DIFFUSION     TEMPERAT=1100 TIME=30 DRYO2

$ Etch oxide
ETCH          OXIDE ALL

$ Save the file
PRINT         LAYERS
SAVEFILE      FILENAME=BOX.EXP EXPORT
STOP
```

Example of flow of the optimization, the first 7 numbered lines are the cards of the command file. The flow has the same format of SUXES-IV.

```
  1 ...  .INPUTFILE  BOXIEF
  3 ...  .ITERATION &EXTRACT &ALL
  4 ...  .SUPREMFILE BOX
  5 ...  .DATAFILES  BOX
  6 ...  .IOPTIONS   LIST=ERR OUT=2 AUTO=Y
  7 ...  .OUTPUT     FILE=BOXOUT

 JACOBIAN EVALUATION
  SSQNEW =    109.133       SSQOLD =    120.376

 ITERATION COMPLETED
 THI1\THI  4.945429166E-03  IN.CHG %  -1.09142      IT.CHG %  -1.09142
 TEM1\TEM   991.673167      IN.CHG % -0.832683      IT.CHG % -0.832683
 TIM1\TIM   93.5319975      IN.CHG %   3.92444      IT.CHG %   3.92444
ITER=  1 EVAL= 12 ABSSSQ=    109.133     AL= 2.500000E-02 GRAD=14216.3
ERMAX %=    252.399     ERMIN %=   5.661878E-02  RMS %=    124.407
XSIGN=    1.42294      RELSSQ=    109.133       SEARCHs=  1

 BROYDENS RANK ONE UPDATE
  SSQNEW =    93.9632       SSQOLD =    109.133

 ITERATION COMPLETED
 THI1\THI  4.897361237E-03  IN.CHG %  -2.05278      IT.CHG % -0.961359
 TEM1\TEM   983.416167      IN.CHG %  -1.65838      IT.CHG % -0.825700
 TIM1\TIM   91.8476916      IN.CHG %   2.05299      IT.CHG %  -1.87145
ITER=  2 EVAL= 13 ABSSSQ=    93.9632     AL= 1.095850E-02 GRAD=12463.2
ERMAX %=    240.682     ERMIN %=   5.658808E-02  RMS %=    114.806
XSIGN=    1.73665      RELSSQ=    93.9632       SEARCHs=  1

 BROYDENS RANK ONE UPDATE
  SSQNEW =    85.2525       SSQOLD =    93.9632

 ITERATION COMPLETED
 THI1\THI  4.814017241E-03  IN.CHG %  -3.71966      IT.CHG %  -1.66688
 TEM1\TEM   971.836941      IN.CHG %  -2.81631      IT.CHG %  -1.15792
 TIM1\TIM   93.6789483      IN.CHG %   4.08772      IT.CHG %   2.03473
ITER=  3 EVAL= 14 ABSSSQ=    85.2525     AL= 3.278762E-03 GRAD=7457.92
ERMAX %=    235.658     ERMIN %=   5.678760E-02  RMS %=    108.678
XSIGN=    1.70889      RELSSQ=    85.2525       SEARCHs=  1
```

```
 BROYDENS RANK ONE UPDATE
  SSQNEW =    1.87419       SSQOLD =    85.2525

 ITERATION COMPLETED
 THI1\THI  5.555533074E-03  IN.CHG %   11.1107      IT.CHG %   14.8303
 TEM1\TEM   966.536016      IN.CHG %  -3.34640      IT.CHG % -0.530092
 TIM1\TIM   87.9543931      IN.CHG %  -2.27290      IT.CHG %  -6.36062
ITER=  4 EVAL= 15 ABSSSQ=    1.87419     AL= 8.196905E-04 GRAD=3499.19
ERMAX %=    47.9332     ERMIN %=   5.663412E-02  RMS %=    14.8541
XSIGN=   0.874605      RELSSQ=    1.87419       SEARCHs=  1

 JACOBIAN EVALUATION
  SSQNEW =    1.32485       SSQOLD =    1.87419

 ITERATION COMPLETED
 THI1\THI  5.551397416E-03  IN.CHG %   11.0279      IT.CHG % -8.271316E-02
 TEM1\TEM   963.939456      IN.CHG %  -3.60605      IT.CHG % -0.259656
 TIM1\TIM   84.3886626      IN.CHG %  -6.23482      IT.CHG %  -3.96192
ITER=  5 EVAL= 20 ABSSSQ=    1.32485     AL= 2.049226E-04 GRAD=874.004
ERMAX %=    42.7316     ERMIN %=   5.663412E-02  RMS %=    12.0657
XSIGN=    1.37414      RELSSQ=    1.32485       SEARCHs=  1

