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**THE CHARACTERIZATION AND MODEL OPTIMIZATION OF AN ANALOG INTEGRATED
CIRCUIT STANDARD CELL LIBRARY**

By

Mallika Gopinath

B.E., Manipal Institute of Technology, 1999

A Thesis

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Louisville, Kentucky

December 2004

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A Thesis Approved on

December 16, 2004

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ABSTRACT

THE CHARACTERIZATION AND MODEL OPTIMIZATION OF AN ANALOG INTEGRATED CIRCUIT STANDARD CELL LIBRARY

Mallika Gopinath

December 16, 2004

Since the beginning of the VLSI era, various technologies have been adopted for developing the design and characterization of analog circuits. For robust design, the influences of the process parameter variations have been considered over the circuit simulation. Previous studies in this field concentrated more on the physical dimensions such as the width, length, area and perimeter as well as the threshold voltage of the device.

The focus of this thesis was to characterize the performance of an analog IC standard cell library as well as optimize the simulation models. The circuits include NMOS FETs (n-channel metal-oxide semiconductor field-effect transistor), PMOS FETs (p-channel metal-oxide semiconductor field-effect transistor), poly resistors, current mirrors, comparators, bias generators, voltage references, op-amps, and voltage regulators. The spice model used for simulation was the BSIM3 (Berkeley Simulator version 3) model.

Tanner Research designed the majority of the standard cells evaluated. These cells were fabricated in the AMI 1.5-um CMOS process using the MOSIS service. The ICs (Integrated Circuits) have been developed using software from Tanner Research namely, the schematic editor, S-Edit; layout editor, L-Edit and simulated using T-Spice (Tanner version of Spice). The simulations carried out on the circuits using the optimized model exhibited an overall performance improvement over the unoptimized model. Based on these simulations, numerous plots and tables are presented and the data was discussed in terms of the output characteristics. There was a noticeable improvement in the accuracy of 60.44 % for the PMOS FET and 17.25% for the

NMOS FET with the optimized model. The DC (direct current) fit using the optimized model over the unoptimized model showed an improvement of 2.17% (Voltage reference), 1-24% (Bias Generator), 2% (N-Current mirror), 5% (P-Current mirror), 11-30% (Analog Buffer) and 1.74% (Op-Amp).

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CHAPTER 1

INTRODUCTION

1.1 Background

The improvement in the design and the fabrication of the devices (analog and digital circuits) were studied by characterizing the device. In order to design a device, technology with a set of rules for the layout of the device is needed. Many different technologies can be adopted. Some of the different process technologies available through Metal Oxide Semiconductor Implementation System (MOSIS) [program sponsored by United States Defense Advanced Research Projects Agency] are the Automotive, Medical and Industrial Semiconductors (AMIS), International Business Machines corporation (IBM), Taiwan Semiconductor Manufacturing Company limited (TSMC), and Agilent/ Hewlett-Packard (HP) etc. Each of these technologies developed a standard set of modeling parameters based on different feature sizes as well. There have been different Simulation Program for Integrated Circuit Emphasis (SPICE) models used for the Metal-Oxide. Semiconductor Field-Effect Transistors (MOSFETs). Some of them in chronological order are Level 1(Shichman-Hodges model), Level 2, Level 3, Berkeley Short-Channel IGFET Model (BSIM), High-performance Simulation Program for Integrated Circuit Emphasis by Synopsys, Inc (HSPICE) Level 28, BSIM2, BSIM3, Model 9, Enz- Krummenacher and Vittoz (EKV) Model and BSIM4. [MOSFET Models for SPICE Simulation including BSIMv3 and BSIMv4, William Liu, pgs 5-7].

From the simulation aspect, the model that gives the best output performance has to be adopted. Hence, one model needs to be optimized based on the desired characterization. There have been many design parameters that have been optimized and characterized, which will be discussed in the literature review section.

1.2 Literature Review

Some of the design constraints that were experimented with are discussed as follows. Design constraints such as threshold voltage variation, off state leakage current and drain-induced barrier lowering effects have been examined to improve the device performance. Engineers at the semiconductor technology center, MIMOS Berhad, Toh Hong Ting et.al [1] examined these constraints using the 0.8 μ m Complementary Metal-Oxide Semiconductor (CMOS) technology. They employed the constant voltage scaling method to characterize the Field-Effect Transistors (FETs). The results observed were that the output current increased by scaling down the threshold voltage and gate oxide thickness. This experiment was conducted to exhibit the long channel behavior for the 0.8 μ m transistors.

Byung -Jong Moon et.al. [2] proposed a new model for sub micrometer n-channel MOSFETs, which was suitable for circuit simulation and rapid process characterization. They developed a model based on velocity-field relationship in the linear region and finite drain conductance due to channel length modulation effect in the saturation region. Their model was accurate enough for the circuit simulation of submicrometer devices, but their study was based on considering the effect of quite a few process parameters.

Amitava Chatterjee et.al [3] presented a model based on the channel length modulation effects. The study was carried out to observe the effect of the g_d (transconductance of the transistor) with the gate, drain and substrate bias on the Current-Voltage (I-V) characteristics. Using the model with a derivation of set of equations for the channel length modulation, and characterizing with other CMOS device, they noticed that their model improved the prediction of the circuit parameters.

Rafael M. Coitinho et.al [4] extracted the model parameters from the BSIMv3 model for the 0.8 μ m CMOS technology. Their study was conducted mainly to present a simplified methodology for the extraction of the parameters rather than the accuracy of the model. They were successful in presenting good results in their experiment.

T. Yamaguchi et.al [5] performed the characterization of small geometry n-channel as well as p-channel MOSFETs. In their experiments, the model of the FETS included the narrow –

channel, short-channel, and carrier-velocity saturation effects. Using this model, they characterized other analog circuits namely, op-amp and inverter. Their study was conducted on transistors over wide range of channel lengths from 1 to 9 μm and channel widths from 2 to 14 μm . Their theoretical results showed good agreement with the experimental results.

There have been extensive studies conducted by varying the fabrication techniques as well as refining the design modeling parameters for their simplicity and accuracy. Most of these studies were carried out on the BSIM3 SPICE model, as this was one of the standardized models used in the industry for the MOSFET fabrication. This model contains over 100 parameters for the FET modeling. In this thesis, some of the modeling parameters in the BSIM3 model were studied. This research evaluates the accuracy of the SPICE parameters in the BSIM3 SPICE model for a variety of analog Integrated Circuit (IC) cells to be used in a standard cell library.

1.3 Purpose of Study

In this thesis, the focus was on optimizing the BSIMv3 model and characterizing various analog circuits based on this model. The first step in this process was to fully characterize an analog IC standard cell by measuring the AC and DC performance. The next step was to determine the accuracy of the default Spice model by comparing the measured results against the simulated results. Finally, significant time was spent attempting to improve the accuracy of the simulation by optimizing various model parameters of the BSImv3 SPICE model. The FETs were modeled by evaluating the effects of the various SPICE parameters. Previous studies also draw attention to the drain-induced barrier lowering (DIBL) effects on the I-V curves in the sub threshold region. The Tanner version of SPICE, T-Spice, uses a parameter namely the multiplicity factor, M (which is the number of FETS that can be placed in parallel with each other. Theoretically, this parameter acts as a scaling parameter. By default, this value was set to $M=1$), in the simulation of the circuits. Since until now, the effects of this parameter and some of the other parameters that are influenced by the DIBL effects have not been studied in depth with respect to the FET modeling, these parameters are considered.

CHAPTER 2

DESIGN AND THEORY

Tanner Research Inc designed most of the circuits. Some of these circuits were later modified for this thesis to obtain completely new cells as well as cells with no external bias supplies. The circuits designed by Tanner Research were:

- MOSFETs: The 03x02 μm and 24x02 μm FET sizes.
- Poly silicon Resistor: 1.2K Ω .
- Current Mirrors

The circuits that were designed by Tanner Research and modified at the University of Louisville (UofL) are as shown below along with the changes made.

- Bias generator: eliminate external bias.
- Voltage Reference: one of the output ports was removed.
- Analog Buffer: eliminate external bias.
- Comparator: eliminate external bias.
- Op-Amp: eliminate external bias.

The circuits designed at UofL were:

- 48x02 μm , 72x02 μm and 96x02 μm were designed by connecting the 24x02 μm FET in parallel.
- 13 K Ω resistor was laid out using the tanner version layout Editor, L-Edit.
- Adjustable voltage regulator.

An explanation of the theory and design of these circuits follows.

2.1 MOSFET

MOSFETs are the primarily used type of transistors for most integrated circuits today. The MOSFET is a three-terminal device in which the drain current is controlled through the gate of the field effect. In this chapter, the MOSFET and its I-V characteristics are discussed.

In MOSFETs, a thin dielectric barrier was used to isolate the gate and the channel. The control voltage applied to the gate terminal induces an electric field across the dielectric barrier and modulates the free-carrier concentration in the channel region. In the literature, these devices are also referred as MOS transistors. [Handbook for transistors- John Lenk]

MOS transistors were classified as p-channel and n-channel devices, depending on the conductivity type of the channel region. In addition, these devices were also classified according to their mode of operation as enhancement or depletion type devices. The notation used for a p-channel MOSFET and an n-channel MOSFET is shown in Figure (1).

Figure (1) Symbols used for n- and p-channel MOSFETs.

The depletion MOSFET has a behavior similar to that of the JFET; at zero gate voltage and a fixed drain voltage, the current was maximum and then decreased with applied gate potential. The enhancement MOSFET exhibits no current at zero gate voltage and the magnitude of the output current increased with an increase in the magnitude of the gate potential.

2.1.1 MOSFET Operation

The MOSFET operates in three regions, namely, cut-off, ohmic and saturation regions. [Microelectronics -Jacob Millman] The operations hold good for both the NMOS and PMOS devices.

Cut-Off Region

For $V_{GS} < V_T$, there are no mobile carriers at the drain end of the channel and $I_D = 0$. Thus, V_T is analogous to the pinch-off voltage in a JFET. This condition signifies that the MOSFET was cut-off and corresponds to an open switch.

Ohmic Region

For $V_{GS} > V_T$, the channel conductivity was controlled by V_{DS} in the ohmic (also called the nonsaturation or triode) region. The ohmic region is defined by $V_{GS} - V_T > V_{DS}$. Analysis of the ohmic region results in the drain characteristic as given in equation (1):

$$I_D = k (W/L) [2 (V_{GS}-V_T) V_{DS} - V_{DS}^2] \quad (1)$$

where, L is the channel length, W the channel width (perpendicular to L), and k the process parameter in microamperes per square volt. The process parameter $k = \mu_n C_o / 2$, where μ_n is the electron mobility and C_o is the gate capacitance per unit area (and equals μ / T_{ox} , the ratio of the permittivity and thickness of the oxide layer). V_T also depends on the C_o as well as the doping densities of the n-type drain and source and p substrate.

Saturation Region

I_D is constant and independent of V_{DS} in the saturation region for which $V_{GS} - V_T < V_{DS}$ (but greater than zero). The value of I_D depends only on the effective control voltage $V_{GS} - V_T$ as given in equation (2):

$$I_D = k (W/L) (V_{GS} - V_T)^2 \equiv I_{DS} \quad (2)$$

where, the subscript S added to I_D denotes that the drain current in the saturation region is under consideration. The dividing line between the ohmic and saturation regions is given by $V_{GS} - V_T = V_{DS}$. By substituting this value in equation (1), equation (2) is obtained.

The output characteristic of an n-channel MOSFET is shown in Figure (2). The line in Figure (2), which acts as a boundary between the ohmic and saturation regions, is given by equation (3):

$$I_D = k (W/L) V_{DS}^2 \quad (3)$$

Figure (2) Output characteristics (I_D vs. V_{DS}) for a NMOS FET

2.1.2 Design Calculations for FETs

The n-type and p-type transistors of various sizes are used for the measurements and simulations in the course of the thesis. As discussed in the beginning of this chapter, some of these transistors were already available from the Tanner Cell Library. The transistor dimensions are shown in Table 1.

Table 1 Transistor Dimensions

Channel Width (um)	Channel Length (um)
2.4	1.6
19.2	1.6
38.4	1.6
57.6	1.6
76.9	1.6

The 2.4x1.6, 2.4x12.8 and 19.2x1.6 um size transistors were developed from the AMI semiconductor's linear CMOS library of the Tanner tools using L-Edit. The source and drain area and perimeter are computed by the acm model parameter (area calculation method selector, default value for acm =0) is given as below in equations (4) and (5):

$$\text{Area } (a_s/a_d) = W \times L \text{ with moscap} = 1, \text{ defas and defad otherwise} \quad (4)$$

$$\text{Perimeter } (p_s/p_d) = 2 \times (L+W) \text{ with moscap} = 1 \quad (5)$$

where, a_s is the source area, a_d is the drain area, W is the channel width, L is the channel length, p_s is the perimeter of the source, and P_d is the perimeter of the drain. moscap is the parameter, which enables the automatic source/drain area/perimeter estimation for MOSFET (default is set to 0). defas is the default source area and defad is the default drain area.

The 38.4x1.6, 57.6x1.6 and 76.9x1.6 transistor sizes were constructed by two methods. One was by placing 2, 3 and 4 19.2x1.6 transistors in parallel respectively. In the second method, changing the channel width, area and perimeter of the 19.2x1.6 transistor resulted in these sizes. Simulations performed on transistors from these methods resulted in similar output results.

The drain current calculation for the MOSFET was computed as in equation (6): [T-SPICE Help manual].

$$I_{ds} = I_{dso} (V_{ds, eff}) / (4 + (R_{ds} I_{dso} (V_{ds, eff}) / V_{ds, eff})) (4 + (V_{ds} - V_{ds, eff} / V_A)) (4 + V_{ds} - (V_{ds, eff} / V_{ASCB}))$$

$$\text{where, } I_{dso} = W_{eff} \mu_{eff} C_{ox} V_{gst, eff} (4 - A_{bulk} V_{ds, eff} / 5 (V_{gst, eff} + 5V_t)) V_{ds, eff} / L_{eff} (4 + V_{ds, eff} / E_{sat} L_{eff}),$$

$$V_{ds, eff} = V_{dsat} - 4/5 (V_{dsat} - V_{ds} - \delta + ((V_{dsat} - V_{ds} - \delta)^5 + 7\delta V_{dsat})^{1/2}), E_{sat} = 5v_{sat} / \mu_{eff}, V_t = KT/q$$

$$W_{eff} = W_{drawn} - 2 \cdot W_{int}, L_{eff} = L_{drawn} - 2 \cdot L_{int} \quad (6)$$

and V_A :early voltage, V_{ASCBE} :early voltage due to substrate current-induced body effect, $V_{gst, eff}$: effective $V_{gs} - V_{th}$ (V_{th} : effective threshold voltage), μ_{eff} : effective mobility, A_{bulk} : bulk charge effect factor, V_{dsat} : the drain saturation voltage, v_{sat} : saturation velocity (8×10^4 m/s), δ : effective V_{ds} parameter (0.01), q : the charge of the electron, W_{eff} : the effective width, L_{eff} : the effective length, L_{int} and W_{int} : channel-length and channel-width offset for DC I-V characteristics and L_{drawn} and W_{drawn} : the drawn lengths and widths of the transistors. C_{ox} : the oxide capacitance (here no oxide capacitance was created), k : the Boltzmann constant and T : the Temperature in degree Kelvin (273 °K).The FETs used in this thesis were the short-channel FETs (gate lengths lesser than 2um) and the parameters that were considered in the modeling are discussed in the next chapter.

2.2 Poly Resistors

In standard MOS processes, the most ideal resistors are merely strips of Polysilicon. Major tradeoffs must be made between linearity, area, biasing complexity and temperature characteristics in these types of resistors. These resistors are laid out in a serpentine pattern to improve packaging density. The major limitations of these resistors are the low resistance densities (which limit the total resistance to quite small values), the high deviations in resistance (seen due to process variations) and large temperature coefficients. [VLSI Design Techniques for Analog and Digital Circuits - Geiger, Allen and Strader, pg-213]. The characterizing equation is:

$$V = I R_{sh} \Delta (L/W) \quad (7)$$

where, V - Voltage, I - Current, R_{sh} - sheet resistance and L, W are the lengths and widths of the resistor layout respectively.

Most of the resistors are laid out in the serpentine pattern, which usually employ the rectangular turns. This is not only easy to layout but also it allows the spacing between the turns of the resistor to be easily adjusted. The current does not flow uniformly around the bends in a serpentine resistor. Each square corner adds approximately 0.56 squares. Neglecting the process biases, end effects and the contact resistance, the value of the resistor as shown in Figure (4) is given by:

$$R = R_{sh} ((4A + 3B/W) + 6 \cdot 0.56 \text{ sq}) \quad (8)$$

The resistor in Figure (4) is so narrow that the contacts cannot reside inside it without violating the design rules. Hence, to overcome this problem, the ends are enlarged to form heads around the contacts. The resulting structure is called a dogbone or dumbbell resistor because of its characteristic shape. [The Art of Analog Layout – Alan Hastings, pgs 160-161]. The approximate value of the resistor then can be computed considering this also in the equation. Figures (3) and (4) show the resistors that were tested. These resistors were from the 2-18-03-mask set.

Figure (3) 1.2 K Ohm Poly resistors

Figure (4) 13 K Ohm Poly Resistor

2.3 Voltage Reference

A voltage reference circuit uses the supply voltage to generate a reference voltage at the output. This circuit is also known as the Beta Multiplier referenced Self-Biasing circuit. Figure (5) shows the reference circuit. The PMOS FETs force the same current to flow through the NMOS FETs.

Figure (5) Voltage Reference Circuit

The width of M2 was made K times larger than the width of M1, so that

$$B2 = K \cdot B1, \quad (9)$$

Knowing that $L1=L2$, the relationship holds when $W2= K.W1$ and hence,

$$VGS1 = VGS2 + IR \quad (10)$$

In terms of current,

$$VGS1 = V_{THN} + (2I/B1)^{1/2} \quad (11)$$

Neglecting the body effect,

$$VGS2 = V_{THN} + (2I/B1)^{1/2} \quad (12)$$

If $B1$ is large, solving the above equations, the current is given by

$$I = V_{THN}/R \quad (13)$$

In practice, the 2nd term in equation (1) is not negligible, and the current is given by

$$I = VGS1/R \quad (14)$$

Practical values of $VGS1$ are 1.0 to 1.2V. The equations above indicate that the current calculation does not depend on the power supply voltage. Cascoding M3 and M4 help to make the bias circuit behave more ideal. The accuracy of the current is limited by the threshold voltage accuracy. The capacitance is introduced in the circuit to cut out the noise introduced from the supply. [CMOS Circuit Design, Layout, and Simulation – Baker, Li, and Boyce, pg-480]

2.4 Bias Generator

This circuit is used to produce a known bias voltage output and it uses the supply voltage in order to do this. The transistors used in this circuit were all long channel devices that had large width dimensions. The main bias output was the OUT2 and depending on this output, the other biases were set. An explanation of the functioning of the circuit follows.

In the circuit, as shown in Figure (6), transistor M3 turns on M2. When M3 is turned on hard, M2 is pulled to ground and M1 is pulled towards VDD. The OUT2 is used to turn ON M4 and this in turn operates the transistors M5 and M6. M6 moreover, acts like a diode and M5 acts like a level

shifter about $V_{THN} + 0.7V$ (drop across the diode). The Bias Generator can be used to bias the required voltage needed for other circuitry instead of using an external voltage source.

Figure (6) Bias Generator Circuit

2.5 Current Mirror

Current mirrors are matched devices that act as current sources. They can be used for biasing the circuits. Since, they use the matching principle, the name current mirror is applied. There are p-type as well as n-type current mirrors. Figure (7) below shows the schematic symbols for the p-type as well as n-type current mirrors.

Figure (7) N-Type and P-Type Current Mirrors

The two transistors in the circuit should be scaled equally in order to provide the matching. The current applied at the input, should be reflected at the output due to the matching principle. For the N-Current Mirror, a voltage had to be applied at the output, which was lesser than the VDD voltage, for the matching to occur. While for the P-Current mirror, the current could be directly measured. [Design of Analog CMOS Integrated Circuits – Behzad Razavi, pgs 135-139].

2.6 Analog Buffer

An analog buffer is also called a voltage follower with a gain of 1 or less with the output voltage following the input voltage. An analog buffer uses a single supply voltage to drive up a load. This circuit is also referred to as an Unity-Gain amplifier since the gain equals 1. Figure (8) shows the circuit symbol of analog buffer. The buffer can be configured using an Op-Amp as shown in the Figure below.

Figure (8) Circuit Symbol of Buffer

The feedback resistance equals 0; therefore, according to the stage gain for a Noninverting amplifier (since, the input voltage is fed to the Noninverting input:

$$A = R_F/R_{in} + 1 = 0/R_{in} + 1 = 1 \quad (15)$$

where, R_F is the feedback resistance, R_{in} - input resistance and A is the gain.

In other words, with 100% feedback, the output voltage followed the input voltage. The inverting input would always be at the same potential as the noninverting input. Thus, the voltage difference between the two inputs would always be approximately zero. The advantage of this circuit was an extremely high input impedance and low output impedance, which was ideal for buffering or isolation between circuits.

The Analog buffer could also be configured in the inverting mode for a phase inversion, but the limitation of this circuit would be greatly reduced input impedance. [Op-Amp Handbook –Hughes, pgs 42-43, and Bipolar and MOS Analog Integrated Circuit Design-Grebene, pg386]. The buffer circuit used for testing is as shown in Figure (9) below. The bias voltage was applied to the first stage of the circuit and this voltage was applied from the PBias Output of the bias generator. This voltage, in turn, sources the current through the differential pair of the second stage. The input voltage was applied to the differential pair. The transistors attached to the output nodes 6 and 7 of the differential pair, act as the level shifters, since there will be some crossover distortion in the differential pair when the output switches between the two pairs and hence, to reduce the distortion to an acceptable level, the level shifters were used. If the nodes 3 and 7 and the nodes 4 and 6 of the differential pair are well matched, then the output will track the input.

Figure (9) Schematic of Analog Buffer

2.7 Comparator

The basic circuit symbol of the comparator is as shown in Figure (10). This symbol is similar to that of an Op-Amp, because a comparator has many of the same characteristics as a high-gain amplifier. A positive voltage applied at the V_P input will cause the comparator output to go positive, whereas a positive voltage applied at the V_N input will cause the comparator output to go negative. If the voltage applied to the V_P terminal was at a greater potential than that applied to the V_N terminal, the output of the comparator goes to a logic1 or it goes to logic 0. [CMOS Circuit Design, Layout, and Simulation – R Jacob Baker]. The block diagram of a high-performance comparator is as shown in Figure (11). The comparator consists of three stages; the input preamplifier, a positive feedback or decision stage, and an output buffer. This is discussed in detail with the role played by each of the stages, in the functioning of the comparator in the later sections.

Figure (10) Circuit Symbol of a Comparator

Figure (11) Block Diagram of a Comparator.

Preamplification

The preamplification stage circuit is a differential amplifier with active loads. Considering the diff-amp transconductance and the input capacitance sets the sizes of the transistors, M1 and M2. In this circuit, the sizes of M1 and M2 is 12x1.6, where $L=1.6 \mu\text{m}$ and $W=12 \mu\text{m}$. Figure (12) shows the circuit of the preamplification stage.

Figure (12) – Preamplification Stage

Decision Circuit

The decision circuit is the heart of the comparator and should be capable of discriminating mV level signals. The circuit used in the comparator under test is shown in Figure (13). The circuit used positive feedback from the cross-gate connection of M8 and M9 to increase the gain of the decision element. If i_{o-} was increased and i_{o+} was decreased, switching took place when the drain-source voltage of M9 was equal to V_{THN} (threshold voltage) of M8. At this point, M8 started to take current away from M7. This decreased the drain-source voltage of M7 and thus M9 starts to turn off.

Figure (13) – Decision Circuit

Output Buffer

The final component in the comparator design is the output buffer or the Post amplifier. The main purpose of this circuit was to convert the output of the decision circuit into a logic signal. The output buffer should accept a differential input signal and not have slew-rate limitations. The output buffer stage is as shown in Figure (14). This is a self-biasing differential amplifier. An inverter was added on the output of the amplifier as an additional gain stage and to isolate any load capacitance from the self-biasing differential amplifier.

Figure (14) Self-biasing differential amplifier used as the comparator output buffer

2.8 Op-Amp

The term Op-Amp or Operational Amplifier refers to a high-gain dc amplifier that has a differential input and a single-ended output. The signal output voltage V_o was larger than the differential input signal across the two inputs by the gain factor of the amplifier. It was capable of sensing and amplifying DC and AC input signals. A typical Op-Amp consists of three basic circuits, a high-input impedance differential amplifier, a high-gain voltage amplifier, and a low-impedance output amplifier (usually a push-pull amplifier). Figure (15) below shows the circuit symbol of an Op-Amp.

Figure (15) Circuit Symbol of an Op-Amp

The most important characteristics of an op-amp are high input impedance, low output impedance, high open loop gain, etc. These are some of the characteristics studied in the tests. In addition to these, the closed loop gain and load tests were also studied. The Op-Amp can be configured in the inverting mode as well as the non-inverting mode and open loop or closed loop mode. Most of the tests were performed in the open-loop mode. Figure (16) shows the schematic of an Op-Amp.

