1. ABSTRACT

A parameter extraction program was developed for automating the process of obtaining CHFET device parameters from measured data. The program requires the use of Mathcad, Matlab, and AIM-Spice. The extraction of p and n type transistors from Honeywell and Motorola provided parameters that produced simulated results, which matched within 15% of the measured data.

2. INTRODUCTION

In order to design gallium arsenide (GaAs) complementary heterostructure field effect transistor (CHFET) integrated circuits (ICs) [1-2], a CHFET model parameter extraction program was developed to work with a unified charge control CHFET model in the AIM-Spice circuit simulator [3]. Typically, a model is only as good as the model parameters used in the device simulation. Hence, a parameter extraction program has been developed to extract CHFET model parameters from sets of measured data. Three sets of measured data, including forward and reverse bias, are required for a complete parameter extraction. The program is written using Mathcad and Matlab. Mathcad is used for the computational capability of the program and Matlab is used mostly for the user interface. The program is semi-automated in the sense that it requires the user to enter curve-fitting values to improve the matching between the measured and simulated data. The user can continue to provide input to further improve the matching through each iteration. The more iterations, the more accurate the results. Upon completion of the extraction process, the resulting model parameters are used for simulation with AIM-Spice. The following sections describe the basic concept of the CHFET model in AIM-Spice and the model parameter extraction procedure and program. Finally, the results of the extraction process are compared with the measured data.

3. CHFET MODEL

Through the rapid evolution of semiconductor technology, transistor sizes have reached the submicron regime. Numerous issues have arisen such as the increasing level of complexity of the fabrication process and the many mechanisms that govern the properties of submicron FETs. As a result, a CHFET physics-based model allows a designer to model and simulate ICs [4-6].
The HFET model in AIM-Spice supports automatic scaling into the deep submicron range. It accurately describes not only the I-V characteristics, but also differential quantities such as $g_m$ and $g_d$, which are necessary for analog circuit simulation. Since the regions of operation for a transistor are contained in a unified model, the derivatives are continuous across different operation regions. This aids in simulation time and less convergence problems for the simulator.

Figure 1 shows the equivalent circuit of the HFET model used in AIM-Spice. The parameters are extracted from the measured data of a transistor and are used by the equivalent circuit for simulation.

![Figure 1. Equivalent Circuit of HFET Model in AIM-Spice](image)

The HFET model contains numerous parameters for modeling a transistor. It is a physics based model that accounts for phenomena that are significant in the submicron regime. The next section shows the parameters used in the model and how they are applied to parameter extraction of measured data.

4. PARAMETER EXTRACTION

In order to apply the HFET model above in circuit simulation, it is necessary to find a practical way of extracting the model parameters from experimental data. The accuracy of the parameter extraction depends on the accuracy of the model and on the accuracy and completeness of the experimental data.
In real life, there are usually problems with both the model and the experimental data. Even though the analytical models reflect many important effects occurring in HFETs, such as velocity saturation, parasitic resistances, the dependence of the threshold voltage on the drain bias, and finite output conductance, many other important phenomena are included indirectly, at best. For example, the model treats the dependence of the mobility on the bias conditions only through effective values and, indirectly, through the fitting parameter λ. Furthermore, many complicated phenomena associated with the threshold voltage dependence on the drain-source voltage are accounted for in a set of simple, empirical formulae.

Therefore, an approach to the device characterization of HFETs is to extract effective device parameters, such as the threshold voltage, \( V_{TO} \), the subthreshold ideality factor, \( \eta \), the source and drain series resistances, \( R_s \) and \( R_d \), the output conductance parameter, \( \lambda \), the knee shape parameter, \( m \), the threshold voltage coefficient, \( \sigma \), and the voltages \( V_{st} \) and \( V_s \) characterizing the dependence of parameter on the gate voltage swing. In other words, we describe a parameter extraction procedure which gives fairly reasonable results without parameter adjustment and which can produce a nearly perfect fit with some parameter adjustment. Note that, even without a precise knowledge of the device geometry and process parameters, one can obtain a good fit to the device characteristics and, hence, predict the circuit performance fairly accurately using the AIM- Spice simulation program. Moreover, one still retains a limited ability to predict how device characteristics will scale with changes in the doping level and profile and device geometry. In other words, the model and parameter extraction procedure attempt to give the best possible answer based on the available information.