 BROYDENS RANK ONE UPDATE
  SSQNEW =    1.36351       SSQOLD =    1.32485
  SSQNEW =    1.27923       SSQOLD =    1.32485

 ITERATION COMPLETED
 THI1\THI  5.553356236E-03  IN.CHG %   11.0671      IT.CHG %  3.917639E-02
 TEM1\TEM   962.609491      IN.CHG %  -3.73905      IT.CHG % -0.132997
 TIM1\TIM   87.6739929      IN.CHG %  -2.58445      IT.CHG %   3.65037
ITER=  6 EVAL= 22 ABSSSQ=    1.27923     AL= 6.659928E-04 GRAD=710.122
ERMAX %=    42.1773     ERMIN %=   5.651134E-02  RMS %=    11.8138
XSIGN=    1.42629      RELSSQ=    1.27923       SEARCHs=  2

 JACOBIAN EVALUATION
  SSQNEW =    1.25021       SSQOLD =    1.27923

 ITERATION COMPLETED
 THI1\THI  5.533843343E-03  IN.CHG %   10.6769      IT.CHG % -0.390258
 TEM1\TEM   959.902488      IN.CHG %  -4.00975      IT.CHG % -0.270700
 TIM1\TIM   87.4682947      IN.CHG %  -2.81301      IT.CHG % -0.228554
ITER=  7 EVAL= 28 ABSSSQ=    1.25021     AL=  1.36395     GRAD=229.684
ERMAX %=    42.1514     ERMIN %=   5.664180E-02  RMS %=    11.6142
XSIGN=    2.45271      RELSSQ=    1.25021       SEARCHs=  1

    ERROR CONDITION:

         THE MARQUARDT PARAMETER (   1396.69    )
          EXCEEDED THE MAXIMUM   (   1000.00    )

---------------------------- SOBS END  ----------------------------
```

Example of output result with termination criteria before the optimization, initial error, and after the optimization :