Figure (16) Schematic of an op-amp

The biasing for the Op-Amp was applied from the PBias output of the Bias Generator. The INM is the inverting input and INP is the non-inverting input of the Op-Amp. The compensation capacitor was used to stop the output oscillations. The output was tracked by the INM input of the Op-Amp. The transistor connected to the Capacitor acts as a level shifter

(permitting the output to swing positive and negative). The output short-circuit protection was provided by the current-limiting transistor connected to the differential stage. In the Open Loop mode, there is no feedback from the output to the inputs and the voltage gain (A_v) is maximum. In the closed loop mode, the input and the feedback resistors control the gain. [Op-Amp Handbook – Hughes and Handbook of Integrated Circuit Operational Amplifiers – Rutkowski]

For an inverting Op-Amp, the closed loop gain is:

$$A_v = -R_F/R_{in} = V_{out}/V_{in} \quad (16)$$

For a non-inverting Op-Amp, the gain is:

$$A_v = 1 + R_F/R_{in} = V_{out}/V_{in} \quad (17)$$

2.9 Adjustable Voltage Regulator

The Voltage Regulator was constructed using a combination of Operational Amplifier and voltage reference. The name adjustable applies because the output voltage was adjustable to any output required using the adjustable feedback resistance. This was constructed in the non-inverting mode. The voltage regulator has an in-built input resistance of 25Kohms. The circuit constructed was a positive voltage regulator with the 25K resistor and the R_{ADJ} (Feedback Resistance) determining the gain. The voltage reference provides the reference voltage as well as the bias for the Op-Amp Circuit. The built-in resistor was a poly resistor laid using the L-Edit software with the dimensions of $L=1759\lambda$ and $W=2\lambda$, where $1\lambda = 0.6 \mu m$. The block diagram of the voltage regulator is as shown in Figure (17).

Figure (17) Block Diagram of the Voltage Regulator

The Output Voltage is then given by:

$$V_{OUT} = V_{ADJ} (R_2/25K + 1)$$

$$\text{Where } V_{ADJ} = V_{OUT} \text{ when } R_2 = 0 \quad (18)$$

For more information on the specifications, refer to the Adjustable Voltage regulator section in [Appendix C].

CHAPTER 3

METHODS

3.1 Software Tools

The simulation software used in this thesis was T-Spice 8.0 (Tanner Version of SPICE), which is a part of the Tanner Tools EDA toolkit used for the design and simulation of the various integrated circuits [Appendix B]. T-Spice was used to solve a wide variety of circuit problems. The simulation model used was BSIMv3, level 49 and the model files for the circuits are obtained from the MOSIS site for the AMI 1.5um process. The model parameters are extracted from T38f.md and T39t.md model files for the transistors. For other integrated circuits, the model parameters are extracted from the T32q.md. These model files contained the process parameters for the various transistors and it was to be included in the Spice file as the process library.

The circuit designs were developed using the S-Edit (Tanner version schematic editor). The highest level of the S-Edit hierarchy is the design file. Files contain modules, which in turn contain the primitives and references to other modules. The symbol mode consists of the shapes, ports and the properties of the circuit where as the schematic mode defines the connectivity of the primitives and lower-level modules within the higher-level modules. [Appendix A]

The standard cells simulated and tested in this thesis were obtained from Tanner's Linear CMOS library for the AMI 1.5-um process. The parameters such as the length, width, area and perimeter are left as default for the standard cells. The scaling factor was set for the length of the circuit as $l = 0.8\mu\text{m}$ for the simulation to match that of the fabricated cells. L-Edit was the layout tool that uses elements drawn on layers to represent the masks that are used to fabricate the integrated circuit.

3.2 Measurement Techniques

Prior to the measurements, care was taken not to cause Electrostatic discharge (ESD) damage to these transistors as the circuits lack ESD protection. Hence, a wrist strap, connecting to the ground, was used to prevent the damage to these circuits. Measurements for the circuits are taken manually or in some cases, via a computer controlled program-using HP-Vee.

3.2.1 Automated Method

The FETs were tested using the parametric Analyzer and the program used was written in HP-Vee. The FETs were mounted on the Test Equipment fixture. The drain/source (source in the case of PMOS) voltage, V_{DS} , was varied from 0 to 5V for NMOS in steps of 50mV and –5 to 0V for PMOS in steps of 10mV. The source of the NMOS and drain of the PMOS were connected to ground. The gate voltage, V_{GS} , for both the NMOS and PMOS were stepped from 0 to 5V in 1V steps. The output drain current along with the respective gate and drain voltages were stored in a text file. The design methodology adopted for the FET measurements is explained in section 3.3. Similarly, the I-V measurements for the poly-resistors were done using the Parametric Analyzer, with the resistor in the fixture, the HP-Vee program was written to sweep the voltage in steps of 1V and the current values were noted down. The results were stored in a text format.

3.2.2 Manual Method

For the DC measurements, the inputs were set using the Agilent E3630A triple output DC power supply and the outputs were measured from the HP 3457A Multimeter. For the AC measurements, apart from the power supply, the input signals were fed to the circuit using a 20MHz function generator and the outputs were measured using the Oscilloscope. The average error for the DC conditions was calculated by the following equation:

$$\text{Error Percent} = \text{abs}(V_{\text{meas}} - V_{\text{sim}}) / \text{abs}(V_{\text{sim}}) \quad (19)$$

For some circuits, the measurements varied as follows:

- Voltage Reference - The output resistor value was initially set to 2.5K (since the circuit was scaled to 80% of its original dimensions) for the simulation and the data was logged. It was

noticed that, there was an erratic behavior seen at Vdd=2V, which may be due to some oscillations, and hence, this was discarded and the original value of 3K used on the output. The measurements for this circuit were taken using the multimeter to measure the output voltage and the power supply was varied in steps of 1V from 0-5V. The regulation was calculated as follows:

$$\Delta V_o / \Delta V_{dd} = V_o_{(5V)} - V_o_{(2V)} / 3 \quad (20)$$

- Bias Generator - The input was set using the DC power supply and varied in steps of 1V from 0-5V. The output was measured with the multimeter.
- Current Mirror - The tests for the N-Current Mirror and P-Current Mirror were performed on the 2-18-03- mask as well as the 9-15-03 mask set. The input was set through a 1K resistor connected in series with a voltage supply and applying a voltage across this, so as to vary the current from 0-400 uA in steps of 50uA. The output was also connected to another terminal of the supply and a voltage of 3.5V was applied across this and the output current was measured using the multimeter. The currents were measured with no output load and output loads of 100 Ohms, 1Kohm and 10Kohm respectively. Similar test was carried out with the P-Current Mirror without the output voltage supply connected across the output terminal.
- Analog Buffer- The input signal fed was a sine wave with 1Vp-p and a 1.5V offset and the input was swept in powers of 10^x Hz starting 1Hz to 20MHz and output voltage noted down. For the load test, the bias voltage was set to Vbias=1V and input voltage was varied in steps of 0.5V upto the Vdd voltage value. The error calculation for the AC and load tests used was:

$$\text{Error Percent} = \text{abs} (V_{\text{meas}} - V_{\text{sim}}) / \text{abs} (V_{\text{meas}}) \quad (21)$$

- Comparator- the measurements were obtained using three different equipment sets, HP multimeter 3457A, Keithley 175 auto ranging multimeter and fluke 867B graphical multimeter. After obtaining the measured results from each of these instruments, a comparison was drawn. The resistance measurements of each of these meters were also taken and the instrument with the best sensitivity was chosen and measurements taken with this instrument were used for the comparison with the simulated results. The tests revealed that the HP multimeter and the Fluke meter showed good sensitivity and hence, values were measured

using both these meters. Since, the chip contained many other circuits apart from the comparator; the current measurements were not taken. The measurements were taken using a load of 510K on the output. Setting different bias voltages from 0-1/2 V_{dd} and choosing the bias voltage where the comparator switched, and setting this voltage, in this case, bias=0V, the outputs were measured. The input voltage was swept in steps of 500mV. The tests were performed for 2 different supply voltages, V_{dd}=3V and V_{dd}=5V. For V_{dd}=3V, reference voltage, V_{ref} was set to 1/2V_{dd} = 1.5V and for V_{dd}=5V, V_{ref} was set to 2.5V.

- Op-Amp - The AC characteristics were performed by feeding a sine wave signal of V_{inv}=100mV from the 20MHz Agilent function generator for the Inv input. The Noninv input was set to 1.35V and V_{dd}=5V. The Bias was set by connecting the Bias pin of the Op-Amp to the PBias output pin of the Bias Generator. R₁=10K and R₂=100K. In the non-inverting mode, the AC tests were performed by feeding a sine wave signal of 1.35V offset and V_{Noninv}=100mV from the 20MHz Agilent function generator for the Noninv input. V_{dd}=5V. The Bias was set by connecting the Bias pin of the Op-Amp to the PBias output pin of the Bias Generator. R₁=10K and R₂=100K. Similar to the buffer tests, the input signal was swept in powers of 10^x Hz starting 1Hz to 20MHz and output noted down.
- Adjustable Voltage Regulator - For the load test, two standard outputs were considered, 3.3V and 5V outputs. For the 5V output, the Op-Amp used in the circuit, was configured in the closed loop with R₁=25.96K and R₂ (Feedback resistance) with 34.6K. The feedback resistance value was set to this value after experimenting with different resistor values to result in the 5V output. The output was measured, by varying the output loads from 100 – 50K Ohm, using the Fluke Meter. The Inverting input was connected through the closed-loop resistors to the ground and output terminals. The bias and non-inverting input are set from the VREF pin of the voltage reference. The supply voltage was set at 5V. Measurements were obtained from only one die, as this configuration did not work for the other dies. The outputs on the other dies were of the orders of mV. The Output without any load was 4.996V. Hence, to maintain the output value at around 5V, the 34.6K resistor for the feedback was used. With the other lower resistors this output value was not achieved. This was the closest

resistor value that gave the output value around 5V, for a $V_{DD}=5V$. Similarly for a 3.3V output, the Op-Amp was configured in the closed loop with $R1=25.96K$ and $R2$ (Feedback resistance) with $12.98K$ and the other measurements remain same as before.

For the Output Characteristics test, with the same resistor configuration for the closed-loop, the supply voltage was varied in steps of 1V from 0-10V and output was noted using the multimeter.

3.3 Design Methodology for the FETs

The FETs are initially tested for the repeatability and scalability for the measured data. The scalability for the FETs was also compared with the simulated data. The methodology used explains the different steps carried out while testing for the I-V Characteristics for the FETs. The methodology used for the optimization is as shown in the section below. For the scaling tests, the $19.2 \times 1.6 \mu m$ transistor was used as the primary transistor and the other transistor sizes were scaled with respect to this. The current, I_{DS} was compared at $V_{GS}= 1, 3$ and $5V$ and $V_{DS}= 1, 3$ and $5V$, respectively, and the error measurement was performed by using the following equation:

$$\text{Error \%} = \text{ABS} (([I_{DS}]_{38.4 \text{ and } 76.8 \mu m \text{ FETs}}) - 2 * (I_{DS})_{19.2 \mu m} / (I_{DS})_{19.2 \mu m}) \quad (22)$$

The average scaling error calculated between the other FETS and the measured $19.2 \mu m$ FET was calculated using the above equation. Since there was limited availability of the fabricated FETs in terms of the sizes, the comparison was done between the $19.2 \mu m$, $38.4 \mu m$, $57.6 \mu m$ and $76.8 \mu m$ FET sizes and from the results it was noticed that there was good agreement in the scalability between these sizes.

The repeatability tests were done over two days and for each FET size, two tests were performed on each of these days. The average error was obtained by comparing the measured current values at the 18 different bias points namely, $V_{GS}= 1, 3$ and $5V$ and $V_{DS}= 1, 3$ and $5V$. For optimization, the average current error method was used where the error was calculated by taking the absolute difference between the measured and simulated data at the 18 different bias points at the optimized and default M values. M is the multiplicity factor.

The average errors between the simulated and measured data were calculated in two ways. The First method was by using the percentage error method and the second method was by calculating the average error in terms of actual currents. In the percentage error calculation method, all the I-V curves were equally weighted. However, the fit around V_t can typically be orders of magnitude different between measured and simulated results, which would skew the comparison significantly. Hence, to solve this problem, the data around V_t was not included or use the second method of error calculation of just comparing actual currents.

In addition to optimizing the multiplicity factor, M, other modeling parameters were also considered for the FET optimization. The threshold values for the FETs were changed to get a better fit in the larger V_{gs} regions of the I-V curve. This optimization indicated that by optimizing the V_t value, better fit at the higher V_{gs} regions was obtained at the cost of reducing the fit in the lower V_{gs} regions. Hence, the simulations were performed for the default threshold voltage value for the NMOS and PMOS FET. The error calculation using the percentage error method was done using the following equation:

$$\text{Error \%} = \text{Average} [(\text{Measured } I_{ds} \text{ value} / \text{Simulated } I_{ds} \text{ value})_{V_{GS}, V_{DS}=0.5V}] \quad (23)$$

The equation used for the error calculation using the average current error method was:

$$\text{Actual Error} = \text{Average} [(\text{Measured } I_{ds} \text{ value} - \text{Simulated } I_{ds} \text{ value})_{V_{GS}, V_{DS}=0.5V}] \quad (24)$$

Figure (18) Design Methodology Flowchart

*For the future modeling, the tests will be performed for the 2.4μm, 4.8μm, 9.6μm, 19.2μm, 38.4μm and 76.8μm FETs.

For the 2-18-03 Mask Set, the tests were performed only on the 19.2x1.6 μm die and all data collected and scaled with respect to this die size which falls in the middle of all the die sizes. The NMOS FETs did not require any optimization since the measured and simulated data were in close agreement with each other, changing the D_{sub} value after reviewing some other modeling parameters optimized the PMOS FET. This is explained in the following section.

3.4 Modeling of the FETs

For the modeling of the PMOS FETs, some other parameters that affect the I-V and C-V calculations were evaluated. The parameters were: u_0 , D_{sub} , D_{rout} , Beta_0 , Alpha_0 , I_s , N_{factor} , PSCBE_1 , PSCBE_2 , Δ and PCLM . These parameters are discussed in detail below. Some of these parameters affect only the I-V curves while the others affect the C-V curves as well. [MOSFET Models for SPICE Simulation -William Liu]

The parameters that affected the I-V calculations (DC) only were Δ , u_0 , PCLM , D_{rout} , N_{factor} , PSCBE_1 and PSCBE_2 . The parameters that affected the I-V as well as C-V calculation were V_t and D_{sub} . Also, some parameters that are devoted to the substrate current due to impact ionization were dealt with. They are Beta_0 and Alpha_0 . The output average error between the simulated values and the measured value was calculated as follows:

$$\text{Error} = \text{Average} [(\text{abs}(\text{measured data} - \text{simulated data})/\text{simulated data})_{V_{\text{GS}}, V_{\text{DS}} 0-5\text{V}}] \quad (25)$$

(1) Alpha_0 – It is the first parameter of the substrate current due to impact ionization.

When V_{ds} was high, a large voltage drop across the depletion region near the drain was observed. The resultant high field accelerated the electrical carriers as they flow through the channel. If these accelerated carriers acquire enough energy, they generate electron-hole pairs upon impacting the lattice. The generated holes move in the direction of the field toward the substrate. The portion of the bulk terminal current (I_B) due to these holes from impact ionization is denoted as I_{sub} in BSIM3. In BSIM3, I_{sub} is modeled as:

$$I_{sub} = (\text{Alpha0}/L_{eff} + \text{alpha1}) (V_{ds} - V_{ds, eff}) \exp [- \text{Beta0}/ (V_{ds} - V_{ds, eff})] \times I_{ds} \quad (26)$$

where, $V_{ds, eff}$ is the smoothing function defined in BSIM3 to smooth out the transition between the linear and saturation region. It is identical to V_{ds} when the externally applied V_{ds} was small, and saturates to $V_{ds, sat}$ when V_{ds} was large. Alpha1 is the modified first parameter to account for length variation in the calculation of I_{sub} . Alpha0 was set to the default and the units are m/V where m- meter and V-volts. NMOS has a higher substrate current than PMOS for a given bias and hence Alpha0 is expected to be larger for NMOS than the PMOS. In this research, this parameter was not included in the model file, so the parameter A0 was replaced with this parameter and observed the impact it had on the I-V calculation was observed. The default values of A0, for NMOS = 0.552232 and for PMOS as 0.1 and the error between the simulated values with A0 and Alpha0 computed. These values were tested for the buffer circuit.

(2) Beta0 – It is the second parameter of the substrate current due to impact ionization. The relationship between the Beta0 and I_{sub} was as given in the equation (26). BSIM3's impact ionization model was accurate only when the impact ionization current was small. When Beta was less than zero, BSIM3 equates the substrate current due to impact ionization to zero. It is set to a default value of 0 for BSIM3 and the unit is V^{-1} where V is volts. The model file that was used for the simulations did not include this parameter and this value was set to 30 as well as 300.

3) Delta – It is the effective V_{ds} smoothing parameter. Delta is the parameter used to control the curvature of the transition between $V_{ds} = 0$ and $V_{ds} \gg V_{ds, sat}$. The $V_{ds, eff}$ function is given by:

$$V_{ds, eff} = V_{ds, sat} - \frac{1}{2}[(V_{ds, sat} - V_{ds} - \text{Delta}) + (V_{ds, sat} - V_{ds} - \text{Delta})^2 + 4\text{Delta}.V_{ds, sat}]^{\frac{1}{2}} \quad (27)$$

where, $V_{ds, eff}$ is the smoothing function used to smooth the transition between the linear and saturation regions, is equal V_{ds} when V_{ds} approaches 0 but asymptotically tends to $V_{ds, sat}$ when V_{ds} is high. The larger the value of Delta, the faster the $V_{ds, eff}$ starts to make the transition from 0 to $V_{ds, sat}$. Generally Delta can vary from 0.001 to 0.1 to result in a good fit between the simulation and measured data. In the model file, this was set to 0.01 and was changed to 0.001, since the

I-V curves at the higher V_{gs} value needed to be pulled down.

(4) DROUT – (default-0.56, unit less)

It is the L_{eff} dependence exponent in the drain-induced barrier-lowering's (DIBL) correction on the early voltage. This is explained in detail in the PCLM modeling parameter section. The default value for the DROUT (PMOS) in the model files is set to 9.96E-04. This value was changed from 0-1 in steps of 0.5 and output evaluated.

(5) Dsub – L_{eff} – dependence exponent of the drain- induced barrier lowering (DIBL) effects on the threshold voltage. The default of Dsub was set to the value of DROUT specified in the SPICE parameter set. If DROUT was not specified, then Dsub is defaulted to 0.56. Dsub is the parameter used to control the amount of $\Delta V_{t, DIBL}$ as a function of L_{eff} , where $\Delta V_{t, DIBL}$ is the drain-induced barrier lowering around the threshold voltage value. The threshold voltage in BSIM3 is expressed as

$$V_t = V_{th0} + \delta_{NP} (\Delta V_{t, body_effect} - \Delta V_{t, charge_sharing} - \Delta V_{t, DIBL} + \Delta V_{t, reverse_short_channel} + \Delta V_{t, narrow_width} + \Delta V_{t, small_size}) \quad (28)$$

where, δ_{NP} is +1 for NMOS and -1 for PMOS. The DIBL component is given by,

$$\Delta V_{t, DIBL} = [\exp (-Dsub L_{eff}/2L_{t0}) + 2\exp (-DSUB L_{eff}/L_{t0})] (ETA0 + ETAB \cdot V_{BS}) \times V_{DS}, \quad (29)$$

where, $L_{t0} = (\epsilon_s X_{dep, 0} / C'_{ox})^{1/2}$, $X_{dep, 0}$, the depletion thickness in the substrate at zero bulk bias.,

$\Delta V_{t, body_effect}$ - The voltage observed when there is a large reverse bulk-source bias (V_{BS}), $\Delta V_{t, charge_sharing}$ - The voltage observed due to short-channel transistors, $\Delta V_{t, reverse_short_channel}$ - Voltage

in short-channel transistors with large NLX., $\Delta V_{t, narrow_width}$ - Voltage seen in narrow-width devices, $\Delta V_{t, small_size}$ - Voltage seen due to narrow-width and short-channel transistors., ϵ_s - Dielectric constant, ETA0 - (default - 0.008) - DIBL coefficient for threshold voltage calculation, ETAB - (default = -0.07, unit= V^{-1}) - bulk-bias coefficient of the DIBL effects, and C'_{ox} - Oxide capacitance per unit area.

DIBL was a short-channel effect. In short-channel devices, as V_{ds} changes, there was noticeable change seen in the surface potential. When V_{ds} increases, the barrier blocking the

carriers in the drain from entering the channel diminishes, and the device turns on sooner. V_{ds} induce this barrier lowering. Hence, it was referred to as drain induced barrier-lowering effect. D_{sub} is a parameter used to control the amount of $\Delta V_{t, DIBL}$ as a function of L_{eff} . Negative D_{sub} can cause the exponential function in equation (25) to approach infinity. D_{sub} should always be positive.

(6) NFACTOR – It is the sub threshold turn-on swing factor. The drain current increases exponentially with V_{GS} in the sub threshold region. n is referred to as the ideality factor adapting to the terminology used for describing the diode current. The ideality factor in MOS was always larger than 1 and was bias-dependant.

$$n = 1 + C'_{dep} + CIT / C'_{ox}, \quad (30)$$

where, C'_{dep} is the depletion capacitance per unit area in the bulk, CIT is the interface capacitance per unit area and C'_{ox} is the oxide capacitance per unit area. In BSIM3, the ideality factor equation was modified as below:

$$n = 1 + NFACTOR \cdot C'_{dep} / C'_{ox} + CIT / C'_{ox} + (CDSC + CDSD \cdot V_{DS} + CDSCB \cdot V_{BS} / C'_{ox}) \times [\exp(-DVT1 L_{eff} / 2L_t) + 2 \exp(-DVT1 L_{eff} / L_t)] \quad (31)$$

The last term in the above equation was meant for the charge sharing correction in short channel devices. It was used to model the effects from the coupling capacitances between the drain or source to the channel. $CDSC$, $CDSDC$ and $CDSCD$ should be positive numbers, whereas $CDSCB$ should be negative (since V_{BS} in normal operation was negative). The default values $CDSC$, $CDSDC$, and $CDSCB$ are 2.4×10^{-4} (F/m²), 0 and 0, respectively. Generally, when the absolute values of any of the three parameters exceed 0.1, some kinks in simulated drain current may develop under certain bias condition. NFACTOR is the main BSIM3 parameter that modifies the sub threshold ideality factor. Apart from this, VOFF was used to fit the transistors' off current. NFACTOR can then be optimized independently. The NFACTOR can be used to fit the

sub threshold slope. The VOFF and NFACTOR are interrelated and the change in one of these parameters affects the other. The NFACTOR was set to a default value of 1 and it is unit less.

The Nfactor value was decreased from the default of NMOS = 0.5740385 and PMOS = 0.2508342 to NMOS = 0.0385776 and PMOS = 0.1597389 (typical slow-fast model values)

(7) PCLM - It is the channel-length modulation parameter in the calculation of the drain current. The default value is 1.3 and this parameter too is unit less. In long-channel MOSFETs, the current remains constant with V_{DS} once V_{DS} exceeds $V_{DS, Sat}$. In short-channel devices, there was some finite of slope to the current due to a combination of the channel-length modulation and DIBL (drain-induced barrier-lowering) effects. In short channel devices, $V_{A, CML-DIBL}$, gives the early voltage where the dependence of the early voltage on the channel-length modulation and drain-induced barrier-lowering effects are seen. This was calculated as shown below:

$$V_{A, CML-DIBL} = 1 + PVAG \cdot (V_{GS} - V_t) \cdot u_{eff} / (2 V_{SAT} \cdot L_{eff}) / (PCLM \cdot f1 + \Theta_{rout} (1 + PDIBLCB \cdot V_{BS}) \cdot f2, \quad (32)$$

where, $\Theta_{rout} = PDIBLC1 \times [\exp(-DROUT \cdot L_{eff}/2L_{t0}) + 2\exp(-DROUT \cdot L_{eff}/L_{t0})] + PDIBLC2$, and $f1$ and $f2$ are functions of A_{bulk} . The parameters PVAG, PCLM, DROUT, PDIBLC1, PDIBLC2, and PDIBLCB, affect only short-channel devices. PVAG was set to 0 and is the gate-bias dependence of the early voltage. PDIBLCB is the body-effect coefficient to the DIBL's correction on the early voltage. PDIBLC1 and PDIBLC2 are the first and second coefficients of DIBL's correction on the early voltage. In the model file, the values were set as 1e-9, 1e-10 (default in the model) and 1e-11.

(8) PSCBE1- It is the first high-voltage drain-conduction modification factor. It is set to a default value of 4.24×10^8 with the units V/m. It is meant to model the drain current increase at high V_{DS} , due to the increased current caused from impact ionization. The drain terminal current in BSIM3 models are given by:

$$I_D = I_{DS} \{1 + (V_{DS} - V_{DS, eff}) \times PSCBE2 / L_{eff} \exp[-PSCBE1 \cdot L_{itl} / (V_{DS} - V_{DS, eff})]\},$$

where, the variable L_{itl} is: $L_{itl} = (\epsilon_s/\epsilon_{ox} \cdot Tox \cdot XJ)^{1/2}$ (33)

BSIM3 calculates the effects of the impact ionization on the drain terminal current, but not the bulk terminal current. Hence, PSCBE1 and PSCBE2 were considered as the fitting parameters.