The parameter extraction procedure is shown in Figure 2. The raw data is read into the extraction program. Various parameters are extracted, analyzed, and simulated. This process is repeated until the simulated data and measured data in agreement within the desired tolerances. Three data sets are required in order to provide a complete set of model parameters for a given device. Two data sets are forward bias data and one is a reverse bias data set.

4.1. Raw Data Format

Three data sets, both forward and reverse bias are needed to extract a complete set of model parameters for a given device. DSET1 consists of \( I_{ds}(V_{ds}) \) at different \( V_{gs} \) (Figure 3). DSET2 consists of \( I_{ds}(V_{gs}) \) at different \( V_{ds} \) (Figure 4). DSET3 consists of \( I_{gs}(V_{gs}) \) at different \( V_{ds} \) (Figure 5).

A specific format is required for the raw data to be read into the extraction program. The first row specifies each gate-source voltage (\( V_{gs} \)). The first column specifies the drain-source voltage (\( V_{ds} \)). Each subsequent column is the drain-source current (\( I_{ds} \)) corresponding the column’s \( V_{gs} \).
Raw Data → Parse Data Into Extraction Program (Mathcad) → Generate Forward and Reverse Bias Data Equations (Mathcad)

Extracted and Measured Data Within Error Tolerance? (Matlab)

Yes → Simulate Transistor with Extracted Parameters (AIM-Spice) → Extract Simulation Parameters From Equations (Mathcad & Matlab)

No → Adjust Extracted Parameter Value (AIM-Spice)

Print Out Results

Figure 2. Flow Diagram of Parameter Extraction

Figure 3. Data set DSET1: $I_{ds}$ vs. $V_{ds}$ for different $V_{gs}$
Figure 4. Data set DSET2: $I_d$ vs. $V_{gs}$ at different $V_{ds}$

Figure 5. Data set DSET3: $I_g$ vs. $V_{gs}$ at different $V_{ds}$
4.2. Extraction Methodology

The following section describes the procedure for extracting each model parameter. Each parameter is extracted from one of the three data sets and is calculated from the measured data.

4.2.1. Read in Measured Data
1. Find the largest $I_{ds}$ from DSET1 and DSET2, $I_{maxd1}$, $I_{maxd2}$ (assuming the last value is the max value)
2. Take the largest value and multiply by 1.1 = $I_{max}$
3. Find $N_{MAXmin} = (I_{max} / \text{ELECHG} \times \text{VSAT} \times \text{GATWID})$
4. if $N_{MAX}$ is not larger than $N_{MAXmin}$, $N_{MAX} = N_{MAXmin}$
5. if $N_{MAX}$ is larger than $N_{MAXmax}$, $N_{MAX} = N_{MAXmax}$

4.2.2. Calculate $\eta$ (Subthreshold Parameter)
1. Determine the minimum $V_{ds}$ curve from DSET2
2. Determine point on curve where constant slope begins and noise ends
3. Take smooth derivative of the curve
4. Find the max slope point
5. Take the average slope of 5 points at the max slope point

\[
\eta = \frac{1}{V_{TH} \cdot \ln(10) \cdot \text{(ave \_slope)}}
\]

\[
V_{TH} = \frac{kT}{q}
\]

4.2.3. Determine $V_{DiodeOn}$ (Gate Diode Turn-On Voltage)
1. Determine $V_{DIODEON}$ where gate current, $I_{gs} = 1 \mu A/\mu m$ gate width at $V_{ds} = 0 \text{ V}$
2. Find curve from DSET1 where $V_{gs} = 0.75 \times V_{DIODEON}$ ($idsatcurve$)
   $V_{gs}$ is within 10% of the $V_{DIODEON}$ voltage