```
*
*       STATISTIC SUMMARY
*
*    DATE AND TIME
*
*    Start :  9-JUL-1988 10:36:24.03
*    End   :  9-JUL-1988 10:40:59.63
*
*     -------------------- MINIMIZATION RESULTS --------------------
*
*          RESIDUAL SUM OF SQUARES     =   120.376
*          NORM OF THE GRADIENT        =   14216.3
*          MARQUARDT SCALING PARAMETER =  0.000000E+00
*          NO. OF SIGNIFICANT DIGITS   =        4
*          NO. OF FUNCTION EVALUATIONS =       18
*          NO. OF ITERATIONS           =        0
*          THE MAX ERROR IS            =   259.568     %
*          THE RMS ERROR IS            =   131.204     %
*
  ------------------------------------------------------------------------
  &PARAMETERS    INITIAL/EXTRACTED        LOWER             UPPER
  THI1\THICKNESS      5.000000E-03      5.000000E-03      5.000000E-03
  TEM1\TEMPER          1000.00           1000.00           1000.00
  TIM1\TIME            90.0000           90.0000           90.0000
*
*       STATISTIC SUMMARY
*
*    DATE AND TIME
*
*    Start :  9-JUL-1988 11:23:30.53
*    End   :  9-JUL-1988 11:30:26.01
*
*     -------------------- MINIMIZATION RESULTS --------------------
*
*          RESIDUAL SUM OF SQUARES     =   1.25021
*          NORM OF THE GRADIENT        =   608.691
*          MARQUARDT SCALING PARAMETER =   1.36395
*          NO. OF SIGNIFICANT DIGITS   =        4
*          NO. OF FUNCTION EVALUATIONS =       39
*          NO. OF ITERATIONS           =        7
*          THE MAX ERROR IS            =   42.1514     %
*          THE RMS ERROR IS            =   11.6142     %
*
  ------------------------------------------------------------------------
  &PARAMETERS    INITIAL/EXTRACTED        LOWER             UPPER
  THI1\THICKNESS      5.533843E-03      1.000000E-03      1.000000E-02
  TEM1\TEMPER          959.902           950.000           1100.00
  TIM1\TIME            87.4683           10.0000           100.000
```

		INITIAL		FINAL	
DEPTH	TARGET	RESULT	ERROR	RESULT	ERROR
3.372E-03	3.258E+16	1.170E+17	-259.	4.627E+16	-42.0
2.047E-02	3.256E+16	1.171E+17	-260.	4.628E+16	-42.2
8.006E-02	3.251E+16	1.149E+17	-253.	4.540E+16	-39.7
0.140	3.248E+16	1.090E+17	-236.	4.308E+16	-32.6
0.197	3.231E+16	1.006E+17	-211.	3.977E+16	-23.1
0.238	3.203E+16	9.328E+16	-191.	3.696E+16	-15.4
0.281	3.119E+16	8.481E+16	-172.	3.371E+16	-8.09
0.305	3.026E+16	7.990E+16	-164.	3.185E+16	-5.22
0.324	2.926E+16	7.591E+16	-159.	3.034E+16	-3.69
0.336	2.774E+16	7.341E+16	-165.	2.940E+16	-5.97
0.346	2.692E+16	7.137E+16	-165.	2.864E+16	-6.40
0.355	2.616E+16	6.940E+16	-165.	2.790E+16	-6.64
0.363	2.570E+16	6.788E+16	-164.	2.734E+16	-6.36
0.370	2.543E+16	6.640E+16	-161.	2.679E+16	-5.34
0.375	2.485E+16	6.541E+16	-163.	2.643E+16	-6.33
0.375	2.394E+16	6.539E+16	-173.	2.642E+16	-10.3
0.382	2.319E+16	6.389E+16	-176.	2.586E+16	-11.5
0.394	2.254E+16	6.146E+16	-173.	2.497E+16	-10.8
0.399	2.187E+16	6.048E+16	-177.	2.461E+16	-12.5
0.413	2.122E+16	5.761E+16	-172.	2.357E+16	-11.1
0.421	2.044E+16	5.618E+16	-175.	2.305E+16	-12.8
0.426	1.945E+16	5.522E+16	-184.	2.270E+16	-16.7
0.430	1.907E+16	5.429E+16	-185.	2.237E+16	-17.3
0.445	1.847E+16	5.156E+16	-179.	2.138E+16	-15.7
0.457	1.764E+16	4.934E+16	-180.	2.059E+16	-16.7
0.474	1.658E+16	4.631E+16	-179.	1.951E+16	-17.7
0.486	1.592E+16	4.421E+16	-178.	1.877E+16	-17.9
0.498	1.539E+16	4.219E+16	-174.	1.806E+16	-17.4
0.505	1.490E+16	4.099E+16	-175.	1.764E+16	-18.4
0.520	1.418E+16	3.869E+16	-173.	1.685E+16	-18.8
0.544	1.328E+16	3.506E+16	-164.	1.560E+16	-17.5
0.558	1.270E+16	3.303E+16	-160.	1.491E+16	-17.4
0.587	1.179E+16	2.924E+16	-148.	1.364E+16	-15.7
0.599	1.142E+16	2.779E+16	-143.	1.316E+16	-15.3
0.630	1.052E+16	2.432E+16	-131.	1.203E+16	-14.3
0.650	1.008E+16	2.241E+16	-122.	1.141E+16	-13.2
0.666	9.733E+15	2.087E+16	-114.	1.093E+16	-12.3
0.724	9.083E+15	1.649E+16	-81.6	9.576E+15	-5.43
0.760	8.751E+15	1.437E+16	-64.2	8.944E+15	-2.21
0.791	8.431E+15	1.286E+16	-52.5	8.508E+15	-0.911
0.827	8.166E+15	1.145E+16	-40.3	8.113E+15	0.657
0.861	7.966E+15	1.041E+16	-30.7	7.828E+15	1.74
0.920	7.689E+15	9.069E+15	-17.9	7.477E+15	2.77
0.983	7.462E+15	8.193E+15	-9.80	7.260E+15	2.70
1.11	7.307E+15	7.337E+15	-0.415	7.066E+15	3.30
1.23	7.155E+15	7.099E+15	0.770	7.018E+15	1.91
1.36	7.056E+15	7.023E+15	0.464	7.004E+15	0.737
3.74	6.996E+15	7.000E+15	-5.657E-02	7.000E+15	-5.664E-02
3.96	6.987E+15	7.000E+15	-0.180	7.000E+15	-0.180

7. References

- D.E.Ward and K.Doganis, Optimized extraction of MOS model parameters, IEEE trans. on CAD/ICAS, Oct 1982.
- K.Doganis and R.W.Dutton, Optimization of IC process using SUPREM, Stanfod Electronics Laboratories, Stanford University, Stanford, California, June 1981.
- L.W.Nagel, SPICE2, A computer program to simulate semiconductor circuits, Memo No. ERL-M520, Electronics Research Laboratory, University of California, Berkeley, May 1975.
- E.Profumo, P.Mancini, JP.Morin, A.Saporito, ST-SPICE 1.0-A User Guide, UNICAD Development, Central R.&D., SGS-Thomsom Microelectronics, July 1988.
- S.Hansen, SUPREM-III User's Manual Version 8520, Stanfod Electronics Laboratories, Stanford University, Stanford, California, May 1985.
- A.Saporito, M.Vanzi, An optimal bipolar AC and DC parameter extraction for circuit simulation, ICCAD 84, Santa Clara, California, Nov 1984.