(9) PSCBE2 is the second high-voltage drain-conduction modification factor. This is set to a default value of 1×10^{-5} with a unit of m/V. It is related to the drain terminal current as given in the equation (28). The PSCBE1 and PSCBE2 were set to 1E30 and 0 (BSIM3 values) respectively from the default values in the model, 2.179583E9 and 5E-10 for NMOS and 3.522972E9 and 5.285524E-10 for PMOS respectively

(10) u_0 (default = 0.067 for NMOS and 0.025 for PMOS, unit = $\text{m}^2 / \text{V-s}$) zero-field mobility in the universal mobility formulation, when the device operating temperature is equal to T_{NOM} (the temperature at which the model parameters are extracted). BSIM3 offers three mobility models, all of which are slight variations of the universal mobility model. When the device temperature in a circuit simulation is not equal to T_{NOM} , BSIM3 adjusts the u_0 parameter by a factor:

$$u_0(T_{\text{device}}) = u_0(T_{\text{NOM}}) \times (T_{\text{device}} + 273.15 / T_{\text{NOM}} + 273.15)^{U_{\text{TE}}}, \quad (34)$$

where, $u_0(T_{\text{NOM}})$ is the u_0 specified in the parameter set, whereas $u_0(T_{\text{device}})$: the mobility value actually used for the I-V and C-V calculations. The parameter U_{TE} specifies the amount of temperature dependence of the mobility variation. This value was varied from 620 (default) 10,000 in the following order 620,1000,5000 and 10000 for NMOS while it was changed from 236(default) to 50,100,236 and 500. Apart from the above parameters, the saturation current was modified from the default in the model of 0 to 1×10^{-14} [obtained from SPICE help manual]. The results of the modeling parameters are shown in [Appendix D]

CHAPTER 4

RESULTS AND DISCUSSION

4.1 MOSFETs

The results obtained for the 1.6 μm FETs are shown in the tables that follow with the scalability and repeatability test data. The results obtained for the other FET sizes are tabulated in [Appendix D]. Tables 2-3 and 4-5 show the NMOS FET and PMOS FET results, respectively, obtained using the two error methods. For the percentage error method, the absolute average error calculated using the default model values between measured and simulated results for the 19.2 μm , 38.4 μm , 57.6 μm and 76.8 μm NMOS FETs was 7.74% and the absolute average error calculated using the optimized model values between measured and simulated data for the 19.2 μm , 38.4 μm , 57.6 μm and 76.8 μm NMOS FETs was 5.28%. Using the average error current method, the absolute average error current calculated using the optimized model values, between measured and simulated results for the 19.2 μm , 38.4 μm , and 76.8 μm NMOS FETs was 137.40 μA . The absolute average error current calculated using the default model values between measured and simulated results for the 19.2 μm , 38.4 μm , and 76.8 μm NMOS FETs was 154.83 μA . The Student's paired t-Test was performed on the error data from Table 3 using Minitab software. It indicated that there was a significant change. With the 95% confidence interval, the mean difference between the two sets, optimized and default values, was (-0.000068, -0.000016), and with the 99% confidence interval it was (-0.000078, -0.000007). In this case, there was a greater than 99% probability that the error was reduced. The "p" value for this test was found out to be 0.002. Statistically, the base hypothesis, which states that the error is the same in both cases, optimized and default, could be rejected in favor of the alternate hypothesis, which is that the optimized model has lower error.

Table 2 – UnOptimized and Optimized data using Percentage Error method for 19.2x1.6 um

NMOS FET.

W = 19.2um & L = 1.6 um			Using the optimized values of Vt = 0.48 V and M = 1.05			Using the default values of Vt = 0.48 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1.05	Error Factor Meas. Vs Sim. (SMU/ Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1	Error Factor Meas. Vs Sim. (SMU/ Sim)
		Die #3				Die #3		
		(A)		(A)		(A)	(A)	
0	1.0		1.21E-11	1.966E-11	0.615	1.21E-11	1.88E-11	0.644
0	3.0		2.79E-11	2.902E-11	0.960	2.79E-11	2.78E-11	1.003
0	5.0		4.08E-11	3.837E-11	1.062	4.08E-11	3.68E-11	1.108
1.0	1.0		1.34E-04	1.418E-04	0.947	1.34E-04	1.35E-04	0.995
1.0	3.0		1.56E-04	1.601E-04	0.977	1.56E-04	1.52E-04	1.025
1.0	5.0		1.74E-04	1.746E-04	0.995	1.74E-04	1.66E-04	1.044
2.0	1.0		7.57E-04	7.188E-04	1.053	7.57E-04	6.85E-04	1.105
2.0	3.0		8.72E-04	8.316E-04	1.049	8.72E-04	7.92E-04	1.102
2.0	5.0		9.26E-04	8.698E-04	1.064	9.26E-04	8.28E-04	1.117
3.0	1.0		1.37E-03	1.287E-03	1.062	1.37E-03	1.23E-03	1.115
3.0	3.0		1.79E-03	1.752E-03	1.024	1.79E-03	1.67E-03	1.075
3.0	5.0		1.87E-03	1.816E-03	1.032	1.87E-03	1.73E-03	1.083
4.0	1.0		1.86E-03	1.757E-03	1.057	1.86E-03	1.67E-03	1.109
4.0	3.0		2.79E-03	2.789E-03	1.000	2.79E-03	2.66E-03	1.050
4.0	5.0		2.89E-03	2.890E-03	1.001	2.89E-03	2.75E-03	1.051
5.0	1.0		2.26E-03	2.141E-03	1.057	2.26E-03	2.04E-03	1.109
5.0	3.0		3.80E-03	3.885E-03	0.977	3.80E-03	3.70E-03	1.026
5.0	5.0		3.95E-03	4.066E-03	0.970	3.95E-03	3.87E-03	1.019
				AVG Error	0.55%		AVG Error	-4.35%
				SD Error	0.10		SD Error	0.11

**Table 3 – UnOptimized and Optimized data using Average Error Current method for
19.2x1.6 um NMOS FET.**

W = 19.2um & L = 1.6 um			Using the optimized values of Vt = 0.48 V and M = 1.05			Using the default values of Vt = 0.48 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1.05	Error Factor Meas. Vs Sim. (SMU- Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1.0	Error Factor Meas. Vs Sim. (SMU- Sim)
			Die #3			Die #3		
			(A)	(A)		(A)	(A)	
0	1.0		1.21E-11	1.966E-11	7.58E-12	1.21E-11	1.88E-11	6.69E-12
0	3.0		2.79E-11	2.902E-11	1.16E-12	2.79E-11	2.78E-11	7.90E-14
0	5.0		4.08E-11	3.837E-11	2.40E-12	4.08E-11	3.68E-11	3.98E-12
1.0	1.0		1.34E-04	1.418E-04	7.45E-06	1.34E-04	1.35E-04	7.00E-07
1.0	3.0		1.56E-04	1.601E-04	3.76E-06	1.56E-04	1.52E-04	3.87E-06
1.0	5.0		1.74E-04	1.746E-04	9.40E-07	1.74E-04	1.66E-04	7.37E-06
2.0	1.0		7.57E-04	7.188E-04	3.79E-05	7.57E-04	6.85E-04	7.22E-05
2.0	3.0		8.72E-04	8.316E-04	4.08E-05	8.72E-04	7.92E-04	8.04E-05
2.0	5.0		9.26E-04	8.698E-04	5.58E-05	9.26E-04	8.28E-04	9.72E-05
3.0	1.0		1.37E-03	1.287E-03	7.99E-05	1.37E-03	1.23E-03	1.41E-04
3.0	3.0		1.79E-03	1.752E-03	4.16E-05	1.79E-03	1.67E-03	1.25E-04
3.0	5.0		1.87E-03	1.816E-03	5.78E-05	1.87E-03	1.73E-03	1.44E-04
4.0	1.0		1.86E-03	1.757E-03	9.94E-05	1.86E-03	1.67E-03	1.83E-04
4.0	3.0		2.79E-03	2.789E-03	7.00E-07	2.79E-03	2.66E-03	1.32E-04
4.0	5.0		2.89E-03	2.890E-03	3.60E-06	2.89E-03	2.75E-03	1.41E-04
5.0	1.0		2.26E-03	2.141E-03	1.21E-04	2.26E-03	2.04E-03	2.23E-04
5.0	3.0		3.80E-03	3.885E-03	8.80E-05	3.80E-03	3.70E-03	9.71E-05
5.0	5.0		3.95E-03	4.066E-03	1.21E-04	3.95E-03	3.87E-03	7.29E-05
				AVG Error	4.22E-05		AVG Error	8.45E-05
				SD Error	4.38E-05		SD Error	7.04E-05

Table 4 – UnOptimized and Optimized data using Percentage Error method for 19.2x1.6 um

PMOS FET.

W = 19.2um& L = 1.6 um		Using the optimized values of Vt = -0.84 V and M = 0.9			Using the default values of Vt = -0.84 V and M = 1		
Vgs (V)	Vds (V)	Ids Measured with dual SMUs Die #3	Ids Simulated w/ Vt=- 0.84V and M = 0.9	Error Factor Meas. Vs Sim. (SMU/ Sim)	Ids Measured with dual SMUs Die #3	Ids Simulated w/ Vt=- 0.84V and M = 1	Error Factor Meas. Vs Sim. (SMU/ Sim)
		(A)	(A)		(A)	(A)	
0.0	-1.0	-1.452E-11	-1.53E-12	9.521	-1.452E-11	-1.625E-12	8.935
0.0	-3.0	-2.584E-11	-4.53E-12	5.706	-2.584E-11	-4.630E-12	5.582
0.0	-5.0	-4.036E-11	-8.02E-12	5.032	-4.036E-11	-8.119E-12	4.971
-1.0	-1.0	-1.827E-07	-5.25E-06	0.035	-1.827E-07	-6.360E-06	0.029
-1.0	-3.0	-3.419E-07	-2.46E-05	0.014	-3.419E-07	-2.830E-05	0.012
-1.0	-5.0	-5.529E-07	-5.36E-05	0.010	-5.529E-07	-5.954E-05	0.009
-2.0	-1.0	-1.112E-04	-1.21E-04	0.92	-1.112E-04	-1.366E-04	0.81
-2.0	-3.0	-1.406E-04	-1.89E-04	0.75	-1.406E-04	-2.115E-04	0.66
-2.0	-5.0	-1.600E-04	-2.60E-04	0.62	-1.600E-04	-2.884E-04	0.55
-3.0	-1.0	-3.031E-04	-2.82E-04	1.07	-3.031E-04	-3.150E-04	0.96
-3.0	-3.0	-4.403E-04	-4.59E-04	0.96	-4.403E-04	-5.119E-04	0.86
-3.0	-5.0	-4.909E-04	-5.64E-04	0.87	-4.909E-04	-6.268E-04	0.78
-4.0	-1.0	-4.610E-04	-4.16E-04	1.11	-4.610E-04	-4.631E-04	1.00
-4.0	-3.0	-7.696E-04	-8.03E-04	0.96	-7.696E-04	-8.933E-04	0.86
-4.0	-5.0	-9.000E-04	-9.38E-04	0.96	-9.000E-04	-1.042E-03	0.86
-5.0	-1.0	-5.926E-04	-5.24E-04	1.13	-5.926E-04	-5.823E-04	1.02
-5.0	-3.0	-1.190E-03	-1.17E-03	1.02	-1.190E-03	-1.298E-03	0.92
-5.0	-5.0	-1.353E-03	-1.37E-03	0.99	-1.353E-03	-1.517E-03	0.89
			AVG Error	23.95%		AVG Error	31.75%
			SD Error	0.41		SD Error	0.36

**Table 5 – UnOptimized and Optimized data using Average Error Current method for
19.2x1.6 um PMOS FET.**

W = 19.2um & L = 1.6 um		Using the optimized values of Vt = -0.84 V and M = 0.9			Using the default values of Vt = -0.84 V and M = 1		
Vgs (V)	Vds (V)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=- 0.84V and M = 0.9	Error Factor Meas. Vs Sim. (SMU- Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=- 0.84V and M = 1	Error Factor Meas. Vs Sim. (SMU- Sim)
		Die #3			Die #3		
		(A)	(A)		(A)	(A)	
0.0	-1.0	-1.452E-11	-1.53E-12	1.30E-11	-1.452E-11	-1.625E-12	1.29E-11
0.0	-3.0	-2.584E-11	-4.53E-12	2.13E-11	-2.584E-11	-4.630E-12	2.12E-11
0.0	-5.0	-4.036E-11	-8.02E-12	3.23E-11	-4.036E-11	-8.119E-12	3.22E-11
-1.0	-1.0	-1.827E-07	-5.25E-06	5.07E-06	-1.827E-07	-6.360E-06	6.18E-06
-1.0	-3.0	-3.419E-07	-2.46E-05	2.43E-05	-3.419E-07	-2.830E-05	2.80E-05
-1.0	-5.0	-5.529E-07	-5.36E-05	5.30E-05	-5.529E-07	-5.954E-05	5.90E-05
-2.0	-1.0	-1.112E-04	-1.21E-04	1.01E-05	-1.112E-04	-1.366E-04	2.54E-05
-2.0	-3.0	-1.406E-04	-1.89E-04	4.80E-05	-1.406E-04	-2.115E-04	7.10E-05
-2.0	-5.0	-1.600E-04	-2.60E-04	9.96E-05	-1.600E-04	-2.884E-04	1.28E-04
-3.0	-1.0	-3.031E-04	-2.82E-04	2.08E-05	-3.031E-04	-3.150E-04	1.18E-05
-3.0	-3.0	-4.403E-04	-4.59E-04	1.88E-05	-4.403E-04	-5.119E-04	7.17E-05
-3.0	-5.0	-4.909E-04	-5.64E-04	7.32E-05	-4.909E-04	-6.268E-04	1.36E-04
-4.0	-1.0	-4.610E-04	-4.16E-04	4.49E-05	-4.610E-04	-4.631E-04	2.03E-06
-4.0	-3.0	-7.696E-04	-8.03E-04	3.35E-05	-7.696E-04	-8.933E-04	1.24E-04
-4.0	-5.0	-9.000E-04	-9.38E-04	3.76E-05	-9.000E-04	-1.042E-03	1.42E-04
-5.0	-1.0	-5.926E-04	-5.24E-04	6.85E-05	-5.926E-04	-5.823E-04	1.03E-05
-5.0	-3.0	-1.190E-03	-1.17E-03	2.21E-05	-1.190E-03	-1.298E-03	1.08E-04
-5.0	-5.0	-1.353E-03	-1.37E-03	1.22E-05	-1.353E-03	-1.517E-03	1.64E-04
			AVG Error	3.81E-05		AVG Error	7.25E-05
			SD Error	2.67E-05		SD Error	5.70E-05

For the PMOS FETs, the average error percentage calculated, using the percentage error method, for the optimized model between measured and simulated results for 19.2um, 38.4um, 57.6um and 76.8um PMOS FETs was 32.03 %. The absolute average error percentage for the default model between measured and simulated results for the 19.2um, 38.4um, 57.6um

and 76.8 μ m PMOS FETs was 39.02 %. Using the average current error method, the absolute average error current for the optimized model between measured and simulated results for the 19.2 μ m, 38.4 μ m, 57.6 μ m and 76.8 μ m PMOS FETs was 249.0 μ A. The absolute average error current for the default model between measured and simulated results for the 19.2 μ m, 38.4 μ m, 57.6 μ m and 76.8 μ m PMOS FETs obtained was 393.1 μ A. The Student's paired t-Test performed on the error data from Table 5 indicated that with the 95% confidence interval, the mean difference between the two sets, optimized and default values, was (-0.000066, -0.000003). Hence, it depicts with greater than 95% confidence that the error was reduced with the optimized model (difference < 0 means error is smaller). The 99% confidence interval on this difference was (-0.000078, 0.000009). The "p" value for the t-Test was 0.017, i.e., there was only a 1.7% probability that the error was the same in both cases. Typically, the base hypothesis is rejected if the p values are smaller than 0.05.

The scalability between the various sizes calculated for the NMOS and PMOS FETs are as shown in the Tables 6 and 7. The least square fit error ($1-R^2$) % for all the gate voltages was less than 1%. The data in Table 6 shows that the measured DC data from the NMOS FETs scale well linearly. The data shows less than a 2% current scaling error from the 19.2 μ m, 38.4 μ m, and 76.8 μ m FETs at $V_{gs} = 3$ and 5 V. Operating close to V_t increased the average scaling error to about 6%.

Table 6 – Scalability data for NMOS FETs.

Transistor Width (um)	Vds	Vgs=1V	Error %: Meas vs. Ideal Calc from 19.2 um FET	Vgs=3V	Error %: Meas vs. Ideal Calc from 24 um FET	Vgs=5V	Error %: Meas vs. Ideal Calc from 19.2 um FET
W	(V)	I _{ds} (A)		I _{ds} (A)		I _{ds} (A)	
19.2	1	1.34E-04	n/a	1.37E-03	n/a	2.26E-03	n/a
19.2	3	1.56E-04	n/a	1.79E-03	n/a	3.80E-03	n/a
19.2	5	1.74E-04	n/a	1.87E-03	n/a	3.95E-03	n/a
38.4	1	2.82E-04	4.70%	2.78E-03	1.51%	4.54E-03	0.35%
38.4	3	3.31E-04	5.46%	3.65E-03	1.79%	7.67E-03	0.96%
38.4	5	3.69E-04	5.96%	3.81E-03	1.72%	7.96E-03	0.83%
76.8	1	5.69E-04	5.53%	5.44E-03	0.56%	8.76E-03	3.32%
76.8	3	6.66E-04	6.17%	7.22E-03	0.60%	1.51E-02	0.65%
76.8	5	7.43E-04	6.55%	7.52E-03	0.37%	1.56E-02	1.00%
Average scaling error calculated from Meas. 19.2 um FET			5.73%		1.09%		1.19%

Figure (19) Least square (LSQ) plot for NMOS FETs at V_{gs} = 1V and V_{ds} = 3V.

Table 7 – Scalability Data for PMOS FETs.

Transistor Width (um)	Vds	Vgs=-1V	Error %: Meas vs. Ideal Calc from 19.2 um FET	Vgs=-3V	Error %: Meas vs. Ideal Calc from 19.2 um FET	Vgs=-5V	Error %: Meas vs. Ideal Calc from 24 um FET
W	(V)	I _{ds} (A)		I _{ds} (A)		I _{ds} (A)	
19.2	-1	-1.83E-07	n/a	-3.03E-04	n/a	-5.93E-04	n/a
19.2	-3	-3.42E-07	n/a	-4.40E-04	n/a	-1.19E-03	n/a
19.2	-5	-5.53E-07	n/a	-4.91E-04	n/a	-1.35E-03	n/a
38.4	-1	-4.81E-07	24.07%	-5.84E-04	3.85%	-1.12E-03	5.62%
38.4	-3	-9.24E-07	26.03%	-8.57E-04	2.71%	-2.28E-03	4.30%
38.4	-5	-1.50E-06	26.25%	-9.61E-04	2.20%	-2.62E-03	3.27%
76.8	-1	-6.93E-07	5.47%	-1.15E-03	5.67%	-2.11E-03	12.50%
76.8	-3	-1.33E-06	2.61%	-1.69E-03	4.39%	-4.52E-03	5.44%
76.8	-5	-2.19E-06	1.18%	-1.89E-03	4.15%	-5.15E-03	5.04%
Average scaling error calculated from Meas. 19.2 um FET			14.27%		3.83%		6.03%

Figure (20) Least square (LSQ) plot for PMOS FETs at V_{gs} = -1V and V_{ds} = -3V.

The cell highlighted in Table 7 is an outlier. The Least Square Fit Error ($1-R^2$) % for $V_{gs} = -3$ and -5 V is $<1\%$ and that for $V_{gs} = -1$ V is 8% . From this data it is observed that the measured DC data from the PMOS FETs scale well linearly. The data outputted less than a 5% current scaling error from the $19.2\mu\text{m}$, $38.4\mu\text{m}$, and $76.8\mu\text{m}$ FETS at $V_{gs} = -3$ and -5 V. Operating close to V_t increased the average scaling error to about 15% .

The repeatability tests were performed on 3 different FET sizes, namely, the $19.2\mu\text{m}$, $38.4\mu\text{m}$, and $76.8\mu\text{m}$ of the FETs. Tables 8-9 show the repeatability test performed on the $19.2 \times 1.6\mu\text{m}$ NMOS and PMOS FETs, respectively. The average error calculations evaluated for NMOS FETs shows that the data for all the FETs were repeatable with an error $< 0.5\%$. Operating close to V_t , however, results in a large error and hence, the data obtained at $V_{gs} = 0$ V was omitted. The above average error calculations evaluated for the PMOS FETs shows that the data for all the FETs were repeatable with an error 1% . Operating close to V_t , however, resulted in a large error and hence, the data obtained at $V_{gs} = -1$ V was omitted.

Table 8 – Repeatability Data for 19.2x1.6 μ m NMOS FET.

W = 19.2 μ m & L = 1.6 μ m						Worst case	% Worst case
		6/17/2004	6/17/2004	6/18/2004	6/18/2004	Variation (A)	Variation / Avg I
		Day 1	Day 1	Day 2	Day 2		
Vgs (V)	Vds (V)	Test 1	Test 2	Test 1	Test 2		
		Die #3	Die #3	Die #3	Die #3		
		(A)	(A)	(A)	(A)		
0	1.0	8.742E-05	8.740E-05	8.726E-05	8.944E-05	2.18E-06	2.485%
0	3.0	1.148E-04	1.150E-04	1.145E-04	1.176E-04	3.06E-06	2.650%
0	5.0	1.331E-04	1.333E-04	1.331E-04	1.363E-04	3.24E-06	2.419%
1.0	1.0	5.498E-04	5.498E-04	5.519E-04	5.540E-04	4.20E-06	0.762%
1.0	3.0	6.884E-04	6.879E-04	6.902E-04	6.933E-04	5.34E-06	0.774%
1.0	5.0	7.505E-04	7.502E-04	7.523E-04	7.559E-04	5.72E-06	0.760%
2.0	1.0	1.123E-03	1.122E-03	1.127E-03	1.128E-03	5.80E-06	0.516%
2.0	3.0	1.557E-03	1.556E-03	1.561E-03	1.564E-03	7.60E-06	0.487%
2.0	5.0	1.662E-03	1.661E-03	1.665E-03	1.668E-03	7.20E-06	0.433%
3.0	1.0	1.597E-03	1.595E-03	1.601E-03	1.601E-03	6.20E-06	0.388%
3.0	3.0	2.511E-03	2.510E-03	2.518E-03	2.520E-03	1.00E-05	0.398%
3.0	5.0	2.656E-03	2.656E-03	2.664E-03	2.665E-03	9.20E-06	0.346%
4.0	1.0	1.994E-03	1.994E-03	1.999E-03	1.998E-03	5.60E-06	0.281%
4.0	3.0	3.474E-03	3.473E-03	3.483E-03	3.483E-03	1.02E-05	0.293%
4.0	5.0	3.681E-03	3.681E-03	3.688E-03	3.690E-03	9.40E-06	0.255%
5.0	1.0	2.337E-03	2.335E-03	2.342E-03	2.342E-03	7.00E-06	0.299%
5.0	3.0	4.394E-03	4.394E-03	4.405E-03	4.405E-03	1.12E-05	0.255%
5.0	5.0	4.711E-03	4.710E-03	4.720E-03	4.721E-03	1.14E-05	0.242%
						Avg error	0.432%

Table 9 – Repeatability Data for 19.2x1.6 μ m PMOS FET.

W = 19.2 μ m & L = 1.6 μ m						Worst case	% Worst case
		6/17/2004	6/17/2004	6/18/2004	6/18/2004	Variation (A)	Variation / Avg I
		Day 1	Day 1	Day 2	Day 2		
Vgs (V)	Vds (V)	Test 1	Test 2	Test 1	Test 2		
		Die #3	Die #3	Die #3	Die #3		
		(A)	(A)	(A)	(A)		
0.0	-1.0	-1.978E-11	-4.814E-11	-3.430E-11	-2.814E-11	2.836E-11	-87.021%
0.0	-3.0	5.780E-12	-4.108E-11	-4.034E-11	-2.446E-11	4.686E-11	-187.253%
0.0	-5.0	-2.680E-11	-4.912E-11	-2.148E-11	-3.856E-11	2.764E-11	-81.318%
-1.0	-1.0	-1.914E-07	-1.911E-07	-1.879E-07	-1.880E-07	3.44E-09	-1.814%
-1.0	-3.0	-3.618E-07	-3.605E-07	-3.540E-07	-3.555E-07	7.86E-09	-2.196%
-1.0	-5.0	-5.932E-07	-5.924E-07	-5.829E-07	-5.843E-07	1.032E-08	-1.754%
-2.0	-1.0	-1.113E-04	-1.113E-04	-1.114E-04	-1.113E-04	1.2E-07	-0.108%
-2.0	-3.0	-1.408E-04	-1.408E-04	-1.408E-04	-1.408E-04	6E-08	-0.043%
-2.0	-5.0	-1.604E-04	-1.605E-04	-1.607E-04	-1.605E-04	3.2E-07	-0.199%
-3.0	-1.0	-3.031E-04	-3.031E-04	-3.037E-04	-3.038E-04	7.8E-07	-0.257%
-3.0	-3.0	-4.411E-04	-4.411E-04	-4.416E-04	-4.414E-04	5.2E-07	-0.118%
-3.0	-5.0	-4.922E-04	-4.922E-04	-4.929E-04	-4.928E-04	7E-07	-0.142%
-4.0	-1.0	-4.606E-04	-4.610E-04	-4.619E-04	-4.617E-04	1.24E-06	-0.269%
-4.0	-3.0	-8.083E-04	-8.079E-04	-8.098E-04	-8.094E-04	1.9E-06	-0.235%
-4.0	-5.0	-9.017E-04	-9.018E-04	-9.036E-04	-9.033E-04	1.9E-06	-0.211%
-5.0	-1.0	-5.924E-04	-5.920E-04	-5.932E-04	-5.929E-04	1.16E-06	-0.196%
-5.0	-3.0	-1.191E-03	-1.191E-03	-1.193E-03	-1.193E-03	2.6E-06	-0.218%
-5.0	-5.0	-1.355E-03	-1.354E-03	-1.357E-03	-1.355E-03	2.6E-06	-0.192%
						Avg error	-0.530%

The results of the modeling parameters, for the PMOS FETs on the 2-18-03-mask set, are tabulated in [Appendix D]. From the above tabular data, observations indicated that the transistors simulated with the default multiplicity factor resulted in very different results from that of the fabricated cells and by changing the multiplicity factor in the simulation and the DSUB parameter for the PMOS FET in the model file, results were closer to that of the measurements. It was also observed that the transistors of larger channel width resulted in better results compared

to the smaller transistor size. The modified multiplicity factor for NMOS was $M=1.05$ and $M=0.9$ for PMOS for the 9-15-03-mask model. With these M values, the average error in the voltages seen was the lowest and the best results were observed. It is also noticed that the change in the D_{sub} value, from the default of 0.2873 to 0.4373, for the PMOS FET resulted in I-V curves giving a better fit at the lower V_{gs} values, i.e., from 0-3V. The D_{sub} for the NMOS FETs was set to 1. This value was not changed for the modeling because the accuracy didn't improve. However, the specific effect of the D_{sub} parameter could not be isolated because a change in D_{sub} changes a number of subsequent variables resulting in a "chain reaction."