4.2.4. Calculate $M_{EXP}$ (Knee Shape Parameter):

The extraction of the knee shape parameter, $M_{EXP}$, occurs in the saturation region with low output conductance, as shown in Figure 6. Two lines represent the slope in the linear region ($g_{ch}$) and the slope in the saturated region ($g_{chs}$). The lines intersect at the saturation current, $I_{sat}$, at the drain-source voltage $V_{ds} = I_{sat} / g_{ch} = V_{sate}$. The equation for $I_{ds}$ vs. $V_{ds}$ is defined as:

\[
I_{d} = \frac{g_{ch} \cdot V_{ds} (1 + \lambda V_{ds})}{[1 + (V_{ds}/V_{sate})^m]^m}
\]
Figure 6. Method for extracting the saturation current ($I_{sat}$), knee shape ($MEXP$), and the output conductance ($\lambda$) parameters

Applying eq. (3) and Figure 6, the real current at this drain-source voltage ($V_{ds} = V_{sat}$) is $I_d = I_{sat} - I = I_{sat}/2^m$. Therefore, by finding the intersection of the two lines and measuring $I_{sat}$ and $I_{sat} - \Delta I$, $m$ can be determined by:

$$m = \frac{\ln(2)}{\ln[I_{sat}/(I_{sat} - \Delta I)]}$$

(4)

Extraction of $m$:
1. Take derivative of $I_d$ vs. $V_{ds}$ (DSET1) curve ($idsatcurve$)
2. Find $gdmin$ & mark this point as the saturation point ($jjsat$)
3. Find slope near $V_{ds} = 0$ ($gch$) using the average slope between first four points
4. Find $gchs$ as average slope near $jjsat$ point from 2 above
5. $idsx = vsate * (gch + gchs)$
6. Find the point on the real curve ($vsate$, $idx$)
7. Find $MEXP$:

$$MEXP = \frac{\ln(2)}{\ln(idsx/idx)}$$

(5)

4.2.5. Calculate Lambda (Output Conductance Parameter):

Extraction of $\lambda$:
1. Take derivative of $I_d$ vs. $V_{ds}$ (DSET1) curve ($idsatcurve$)
2. Find $gdmin$ & mark this point as the saturation point ($jjsat$)
3. Find slope near $V_{ds} = 0$ ($gch$) using the average slope between first four points
4. Find $gchs$ as average slope near $jjsat$ point from 2 above
5. Calculate the saturation current, saturation voltage as:

$$isat = ids[jjsat] - VDS1[jjsat] * gchs$$

(6)
vsate = isat / gch  \quad (7) \quad LAMBDA = gchs / isat \quad (8)

Extra Parameters:
1. vsatemin = 0.4 * vsate
2. vsatemax = 1.5 * vsate
3. Find curves in DSET2 where:
   - largest Vds where VDS2 < vsatemin
   - smallest Vds where VDS2 > vsatemax

4.2.6. Threshold Voltage Parameters \((VTO, \beta1, \text{SIGMA0}, \text{SIGMAT})\)
1. Print a table of \(VTH\) (1 \(\mu\)A/\(\mu\)m) and \(VTO\) for each curve in DSET2
   \[ VTH = VTO - \sigma_0 \cdot VDS \]
2. If there is a curve in DSET2 that has \(VDS[satind40] < vsatemin\), then find \(VTO\) from this curve
   - Find \(gmax\) point along this curve
   - Find \(VTO\) as the intercept point along the x-axis using straight line fit \((y = mx + b)\)
     \[ VTO = -idexp / gmax + VGS2[gindeks] \quad (9) \]
     \[ \beta1 = gmax / VDS2[satind40] \quad (10) \]
3. Find the range of \(VTO\)
   \[ VTO - 0.3 < VTO < VTO + 0.3 \]
4. If \((HDIKNOWN)\), estimate lower boundary of \(NMAX\)
5. Otherwise, estimate \(VTO\) from the transconductance using the largest value of \(VDS\)

4.2.7. Sigma:
1. Determine \(I_t\) as a constant where:
   \[ I_{th1p} = \frac{W \mu C \eta V_{th}^2}{L(d_i + \Delta d)} \cdot 2 \ln(1.5) \left( 1 + \sqrt{1 + HDELTA^2} \right) \]
2. For all curves, find:
   \[ I_{thij} = I_{th1p} \cdot (1 + LAMBDA \cdot VDS2[ij]) \]
3. Find \(VT\) of \(VDS[ij]\) at each \(I_{th}\) point
4. Plot \(VT\) of \(VDS[ij]\) vs. \(VDS\)
   Sigma is taken to be the slope of the last 2 points since as \(VDS\) grows large, \(\sigma \to \sigma_0\)
5. \(VSIGMAT = 0.3\) (default value)
   \(VSIGMA = 0.1\) (default value)
   \[ \sigma = \frac{\sigma_0}{1 + e^{\frac{V_{gto} - VSIGMAT}{VSIGMA}}} \quad (11) \]