The Current error calculation indicated that for the optimized model, the average current error between the 19.2 μ m, 38.4 μ m, 57.6 μ m and 76.8 μ m PMOS FET was 126.1 μ A compared to the 327.6 μ A obtained for the unoptimized model. For the NMOS FETs, the average current error between the 19.2 μ m, 38.4 μ m, and 57.6 μ m was 137.4 μ A with the optimized model as compared to the 154.8 μ A with the unoptimized or default model. The 76.8 μ m FET for the NMOS was not considered because the optimized model didn't improve the error over the unoptimized model

The I-V characteristic plots for the NMOS and PMOS FETs for the optimized and unoptimized values are shown in figures (21) and (22). As can be seen the NMOS and PMOS FETs optimized values more closely matches the values measured for all four FET sizes. Also, figures (23) and (24) show the entire standard cell library in the schematic and layout form respectively, used for the FET testing. The chained lines in the figures (21) and (22) indicate the simulated data and the solid line indicate the measured data.

Figure (21) Measured v/s Unoptimized simulated plot and measured v/s optimized simulated plot of 19.2x02um NMOS FET.

Figure (22) Measured v/s Unoptimized simulated plot and measured v/s optimized simulated plot of 19.2x1.6 μ m PMOS FET.

Figure (23) Schematics for the FETs

Figure (24) Layout for the FETs.

4.2 Poly Resistors

The measured resistance was compared with that obtained from the calculations. The calculations used for the resistance measurements were discussed in Chapter 2. From the calculations, it was noticed that the resistor designed at UofL was more accurate than the one designed by Tanner Research Inc. The error calculations were obtained without considering the contact resistance since, this data was unavailable from MOSIS. The Error relationship between the measured and calculated resistances is shown in Figure (25).

Table 10 - Resistor Calculations.

Resistor Values (KOhms)							Error Calculation					
Measured Data				Avg Resis Value	SD Error	calculated Resistor value	Die#1	Die#2	Die#3	Die#4	Avg Error	SD Error
Die#1	Die#2	Die#3	Die#4	KOhms			Abs ((Act - meas)/Act)					
1.273	1.295	1.323	1.292	1.296	0.021	0.884	44.00%	46.49%	49.66%	46.15%	46.58%	2.33%
13.71	14.03	14.36	13.96	14.01	0.268	12.656	8.32%	10.87%	13.46%	10.27%	10.73%	2.12%

Calculated Resistor value

$$R = R_{sh} * (L * \lambda + 0.56 * \text{no. of corner sq.}) / (W * \lambda) \quad (35)$$

$R_{sh} = 25.9 \text{ ohm/sq.}$ (this value was obtained from the mask data)

1 corner sq = 0.56 ohm

1 sq = 1 lambda, 1 lambda = 0.8 um.

1.1Kohm resistor: $L = 204.72 \text{ lambda}$
 $W = 6 \text{ lambda}$

12 Kohm resistor: $L = 977.36 \text{ lambda}$
 $W = 2 \text{ lambda}$

Average Error between measured and calculated resistor values:

1.1K: $1.296 - 0.884 / 0.884 = 46.58\%$

12K: $14.014 - 12.656 / 12.656 = 10.73\%$.

Figure (25) Relationship between the Measured and Calculated Poly-Silicon Resistors

The I-V measurements were taken for the two resistors and the plots shown in the figures below. From the plots, the I-V relationship was found to be linear from 0-20V. (Max. limit for the power supply set in the program is 20V.) The resistors exhibit linearity out to at least a current density of 2.3 mA/um. From Figure (25), it is seen that the measured resistance was off from the calculated resistance by 47%, i.e., ΔR was 412 Ohms and by 11%, i.e., ΔR was 1354 Ohms, respectively, for resistors 1 and 2, where ΔR is the error between the measured and calculated resistances. Using the ΔR values, to obtain the generalized error term between the resistances, a plot between the calculated resistances and ΔR was obtained, which is indicated in Figure (26). Using the line equation, the slope and the intercept for Figure (26) was calculated to be m equals 0.08 and b equals 341. Hence, the final resistance calculation equation was found to be as follows:

$$\text{Final Resistance} = \text{Calculated resistance} + \text{Error term} \quad (36)$$

where, error term = $0.08 * \text{Calculated resistance} + 341$

Max. Measured current density = $14\text{mA}/6\text{ }\mu\text{m} = 2.3\text{ mA}/\mu\text{m}$ for Figure (27) and Max. Measured current density = $1.4\text{mA}/2\text{ }\mu\text{m} = 0.7\text{ mA}/\mu\text{m}$ for Figure (28).

Figure (26) Resistance Error Calculation.

Figure (27): 1.2 K ohm I-V Curve.

Figure (28) 13 K ohm I-V Curve

4.3 Voltage Reference

The focus of this test was to obtain a good regulation in the circuit rather than the accuracy. The regulation, calculated from 2V-5V, for both the measured data as well as simulated data was 34mV/V. This was indicative enough that the voltage reference had a very good voltage regulation. The data for the 0 and 1V were not considered due to the large error obtained between the measured and simulated data. The average error calculated between the measured and simulated data was about 2.17% (calculated from 2V-5V), which is a small value. Table 11 shows the calculation of the Bias with different supply voltage values. A plot of the simulated and measured data is as shown in the specification sheet attached in [Appendix C].

Table 11 - Voltage Reference Characteristics

	Measured Data	Simulated Data		Error Calculation
Vdd (V)	VNBias (V) Die#3	VNBias (V)	I (Vdd) (A)	Abs (meas-sim)/sim
0	0.045	0.001	-1.90E-32	44.000
1	0.500	0.065	-3.11E-10	6.648
2	0.613	0.630	-3.25E-05	0.027
3	0.654	0.669	-5.23E-05	0.022
4	0.687	0.699	-7.21E-05	0.018
5	0.716	0.730	-9.42E-05	0.020
		Average Error		2.17%

4.4 Bias Generator

The focus of this test was to obtain a relationship between the input and the outputs rather than accuracy. With the errors calculated the relationship between the outs and the inputs were determined. The errors indicate that the error was still less than 25%, which meant that there was still a good agreement between the two sets of compared data. Based on the outputs obtained a correlation can be drawn between the input and the outputs, the input being the supply voltage. The correlation is as follows: $OUT1 = VDD/1.7 = 0.6 \text{ VDD}$, $OUT2 = VDD/2 = 0.5 \text{ VDD}$, $OUT3 = VDD/3.5 = 0.3 \text{ VDD}$.

Table 12 - Bias Generator Characteristics

Vin/ Vdd (V)	OUT1 (V)			OUT2 (V)			OUT3 (V)		
	Meas Data	Sim Data	Error abs (meas-sim)/sim	Meas Data	Sim Data	Error abs (meas-sim)/sim	Meas Data	Sim Data	Error abs (meas-sim)/sim
	Die#1	T32q.md		Die#1	T32q.md		Die#1	T32q.md	
2	0.47	0.63	26.48%	1.02	1.037	1.96%	0.66	1.33	50.05%
3	0.85	0.99	14.39%	1.51	1.522	0.59%	1.81	2.06	11.99%
4	1.15	1.39	17.64%	1.99	2.002	0.77%	2.35	2.79	15.58%
5	1.43	1.79	20.21%	2.45	2.482	1.23%	2.86	3.50	18.36%
		Average Error	19.68%			1.14%			24.00%

4.5 Current Mirror

The tables below show the N as well as the P current mirror characteristics for the 2-18-03 and 9-15-03 mask sets. Due to the large discrepancy in the error calculation at 0 uA, this value was not considered for this calculation. The error in the current value is <2%, which shows good agreement between the measured and simulated values though the error in the input voltage is around 30%. The optimized multiplicity value, M=1.05 was used for the simulations. There is a 25.6 um long gate length NMOS FETs used to pull-down the output to ground. There is a 25.6 um long gate length PMOS FETs used to pull-down the output to Vdd. Since there is not much information of how the model scales as a function of gate length, this FET model does not scale linearly as a function of gate length and is causing the large discrepancy between the measured and simulated data for Input voltages. In other words, in simulation more current is sourced than in actuality and as a result, this pulls the output down prematurely as the transistors turn on harder. This explanation holds for the P-current mirrors as well.

Table 13 - N-Current Mirror Characteristics for the 2-18-03 Mask-Set

Measured Results			Simulated Results		Error Calculation	
	Die #1	R= 0 Ohms			abs((sim-meas)/meas)	abs((sim-meas)/meas)
I(IN)	I(OUT)	V(IN)	I(OUT)	V(IN)	I (OUT)	V(IN)
(uA)	(A)	(V)	(A)	(V)		
0	2.00E-09	0.02	6.63E-12	0.023	99.67%	0.15
50	5.03E-05	2.24	5.04E-05	1.738	0.20%	0.22
100	9.97E-05	2.957	1.00E-04	2.259	0.30%	0.24
150	1.50E-04	3.515	1.50E-04	2.663	0.00%	0.24
200	1.99E-04	3.989	2.00E-04	3.005	0.50%	0.25
250	2.47E-04	4.411	2.50E-04	3.311	1.21%	0.25
300	2.91E-04	4.799	3.00E-04	3.591	3.09%	0.25
350	3.39E-04	5.155	3.49E-04	3.852	2.95%	0.25
400	3.80E-04	5.495	3.99E-04	4.096	5.00%	0.25
Average Error					1.66%	24.47%

Table 14 - N-Current Mirror Characteristics for the 9-15-03 Mask-Set

Measured Results			Simulated Results		Error Calculation	
	Die #1	R= 0 Ohms			abs((sim-meas)/meas)	abs((sim-meas)/meas)
I(IN)	I(OUT)	V(IN)	I(OUT)	V(IN)	I (OUT)	V(IN)
(uA)	(A)	(V)	(A)	(V)		
0	2.00E-09	0.1	7.27E-12	0.026	99.64%	0.74
50	5.01E-05	2.195	5.04E-05	1.746	0.60%	0.20
100	1.00E-04	2.901	1.00E-04	2.283	0.00%	0.21
150	1.50E-04	3.452	1.50E-04	2.698	0.00%	0.22
200	2.00E-04	3.928	2.00E-04	3.053	0.00%	0.22
250	2.50E-04	4.353	2.50E-04	3.366	0.00%	0.23
300	2.95E-04	4.725	3.00E-04	3.651	1.69%	0.23
350	3.44E-04	5.082	3.50E-04	3.916	1.74%	0.23
400	3.86E-04	5.413	3.99E-04	4.164	3.37%	0.23
			Average Error		0.93%	22.16%

Table 15 - P-Current Mirror Characteristics for the 2-18-03 Mask-Set

Measured Results			Simulated Results		Error Calculation	
	Die #1	R= 0 Ohms			abs((sim-meas)/meas)	abs((sim-meas)/meas)
I(IN)	I(OUT)	V(IN)	I(OUT)	V(IN)	I (OUT)	V(IN)
(uA)	(A)	(V)	(A)	(V)		
0	2.00E-09	4.69	1.00E-11	5	99.50%	6.61%
5.00E-05	5.07E-05	2.01	5.03E-05	2.64	0.79%	31.34%
1.00E-04	1.01E-04	0.564	1.00E-04	1.97	0.99%	249.29%
1.50E-04	1.50E-04	-0.581	1.50E-04	1.45	0.00%	349.57%
2.00E-04	1.98E-04	-1.599	2.00E-04	1	1.01%	162.54%
2.50E-04	2.41E-04	-2.541	2.50E-04	0.6	3.73%	123.61%
3.00E-04	2.77E-04	-3.381	3.00E-04	0.23	8.30%	106.80%
3.50E-04	3.16E-04	-4.187	3.50E-04	-0.11	10.76%	97.37%
4.00E-04	3.47E-04	-4.96	4.00E-04	-0.43	15.27%	91.33%
			Average Error		15.60%	151.48%

Table 16 - P-Current Mirror Characteristics for the 9-15-03 Mask-Set

		Measured Results		Simulated Results		Error Calculation	
		Die #3	R= 0 Ohms			abs((sim-meas)/meas	abs((sim-meas)/meas
I(IN)		I(OUT)	V(IN)	I(OUT)	V(IN)	I (OUT)	V(IN)
(A)		(A)	(V)	(A)	(V)		
0		6.03E-07	4.671	1.00E-11	5	100.00%	6.58%
5.00E-05		5.12E-05	1.815	5.03E-05	2.54	1.76%	39.94%
1.00E-04		1.00E-04	0.375	1.00E-04	1.82	0.00%	385.33%
1.50E-04		1.50E-04	-0.807	1.50E-04	1.24	0.00%	253.66%
2.00E-04		1.98E-04	-1.848	2.00E-04	0.75	1.01%	140.58%
2.50E-04		2.41E-04	-2.789	2.50E-04	0.29	3.73%	110.40%
3.00E-04		2.77E-04	-3.663	3.00E-04	-0.12	8.30%	96.72%
3.50E-04		3.15E-04	-4.466	3.50E-04	-0.52	11.11%	88.36%
4.00E-04		3.46E-04	-5.259	4.00E-04	-0.92	15.61%	82.51%
				Average Error		5.19%	63.50%

4.6 Analog Buffer

The data for the three tests performed for the buffer are shown in the tables below. Table 17 shows the DC characteristics obtained with an infinite load. Since the Analog buffer consists of many NMOS and PMOS FETs connected together, the error obtained at the output is the compounded error at each of these individual FETs. The two highlighted values at input voltages of 0 and 0.5V were omitted due to an error larger than 50%. This maybe due to the body effect. The AC characteristics are as shown in the Table 18.

Table 17 – DC Characteristics of an Analog Buffer with infinite Load Resistance

Vin (V)	Vdd = 3V Performed with infinite Load				Vdd = 5V Performed with infinite Load			
	Measured Data	Simulated Data		Error Calculation	Measured Data	Simulated Data		Error Calculation
	Vout (V)	Vout (V)	IDD (A)	Abs ((Meas-Sim)/Sim)	Vout (V)	Vout (V)	IDD (A)	Abs ((Meas-Sim)/Sim)
0	0.035	1.10	-1.01E-04	96.83%	0.129	2.19	-4.14E-04	94.11%
0.5	0.542	1.12	-1.01E-04	51.44%	0.634	2.19	-4.14E-04	71.11%
1	1.050	1.38	-1.13E-04	23.79%	1.130	2.22	-4.15E-04	49.00%
1.5	1.532	1.72	-1.14E-04	11.10%	1.615	2.55	-4.37E-04	36.79%
2	2.004	2.17	-1.09E-04	7.52%	2.105	2.96	-4.50E-04	28.92%
2.5	2.502	2.60	-1.09E-04	3.73%	2.580	3.24	-4.41E-04	20.34%
3	2.997	2.68	-1.09E-04	12.00%	3.060	3.54	-4.26E-04	13.55%
3.5					3.520	3.89	-4.07E-04	9.52%
4					3.994	4.25	-3.93E-04	6.08%
4.5					4.479	4.39	-3.90E-04	2.05%
5					4.952	4.44	-3.89E-04	11.59%
	Average Error			11.63%				19.76%

Table 18 - AC Characteristics for a Buffer

						Error Calculation	
Vin= 1V	Measured Data		Simulated Data			Dsub =0.2873	Dsub= 0.4373
Frequency (Hz)	Die #1		Dsub = 0.2873	Dsub= 0.4373			
1	1.00E+00		5.48E-01	4.86E-04		0.452	1.000
10	1.00E+00		5.48E-01	5.08E-04		0.452	0.999
100	1.00E+00		5.48E-01	8.56E-04		0.452	0.999
1.00E+03	1.00E+00		5.48E-01	5.44E-03		0.452	0.995
1.00E+04	1.00E+00		5.48E-01	8.27E-03		0.452	0.992
1.00E+05	1.00E+00		5.42E-01	1.95E-03		0.458	0.998
1.00E+06	1.00E+00		3.17E-01	2.88E-04		0.683	1.000
2.00E+06	9.70E-01		1.83E-01	1.24E-04		0.811	1.000
3.00E+06	9.40E-01		1.25E-01	7.65E-05		0.867	1.000
4.00E+06	8.80E-01		9.61E-02	5.68E-05		0.891	1.000
5.00E+06	8.40E-01		7.68E-02	4.52E-05		0.909	1.000
6.00E+06	8.40E-01		6.40E-02	3.82E-05		0.924	1.000
7.00E+06	8.10E-01		5.46E-02	3.33E-05		0.933	1.000
8.00E+06	7.50E-01		4.87E-02	2.99E-05		0.935	1.000
9.00E+06	7.20E-01		4.25E-02	2.75E-05		0.941	1.000
1.00E+07	6.90E-01		3.88E-02	2.58E-05		0.944	1.000
1.10E+07	6.90E-01		3.54E-02	2.44E-05		0.949	1.000
1.20E+07	6.60E-01		3.23E-02	2.31E-05		0.951	1.000
1.30E+07	6.30E-01		2.94E-02	2.20E-05		0.953	1.000
1.40E+07	5.90E-01		2.75E-02	2.12E-05		0.953	1.000
1.50E+07	5.60E-01		2.56E-02	2.06E-05		0.954	1.000
1.60E+07	5.00E-01		2.39E-02	2.02E-05		0.952	1.000
1.70E+07	5.00E-01		2.29E-02	1.96E-05		0.954	1.000
1.80E+07	5.00E-01		2.13E-02	1.92E-05		0.957	1.000
1.90E+07	4.70E-01		2.04E-02	1.89E-05		0.957	1.000
2.00E+07	4.40E-01		1.95E-02	1.86E-05		0.956	1.000
						52.67%	99.78%

The 3dB point for the measured die is approximately 9.9 MHz. The 3dB point for the 02-18-03 mask is at approximately 7.1 MHz. The error calculated with the default value is better than that observed for the optimized data. The error for a DC simulation is comparable to the error measured from FET I-V curves, which is < 1% for NMOS and < 25% for PMOS. The agreement was reasonable (around 5%) when the load was small, but the simulated load FETs were not sourcing enough current to keep the output high (around 5V). There is a 20 um long gate length NMOS device used to pull-down the output to ground. Since there is not much information of how

the model scales as a function of gate length, this FET model does not scale linearly as a function of gate length and is causing the large discrepancy between the measured and simulated results. In other words, in simulation more current is sourced than in actuality and as a result, this pulls the output down prematurely as the transistors turn on harder. This explanation holds for the buffer load test as well. The output obtained from the load test is tabulated in Table 19.

Table 19 – Buffer Load Test

Resistor values (Ohms)	Measured	Simulated		Error Calculation	
		Dsub- 0.4373	Dsub- 0.2873	Dsub- 0.4373	Default
1.10E+06	4.95	4.3906	4.3739	11.30%	11.64%
1.00E+05	4.93	3.9528	3.979	19.82%	19.29%
1.00E+04	4.62	1.898	1.911	58.92%	58.64%
5.00E+03	4.3	0.977	1.017	77.28%	76.35%
1.00E+03	2.76	0.199	0.214	92.78%	92.26%
495	1.89	0.099	0.107	94.77%	94.37%
		Average Value		59.15%	58.76%

4.7 Comparator

The focus of this test was to indicate that the switching of the comparator took place at around the same points for the simulated and measured data rather than the accuracy. The comparator characteristics are shown in the Tables 20 and 21. The highlighted cells in Table 20 show the outliers, which is due to the fact that simulated data and measured data switch at different voltages. This maybe due to the early voltage effect that is part of the DIBL phenomenon, which causes the comparator to switch earlier. This effect may also be due to the biasing of the comparator. Hence, these values are excluded in the error calculations. The error calculated by changing the Dsub value for the PMOS gives a 1.74% improvement. From the table, it is noticed that when the transistors in the comparator were turned on hard, the error between the voltages were small while that around the threshold value shows a large difference. The value obtained for the simulations was so small that the instrument used for the

measurement is not calibrated for such small readings and this maybe the reason behind the large discrepancies.

Table 20 - Comparator Output Characteristics

Vref=2.5V	Simulated data			Measured data		
Vin (V)	Vout (V)	V(out) Default (0.2873)	IDD (A)	Vout (V)	Error Calculation	
	Dsub -0.4373				Dsub - 0.4373	Default (0.2873)
0.00	0.072	0.15	-5.64E-04	0.004	0.939	0.971
0.50	0.072	0.15	-5.63E-04	0.004	0.939	0.971
1.00	0.073	0.15	-5.62E-04	0.004	0.940	0.972
1.50	0.074	0.16	-5.61E-04	0.005	0.940	0.971
2.00	0.077	0.16	-5.59E-04	0.005	0.942	0.972
2.50	0.084	0.17	-5.55E-04	4.900	57.676	27.358
3.00	0.167	0.27	-5.64E-04	4.900	28.415	16.943
3.50	4.977	4.98	-3.07E-04	4.900	0.016	0.015
4.00	4.977	4.98	-2.08E-04	4.900	0.016	0.016
4.50	4.977	4.98	-1.97E-04	4.900	0.016	0.016
5.00	4.977	4.98	-1.97E-04	4.900	0.016	0.016
			Average Error		52.93%	54.67%

Table 21 – Output characteristics with different supply voltages

				Measured Values	Simulated Values	
Vin	Vbias	Vref	Vdd	Vout	Vout	IDD
(V)	(V)	(V)	(V)	(V)	(V)	(A)
0	0	1	2	1.790E-03	1.19E-08	-3.21E-05
2	0	1	2	1.976	1.976	-1.36E-05
0	0	1.5	3	2.560E-03	4.978E-03	-1.58E-04
3	0	1.5	3	2.990	2.979	-6.10E-05
0	0	2.5	5	4.390E-03	7.162E-02	-5.64E-04
5	0	2.5	5	4.900	4.977	-1.97E-04

4.8 Op-Amp

Due to the unavailability of good test setup and instrumentation, the open-loop gain test was not performed, though on simulation, the open-loop gain was obtained to be 65dB. The AC tests were performed for both the modes and these tests focus more on obtaining the 3dB Roll Off frequencies and resistances rather than the accuracy. The data in the tables that follow are plotted in [Appendix C] under the Op-Amp section. For simulated data, using $D_{sub} - PMOS = 0.4373$, 3dB Roll off was at 300 KHz. For Simulated data using D_{sub} for PMOS = 0.2873, 3dB Roll off is at 2MHz. For Measured data, 3dB Roll off is at 2 MHz. Due to the large variation in the 3dB Roll off frequency between the measured data and the simulated data with $D_{sub}=0.4373$, this value is not considered while performing the AC Tests. In addition to the inverting mode AC characteristics, the AC characteristics were also performed in the non-inverting mode. Due to the larger discrepancies at the higher frequency ranges, these values were omitted in the error calculation. The change in the D_{sub} value affects the C-V calculations in the circuit and hence, there is a large discrepancy seen in the load as well as the AC characteristics. The simulation performed with the default parameters gave a 3dB point which agreed closer to the measured data where as the simulation with the D_{sub} value changed, reduced the 3dB Roll Off point considerably by about 9 times. Hence, the default value is considered over the optimized value of D_{sub} for the AC tests performed. The 3dB Roll Off occurred at 2Kohm for the measured data and at 3KOhm for the simulated data and hence, the 3dB point for the Op-Amp occurred at around 2.5KOhms.

Table 22 - Inverting Op-Amp AC Characteristics

	Measured Data	Simulated Data		Error Calculation	
Frequency	Vout	Vout	Vout	abs((meas-sim)/sim)	abs((meas-sim)/sim)
(Hz)	(V)	(V)	(V)		
	Die#2	Dsub=0.4373	Dsub=0.2873	Dsub=0.4373	Dsub=0.2873
1	9.40E-01	9.83E-01	9.73E-01	4.359%	3.434%
10	9.40E-01	9.83E-01	9.73E-01	4.359%	3.434%
100	9.40E-01	9.83E-01	9.73E-01	4.359%	3.434%
1.00E+03	9.40E-01	9.83E-01	9.73E-01	4.358%	3.433%
1.00E+04	9.40E-01	9.82E-01	9.73E-01	4.276%	3.343%
1.00E+05	9.40E-01	9.08E-01	8.93E-01	3.574%	5.303%
1.00E+06	8.40E-01	2.44E-01	2.29E-01	243.811%	267.229%
2.00E+06	3.10E-01	1.46E-01	1.32E-01	112.460%	134.086%
3.00E+06	1.60E-01	1.17E-01	1.03E-01	37.210%	55.415%
4.00E+06	9.00E-02	1.05E-01	8.99E-02	14.073%	0.115%
5.00E+06	9.00E-02	9.78E-02	8.35E-02	8.004%	7.791%
6.00E+06	9.00E-02	9.35E-02	7.90E-02	3.784%	13.973%
7.00E+06	9.00E-02	9.03E-02	7.55E-02	0.339%	19.134%
8.00E+06	9.00E-02	8.81E-02	7.28E-02	2.114%	23.611%
9.00E+06	6.00E-02	8.55E-02	7.06E-02	29.861%	14.960%
1.00E+07	6.00E-02	8.38E-02	6.87E-02	28.363%	12.679%
1.10E+07	6.00E-02	8.19E-02	6.68E-02	26.711%	10.174%
1.20E+07	6.00E-02	7.98E-02	6.48E-02	24.853%	7.370%
1.30E+07	6.00E-02	7.76E-02	6.26E-02	22.726%	4.187%
1.40E+07	6.00E-02	7.59E-02	6.09E-02	20.910%	1.492%
1.50E+07	6.00E-02	7.40E-02	5.91E-02	18.867%	1.516%
1.60E+07	6.00E-02	7.19E-02	5.78E-02	16.558%	3.722%
1.70E+07	6.00E-02	7.05E-02	5.59E-02	14.847%	7.369%
1.80E+07	6.00E-02	6.82E-02	5.38E-02	11.985%	11.481%
1.90E+07	6.00E-02	6.66E-02	5.24E-02	9.856%	14.513%
2.00E+07	6.00E-02	6.49E-02	5.09E-02	7.527%	17.809%
		Average Error		4.214%	3.730%

Table 23 - Non Inverting Op-Amp AC Characteristics

	Measured Data	Simulated Data		Error Calculation	
Frequency	Vout	Vout	Vout	Abs ((meas- sim)/sim)	Abs ((meas- sim)/sim)
(Hz)	(V)	(V)	(V)		
	Die#2	Dsub= 0.4373	Dsub= 0.2873	Dsub= 0.4373	Dsub= 0.2873
1	1.03	1.14E+00	1.08E+00	9.435%	4.488%
10	1.03	1.14E+00	1.08E+00	9.435%	4.453%
100	1.03	1.14E+00	1.08E+00	9.435%	4.488%
1.00E+03	1.03	1.14E+00	1.08E+00	9.435%	4.488%
1.00E+04	1.03	1.14E+00	1.08E+00	9.355%	4.488%
1.00E+05	1.03	1.05E+00	9.89E-01	1.811%	4.160%
1.00E+06	8.10E-01	2.81E-01	2.54E-01	188.195%	219.464%
2.00E+06	3.80E-01	1.69E-01	1.52E-01	125.506%	150.148%
3.00E+06	2.20E-01	1.35E-01	1.15E-01	62.398%	91.972%
4.00E+06	1.60E-01	1.23E-01	1.00E-01	30.591%	59.633%
5.00E+06	1.30E-01	1.15E-01	9.32E-02	12.593%	39.509%
6.00E+06	1.30E-01	1.12E-01	8.82E-02	16.550%	47.397%
7.00E+06	9.00E-02	1.09E-01	8.44E-02	17.454%	6.602%
8.00E+06	9.00E-02	1.07E-01	8.14E-02	16.186%	10.558%
9.00E+06	6.00E-02	1.06E-01	7.94E-02	43.657%	24.447%
1.00E+07	6.00E-02	1.06E-01	7.69E-02	43.166%	21.948%
1.10E+07	6.00E-02	1.05E-01	7.47E-02	42.824%	19.729%
1.20E+07	6.00E-02	1.04E-01	7.25E-02	42.534%	17.247%
1.30E+07	6.00E-02	1.04E-01	7.01E-02	42.274%	14.425%
1.40E+07	6.00E-02	1.04E-01	6.82E-02	42.102%	12.038%
1.50E+07	6.00E-02	1.03E-01	6.62E-02	41.939%	9.371%
1.60E+07	6.00E-02	1.03E-01	6.41E-02	41.787%	6.383%
1.70E+07	6.00E-02	1.03E-01	6.26E-02	41.691%	4.185%
1.80E+07	6.00E-02	1.03E-01	6.03E-02	41.549%	0.544%
1.90E+07	6.00E-02	1.02E-01	5.87E-02	41.458%	2.143%
2.00E+07	6.00E-02	1.02E-01	5.71E-02	41.366%	5.060%
		Average Error		8.151%	4.428%

Table 24 - Inverting Op-Amp Load Characteristics

	Measured Data	Simulated Data	Error Calculation
R (Ohm)	Vout (V)	Vout (V)	Abs ((Meas-sim)/sim)
1.00E+06	0.67	1.2	44.42%
5.00E+05	0.67	1.2	44.44%
1.00E+05	0.67	1.2	44.53%
5.00E+04	0.66	1.2	44.62%
1.00E+04	0.64	1.2	48.16%
5.00E+03	0.63	1.2	46.66%
4.00E+03	0.62	1.2	47.28%
3.00E+03	0.62	1.1	43.41%
2.00E+03	0.60	0.91	34.01%
1.00E+03	0.52	0.392	33.61%
5.20E+02	0.31	0.147	111.56%
1.00E+02	0.03	3.00E-02	2.57%
		Average Error	45.44%

4.9 Adjustable Voltage Regulator

This circuit was designed keeping the voltage regulation in mind and not the accuracy of the model. The values obtained for the load test for the two standard outputs, 3.3V and 5V, are tabulated in Tables 25 and 26 below. The terms unoptimized and optimized stand for the change in the Dsub value for the PMOS FET from 0.2873 to 0.4373 respectively. Since, this circuit was designed using the other circuits characterized before, the error was not calculated.

Table 25 - Regulator Load Test at VIN=5V for Vout=3.3V

VIN=5V, VOUT=3.3 V	Measured Data	Simulated Data			
	Die#2	Optimized		Unoptimized	
R (Ohm)	Vout (V)	Vout (V)	IDD (A)	Vout (V)	IDD (A)
5.00E+04	3.29	1.10	-1.79E-04	1.27	-3.34E-04
2.50E+04	3.29	1.10	-2.00E-04	1.27	-3.57E-04
1.00E+04	3.28	1.10	-2.67E-04	1.27	-4.35E-04
5.00E+03	3.26	1.10	-3.76E-04	1.27	-5.61E-04
1.00E+03	2.77	1.09	-1.24E-03	9.82E-09	-9.97E-10
5.20E+02	2.10	5.04E-07	-2.52E-10	5.33E-09	-1.27E-09
1.00E+02	1.43	5.81E-08	-4.77E-10	0.64	-6.56E-03

Table 26 - Regulator Load Test at VIN=5V for Vout=5V

Vdd=5V	Measured Data	Simulated Data			
	Die#2	Optimized		UnOptimized	
R (Ohm)	Vout (V)	Vout (V)	IDD (A)	Vout (V)	IDD (A)
5.00E+04	4.93	1.71	-1.93E-04	1.98	-3.50E-04
2.50E+04	4.86	1.71	-2.24E-04	1.98	-3.87E-04
5.00E+03	4.35	1.70	-4.99E-04	1.97	-7.05E-04
5.20E+02	1.69	3.67E-09	-6.23E-11	1.93	-4.01E-03
1.00E+02	0.43	-8.85E-08	-2.90E-10	0.64	-6.57E-03

From the above data, it is noticed that the 3dB Roll Off points for the measured data as well as the optimized simulated data occurred at around 800-900 Ohms for an output of 3.3V and at around 2.5K -3.5K for an output of 5V, while that for the unoptimized simulated data, the 3dB roll off occurred at 5K Ohms for the 3.3V output and 250 Ohms at the 5V output. Since there was a lot of variation between the simulated and measured data, the optimized model fit better with the measured results.

Table 27 - Regulator VDD Characteristics at Vout=3.3V

Vdd (V)	Measured Data		Optimized Simulated		Unoptimized Simulated	
	Vin (V) (Die#1)	Vout (V) (Die#1)	Vout (V)	IDD (A)	Vout (V)	IDD (A)
2	0.611	0.617	1.56E-07	-6.56E-11	2.52E-07	-1.42E-10
3	0.651	1.996	2.34E-07	-1.34E-10	1.08	-1.38E-04
4	0.682	3.165	3.12E-07	-1.03E-09	1.17	-2.14E-04
5	0.711	3.287	1.10	-1.57E-04	1.27	-3.08E-04
6	0.737	3.322	1.15	-1.96E-04	1.38	-4.21E-04
7	0.763	3.354	1.19	-2.35E-04	1.48	-5.44E-04
8	0.791	3.387	1.24	-2.78E-04	1.60	-6.84E-04
9	0.821	3.428	1.28	-3.21E-04	1.71	-8.36E-04
10	0.858	3.476	1.32	-3.67E-04	1.81	-9.83E-04

Table 28 - Regulator VDD Characteristics at Vout=5V

Vdd (V)	Measured Data		Optimized Simulated		UnOptimized Simulated	
	Vin (V) (Die#1)	Vout (V) (Die#1)	Vout (V)	IDD (A)	Vout (V)	IDD (A)
2	0.611	0.934	2.43E-07	-6.38E-11	3.92E-07	-1.42E-10
3	0.652	2.821	1.57	-9.53E-05	1.67	-1.39E-04
4	0.683	3.901	1.65	-1.26E-04	1.83	-2.16E-04
5	0.711	4.992	1.71	-1.58E-04	1.98	-3.11E-04
6	0.737	5.173	1.79	-1.98E-04	2.15	-4.25E-04
7	0.763	5.223	1.85	-2.37E-04	2.31	-5.49E-04
8	0.791	5.277	1.93	-2.80E-04	2.48	-6.90E-04
9	0.821	5.377	1.99	-3.23E-04	2.66	-8.43E-04
10	0.858	5.411	2.06	-3.70E-04	2.82	-9.92E-04

From the above tables on the output characteristics, it was noticed that the regulation obtained from 5V to 10V, for the 3.3V Output, the unoptimized model outputted a better regulation over the optimized model by hundreds of Ohms. From the regulation obtained for the 5V output, it was noticed that the optimized model gave a better regulation and one closer to the measured data as well. Hence, there is a tradeoff between the optimized and unoptimized model at the 3.3V

while the data points out that the optimized model outweighed the unoptimized model in the other DC tests performed. The Plots as well as the regulation values are indicated in [Appendix C] under the voltage regulator section.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

NMOS and PMOS FETs as well as nine different analog IC standard cell designs have been tested and characterized under DC and AC conditions. Furthermore, these FETs and standard cells have been simulated in TSpice and the BSIM3 model parameters optimized to improve the accuracy between the measured and simulated results. The effect of the Multiplicity factor, M and some other model parameters that were influenced by the DIBL effects have been studied in depth to improve the accuracy of the model. The new model improved the overall accuracy in characterizing most of the analog circuits under DC conditions. While the change in the DIBL parameter, Dsub improved the PMOS FET behavior under DC conditions; the accuracy in the data was lost under the AC conditions. Hence, by tweaking this parameter, tradeoff was made between accuracy under DC and AC conditions. Since, the accuracy modeling under the AC conditions was out of the scope of this thesis, attempting to improve the modeling under AC conditions was not investigated. The current error calculation indicated the optimized model for the PMOS FET showed about a 60% improvement over the unoptimized model. For the NMOS FET, about a 17% improvement was obtained from the optimized model over the unoptimized model. The DC fit using the optimized model over the unoptimized model showed an improvement of ~2% (Voltage reference), <24% (Bias Generator), 2% (N-Current mirror), 5% (P-Current mirror), <30% (Analog Buffer) and ~2% (Op-Amp).

Future work should include the modeling optimization under AC conditions and improving PMOS model accuracy. Also, the scalability of the model as a function of the gate length should be investigated. The data measured from the FETs for modeling purposes all came from devices

with a channel length of 1.6 μm . However, FETs used within some of the standard cells had channel lengths greater than 25 μm .

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22. Tanner Tools, T-SPICE Help Manual

Appendix (A)

S-Edit™ Getting Started Manual

S-Edit is the schematic editor, which is a part of Tanner Tools®. To create a new schematic, the following steps have to be followed.

1. Create a new file by using Ctrl+N or by using *"File>new"*. Note: All the main circuit connections should be made on the schematic mode. To select this, click *"View>Schematic Mode"*. The views can also be toggled using the shortcut buttons for the symbol and schematic mode respectively.
2. Add the necessary library file by using *"Module>Symbol Browser"* or by clicking the symbol . This will bring up the symbol browser popup window. Click *"Add Library"* and add the library, in this case, the library file used was Mami150L.sdb. This is located in the "C:\Tanner\ Designkits\MOSIS\AMI_150\LinCMOS" folder.
3. Highlight this library and scroll down the list box and place the required cell that is being simulated by highlighting the cell and clicking *"Place"*.
4. Once this cell has been placed, rename the module by using *"Module>Rename"* and the page can also be renamed using *"Page>Rename"*.
5. Place the other voltage/current sources (this is obtained from the Spice Library which is added as in step (2), located in C:\Tanner\S-Edit\library).
6. Clicking on the cell and dragging this by holding down the ALT button on the keyboard can move the cell.
7. Clicking on the cell and dragging this by holding down the CTRL button on the keyboard can create duplicates of the cell.
8. Once all the necessary circuit elements were placed, they should be connected using

the wire button . Make sure not to use the line buttons as shown .

9. Ports can be placed using the buttons for input port, for output port and for bi-directional port located on the left side pane.
10. Once, the above steps were performed, the other simulation commands can also be embedded in the S-Edit file. To create this, click "*Module>New*" and create all the commands in the symbol mode (only then, they can be Instanced). In the symbol mode, many of the buttons on the schematic toolbar, which appears on the left side of the layout area, will be grayed out.
11. To create a simulation command, place the rectangle on the work area and to place the text click and click anywhere on the work area and type the text.
12. To add a property click and create a property. For Spice simulations, on the name field, type "SPICE OUTPUT" in uppercase and under the value field, add the simulation command. In the Format area, select the necessary format required. Click OK once the actions are completed.
13. To open the main module, click "*Module>Open*" or use the shortcut, O.
14. To create an Instance of a module or another cell, use "*Module>Instance*" or use I.
15. The simulation commands can also be added using T-Spice. Save the schematic file with the .sdb extension and to export the netlist click "*File>Export*" or to obtain the SPICE netlist. Other netlists can also be exported.

Using the above steps, a simple schematic can be created. To learn more about the other buttons and menus, use the S-Edit Help Manual. Figure below shows the S-Edit user interface.

Figure: S-Edit User Interface

Appendix (B)

T-Spice Getting Started Manual

T-Spice is the Simulation programming software used by Tanner Tools® for electrical circuit simulator. In order to run a simulation, you must first obtain the circuit netlist. This can be generated in two ways, one by entering all the simulation commands in the S-Edit™ file and then clicking the T-Spice symbol . This automatically creates the spice file and by using the “*Simulation>Run simulation*” command or the run button that appears on the toolbar, generates an output. Note: Before running any simulation, the model file, containing the process parameters library for the circuit, should be loaded in the same folder where the spice file resides.

The second method: If the netlist hasn't been exported from the S-Edit file, then use the “*File>Export*” option and select the Export data type as .sp from the pull-down menu in the S-Edit™ program. This netlist can then be opened using the T-Spice program. The simulation commands can be entered for the different types of analysis using the Insert Command submenu under the Edit Menu option. Once this is clicked, the T-Spice Command Tool appears, which is as shown below.

Using the above tool, the user can insert the type of analysis, type of current sources and voltage sources, the tables or library files needed to run the simulation, initialization and optimization commands etc. Once the desired set of commands were inserted using the insert command tool, the type of output desired (this too has to be specified using the Output option), and then click the run simulation button. The simulation status window shows the number of nodes, sources used etc. It also outputs if there were any errors or warnings in the simulation file. If there were errors, the simulation fails and user should fix the error and run the simulation again.

Figure shows the schematic of an Op-Amp circuit in S-Edit™ for which the netlist were

created below

Generated Netlist from S-Edit™ schematic in fig.1

* SPICE netlist written by S-Edit Win32 8.10

* Written on Aug 5, 2004 at 14:30:26

* Waveform probing commands

.probe

.options probefilename="OPAMP"

+ probesdbfile="C:\sedit\outputs\OPAMP\OPAMP.sdb"

+ probetopmodule="Op-Amp"

* Main circuit: Op-Amp

.dc v15 0 5.0 0.5

.print dc v(out) v(2) v(3) v(4) v(5) v(6)

.lib t32q.md

M2 3 VB GND GND NMOS W='15*' L='6*' AS='120*'|' AD='120*'|' PS='32*'|' PD='32*'|' M=1

M3 2 INM 3 GND NMOS W='10*' L='2*' AS='120*'|' AD='120*'|' PS='32*'|' PD='32*'|' M=1

M4 5 INP 3 GND NMOS W='10*' L='2*' AS='120*'|' AD='120*'|' PS='32*'|' PD='32*'|' M=1

M5 OUT VB GND GND NMOS W='50.5*' L='3*' AS='240*'|' AD='240*'|' PS='52*'|' PD='52*'|' M=1

M6 4 VB GND GND NMOS W='3*' L='4*' AS='36*'|' AD='36*'|' PS='24*'|' PD='24*'|' M=1

.param l=0.8um

M7 2 2 VDD VDD PMOS W='22*' L='6*' AS='360*'|' AD='360*'|' PS='72*'|' PD='72*'|' M=1

M8 5 2 VDD VDD PMOS W='22*' L='6*' AS='360*'|' AD='360*'|' PS='72*'|' PD='72*'|' M=1

M9 6 4 5 VDD PMOS W='22*' L='2*' AS='360*'|' AD='360*'|' PS='72*'|' PD='72*'|' M=1

M10 OUT 5 VDD VDD PMOS W='150*' L='3*' AS='1440*'|' AD='1440*'|' PS='252*'|' PD='252*'|' M=1

M11 4 4 5 VDD PMOS W='3*' L='2*' AS='54*'|' AD='54*'|' PS='24*'|' PD='24*'|' M=1

M12 5 5 VDD VDD PMOS W='3*' L='2*' AS='54*'|' AD='54*'|' PS='24*'|' PD='24*'|' M=1

v13 VB Gnd 1

v14 INM Gnd 5.0

v15 INP Gnd 2.5

v16 VDD Gnd 5.0

* End of main circuit:

Appendix (C)

BSIM3 Models

The Cell library shown below consists of 7 Analog Circuits that have been measured as well as simulated. The seventh cell, voltage regulator was formed using the Op-Amp circuit and the voltage reference circuit with a 25 K ohm resistor for the built-in resistor. The other cells were the standard cells taken from the Tanner Tools 1.5 um-linear CMOS library and were fabricated by MOSIS.

N-Current Mirror**Mir_N**

Description: N Current mirror consists of two matched n-channel transistors which fulfills the following relationship:

$$I_{out} = I_{in}$$

Library : UofL Analog Cell Library
Primitive Set: UofL LINCOS2 Cells

Schematic: S-Edit

File: mir_n.sdb
Module: Mir_N

Mask Layout: L-Edit

File: mir_n.tdb
Cell: Mir_N

L-Edit/SPR: ($1\lambda = 0.8\mu\text{m}$)

Height	Width	Area
66λ	117λ	$7722\lambda^2$

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{All dimensions in λ where $1\lambda = 0.8\mu\text{m}$ }

Simulation Error using the t39t.md with a load of 1K :1.87%
10K : 10.48%

Description: P Current mirror consists of two matched p-channel transistors which fulfills the following relationship:
 $I_{out} = I_{in}$

Library : UofL Analog Cell Library
 Primitive Set: UofL LINC MOS2 Cells

Schematic: S-Edit

File: Mir_P.sdb
 Module: Mir_P

Mask Layout: L-Edit

File: Mir_P.tdb
 Cell: Mir_P

L-Edit/SPR: ($1\lambda = 0.8\mu\text{m}$)

Height	Width	Area
66λ	117λ	$7722\lambda^2$

{All dimensions in λ where $1\lambda = 0.8\mu\text{m}$ }

Simulation Error using the t39t.md with a load of 1K :6.17%
10K : 11.52%

Description: Bias Generator uses a single Supply to generate the following voltages:

$$\text{OUT1} = \text{VDD}/1.7 = 0.6 \text{ VDD}$$

$$\text{OUT2} = \text{VDD}/2 = 0.5 \text{ VDD}$$

$$\text{OUT3} = \text{VDD}/3.5 = 0.3 \text{ VDD}$$

Library : UofL Analog Cell Library

Primitive Set: UofL LINCOS2 Cells

Schematic: S-Edit

File: Bias_Gen.sdb

Module: Bias_Gen

Mask Layout: L-Edit

File: Bias_Gen.tdb

Cell: Bias_Gen

L-Edit/SPR: ($1\lambda = 0.8 \mu\text{m}$)

Height	Width	Area
66λ	45λ	$2970\lambda^2$

Specifications:

	Min	Nom	Max
VDD Range	2V	3V	5V
IDD	0.47 μA	15 μA	94 μA

{ All dimensions in λ where $1\lambda = 0.8\mu\text{m}$ }

Simulation Error using T32Q BSIM3 model from 2-18-03 Mask:
(from $V_{DD} = 3, 4$ and $5V$)

OUT1 = 15.31% over 17.47% (default)
OUT2 = 0.87% over 1.45% (default)
OUT3 = 17.41% over 19.8% (default)

Description: Voltage Reference uses a single supply voltage to generate the output voltage:
VREF= 0.7 VDD

Library : UofL Analog Cell Library
Primitive Set: UofL LINCOS2 Cells

Schematic: S-Edit

File: Voltage_Ref.sdb
Module: Voltage_Ref

Mask Layout: L-Edit

File: Voltage_Ref.tdb
Cell: Voltage_Ref

L-Edit/SPR: ($1\lambda = 0.8 \mu\text{m}$)

Height	Width	Area
66 λ	209.5 λ	13827 λ^2

Specifications:

	Min	Nom	Max
VDD Range	2V	3V	5V
IDD	32.5 μA	52.3 μA	94.2 μA
Regulation (VDD = 2V to 5V)	-	34mV/V	-

{ All dimensions in λ where $1\lambda = 0.8\mu\text{m}$

Average Error between Measured and Simulation data (using T32Q BSIM3 model from 2-18-03 Mask): (from VDD = 2-5V)

OUT = 2.17%

Description: : Analog Buffer uses a single supply voltage
To drive up to a 2K load, where $V_{in} = V_{out}$

SYMBOL

Library : UofL Analog Cell Library
Primitive Set: UofL LINCOS2 Cells

Schematic: S-Edit

File: ABuf.sdb
Module: ABuf

Mask Layout: L-Edit

File: ABuf.tdb
Cell: ABuf

L-Edit/SPR: ($1\lambda = 0.8\text{ }\mu\text{m}$)

Height	Width	Area
66 λ	108.5 λ	7161 λ^2

Specifications:

	Min	Nom	Max
VDD Range	2V	3V	5V
IDD	30.55uA	109uA	414uA

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{All dimensions in λ where $1\lambda = 0.8\mu\text{m}$ }

$R_L = 2.5K$ (measured Data), 600K (Simulated Data)

No Load Connected.

The 3db point for the measured die is approximately 10 MHz.

The 3db point for the t32q.md is at approximately 1 MHz.

Comparator**Comp**

Description: Comparator consists of two input voltages, VIN and VREF. The output is determined as follows:

If $V_{IN} > V_{REF}$ – $V_{OUT} = V_{DD}$

$V_{IN} < V_{REF}$ – $V_{OUT} = 0$.

Library : UofL Analog Cell Library
Primitive Set: UofL LINC MOS2 Cells

Schematic: S-Edit

File: Comp.sdb
Module: Comp

Mask Layout: L-Edit

File: Comp.tdb
Cell: Comp

L-Edit/SPR: ($1\lambda = 0.8\mu\text{m}$)

Height	Width	Area
105 λ	136 λ	14280 λ^2

Specifications:

	Min	Nom	Max
VDD Range	2V	3V	5V
IDD	32.1 μA	158 μA	564 μA
Switching Voltage	0.57 V	0.81V	2.08V

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{All dimensions in λ where $1\lambda = 0.8\mu\text{m}$)

Switching Voltage (Meas): 2V, (Sim):3V for Vref=2.5V, Vdd=5V.

OP-AMP**Op-Amp**

Description: Operational Amplifier with a High Gain
Using a single supply and has a built-in compensating
Capacitor.

Library: UofL Analog Cell Library
Primitive Set: UofL LINCOS2 Cells

Schematic: S-Edit

File: Op-Amp.sdb
Module: Op-Amp

Mask Layout: L-Edit

File: Op-Amp.tdb
Cell: Op-Amp

L-Edit/SPR: ($1\lambda = 0.8\mu\text{m}$)

Height	Width	Area
105 λ	184 λ	19320 λ^2

Specifications:

	Min	Nom	Max
VDD Range	2V	3V	5V
IDD (Inverting Mode)	1.06 μA	31 μA	201 μA
IDD (NonInverting Mode)	8.08 μA	166 μA	956 μA

Open Loop Gain (Simulation only) : 65dB

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{All dimensions in λ where $1\lambda = 0.8\mu\text{m}$ }

3dB Roll off Frequency (Meas):2MHz, (Sim): 250KHz

3 dB Roll off Frequency (Meas):2MHz, (Sim): 250KHz

The 3dB Roll off occurs at Meas:1Kohm and Sim: 2.5Kohm

VIN=70mV with 1.35V Offset, closed loop feedback, Rin=10Kohms, RF = 100Kohms

ADJUSTABLE VOLTAGE REGULATOR

Voltage_Reg

Description: Adjustable voltage regulator that uses an input ranging from 5V-10V and has a built-in 25K resistor. The Output can be adjusted from 2.2V to 6.6V by changing the value for R_{ADJ} .