4.2.8. Extrinsic Parameters:

Resistance (Method 1):
1. Find \(gch\) in the linear region for each \(Vgs\) curve in DSET1
2. Find $gch$ from first 4 points if they cover $V_{ds} = 0.1$ V range or use number of points covering range to $V_{ds} = 0.1$ V

3. Calculate $gch$ and $vgt$

$$gch = \frac{ids(jave) - ids(0)}{jave \cdot \Delta j}$$

$$vgt = V_{gs} - V_{TO}$$

4. Plot $1/gch$ vs $1/vgt$ above saturation

5. Make sure you have at least 3 curves to fit a Least Squares line

6. The y intercept is the $R_t$ value where: $R_t = R_d + R_s$

7. The slope is used to determine $beta_2$ where: $beta_2 = 1/slope$

Resistance (Method 2):

1. Find the gate resistance $gres$, using the $V_{ds} = 0.0$ V curve in DSET 3

2. Find the $V_{ds} = 0.0$ V curve in DSET2. Determine the closest $Vgs$ value in DSET3 curve that matches the max $Vgs$ in DSET2

3. Abort if you don’t have both $V_{ds} = 0.0$ V curves

4. Find the difference in $Ids$ from DSET2 and the difference in $Igs$ from DSET3

5. Calculate $HRS$ as the slope of DSET2 curve and $HRD$ as the voltage across $RD$ divided by $IS$

- find $delta id$, $delta ig$, and $delta jave$

- $is1 = ig1 - id1$

- $delvrg = delig \ast gres$

- $delvrd = delvg - delvrg$

- $HRD = delvrd / delid$

- $HRS = (HRD \ast id1) / is1$

$beta_3$:

1. Determine $beta_3$ in the saturation region using the maximum $V_{ds}$ curve in DSET2

2. Determine the limits to examine; start where sigma is negligible (< 0.02) and ending at the maximum transconductance point

3. Determine at each point $gmi$ and $VGS$

$$VGT = Vgs[jcol] - V_{TO} - HRS \ast ids[jcol]$$

$$gmi = \frac{gch}{1 - gch \cdot HRS}$$

4. Plot $1/gmi^2$ versus $1/VGT^2$ and make a Least Squares linear approximation ($y=mx+b$)

$$beta_3 = \frac{1}{\sqrt{m}} \cdot \frac{1}{1 + \lambda \cdot V_{ds}} \quad (12)$$

$$VL = \frac{1}{\sqrt{b \cdot beta_3}} \quad (13)$$

$beta$:

1. $beta = beta_3$ in the saturation regime

2. $beta_1$ is determined from $V_{ds}$ below saturation $VDS2[satind40]$
3. \( \beta_2 \) is determined from \( 1/g_{ch} \) vs \( 1/v_{gt} \) data
4. \( \beta_3 \) is determined from the maximum \( V_{ds} \) value in DSET2
   \( V_{DS2[NCOL[2]]} \)

Material Parameters (\( HDI, MOBILITY \)):
1. if (\( HDI\text{KNOWN} \))
   else \( HDI = (\beta_{ap/\beta}) * MOBILITY \)
   \( HDI\text{KNOWN} \) is a variable set in the structure file. \( HDI \) is generally considered not known if the value of \( HDI \) has not been measured and is a guess.
2. Make a new estimate of \( VSAT \) based on the measured mobility value
   \( VSAT = VL * MOBILITY / GATLEN \)

Gate Current Parameters (\( M1, IS1, M2, IS2, R_{gd}, R_{gs} \)):
1. Find maximum \( V_{ds} \) curve in DSET3 (\( vindeks \))
2. Plot \( \ln(I_{gs}) \) versus \( V_{gs} \)
3. Find the maximum slope point \( g_{max} (j_{max}) \)
4. Search for the range of slopes below and above \( j_{max} \) that are within ±5% of \( g_{max} \)
5. Find the slope and intercept using Least Squares Method
   \( m1 = 1.0 / (V_{TH} * \text{slope}) \)
   \( is1 = \exp(\text{intercept}) \)
6. Determine the gate resistance by finding the difference between the straight line approximation and the maximum \( I_{gs} \) point on the actual curve
   \( R_{gd} = (v_{gcurve} - v_{gsline}) / \text{ig} \)
7. The gate resistance approaches its terminal value as the \( V_{gs} \) gets big. The fit to this curve is a power law
8. The derivative is smoothed before estimating slopes, etc.

Two Diode Model:
1. Determine diode parameters in two different ranges
2. Find first diode, search for the max slope point and determine range of slope within 15%
3. First diode between
   - \( 0.8 < V_{gs} < 0.975 \)
   - find \( m1 \) and \( is1 \)
4. Find second diode, search for max second derivative point above the minimum second derivative point
5. Second diode between
   - \( 0.975 < V_{gs} < 1.825 \)
   - find \( m2 \) and \( is2 \)
6. Determine the gate resistance by finding the difference between the straight line approximation of the second diode and the maximum \( I_{gs} \) point on the actual curve
   \( R_{gs} = (v_{gcurve} - v_{gsline}) / \text{ig} \)
Current Density Parameters (JS1D, JS1S, JS2D, JS2S, RGD, RGS):

1. Determine the current density and gate resistor values
   - \( JS1D = \frac{i_{s1d}}{GATELEN \times GATEWID} \) or \( JG_{min} \) whichever is larger
   - \( JS1S = \frac{i_{s1s}}{GATELEN \times GATEWID} \) or \( JG_{min} \) whichever is larger
   and if \( GTYPE = 2 \),
   - \( JS2D = \frac{i_{s2d}}{GATELEN \times GATEWID} \) or \( JG_{min} \) whichever is larger
   - \( JS2S = \frac{i_{s2s}}{GATELEN \times GATEWID} \) or \( JG_{min} \) whichever is larger

2. \( RGD = RGS = gateresistance \times 2 \)

3. The gate resistance is to be split among drain and source parallel resistors.
   If \( (RGS > HRS) \lor (RGD < HRD) \)
   - \( HRD = HRS = gateresistance \times 2 \)
   else
   - \( RGD = RGD - HRD; RGS = RGS - HRS \)

Resistors (RGD, RGS):

1. \( RGD = RGS = gateresistance \)
2. if \( (RGS < HRS) \lor (RGD < HRD) \)
   - \( HRD = HRS = gateresistance \)
   - \( RGD = RGS = 0.0 \)
   else
   - \( RGD = RGD - HRD; RGS = RGS - HRS \)

One Diode Model:

Current Density Parameters (JS1D, JS1S, JS2D, JS2S, RGD, RGS):

1. \( RGD = RGS = gateresistance \times 2 \)
2. The gate resistance is to be split among drain and source parallel resistors.
   If \( (RGS < HRS) \lor (RGD < HRD) \)
   - \( HRD = HRS = gateresistance \times 2 \)
   else
   - \( RGD = RGD - HRD; RGS = RGS - HRS \)

5. Data Matching

Data matching requires the drain-source current versus drain-source voltage curve in order to extract the necessary parameters for the HFET model. Table 1 lists the parameters used to model the CHFET in AIM-Spice. These are the parameters used in the following simulations in order to match with the measured data.

Two sets of devices (Honeywell and Motorola) are characterized in order to simulate with AIM-Spice. The parameters are extracted, simulated and then compared with the measured data. The Honeywell data includes two transistors, two p-channel and two n-channel transistors (PFET & FET, respectively). The Motorola data includes four transistors, a low temperature growth PFET, a regular PFET and two regular
NFETs. For each set of I-V curves, the difference between the measured and simulated values is calculated and plotted on a histogram. The mean (μ), median (u), and standard deviation (σ) are calculated. These parameters are used to ensure that most of the data matches within 10%.