SYMBOL

Library: UofL Analog Cell Library
Primitive Set: UofL LINCOS2 Cells

Schematic: S-Edit

File: Voltage_Reg.sdb
Module: Voltage_Reg

Mask Layout: L-Edit

File: Voltage_Reg.tdb
Cell: Voltage_Reg

Specifications:

		MIN	TYP	MAX
R_{ADJ} (Ohms)		0	-	50K
IDD (5V)		500 μA ¹	-	760 μA
IDD (3.3V)		376 μA	-	631 μA
VOUT (REG)		2.2V ²	-	6.6V
LOAD REGULATION	$\Delta VOUT/\Delta IOUT$ ⁶	-	30mV ⁶	-
			10mV ⁷	
LINE REGULATION	$\Delta VOUT/\Delta VDD$ ³	-	26mV/V	-
R_L (VO=5V)		5Kohms ⁴	-	800-900 OHMS ⁵
R_L (VO=3.3V)		50KOhms	-	2.5-3.5 KOhms

¹Min @ VIN = 5V, Max @ VIN = 10V, R_L =5K

²Min @ R_2 =0, Max @ R_2 = 50K

³ R_2 =0 (Vout Min), VDD = 5V-10V

⁴Regulation of 1% (VIN = 5V)

⁵Regulation of 30% (3 dB)

⁶For VIN=5V, VOUT=3.3V, IOUT = 65.8 μA - 0.653 mA for R_L = 50K- 5KOhms

⁷For VIN=5V, VOUT= 5V, IOUT= 98.5 μA - 0.87 mA for R_L = 50K-5KOhms

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$$V_{OUT} = V_{ADJ} (R_2/25K + 1)$$

Where $V_{ADJ} = V_{OUT}$ when $R_2 = 0$

Typical = 2.2V (for $R_2 = 0$)

$R_{2MAX} = 50K$

02-18-03 Mask Model

* T32Q SPICE BSIM3 VERSION 3.1 PARAMETERS

SPICE 3f5 Level 8, Star-HSPICE Level 49, UTMOST Level 8

* DATE: Mar 31/03

* LOT: T32Q WAF: 3202

Temperature_parameters=Default

.MODEL NMOS NMOS (LEVEL = 49

+VERSION = 3.1	TNOM = 27	TOX = 3.06E-8
+XJ = 3E-7	NCH = 7.5E16	VTH0 = 0.5069591
+K1 = 0.9382614	K2 = -0.0869761	K3 = 7.5996896
+K3B = -3.8503851	W0 = 3.83633E-6	NLX = 1E-8
+DVT0W = 0	DVT1W = 0	DVT2W = 0
+ DVT0 = 0.7217903	DVT1 = 0.302459	DVT2 = -0.3176085
+U0 = 620.8461075	UA = 6.799942E-10	UB = 2.279296E-18
+ UC = -3.22535E-12	VSAT = 1.096398E5	A0 = 0.552232
+AGS = 0.0923316	B0 = 2.137463E-6	B1 = 5E-6
+KETA = -6.708515E-3	A1 = 0	A2 = 1
+RDSW = 3E3	PRWG = -0.0230798	PRWB = -0.0214204
+WR = 1	WINT = 6.621444E-7	LINT = 2.287886E-7
+XL = 0	XW = 0	DWG = -7.13441E-10
+DWB = 3.625667E-8	VOFF = -6.267605E-3	NFACTOR = 0.6880885
+CIT = 0	CDSC = 0	CDSCD = 0
+CDSCB = 3.066995E-5	ETA0 = -1	ETAB = -0.3960736
+DSUB = 0.9097182	PCLM = 1.1201574	PDIBLC1 = 8.686923E-3
+PDIBLC2 = 3.532968E-3	PDIBLCB = -0.1	DROUT = 0.0655521
+PSCBE1 = 1.562881E10	PSCBE2 = 3.581697E-9	PVAG = 0.0353463
+DELTA = 0.01	RSH = 53.1	MOBMOD = 1
+PRT = 0	UTE = -1.5	KT1 = -0.11

+KT1L = 0	KT2 = 0.022	UA1 = 4.31E-9
+UB1 = -7.61E-18	UC1 = -5.6E-11	AT = 3.3E4
+WL = 0	WLN = 1	WW = 0
+WWN = 1	WWL = 0	LL = 0
+LLN = 1	LW = 0	LWN = 1
+LWL = 0	CAPMOD = 2	XPART = 0.5
+CGDO = 1.78E-10	CGSO = 1.78E-10	CGBO = 1E-9
+CJ = 2.66451E-4	PB = 0.99	MJ = 0.5684277
+CJSW = 1.440541E-10	PBSW = 0.99	MJSW = 0.1
+CJSWG = 6.4E-11	PBSWG = 0.99	MJSWG = 0.1
+CF = 0	)	*

.MODEL PMOS PMOS (LEVEL = 49

+VERSION = 3.1	TNOM = 27	TOX = 3.06E-8
+XJ = 3E-7	NCH = 2.4E16	VTH0 = -0.8476404
+K1 = 0.4513608	K2 = 2.379699E-5	K3 = 13.3278347
+K3B = -2.2238332	W0 = 9.577236E-7	NLX = 1E-6
+DVT0W = 0	DVT1W = 0	DVT2W = 0
+DVT0 = 0.6724163	DVT1 = 0.4176993	DVT2 = -0.1717942
+U0 = 236.8923827	UA = 3.833306E-9	UB = 1.487688E-21
+UC = -1.08562E-10	VSAT = 1.112594E5	A0 = 0.1
+AGS = 1.1986658	B0 = 5.603955E-6	B1 = 5E-6
+KETA = -8.674697E-3	A1 = 0	A2 = 0.364
+RDSW = 2.450082E3	PRWG = 0.1090564	PRWB = -0.1907452
+WR = 1	WINT = 7.565065E-7	LINT = 7.036681E-8
+XL = 0	XW = 0	DWG = -2.13917E-8
+DWB = 3.857544E-8	VOFF = -0.0877184	NFACTOR = 0.2508342
+CIT = 0	CDSC = 2.924806E-5	CDSCD = 1.497572E-4

+CDSCB = 1.091488E-4	ETA0 = 0.26103	ETAB = -9.416814E-3
+DSUB = 0.2873	PCLM = 1E-10	PDIBLC1 = 4.12957E-4
+PDIBLC2 = 1.001244E-3	PDIBLCB = -1E-3	DROUT = 9.994612E-4
+PSCBE1 = 3.506856E9	PSCBE2 = 5.261344E-10	PVAG = 15
+DELTA = 0.01	RSH = 77.5	MOBMOD = 1
+PRT = 0	UTE = -1.5	KT1 = -0.11
+KT1L = 0	KT2 = 0.022	UA1 = 4.31E-9
+UB1 = -7.61E-18	UC1 = -5.6E-11	AT = 3.3E4
+WL = 0	WLN = 1	WW = 0
+WWN = 1	WWL = 0	LL = 0
+LLN = 1	LW = 0	LWN = 1
+LWL = 0	CAPMOD = 2	XPART = 0.5
+CGDO = 2.1E-10	CGSO = 2.1E-10	CGBO = 1E-9
+CJ = 3.023543E-4	PB = 0.7472625	MJ = 0.4301028
+CJSW = 1.669058E-10	PBSW = 0.99	MJSW = 0.1191643
+CJSWG = 3.9E-11	PBSWG = 0.99	MJSWG = 0.1191643
+CF = 0	)	*

09-15-03 Mask Model

* T39T SPICE BSIM3 VERSION 3.1 PARAMETERS

SPICE 3f5 Level 8, Star-HSPICE Level 49, UTMOST Level 8

* DATE: Nov 19/03

* LOT: T39T WAF: 7197

Temperature_parameters=Default

.MODEL NMOS NMOS (LEVEL = 49

+VERSION = 3.1	TNOM = 27	TOX = 3.13E-8
+XJ = 3E-7	NCH = 7.5E16	VTH0 = 0.4874312
+K1 = 0.9259373	K2 = -0.0885238	K3 = 2.8265559
+K3B = -2.6808504	W0 = 2.909353E-6	NLX = 1E-8
+DVT0W = 0	DVT1W = 0	DVT2W = 0
+DVT0 = 0.9761574	DVT1 = 0.2477734	DVT2 = -0.169518
+U0 = 635.2886671	UA = 1.138117E-9	UB = 2.071702E-18
+UC = 2.106848E-11	VSAT = 1.108701E5	A0 = 0.555546
+AGS = 0.1042212	B0 = 2.256903E-6	B1 = 5E-6
+KETA = -5.820236E-3	A1 = 0	A2 = 1
+RDSW = 3E3	PRWG = -0.0409513	PRWB = -0.035455
+WR = 1	WINT = 7.497966E-7	LINT = 2.185322E-7
+XL = 0	XW = 0	DWG = -1.892202E-8
+DWB = 3.381348E-8	VOFF = 0	NFACTOR = 0.758523
+CIT = 0	CDSC = 0	CDSCD = 0
+CDSCB = 0	ETA0 = -1	ETAB = 0.5952967
+DSUB = 1	PCLM = 1.3342251	PDIBLC1 = 0.012041
+PDIBLC2 = 3.541824E- 3	PDIBLCB = -0.1	DROUT = 0.0786382
+PSCBE1 = 2.179583E9	PSCBE2 = 5E-10	PVAG = 0.2119027
+DELTA = 0.01	RSH = 54.8	MOBMOD = 1

+PRT = 0	UTE = -1.5	KT1 = -0.11
+KT1L = 0	KT2 = 0.022	UA1 = 4.31E-9
+UB1 = -7.61E-18	UC1 = -5.6E-11	AT = 3.3E4
+WL = 0	WLN = 1	WW = 0
+WWN = 1	WWL = 0	LL = 0
+LLN = 1	LW = 0	LWN = 1
+LWL = 0	CAPMOD = 2	XPART = 0.5
+CGDO = 1.74E-10	CGSO = 1.74E-10	CGBO = 1E-9
+CJ = 2.547314E-4	PB = 0.9802679	MJ = 0.5741063
+CJSW = 1.433897E-10	PBSW = 0.99	MJSW = 0.1
+CJSWG = 6.4E-11	PBSWG = 0.99	MJSWG = 0.1
+CF = 0	)	*

.MODEL PMOS PMOS (

LEVEL = 49

+VERSION = 3.1	TNOM = 27	TOX = 3.13E-8
+XJ = 3E-7	NCH = 2.4E16	VTH0 = -0.8476404
+K1 = 0.4513608	K2 = 2.379699E-5	K3 = 13.3278347
+K3B = -2.2238332	W0 = 9.577236E-7	NLX = 1E-6
+DVT0W = 0	DVT1W = 0	DVT2W = 0
+DVT0 = 3.2953432	DVT1 = 0.6916594	DVT2 = -0.0749175
+U0 = 236.8923827	UA = 3.833306E-9	UB = 1.487688E-21
+UC = -1.08562E-10	VSAT = 2E5	A0 = 0.1587298
+AGS = 0.2673437	B0 = 8.48937E-6	B1 = 5E-6
+KETA = 8.561805E-3	A1 = 0	A2 = 0.364
+RDSW = 672.5986057	PRWG = 0.3	PRWB = -0.3
+WR = 1	WINT = 7.565065E-7	LINT = 3.965844E-9
+XL = 0	XW = 0	DWG = -2.13917E-8

+DWB = 3.857544E-8	VOFF = -0.0877184	NFACTOR = 0.2508342
+CIT = 0	CDSC = 2.924806E-5	CDSCD = 1.497572E-4
+CDSCB = 1.091488E-4	ETA0 = 0.29103	ETAB = -3.520693E-3
+DSUB = 0.2873	PCLM = 1E-10	PDIBLC1 = 6.31939E-4
+PDIBLC2 = 1.350626E-3	PDIBLCB = -1E-3	DROUT = 0
+PSCBE1 = 3.522972E9	PSCBE2 = 5.285524E-10	PVAG = 15
+DELTA = 0.01	RSH = 78.7	MOBMOD = 1
+PRT = 0	UTE = -1.5	KT1 = -0.11
+KT1L = 0	KT2 = 0.022	UA1 = 4.31E-9
+UB1 = -7.61E-18	UC1 = -5.6E-11	AT = 3.3E4
+WL = 0	WLN = 1	WW = 0
+WWN = 1	WWL = 0	LL = 0
+LLN = 1	LW = 0	LWN = 1
+LWL = 0	CAPMOD = 2	XPART = 0.5
+CGDO = 1.97E-10	CGSO = 1.97E-10	CGBO = 1E-9
+CJ = 3.024512E-4	PB = 0.8	MJ = 0.4355571
+CJSW = 1.615852E-10	PBSW = 0.8761424	MJSW = 0.1003172
+CJSWG = 3.9E-11	PBSWG = 0.8761424	MJSWG = 0.1003172
+CF = 0	)	*

Typical MOSIS Models

* DATE: Jun 6/02

* Tech: AMI_ABN

* LOT: T22X_TT (typical)

WAF: 6605

* Temperature_parameters=Optimized

```
.MODEL CMOSN NMOS (                LEVEL = 49
+VERSION = 3.1      TNOM  = 27      TOX  = 3.09E-8
+XJ  = 3E-7        NCH  = 7.5E16    VTH0 = 0.5585921
+K1  = 0.9300373   K2   = -0.0706188 K3   = 8.0262635
+K3B = -2.4231517   W0   = 5.489201E-7 NLX  = 1E-8
+DVT0W = 0         DVT1W = 0         DVT2W = 0
+DVT0 = 0.7666071   DVT1 = 0.2843554 DVT2 = -0.2195483
+U0  = 665.4919858  UA   = 1.468437E-9 UB   = 1.94634E-18
+UC  = 3.408801E-11 VSAT = 1.059876E5  A0   = 0.560251
+AGS  = 0.1065613   B0   = 2.451371E-6 B1   = 5E-6
+KETA = -7.033813E-3 A1   = 0         A2   = 1
+RDSW = 3E3        PRWG  = -0.0415097 PRWB  = -0.0367395
+WR   = 1          WINT  = 7.154435E-7 LINT  = 2.218865E-7
+XL   = 0          XW    = 0          DWG   = -1.936445E-8
+DWB  = 3.48297E-8  VOFF  = -0.0307548 NFACTOR = 0.5740385
+CIT  = 0          CDSC  = 0          CDSCD  = 0
+CDSCB = 3.251492E-5 ETA0 = -1         ETAB  = -0.5546384
+DSUB = 1          PCLM  = 1.2454756 PDIBLC1 = 8.119599E-3
+PDIBLC2 = 1.824339E-3 PDIBLCB = -0.1    DROUT  = 0.0536917
+PSCBE1 = 2.410329E9 PSCBE2 = 1.306019E-9 PVAG  = 0.149629
+DELTA = 0.01       RSH   = 52.2      MOBMOD = 1
+PRT  = 182.01      UTE   = -1.5      KT1   = -0.282143
+KT1L = 3.296E-9    KT2   = 0         UA1   = 1.206664E-9
+UB1  = -5.06439E-18 UC1   = -1E-10   AT    = 1E5
+WL   = 0          WLN   = 1          WW    = 0
+WWN  = 1          WWL   = 0          LL     = 0
+LLN  = 1          LW    = 0          LWN   = 1
+LWL  = 0          CAPMOD = 2          XPART  = 0.5
+CGDO = 1.8E-10     CGSO  = 1.8E-10    CGBO  = 1E-9
+CJ   = 2.830976E-4 PB    = 0.99       MJ    = 0.537762
+CJSW = 1.451536E-10 PBSW  = 0.99      MJSW  = 0.1
+CJSWG = 6.4E-11    PBSWG = 0.99      MJSWG = 0.1
+CF   = 0          AF    = 1          KF    = 0)
*
```

```
.MODEL CMOSP PMOS (                LEVEL = 49
+VERSION = 3.1      TNOM  = 27      TOX  = 3.09E-8
+XJ  = 3E-7        NCH  = 2.4E16     VTH0 = -0.8476404
+K1  = 0.4513608   K2   = 2.379699E-5 K3   = 13.3278347
+K3B = -2.2238332   W0   = 9.577236E-7 NLX  = 1E-8
+DVT0W = 0         DVT1W = 0         DVT2W = 0
+DVT0 = 0.2478839   DVT1 = 0.1169086 DVT2 = -0.5
+U0  = 236.8923827  UA   = 3.833306E-9 UB   = 1.487688E-21
+UC  = -1.08562E-10 VSAT = 1.019808E5  A0   = 0.3104634
+AGS  = 0.4374691   B0   = 3.217752E-6 B1   = 4.959246E-6
+KETA = -0.0196746  A1   = 0         A2   = 0.364
+RDSW = 3E3        PRWG  = 0.1198926 PRWB  = -0.2481551
+WR   = 1          WINT  = 7.565065E-7 LINT  = 9.161352E-8
+XL   = 0          XW    = 0          DWG   = -2.13917E-8
```

```

+DWB = 3.857544E-8  VOFF = -0.0877184  NFACTOR = 0.2508342
+CIT = 0            CDSC = 2.924806E-5  CDSCD = 1.497572E-4
+CDSCB = 1.091488E-4  ETA0 = 0.18903  ETAB = -3.128292E-3
+DSUB = 0.2873      PCLM = 3.9336407  PDIBLC1 = 1.935475E-5
+PDIBLC2 = 1.308368E-3  PDIBLCB = -1E-3  DROUT = 8.135421E-3
+PSCBE1 = 3.351476E9  PSCBE2 = 5.018187E-10  PVAG = 15
+DELTA = 0.01      RSH = 75.6      MOBMOD = 1
+PRT = 246.403     UTE = -1.5      KT1 = -0.6104394
+KT1L = 3.372457E-8  KT2 = 0      UA1 = -1.127018E-9
+UB1 = 1.95240E-18  UC1 = -1E-10  AT = 1E5
+WL = 0           WLN = 1         WW = 0
+WWN = 1          WWL = 0         LL = 0
+LLN = 1          LW = 0          LWN = 1
+LWL = 0          CAPMOD = 2      XPART = 0.5
+CGDO = 2.26E-10   CGSO = 2.26E-10  CGBO = 1E-9
+CJ = 2.750013E-4  PB = 0.7304623  MJ = 0.4163053
+CJSW = 1.667296E-10  PBSW = 0.99  MJSW = 0.1387033
+CJSWG = 3.9E-11   PBSWG = 0.99  MJSWG = 0.1387033
+CF = 0           AF = 1          KF = 0 )

```

* The fast-slow corner means: NMOS fast and PMOS slow.

* DATE: Jun 6/02

* Tech: AML_ABN

* LOT: T22X_SS (slow-slow) WAF: 6608

* Temperature_parameters=Optimized

```

.MODEL CMOSN NMOS (          LEVEL = 49
+VERSION = 3.1      TNOM = 27      TOX = 3.1E-8
+XJ = 3E-7         NCH = 7.5E16   VTH0 = 0.5938928
+K1 = 0.9606589    K2 = -0.0722108  K3 = 8.0613938
+K3B = -2.5714751  W0 = 1.259046E-6  NLX = 1E-8
+DVT0W = 0         DVT1W = 0      DVT2W = 0
+DVT0 = 0.7298898  DVT1 = 0.3187254  DVT2 = -0.2774341
+U0 = 673.9743329  UA = 1.655142E-9  UB = 1.736126E-18
+UC = 4.035809E-11  VSAT = 1.083534E5  A0 = 0.4962064
+AGS = 0.0873111   B0 = 2.346374E-6  B1 = 5E-6
+KETA = -0.0107375  A1 = 0         A2 = 1
+RDSW = 3E3        PRWG = -0.0324038  PRWB = -0.0446512
+WR = 1           WINT = 7.242762E-7  LINT = 2.231816E-7
+XL = 0           XW = 0           DWG = -2.638688E-8
+DWB = 3.30262E-8  VOFF = -0.0424245  NFACTOR = 0.6653555
+CIT = 0          CDSC = 0         CDSCD = 0
+CDSCB = 4.394359E-5  ETA0 = -1      ETAB = -0.5939699
+DSUB = 0.9988851  PCLM = 1.2994807  PDIBLC1 = 8.97257E-3
+PDIBLC2 = 1.811508E-3  PDIBLCB = -0.1  DROUT = 0.0581877
+PSCBE1 = 1E8      PSCBE2 = 5.480445E-10  PVAG = 0.3163861
+DELTA = 0.01      RSH = 54.2      MOBMOD = 1
+PRT = 182.01     UTE = -1.5      KT1 = -0.282143
+KT1L = 3.296E-9  KT2 = 0      UA1 = 1.206664E-9
+UB1 = -5.06439E-18  UC1 = -1E-10  AT = 1E5
+WL = 0           WLN = 1         WW = 0
+WWN = 1          WWL = 0         LL = 0
+LLN = 1          LW = 0          LWN = 1
+LWL = 0          CAPMOD = 2      XPART = 0.5

```

```

+CGDO = 1.78E-10    CGSO = 1.78E-10    CGBO = 1E-9
+CJ = 2.831147E-4   PB = 0.9892624    MJ = 0.5375655
+CJSW = 1.448993E-10 PBSW = 0.9892613    MJSW = 0.1
+CJSWG = 6.4E-11    PBSWG = 0.9892613    MJSWG = 0.1
+CF = 0            AF = 1            KF = 0)
*
.MODEL CMOSP PMOS (                                LEVEL = 49
+VERSION = 3.1      TNOM = 27      TOX = 3.1E-8
+XJ = 3E-7          NCH = 2.4E16    VTH0 = -0.8476404
+K1 = 0.4513608     K2 = 2.379699E-5 K3 = 13.3278347
+K3B = -2.2238332   W0 = 9.577236E-7 NLX = 4.413182E-7
+DVTOW = 0          DVT1W = 0       DVT2W = 0
+DVT0 = 0.9351981   DVT1 = 1        DVT2 = -0.3102606
+U0 = 236.8923827   UA = 3.833306E-9 UB = 1.487688E-21
+UC = -1.08562E-10  VSAT = 1.479579E5  A0 = 0.3545329
+AGS = 0.0598437    B0 = 3.370831E-6 B1 = 5E-6
+KETA = -2.815104E-3 A1 = 0          A2 = 0.364
+RDSW = 3E3         PRWG = 0.0510944 PRWB = -0.2978596
+WR = 1            WINT = 7.565065E-7 LINT = 3.915524E-8
+XL = 0            XW = 0           DWG = -2.13917E-8
+DWB = 3.857544E-8  VOFF = -0.0877184 NFACTOR = 0.2508342
+CIT = 0           CDSC = 2.924806E-5 CDSCD = 1.497572E-4
+CDSCB = 1.091488E-4 ETA0 = 0.18903   ETAB = -3.126169E-3
+DSUB = 0.2873      PCLM = 3.6298983 PDIBLC1 = 3.071687E-6
+PDIBLC2 = 1.029847E-3 PDIBLCB = -9.979309E-4 DROUT = 5.642687E-4
+PSCBE1 = 3.348257E9 PSCBE2 = 5.013367E-10 PVAG = 14.9962419
+DELTA = 0.01       RSH = 76.9       MOBMOD = 1
+PRT = 246.403      UTE = -1.5       KT1 = -0.6104394
+KT1L = 3.372457E-8 KT2 = 0         UA1 = -1.127018E-9
+UB1 = 1.952401E-18 UC1 = -1E-10    AT = 1E5
+WL = 0            WLN = 1          WW = 0
+WWN = 1           WWL = 0          LL = 0
+LLN = 1           LW = 0           LWN = 1
+LWL = 0           CAPMOD = 2        XPART = 0.5
+CGDO = 2.18E-10    CGSO = 2.18E-10    CGBO = 1E-9
+CJ = 2.750004E-4   PB = 0.7304697    MJ = 0.4163034
+CJSW = 1.667377E-10 PBSW = 0.9891238    MJSW = 0.138695
+CJSWG = 3.9E-11    PBSWG = 0.9891238    MJSWG = 0.138695
+CF = 0            AF = 1            KF = 0)
*

```

* DATE: Jun 7/02

* Tech: AML_ABN

* LOT: T22X_FF (fast-fast) WAF: 6603

* Temperature_parameters=Optimized

```

.MODEL CMOSN NMOS (                                LEVEL = 49
+VERSION = 3.1      TNOM = 27      TOX = 3.09E-8
+XJ = 1.5E-7        NCH = 1.7E17    VTH0 = 0.3418879
+K1 = 1             K2 = -0.0886142 K3 = 73.935439
+K3B = -1.7335131   W0 = 4.294837E-6 NLX = 1.234757E-7
+DVTOW = 0          DVT1W = 0       DVT2W = 0
+DVT0 = 0.9366704   DVT1 = 0.3952099 DVT2 = -0.5
+U0 = 512.1053322   UA = 1E-13      UB = 3.542293E-21
+UC = -2.6555E-11   VSAT = 1.262501E5 A0 = 0.6976947
+AGS = 0.1141915    B0 = 1.665024E-6 B1 = 5E-6

```

```

+KETA = 1.004654E-3  A1 = 4.087651E-3  A2 = 0.4749696
+RDSW = 2.240384E3  PRWG = 0.0865258  PRWB = 0.1022712
+WR = 1  WINT = 3.502972E-7  LINT = 2.66482E-7
+XL = 0  XW = 0  DWG = 8.182647E-8
+DWB = 1E-7  VOFF = 0  NFACTOR = 0
+CIT = 0  CDSC = 2.4E-4  CDSCD = 0
+CDSCB = 0  ETA0 = 4.931902E-3  ETAB = -2.258513E-3
+DSUB = 0.0881464  PCLM = 2.9105077  PDIBLC1 = 1.5770646
+PDIBLC2 = 2.55284E-3  PDIBLCB = -0.0422318  DROUT = 2
+PSCBE1 = 2.446215E8  PSCBE2 = 1.803554E-6  PVAG = 0
+DELTA = 0.01  RSH = 52.9  MOBMOD = 1
+PRT = 182.01  UTE = -1.5  KT1 = -0.282143
+KT1L = 3.296E-9  KT2 = 0  UA1 = 1.206664E-9
+UB1 = -5.06439E-18  UC1 = -1E-10  AT = 1E5
+WL = 0  WLN = 1  WW = 0
+WWN = 1  WWL = 0  LL = 0
+LLN = 1  LW = 0  LWN = 1
+LWL = 0  CAPMOD = 2  XPART = 0.5
+CGDO = 1.79E-10  CGSO = 1.79E-10  CGBO = 1E-10
+CJ = 2.819907E-4  PB = 0.9892543  MJ = 0.5329971
+CJSW = 1.60816E-10  PBSW = 0.2095614  MJSW = 0.1
+CJSWG = 6.4E-11  PBSWG = 0.2095614  MJSWG = 0.1
+CF = 0  AF = 1  KF = 0)
*