<table>
<thead>
<tr>
<th>Table 1. HFET Model Parameters</th>
</tr>
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<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>D2</td>
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<tr>
<td>DELTA</td>
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<tr>
<td>D1</td>
</tr>
<tr>
<td>EPSI</td>
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<tr>
<td>ETA</td>
</tr>
<tr>
<td>ETA2</td>
</tr>
<tr>
<td>LAMBD</td>
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<tr>
<td>M</td>
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</tr>
<tr>
<td>RD</td>
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<td>SIGMA0</td>
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<tr>
<td>VTO</td>
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<tr>
<td>GAMMA</td>
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</tbody>
</table>

5.1. Honeywell Data

PFET and NFETs from Honeywell paper [7] are characterized in order to obtain the parameters for AIM-Spice. Figure 7 shows the histogram for the normalized difference between the measured and simulated parameters for each data point of the PFET. The histogram shows that there is the data that can differ by as much as 70% but the average error is 12%. The standard deviation, σ, is 22%. The large statistic values is due to the mismatch at V_{GS} = -1.0 V. This is due to the “low” Ids values, which enhance the error values. If the last two curves (V_{GS} = -1.25 V and V_{GS} = -1.0V) are removed, the resulting statistics are (μ = 2%, u = 2%, σ = 3%). Therefore, care must be taken when analyzing the statistics. Differences at higher V_{GS} values due not skew the statistics as significantly as differences at lower V_{GS} values. Figure 8 shows the histogram for the NFET. This set of data points matches better than the PFET. Most data points differ by 3% with an average of 6% but the spread is much less than in the case of the PFET. The maximum difference is 20% with σ = 6%.
5.3. Motorola Data

First, data matching occurs for a 0.5 x 10 \( \mu \)m PFET transistor using Motorola’s low temperature growth (LTG) [8]. The data has an average difference of 4% with a median value of 2%. Then a comparison between the simulated data and the measured I-V curve of a 0.3 x 10 \( \mu \)m PFET from Motorola is made [9]. The PFET does not match as closely as the NFET. These data values have an average difference of 8% and a median of 2%. But it is still less than the predefined criteria of an error difference less than 10%. Finally, a comparison is made between the simulated and measured I-V curves of 1 x 10 \( \mu \)m Motorola NFET [10]. The mean is 4% with a median of 2%.
6. Matlab Extraction Program

The extraction program is programmed using Matlab. The overall program is comprised of modular programs. Table 2 lists the function names and their operation. Figure 9 shows the result of some of the parameters extracted from DSET1. The measured and curve-fitted data are plotted for the user to visually determine if the data are match properly. The resulting extracted parameters are displayed at each step of the extraction process to ensure that the values are within reason. If not, the user can adjust the extraction process, by entering varying curve-fitting values, to achieve results within the error tolerance.

**Table 2. Extraction Program Functions**

<table>
<thead>
<tr>
<th>Matlab Program</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>compare.m</td>
<td>Compares measured and simulated data</td>
</tr>
<tr>
<td>extract.m</td>
<td>The main extraction program</td>
</tr>
<tr>
<td>extract1.m</td>
<td>Extract parameters from DSET1</td>
</tr>
<tr>
<td>extract2.m</td>
<td>Extract parameters from DSET2</td>
</tr>
<tr>
<td>extract3.m</td>
<td>Extract parameters from DSET3</td>
</tr>
<tr>
<td>opend1.m</td>
<td>Prompt user to load DSET1</td>
</tr>
<tr>
<td>opend2.m</td>
<td>Prompt user to load DSET2</td>
</tr>
<tr>
<td>opend3.m</td>
<td>Prompt user to load DSET3</td>
</tr>
<tr>
<td>usermenu.m</td>
<td>Create graphical user interface (GUI)</td>
</tr>
</tbody>
</table>

Figure 9. Extracted parameters from DSET1
7. Conclusion

A CHFET model parameter extraction program was developed for automating the process of obtaining device parameters from measured data. The program requires the use of Mathcad, Matlab, and Aim-Spice. The extraction of PFETs and NFETs from Honeywell and Motorola provided parameters that produced simulated results, which matched within 15% of the measured data. The accuracy of the match may be improved by going through further iterations with monitoring and input from the user during extraction.

8. References