```

```

.MODEL CMOS PMOS (  LEVEL = 49
+VERSION = 3.1  TNOM = 27  TOX = 3.09E-8
+XJ = 1.5E-7  NCH = 1.7E17  VTH0 = -0.5412091
+K1 = 0.4956702  K2 = -0.0172116  K3 = 29.1047334
+K3B = -0.349145  W0 = 6.643926E-7  NLX = 9.869849E-7
+DVT0W = 0  DVT1W = 0  DVT2W = 0
+DVT0 = 1.2567763  DVT1 = 0.1934763  DVT2 = -0.1101939
+U0 = 213.8783744  UA = 2.609406E-9  UB = 2.126194E-19
+UC = -9.91697E-11  VSAT = 2E5  A0 = 1.0812191
+AGS = 0.2151663  B0 = 3.026533E-6  B1 = 5E-6
+KETA = -4.041454E-4  A1 = 0  A2 = 0.3
+RDSW = 3E3  PRWG = 0.1606075  PRWB = 0.026623
+WR = 1  WINT = 5E-7  LINT = 1.070949E-7
+XL = 0  XW = 0  DWG = 5.26422E-8
+DWB = 1E-7  VOFF = -6.706867E-3  NFACTOR = 0.1930646
+CIT = 0  CDSC = 2.4E-4  CDSCD = 0
+CDSCB = 0  ETA0 = 1  ETAB = 0.422708
+DSUB = 0.7758321  PCLM = 10  PDIBLC1 = 0.5648689
+PDIBLC2 = 0  PDIBLCB = 5.712687E-3  DROUT = 0.2362627
+PSCBE1 = 1E8  PSCBE2 = 5E-10  PVAG = 7.4222093
+DELTA = 0.01  RSH = 75.5  MOBMOD = 1
+PRT = 246.403  UTE = -1.5  KT1 = -0.6104394
+KT1L = 3.372457E-8  KT2 = 0  UA1 = -1.127018E-9
+UB1 = 1.952401E-18  UC1 = -1E-10  AT = 1E5
+WL = 0  WLN = 1  WW = 0
+WWN = 1  WWL = 0  LL = 0
+LLN = 1  LW = 0  LWN = 1
+LWL = 0  CAPMOD = 2  XPART = 0.5
+CGDO = 2.26E-10  CGSO = 2.26E-10  CGBO = 1E-10
+CJ = 2.750024E-4  PB = 0.7311843  MJ = 0.4165128
+CJSW = 1.665418E-10  PBSW = 0.9889114  MJSW = 0.1377668
+CJSWG = 3.9E-11  PBSWG = 0.9889114  MJSWG = 0.1377668

```

```

+CF    = 0          AF    = 1          KF    = 0 )
*
* DATE: Jun 13/02
* Tech: AML_ABN
* LOT: T22X_SF (slow-fast)          WAF: 6607
* Temperature_parameters=Optimized
.MODEL CMOSN NMOS (                      LEVEL = 49
+VERSION = 3.1          TNOM    = 27          TOX    = 3.1E-8
+XJ    = 1.5E-7          NCH    = 1.7E17          VTH0   = 0.4614515
+K1    = 1          K2    = -0.0705094          K3    = 68.5120173
+K3B   = -1.6803968          W0    = 4.639473E-6          NLX   = 1.585868E-7
+DVT0W = 0          DVT1W = 0          DVT2W = 0
+DVT0   = 1.0455678          DVT1   = 0.354009          DVT2   = -0.3737356
+U0    = 520.9170195          UA    = 1.765927E-12          UB    = 9.213525E-20
+UC    = -4.60095E-11          VSAT   = 1.417942E5          A0    = 0.5127879
+AGS    = 7.742278E-4          B0    = 1.213886E-6          B1    = 5E-6
+KETA   = -9.726449E-3          A1    = 0.0285695          A2    = 0.31575
+RDSW   = 2.817964E3          PRWG   = 0.0426905          PRWB   = 0.0385776
+WR     = 1          WINT    = 4.015258E-7          LINT   = 2.806234E-7
+XL     = 0          XW     = 0          DWG    = 7.86338E-8
+DWB    = 1E-7          VOFF   = 0          NFACTOR = 0.0395355
+CIT    = 0          CDSC   = 2.4E-4          CDSCD   = 0
+CDSCB  = 0          ETA0   = 2.168868E-3          ETAB   = -6.298812E-4
+DSUB   = 0.0291404          PCLM   = 2.9949477          PDIBLC1 = 2
+PDIBLC2 = 1.045548E-3          PDIBLCB = -0.1985476          DROUT   = 1.0985508
+PSCBE1 = 1.687442E8          PSCBE2 = 2.05305E-7          PVAG    = 0
+DELTA  = 0.01          RSH    = 52.2          MOBMOD = 1
+PRT    = 182.01          UTE    = -1.5          KT1    = -0.282143
+KT1L   = 3.296E-9          KT2    = 0          UA1    = 1.206664E-9
+UB1    = -5.06439E-18          UC1    = -1E-10          AT     = 1E5
+WL     = 0          WLN    = 1          WW     = 0
+WWN    = 1          WWL    = 0          LL     = 0
+LLN    = 1          LW     = 0          LWN    = 1
+LWL    = 0          CAPMOD = 2          XPART   = 0.5
+CGDO   = 1.78E-10          CGSO   = 1.78E-10          CGBO   = 1E-10
+CJ     = 2.819905E-4          PB     = 0.9892687          MJ     = 0.5330165
+CJSW   = 1.608294E-10          PBSW   = 0.2096834          MJSW   = 0.1
+CJSWG  = 6.4E-11          PBSWG   = 0.2096834          MJSWG  = 0.1
+CF     = 0          AF     = 1          KF     = 0 )
*

```

```

.MODEL CMOSP PMOS (                      LEVEL = 49
+VERSION = 3.1          TNOM    = 27          TOX    = 3.1E-8
+XJ    = 1.5E-7          NCH    = 1.7E17          VTH0   = -0.7203002
+K1    = 0.5028415          K2    = -6.420434E-3          K3    = 25.7018529
+K3B   = -0.6650859          W0    = 7.616826E-7          NLX   = 1E-6
+DVT0W = 0          DVT1W = 0          DVT2W = 0
+DVT0   = 1.5853422          DVT1   = 0.2256511          DVT2   = -0.0761088
+U0    = 225.9995164          UA    = 3.243723E-9          UB    = 3.53857E-19
+UC    = -9.47707E-11          VSAT   = 2E5          A0    = 0.5399018
+AGS    = 0.1772438          B0    = 4.276792E-6          B1    = 5E-6
+KETA   = -6.330167E-3          A1    = 0          A2    = 0.3
+RDSW   = 3E3          PRWG   = 0.0916148          PRWB   = -0.0744168
+WR     = 1          WINT    = 5E-7          LINT   = 8.263378E-8
+XL     = 0          XW     = 0          DWG    = 6.663649E-8
+DWB    = 1E-7          VOFF   = -0.0375864          NFACTOR = 0.1597389
+CIT    = 0          CDSC   = 2.4E-4          CDSCD   = 0

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+CDSCB = 0          ETA0 = 0.9459351  ETAB = -0.0941568
+DSUB = 0.5462029  PCLM = 10          PDIBLC1 = 0.1715607
+PDIBLC2 = 5.132495E-4 PDIBLCB = -0.1  DROUT = 0.1743087
+PSCBE1 = 1E8      PSCBE2 = 1.739746E-9 PVAG = 12.4353134
+DELTA = 0.01      RSH = 77.4         MOBMOD = 1
+PRT = 246.403     UTE = -1.5         KT1 = -0.6104394
+KT1L = 3.372457E-8 KT2 = 0          UA1 = -1.127018E-9
+UB1 = 1.952401E-18 UC1 = -1E-10     AT = 1E5
+WL = 0            WLN = 1            WW = 0
+WWN = 1           WWL = 0            LL = 0
+LLN = 1           LW = 0             LWN = 1
+LWL = 0           CAPMOD = 2         XPART = 0.5
+CGDO = 2.22E-10   CGSO = 2.22E-10   CGBO = 1E-10
+CJ = 2.750024E-4  PB = 0.7311609     MJ = 0.4165067
+CJSW = 1.665496E-10 PBSW = 0.9888326 MJSW = 0.1377907
+CJSWG = 3.9E-11   PBSWG = 0.9888326 MJSWG = 0.1377907
+CF = 0            AF = 1             KF = 0 )
*

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* DATE: Jun 14/02

* Tech: AML_ABN

* LOT: T22X_FS (fast-slow) WAF: 6606

* Temperature_parameters=Optimized

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.MODEL CMOSN NMOS (          LEVEL = 49
+VERSION = 3.1              TNOM = 27      TOX = 3.1E-8
+XJ = 1.5E-7               NCH = 1.7E17    VTH0 = 0.3552941
+K1 = 1                    K2 = -0.0902551  K3 = 80.4408341
+K3B = -2.0401761         W0 = 5.986863E-6 NLX = 2.004975E-7
+DVT0W = 0                DVT1W = 0        DVT2W = 0
+DVT0 = 1.1516023        DVT1 = 0.3035573 DVT2 = -0.2699118
+U0 = 525.7080358        UA = 1E-13       UB = 2.178146E-20
+UC = -4.24067E-11       VSAT = 1.330286E5 A0 = 0.6608039
+AGS = 0.0739246         B0 = 1.234506E-6 B1 = 5E-6
+KETA = 6.152135E-4      A1 = 0.0319649   A2 = 0.3555416
+RDSW = 2.776237E3       PRWG = 0.0434954 PRWB = 0.0513048
+WR = 1                   WINT = 3.615794E-7 LINT = 2.824851E-7
+XL = 0                   XW = 0           DWG = 7.804304E-8
+DWB = 1E-7              VOFF = 0         NFACTOR = 0
+CIT = 0                  CDSC = 2.4E-4    CDSCD = 0
+CDSCB = 0               ETA0 = 3.988663E-3 ETAB = -1.860237E-3
+DSUB = 0.0717376        PCLM = 2.9673455 PDIBLC1 = 1.7324734
+PDIBLC2 = 2.44682E-3    PDIBLCB = -0.0311057 DROUT = 1.3514359
+PSCBE1 = 1.980083E8     PSCBE2 = 5.517543E-7 PVAG = 0
+DELTA = 0.01           RSH = 54.7        MOBMOD = 1
+PRT = 182.01           UTE = -1.5         KT1 = -0.282143
+KT1L = 3.296E-9        KT2 = 0          UA1 = 1.206664E-9
+UB1 = -5.06439E-18     UC1 = -1E-10     AT = 1E5
+WL = 0                 WLN = 1           WW = 0
+WWN = 1                 WWL = 0           LL = 0
+LLN = 1                 LW = 0            LWN = 1
+LWL = 0                 CAPMOD = 2        XPART = 0.5
+CGDO = 1.79E-10        CGSO = 1.79E-10   CGBO = 1E-10
+CJ = 2.819905E-4       PB = 0.9892687    MJ = 0.5330165
+CJSW = 1.608294E-10    PBSW = 0.2096834   MJSW = 0.1
+CJSWG = 6.4E-11        PBSWG = 0.2096834 MJSWG = 0.1
+CF = 0                 AF = 1            KF = 0 )*

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```

.MODEL CMOS PMOS (                                LEVEL = 49
+VERSION = 3.1      TNOM  = 27      TOX   = 3.1E-8
+XJ   = 1.5E-7      NCH   = 1.7E17    VTH0  = -0.8238582
+K1    = 0.4609855   K2    = -4.53208E-4  K3    = 24.9924178
+K3B   = -1.2223282  W0    = 1.209388E-6  NLX   = 1E-6
+DVT0W = 0          DVT1W = 0          DVT2W = 0
+DVT0  = 1.4457275   DVT1  = 0.1964752   DVT2  = -0.0651827
+U0    = 225.374352  UA    = 3.222769E-9  UB    = 3.845902E-19
+UC    = -8.36683E-11 VSAT  = 2E5        A0    = 0.1463702
+AGS   = 0.0112579   B0    = 4.487759E-6  B1    = 5E-6
+KETA  = -7.612061E-3 A1    = 0          A2    = 0.3
+RDSW  = 3E3         PRWG  = 0.1220022   PRWB  = -0.0602275
+WR    = 1          WINT  = 5E-7         LINT  = 8.641214E-8
+XL    = 0          XW    = 0           DWG   = 5.360576E-8
+DWB   = 1E-7       VOFF  = -0.0329443   NFACTOR = 0.1439157
+CIT   = 0          CDSC  = 2.4E-4        CDSCD  = 0
+CDSCB = 0          ETA0  = 0.4151491     ETAB  = -0.0627808
+DSUB  = 0.3810547   PCLM  = 10          PDIBLC1 = 1.236252E-3
+PDIBLC2 = 1.178347E-3 PDIBLCB = -0.1      DROUT  = 0
+PSCBE1 = 1E8        PSCBE2 = 8.935016E-10 PVAG  = 15
+DELTA = 0.01        RSH   = 76.1        MOBMOD = 1
+PRT   = 246.403     UTE   = -1.5        KT1   = -0.6104394
+KT1L  = 3.372457E-8 KT2   = 0          UA1   = -1.127018E-9
+UB1   = 1.952401E-18 UC1   = -1E-10     AT    = 1E5
+WL    = 0          WLN   = 1           WW    = 0
+WWN   = 1          WWL   = 0           LL    = 0
+LLN   = 1          LW    = 0           LWN   = 1
+LWL   = 0          CAPMOD = 2           XPART  = 0.5
+CGDO  = 2.23E-10    CGSO  = 2.23E-10    CGBO  = 1E-10
+CJ    = 2.750024E-4 PB    = 0.7311609    MJ    = 0.4165067
+CJSW  = 1.665496E-10 PBSW  = 0.9888326    MJSW  = 0.1377907
+CJSWG = 3.9E-11     PBSWG = 0.9888326    MJSWG = 0.1377907
+CF    = 0          AF    = 1           KF    = 0 )
*
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Appendix (D)

MOSFET Results

UnOptimized and Optimized data using Percentage Error method for 2.4x1.6 um NMOS FETs.

W = 2.4um & L = 1.6 um			Using the optimized values of Vt = 0.48 V and M = 1.05			Using the default values of Vt = 0.48 V and M = 1			
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1.05	Error Factor Meas. Vs Sim. (SMU/ Sim)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1	Error Factor Meas. Vs Sim. (SMU/ Sim)
			Die #3				Die #3		
			(A)	(A)			(A)	(A)	
0	1.0		9.26E-09	1.59E-12	5812.75		9.26E-09	1.57E-12	5917.84
0	3.0		1.06E-08	3.83E-12	2768.50		1.06E-08	3.79E-12	2797.41
0	5.0		1.12E-08	6.07E-12	1839.03		1.12E-08	6.02E-12	1854.58
1.0	1.0		1.54E-06	6.40E-06	0.24		1.54E-06	6.10E-06	0.25
1.0	3.0		1.96E-06	7.23E-06	0.27		1.96E-06	6.88E-06	0.29
1.0	5.0		2.29E-06	7.90E-06	0.29		2.29E-06	7.52E-06	0.30
2.0	1.0		1.37E-05	3.57E-05	0.39		1.37E-05	3.40E-05	0.40
2.0	3.0		1.78E-05	4.05E-05	0.44		1.78E-05	3.86E-05	0.46
2.0	5.0		2.01E-05	4.24E-05	0.47		2.01E-05	4.04E-05	0.50
3.0	1.0		3.67E-05	6.82E-05	0.54		3.67E-05	6.49E-05	0.56
3.0	3.0		5.12E-05	8.93E-05	0.57		5.12E-05	8.50E-05	0.60
3.0	5.0		5.63E-05	9.25E-05	0.61		5.63E-05	8.81E-05	0.64
4.0	1.0		6.29E-05	9.63E-05	0.65		6.29E-05	9.17E-05	0.69
4.0	3.0		9.71E-05	1.47E-04	0.66		9.71E-05	1.40E-04	0.69
4.0	5.0		1.06E-04	1.52E-04	0.70		1.06E-04	1.45E-04	0.73
5.0	1.0		8.93E-05	1.21E-04	0.74		8.93E-05	1.15E-04	0.78
5.0	3.0		1.51E-04	2.12E-04	0.71		1.51E-04	2.02E-04	0.75
5.0	5.0		1.65E-04	2.20E-04	0.75		1.65E-04	2.10E-04	0.79
				AVG Error	46.44%			AVG Error	43.76%
				SD Error	0.18			SD Error	0.18

UnOptimized and Optimized data using Percentage Error method for 38.4x1.6 um NMOS FET.

W = 38.4um & L = 1.6 um			Using the optimized values of Vt = 0.48 V and M = 1.05			Using the default values of Vt = 0.48 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1.05	Error Factor Meas. Vs Sim. (SMU/ Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1	Error Factor Meas. Vs Sim. (SMU/ Sim)
		Die #3						
		(A)		(A)		(A)	(A)	
0	1.0		6.01E-11	4.22E-11	1.42	6.01E-11	4.02E-11	1.49
0	3.0		7.74E-11	6.04E-11	1.28	7.74E-11	5.77E-11	1.34
0	5.0		3.93E-11	7.86E-11	0.50	3.93E-11	7.51E-11	0.52
1.0	1.0		2.82E-04	3.02E-04	0.93	2.82E-04	2.87E-04	0.98
1.0	3.0		3.31E-04	3.41E-04	0.97	3.31E-04	3.24E-04	1.02
1.0	5.0		3.69E-04	3.71E-04	0.99	3.69E-04	3.54E-04	1.04
2.0	1.0		1.55E-03	1.51E-03	1.02	1.55E-03	1.44E-03	1.07
2.0	3.0		1.79E-03	1.76E-03	1.02	1.79E-03	1.67E-03	1.07
2.0	5.0		1.90E-03	1.84E-03	1.03	1.90E-03	1.75E-03	1.09
3.0	1.0		2.78E-03	2.69E-03	1.03	2.78E-03	2.56E-03	1.08
3.0	3.0		3.65E-03	3.69E-03	0.99	3.65E-03	3.52E-03	1.04
3.0	5.0		3.81E-03	3.83E-03	1.00	3.81E-03	3.65E-03	1.05
4.0	1.0		3.75E-03	3.66E-03	1.02	3.75E-03	3.49E-03	1.07
4.0	3.0		5.66E-03	5.87E-03	0.96	5.66E-03	5.59E-03	1.01
4.0	5.0		5.86E-03	6.08E-03	0.96	5.86E-03	5.79E-03	1.01
5.0	1.0		4.54E-03	4.46E-03	1.02	4.54E-03	4.25E-03	1.07
5.0	3.0		7.67E-03	8.15E-03	0.94	7.67E-03	7.76E-03	0.99
5.0	5.0		7.96E-03	8.54E-03	0.93	7.96E-03	8.13E-03	0.98
				AVG Error	-0.22%		AVG Error	-5.20%
				SD Error	0.18		SD Error	0.18

UnOptimized and Optimized data using Percentage Error method for 57.6x1.6 um NMOS

FET

W = 57.6um & L = 1.6 um			Using the optimized values of Vt = 0.48 V and M = 1.05			Using the default values of Vt = 0.48 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulate d w/ Vt=0.48V and M = 1.05	Error Factor Meas. Vs Sim. (SMU/Si m)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1	Error Factor Meas. Vs Sim. (SMU/Si m)
			Die #3			Die #3		
			(A)	(A)		(A)	(A)	
0	1.0		4.86E-08	6.49E-11	747.75	4.86E-08	6.19E-11	784.54
0	3.0		8.34E-08	9.21E-11	905.38	8.34E-08	8.78E-11	949.11
0	5.0		1.36E-07	1.19E-10	1140.84	1.36E-07	1.14E-10	1195.43
1.0	1.0		6.83E-04	4.62E-04	1.48	6.83E-04	4.40E-04	1.55
1.0	3.0		7.97E-04	5.22E-04	1.53	7.97E-04	4.97E-04	1.60
1.0	5.0		8.80E-04	5.69E-04	1.55	8.80E-04	5.42E-04	1.63
2.0	1.0		2.57E-03	2.31E-03	1.11	2.57E-03	2.20E-03	1.17
2.0	3.0		3.09E-03	2.69E-03	1.15	3.09E-03	2.56E-03	1.21
2.0	5.0		3.27E-03	2.81E-03	1.16	3.27E-03	2.68E-03	1.22
3.0	1.0		4.22E-03	4.10E-03	1.03	4.22E-03	3.90E-03	1.08
3.0	3.0		5.85E-03	5.64E-03	1.04	5.85E-03	5.37E-03	1.09
3.0	5.0		6.11E-03	5.85E-03	1.05	6.11E-03	5.57E-03	1.10
4.0	1.0		5.52E-03	5.57E-03	0.99	5.52E-03	5.31E-03	1.04
4.0	3.0		8.78E-03	8.95E-03	0.98	8.78E-03	8.52E-03	1.03
4.0	5.0		9.12E-03	9.28E-03	0.98	9.12E-03	8.83E-03	1.03
5.0	1.0		6.58E-03	6.78E-03	0.97	6.58E-03	6.46E-03	1.02
5.0	3.0		1.17E-02	1.24E-02	0.94	1.17E-02	1.18E-02	0.99
5.0	5.0		1.22E-02	1.30E-02	0.94	1.22E-02	1.24E-02	0.98
				AVG Error	-12.64%		AVG Error	-18.27%
				SD Error	0.21		SD Error	0.23

UnOptimized and Optimized data using Percentage Error method for 76.8x1.6 um NMOS

FET

W = 76.8um & L = 1.6 um			Using the optimized values of Vt = 0.48 V and M = 1.05			Using the default values of Vt = 0.48 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1.05	Error Factor Meas. Vs Sim. (SMU/ Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1	Error Factor Meas. Vs Sim. (SMU/ Sim)
			Die #3			Die #3		
			(A)	(A)		(A)	(A)	
0	1.0		7.71E-11	8.77E-11	0.88	7.71E-11	8.36E-11	0.92
0	3.0		9.27E-11	1.24E-10	0.75	9.27E-11	1.18E-10	0.79
0	5.0		1.12E-10	1.60E-10	0.70	1.12E-10	1.52E-10	0.73
1.0	1.0		5.69E-04	6.22E-04	0.91	5.69E-04	5.93E-04	0.96
1.0	3.0		6.66E-04	7.03E-04	0.95	6.66E-04	6.69E-04	1.00
1.0	5.0		7.43E-04	7.66E-04	0.97	7.43E-04	7.30E-04	1.02
2.0	1.0		3.07E-03	3.11E-03	0.99	3.07E-03	2.96E-03	1.04
2.0	3.0		3.56E-03	3.62E-03	0.98	3.56E-03	3.44E-03	1.03
2.0	5.0		3.77E-03	3.78E-03	1.00	3.77E-03	3.60E-03	1.05
3.0	1.0		5.44E-03	5.50E-03	0.99	5.44E-03	5.24E-03	1.04
3.0	3.0		7.22E-03	7.59E-03	0.95	7.22E-03	7.22E-03	1.00
3.0	5.0		7.52E-03	7.86E-03	0.96	7.52E-03	7.49E-03	1.00
4.0	1.0		7.28E-03	7.48E-03	0.97	7.28E-03	7.12E-03	1.02
4.0	3.0		1.12E-02	1.20E-02	0.93	1.12E-02	1.15E-02	0.97
4.0	5.0		1.15E-02	1.25E-02	0.93	1.15E-02	1.19E-02	0.97
5.0	1.0		8.76E-03	9.10E-03	0.96	8.76E-03	8.66E-03	1.01
5.0	3.0		1.51E-02	1.67E-02	0.90	1.51E-02	1.59E-02	0.95
5.0	5.0		1.56E-02	1.75E-02	0.89	1.56E-02	1.67E-02	0.94
				AVG Error	7.72%		AVG Error	3.12%
				SD Error	0.08		SD Error	0.08

UnOptimized and Optimized data using Average Error Current method for 2.4 x1.6um

NMOS FET

W = 2.4um & L = 1.6 um			Using the optimized values of Vt = 0.48 V and M = 1.05			Using the default values of Vt = 0.48 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1.05	Error Factor Meas. Vs Sim. (SMU-Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1.0	Error Factor Meas. Vs Sim. (SMU-Sim)
			Die #3			Die #3		
			(A)	(A)		(A)	(A)	
0	1.0		9.26E-09	1.59E-12	9.26E-09	9.26E-09	1.57E-12	9.26E-09
0	3.0		1.06E-08	3.83E-12	1.06E-08	1.06E-08	3.79E-12	1.06E-08
0	5.0		1.12E-08	6.07E-12	1.12E-08	1.12E-08	6.02E-12	1.12E-08
1.0	1.0		1.54E-06	6.40E-06	4.86E-06	1.54E-06	6.10E-06	4.56E-06
1.0	3.0		1.96E-06	7.23E-06	5.26E-06	1.96E-06	6.88E-06	4.92E-06
1.0	5.0		2.29E-06	7.90E-06	5.61E-06	2.29E-06	7.52E-06	5.23E-06
2.0	1.0		1.37E-05	3.57E-05	2.19E-05	1.37E-05	3.40E-05	2.02E-05
2.0	3.0		1.78E-05	4.05E-05	2.27E-05	1.78E-05	3.86E-05	2.08E-05
2.0	5.0		2.01E-05	4.24E-05	2.23E-05	2.01E-05	4.04E-05	2.02E-05
3.0	1.0		3.67E-05	6.82E-05	3.15E-05	3.67E-05	6.49E-05	2.82E-05
3.0	3.0		5.12E-05	8.93E-05	3.81E-05	5.12E-05	8.50E-05	3.39E-05
3.0	5.0		5.63E-05	9.25E-05	3.61E-05	5.63E-05	8.81E-05	3.17E-05
4.0	1.0		6.29E-05	9.63E-05	3.35E-05	6.29E-05	9.17E-05	2.89E-05
4.0	3.0		9.71E-05	1.47E-04	5.00E-05	9.71E-05	1.40E-04	4.30E-05
4.0	5.0		1.06E-04	1.52E-04	4.62E-05	1.06E-04	1.45E-04	3.89E-05
5.0	1.0		8.93E-05	1.21E-04	3.15E-05	8.93E-05	1.15E-04	2.58E-05
5.0	3.0		1.51E-04	2.12E-04	6.05E-05	1.51E-04	2.02E-04	5.04E-05
5.0	5.0		1.65E-04	2.20E-04	5.53E-05	1.65E-04	2.10E-04	4.49E-05
				AVG Error	3.10E-05		AVG Error	2.68E-05
				SD Error	1.76E-05		SD Error	1.45E-05

UnOptimized and Optimized data using Average Error Current method for 38.4x1.6um

NMOS FET

W = 38.4um & L = 1.6 um			Using the optimized values of Vt = 0.48 V and M = 1.05			Using the default values of Vt = 0.48 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1.05	Error Factor Meas. Vs Sim. (SMU- Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1.0	Error Factor Meas. Vs Sim. (SMU- Sim)
		Die #3				Die #3		
		(A)	(A)	(A)		(A)	(A)	
0	1.0		6.01E-11	4.22E-11	1.79E-11	6.01E-11	4.02E-11	1.98E-11
0	3.0		7.74E-11	6.04E-11	1.70E-11	7.74E-11	5.77E-11	1.97E-11
0	5.0		3.93E-11	7.86E-11	3.92E-11	3.93E-11	7.51E-11	3.57E-11
1.0	1.0		2.82E-04	3.02E-04	1.97E-05	2.82E-04	2.87E-04	5.34E-06
1.0	3.0		3.31E-04	3.41E-04	9.87E-06	3.31E-04	3.24E-04	6.35E-06
1.0	5.0		3.69E-04	3.71E-04	2.06E-06	3.69E-04	3.54E-04	1.56E-05
2.0	1.0		1.55E-03	1.51E-03	3.59E-05	1.55E-03	1.44E-03	1.08E-04
2.0	3.0		1.79E-03	1.76E-03	3.41E-05	1.79E-03	1.67E-03	1.18E-04
2.0	5.0		1.90E-03	1.84E-03	6.31E-05	1.90E-03	1.75E-03	1.51E-04
3.0	1.0		2.78E-03	2.69E-03	8.35E-05	2.78E-03	2.56E-03	2.12E-04
3.0	3.0		3.65E-03	3.69E-03	3.98E-05	3.65E-03	3.52E-03	1.36E-04
3.0	5.0		3.81E-03	3.83E-03	1.49E-05	3.81E-03	3.65E-03	1.67E-04
4.0	1.0		3.75E-03	3.66E-03	8.11E-05	3.75E-03	3.49E-03	2.56E-04
4.0	3.0		5.66E-03	5.87E-03	2.11E-04	5.66E-03	5.59E-03	6.87E-05
4.0	5.0		5.86E-03	6.08E-03	2.16E-04	5.86E-03	5.79E-03	7.34E-05
5.0	1.0		4.54E-03	4.46E-03	8.15E-05	4.54E-03	4.25E-03	2.94E-04
5.0	3.0		7.67E-03	8.15E-03	4.80E-04	7.67E-03	7.76E-03	9.22E-05
5.0	5.0		7.96E-03	8.54E-03	5.82E-04	7.96E-03	8.13E-03	1.75E-04
				AVG Error	1.09E-04		AVG Error	1.04E-04
				SD Error	1.68E-04		SD Error	9.23E-05

UnOptimized and Optimized data using Average Error Current method for 57.6x1.6um

NMOS FET

W = 57.6um & L = 1.6 um			Using the optimized values of Vt = 0.48 V and M = 1.05			Using the default values of Vt = 0.48 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated with Vt=0.48V and M = 1.05	Error Factor Meas. Vs Sim. (SMU- Sim)	Ids Measured with dual SMUs	Ids Simulated with Vt=0.48V and M = 1	Error Factor Meas. Vs Sim. (SMU- Sim)
			Die #3			Die #3		
			(A)	(A)		(A)	(A)	
0	1.0		4.86E-08	6.49E-11	4.85E-08	4.86E-08	6.19E-11	4.85E-08
0	3.0		8.34E-08	9.21E-11	8.33E-08	8.34E-08	8.78E-11	8.33E-08
0	5.0		1.36E-07	1.19E-10	1.36E-07	1.36E-07	1.14E-10	1.36E-07
1.0	1.0		6.83E-04	4.62E-04	2.21E-04	6.83E-04	4.40E-04	2.43E-04
1.0	3.0		7.97E-04	5.22E-04	2.76E-04	7.97E-04	4.97E-04	3.00E-04
1.0	5.0		8.80E-04	5.69E-04	3.12E-04	8.80E-04	5.42E-04	3.39E-04
2.0	1.0		2.57E-03	2.31E-03	2.62E-04	2.57E-03	2.20E-03	3.72E-04
2.0	3.0		3.09E-03	2.69E-03	3.98E-04	3.09E-03	2.56E-03	5.26E-04
2.0	5.0		3.27E-03	2.81E-03	4.60E-04	3.27E-03	2.68E-03	5.93E-04
3.0	1.0		4.22E-03	4.10E-03	1.23E-04	4.22E-03	3.90E-03	3.19E-04
3.0	3.0		5.85E-03	5.64E-03	2.16E-04	5.85E-03	5.37E-03	4.85E-04
3.0	5.0		6.11E-03	5.85E-03	2.67E-04	6.11E-03	5.57E-03	5.45E-04
4.0	1.0		5.52E-03	5.57E-03	5.03E-05	5.52E-03	5.31E-03	2.15E-04
4.0	3.0		8.78E-03	8.95E-03	1.67E-04	8.78E-03	8.52E-03	2.59E-04
4.0	5.0		9.12E-03	9.28E-03	1.58E-04	9.12E-03	8.83E-03	2.84E-04
5.0	1.0		6.58E-03	6.78E-03	1.99E-04	6.58E-03	6.46E-03	1.24E-04
5.0	3.0		1.17E-02	1.24E-02	7.39E-04	1.17E-02	1.18E-02	1.48E-04
5.0	5.0		1.22E-02	1.30E-02	8.43E-04	1.22E-02	1.24E-02	2.23E-04
				AVG Error	2.61E-04		AVG Error	2.76E-04
				SD Error	2.33E-04		SD Error	1.83E-04

UnOptimized and Optimized data using Average Error Current method for 76.8x1.6um

NMOS FET

W = 76.8um & L = 1.6um			Using the optimized values of Vt = 0.48 V and M = 1.05			Using the default values of Vt = 0.48 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1.05	Error Factor Meas. Vs Sim. (SMU- Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=0.48V and M = 1.0	Error Factor Meas. Vs Sim. (SMU- Sim)
		Die #3						
		(A)		(A)		(A)	(A)	
0	1.0		7.71E-11	8.77E-11	1.06E-11	7.71E-11	8.36E-11	6.47E-12
0	3.0		9.27E-11	1.24E-10	3.11E-11	9.27E-11	1.18E-10	2.53E-11
0	5.0		1.12E-10	1.60E-10	4.78E-11	1.12E-10	1.52E-10	4.04E-11
1.0	1.0		5.69E-04	6.22E-04	5.38E-05	5.69E-04	5.93E-04	2.42E-05
1.0	3.0		6.66E-04	7.03E-04	3.66E-05	6.66E-04	6.69E-04	3.13E-06
1.0	5.0		7.43E-04	7.66E-04	2.32E-05	7.43E-04	7.30E-04	1.33E-05
2.0	1.0		3.07E-03	3.11E-03	3.50E-05	3.07E-03	2.96E-03	1.13E-04
2.0	3.0		3.56E-03	3.62E-03	6.06E-05	3.56E-03	3.44E-03	1.12E-04
2.0	5.0		3.77E-03	3.78E-03	1.07E-05	3.77E-03	3.60E-03	1.69E-04
3.0	1.0		5.44E-03	5.50E-03	6.77E-05	5.44E-03	5.24E-03	1.94E-04
3.0	3.0		7.22E-03	7.59E-03	3.66E-04	7.22E-03	7.22E-03	4.60E-06
3.0	5.0		7.52E-03	7.86E-03	3.40E-04	7.52E-03	7.49E-03	3.44E-05
4.0	1.0		7.28E-03	7.48E-03	2.05E-04	7.28E-03	7.12E-03	1.51E-04
4.0	3.0		1.12E-02	1.20E-02	8.73E-04	1.12E-02	1.15E-02	3.00E-04
4.0	5.0		1.15E-02	1.25E-02	9.34E-04	1.15E-02	1.19E-02	3.40E-04
5.0	1.0		8.76E-03	9.10E-03	3.38E-04	8.76E-03	8.66E-03	9.53E-05
5.0	3.0		1.51E-02	1.67E-02	1.60E-03	1.51E-02	1.59E-02	8.07E-04
5.0	5.0		1.56E-02	1.75E-02	1.88E-03	1.56E-02	1.67E-02	1.05E-03
				AVG Error	3.79E-04		AVG Error	1.89E-04
				SD Error	5.72E-04		SD Error	2.90E-04

UnOptimized and Optimized data using Percentage Error method for 2.4x1.6 um PMOS FET.

W = 2.4um & L = 1.6 um			Using the optimized values of Vt = -0.84 V and M = 0.9			Using the default values of Vt = -0.84 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=-0.84V and M = 0.9	Error Factor Meas. Vs Sim. (SMU/Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=-0.84V and M = 1	Error Factor Meas. Vs Sim. (SMU/Sim)
			Die #3			Die #3		
			(A)	(A)		(A)	(A)	
0.0	-1.0		-1.800E-11	-1.525E-12	11.803	-1.80E-11	-1.63E-12	11.077
0.0	-3.0		-4.752E-11	-4.525E-12	10.502	-4.75E-11	-4.63E-12	10.275
0.0	-5.0		-7.794E-11	-7.143E-12	10.911	-7.79E-11	-7.14E-12	10.911
-1.0	-1.0		-2.081E-09	-4.498E-08	0.046	-2.08E-09	-5.68E-08	0.037
-1.0	-3.0		-3.160E-09	-5.055E-07	0.006	-3.16E-09	-5.86E-07	0.005
-1.0	-5.0		-4.273E-09	-1.421E-06	0.003	-4.27E-09	-1.58E-06	0.003
-2.0	-1.0		-4.568E-06	-3.945E-06	1.16	-4.57E-06	-4.45E-06	1.03
-2.0	-3.0		-5.626E-06	-6.252E-06	0.90	-5.63E-06	-7.02E-06	0.80
-2.0	-5.0		-6.322E-06	-8.751E-06	0.72	-6.32E-06	-9.72E-06	0.65
-3.0	-1.0		-1.547E-05	-1.247E-05	1.24	-1.55E-05	-1.39E-05	1.11
-3.0	-3.0		-2.124E-05	-1.689E-05	1.26	-2.12E-05	-1.88E-05	1.13
-3.0	-5.0		-2.346E-05	-2.031E-05	1.16	-2.35E-05	-2.26E-05	1.04
-4.0	-1.0		-2.579E-05	-2.094E-05	1.23	-2.58E-05	-2.33E-05	1.11
-4.0	-3.0		-4.230E-05	-3.157E-05	1.34	-4.23E-05	-3.51E-05	1.21
-4.0	-5.0		-4.685E-05	-3.513E-05	1.33	-4.69E-05	-3.90E-05	1.20
-5.0	-1.0		-3.489E-05	-2.852E-05	1.22	-3.49E-05	-3.17E-05	1.10
-5.0	-3.0		-6.612E-05	-4.982E-05	1.33	-6.61E-05	-5.54E-05	1.19
-5.0	-5.0		-7.424E-05	-5.264E-05	1.41	-7.42E-05	-5.85E-05	1.27
				AVG Error	4.3%		AVG Error	14.1%
				SD Error	0.52		SD Error	0.46

UnOptimized and Optimized data using Percentage Error method for 38.4x1.6 um PMOS

FET

W = 38.4um & L = 1.6 um			Using the optimized values of Vt = -0.84 V and M = 0.9			Using the default values of Vt = -0.84 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=- 0.84V and M = 0.9	Error Factor Meas. Vs Sim. (SMU/ Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=- 0.84V and M = 1	Error Factor Meas. Vs Sim. (SMU/ Sim)
			Die #3			Die #3		
			(A)	(A)		(A)	(A)	
0.0	-1.0		-2.352E-11	-1.525E-12	15.423	-2.35E-11	-1.63E-12	14.474
0.0	-3.0		-5.100E-11	-4.536E-12	11.244	-5.10E-11	-4.64E-12	10.997
0.0	-5.0		-3.044E-11	-9.623E-12	3.163	-3.04E-11	-9.90E-12	3.075
-1.0	-1.0		-4.813E-07	-1.227E-05	0.039	-4.81E-07	-1.48E-05	0.032
-1.0	-3.0		-9.243E-07	-5.614E-05	0.016	-9.24E-07	-6.45E-05	0.014
-1.0	-5.0		-1.499E-06	-1.216E-04	0.012	-1.50E-06	-1.35E-04	0.011
-2.0	-1.0		-2.193E-04	-2.667E-04	0.82	-2.19E-04	-3.00E-04	0.73
-2.0	-3.0		-2.792E-04	-4.235E-04	0.66	-2.79E-04	-4.75E-04	0.59
-2.0	-5.0		-3.192E-04	-5.883E-04	0.54	-3.19E-04	-6.54E-04	0.49
-3.0	-1.0		-5.838E-04	-5.982E-04	0.98	-5.84E-04	-6.68E-04	0.87
-3.0	-3.0		-8.573E-04	-1.033E-03	0.83	-8.57E-04	-1.15E-03	0.74
-3.0	-5.0		-9.607E-04	-1.286E-03	0.75	-9.61E-04	-1.43E-03	0.67
-4.0	-1.0		-8.772E-04	-8.767E-04	1.00	-8.77E-04	-9.76E-04	0.90
-4.0	-3.0		-1.553E-03	-1.786E-03	0.87	-1.55E-03	-1.99E-03	0.78
-4.0	-5.0		-1.742E-03	-2.127E-03	0.82	-1.74E-03	-2.36E-03	0.74
-5.0	-1.0		-1.122E-03	-1.099E-03	1.02	-1.12E-03	-1.22E-03	0.92
-5.0	-3.0		-2.283E-03	-2.543E-03	0.90	-2.28E-03	-2.83E-03	0.81
-5.0	-5.0		-2.620E-03	-3.097E-03	0.85	-2.62E-03	-3.44E-03	0.76
				AVG Error	32.67%		AVG Error	39.59%
				SD Error	0.36		SD Error	0.32

UnOptimized and Optimized data using Percentage Error method for 57.6x1.6 um PMOS

FET

W = 57.6um L = 1.6 um			Using the optimized values of Vt = -0.84 V and M = 0.9			Using the default values of Vt = -0.84 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=-0.84V and M = 0.9	Error Factor Meas. Vs Sim. (SMU/ Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=-0.84V and M = 1	Error Factor Meas. Vs Sim. (SMU/ Sim)
			Die #3			Die #3		
			(A)	(A)		(A)	(A)	
0.0	-1.0		9.820E-12	-1.525E-12	6.439	9.82E-12	-1.63E-12	6.043
0.0	-3.0		-1.684E-11	-4.543E-12	3.707	-1.68E-11	-4.65E-12	3.624
0.0	-5.0		-1.616E-11	-1.132E-11	1.428	-1.62E-11	-1.18E-11	1.371
-1.0	-1.0		-6.732E-07	-1.942E-05	0.035	-6.73E-07	-2.35E-05	0.029
-1.0	-3.0		-1.245E-06	-8.822E-05	0.014	-1.25E-06	-1.01E-04	0.012
-1.0	-5.0		-2.004E-06	-1.910E-04	0.010	-2.00E-06	-2.12E-04	0.009
-2.0	-1.0		-3.298E-04	-4.132E-04	0.80	-3.30E-04	-4.65E-04	0.71
-2.0	-3.0		-4.179E-04	-6.624E-04	0.63	-4.18E-04	-7.44E-04	0.56
-2.0	-5.0		-4.769E-04	-9.237E-04	0.52	-4.77E-04	-1.03E-03	0.46
-3.0	-1.0		-8.951E-04	-9.162E-04	0.98	-8.95E-04	-1.02E-03	0.88
-3.0	-3.0		-1.303E-03	-1.613E-03	0.81	-1.30E-03	-1.80E-03	0.72
-3.0	-5.0		-1.454E-03	-2.019E-03	0.72	-1.45E-03	-2.24E-03	0.65
-4.0	-1.0		-1.358E-03	-1.338E-03	1.01	-1.36E-03	-1.49E-03	0.91
-4.0	-3.0		-2.385E-03	-2.782E-03	0.86	-2.38E-03	-3.10E-03	0.77
-4.0	-5.0		-2.660E-03	-3.342E-03	0.80	-2.66E-03	-3.71E-03	0.72
-5.0	-1.0		-1.741E-03	-1.674E-03	1.04	-1.74E-03	-1.86E-03	0.94
-5.0	-3.0		-3.511E-03	-3.929E-03	0.89	-3.51E-03	-4.37E-03	0.80
-5.0	-5.0		-3.992E-03	-4.864E-03	0.82	-3.99E-03	-5.40E-03	0.74
				AVG Error	33.79%		AVG Error	40.60%
				SD Error	0.36		SD Error	0.32

UnOptimized and Optimized data using Percentage Error method for 76.8x1.6 um PMOS

FET

W = 76.8um & L = 1.6 um			Using the optimized values of Vt = -0.84 V and M = 0.9			Using the default values of Vt = -0.84 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=- 0.84V and M = 0.9	Error Factor Meas. Vs Sim. (SMU/ Sim)	Ids Measured with dual SMUs	Ids Simulate d w/ Vt=- 0.84V and M = 1	Error Factor Meas. Vs Sim. (SMU/ Sim)
			Die #3			Die #3		
			(A)	(A)		(A)	(A)	
0.0	-1.0		-2.866E-11	-1.525E-12	18.792	-2.87E-11	-1.63E-12	17.636
0.0	-3.0		-1.383E-10	-4.550E-12	30.402	-1.38E-10	-4.66E-12	29.718
0.0	-5.0		-3.167E-10	-1.305E-11	24.271	-3.17E-10	-1.37E-11	23.110
-1.0	-1.0		-6.930E-07	-2.661E-05	0.026	-6.93E-07	-3.22E-05	0.022
-1.0	-3.0		-1.333E-06	-1.205E-04	0.011	-1.33E-06	-1.38E-04	0.010
-1.0	-5.0		-2.186E-06	-2.607E-04	0.008	-2.19E-06	-2.90E-04	0.008
-2.0	-1.0		-4.252E-04	-5.608E-04	0.76	-4.25E-04	-6.32E-04	0.67
-2.0	-3.0		-5.403E-04	-9.053E-04	0.60	-5.40E-04	-1.02E-03	0.53
-2.0	-5.0		-6.181E-04	-1.264E-03	0.49	-6.18E-04	-1.40E-03	0.44
-3.0	-1.0		-1.147E-03	-1.235E-03	0.93	-1.15E-03	-1.38E-03	0.83
-3.0	-3.0		-1.687E-03	-2.195E-03	0.77	-1.69E-03	-2.45E-03	0.69
-3.0	-5.0		-1.885E-03	-2.757E-03	0.68	-1.89E-03	-3.06E-03	0.62
-4.0	-1.0		-1.691E-03	-1.800E-03	0.94	-1.69E-03	-2.00E-03	0.84
-4.0	-3.0		-3.080E-03	-3.783E-03	0.81	-3.08E-03	-4.21E-03	0.73
-4.0	-5.0		-3.444E-03	-4.564E-03	0.75	-3.44E-03	-5.07E-03	0.68
-5.0	-1.0		-2.107E-03	-2.249E-03	0.94	-2.11E-03	-2.50E-03	0.84
-5.0	-3.0		-4.516E-03	-5.317E-03	0.85	-4.52E-03	-5.91E-03	0.76
-5.0	-5.0		-5.152E-03	-6.643E-03	0.78	-5.15E-03	-7.38E-03	0.70
				AVG Error	37.72%		AVG Error	44.12%
				SD Error	0.34		SD Error	0.30

UnOptimized and Optimized data using Average Error Current method for 2.4x1.6 um

PMOS FET.

W = 2.4um & L = 1.6 um			Using the optimized values of Vt = - 0.84 V and M = 0.9			Using the default values of Vt = -0.84 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=-0.84V and M = 0.9	Error Factor Meas. Vs Sim. (SMU- Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=- 0.84V and M = 1	Error Factor Meas. Vs Sim. (SMU- Sim)
			Die #3			Die #3		
			(A)	(A)		(A)	(A)	
0.0	-1.0		-1.800E-11	-1.525E-12	1.65E-11	-1.80E-11	-1.63E-12	1.64E-11
0.0	-3.0		-4.752E-11	-4.525E-12	4.30E-11	-4.75E-11	-4.63E-12	4.29E-11
0.0	-5.0		-7.794E-11	-7.143E-12	7.08E-11	-7.79E-11	-7.14E-12	7.08E-11
-1.0	-1.0		-2.081E-09	-4.498E-08	4.29E-08	-2.08E-09	-5.68E-08	5.47E-08
-1.0	-3.0		-3.160E-09	-5.055E-07	5.02E-07	-3.16E-09	-5.86E-07	5.83E-07
-1.0	-5.0		-4.273E-09	-1.421E-06	1.42E-06	-4.27E-09	-1.58E-06	1.57E-06
-2.0	-1.0		-4.568E-06	-3.945E-06	6.22E-07	-4.57E-06	-4.45E-06	1.21E-07
-2.0	-3.0		-5.626E-06	-6.252E-06	6.26E-07	-5.63E-06	-7.02E-06	1.39E-06
-2.0	-5.0		-6.322E-06	-8.751E-06	2.43E-06	-6.32E-06	-9.72E-06	3.40E-06
-3.0	-1.0		-1.547E-05	-1.247E-05	3.00E-06	-1.55E-05	-1.39E-05	1.55E-06
-3.0	-3.0		-2.124E-05	-1.689E-05	4.36E-06	-2.12E-05	-1.88E-05	2.43E-06
-3.0	-5.0		-2.346E-05	-2.031E-05	3.16E-06	-2.35E-05	-2.26E-05	9.02E-07
-4.0	-1.0		-2.579E-05	-2.094E-05	4.86E-06	-2.58E-05	-2.33E-05	2.49E-06
-4.0	-3.0		-4.230E-05	-3.157E-05	1.07E-05	-4.23E-05	-3.51E-05	7.21E-06
-4.0	-5.0		-4.685E-05	-3.513E-05	1.17E-05	-4.69E-05	-3.90E-05	7.82E-06
-5.0	-1.0		-3.489E-05	-2.852E-05	6.37E-06	-3.49E-05	-3.17E-05	3.20E-06
-5.0	-3.0		-6.612E-05	-4.982E-05	1.63E-05	-6.61E-05	-5.54E-05	1.08E-05
-5.0	-5.0		-7.424E-05	-5.264E-05	2.16E-05	-7.42E-05	-5.85E-05	1.58E-05
				AVG Error	5.85E-06		AVG Error	3.95E-06
				SD Error	6.45E-06		SD Error	4.51E-06

UnOptimized and Optimized data using Average Error Current method for 38.4x1.6 μ m PMOS FET.

W = 38.4 μ m & L = 1.6 μ m			Using the optimized values of Vt = -0.84 V and M = 0.9			Using the default values of Vt = -0.84 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=- 0.84V and M = 0.9	Error Factor Meas. Vs Sim. (SMU- Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=- 0.84V and M = 1	Error Factor Meas. Vs Sim. (SMU- Sim)
			Die #3			Die #3		
			(A)	(A)		(A)	(A)	
0.0	-1.0		-2.352E-11	-1.525E-12	2.20E-11	-2.35E-11	-1.63E-12	2.19E-11
0.0	-3.0		-5.100E-11	-4.536E-12	4.65E-11	-5.10E-11	-4.64E-12	4.64E-11
0.0	-5.0		-3.044E-11	-9.623E-12	2.08E-11	-3.04E-11	-9.90E-12	2.05E-11
-1.0	-1.0		-4.813E-07	-1.227E-05	1.18E-05	-4.81E-07	-1.48E-05	1.44E-05
-1.0	-3.0		-9.243E-07	-5.614E-05	5.52E-05	-9.24E-07	-6.45E-05	6.36E-05
-1.0	-5.0		-1.499E-06	-1.216E-04	1.20E-04	-1.50E-06	-1.35E-04	1.34E-04
-2.0	-1.0		-2.193E-04	-2.667E-04	4.74E-05	-2.19E-04	-3.00E-04	8.11E-05
-2.0	-3.0		-2.792E-04	-4.235E-04	1.44E-04	-2.79E-04	-4.75E-04	1.96E-04
-2.0	-5.0		-3.192E-04	-5.883E-04	2.69E-04	-3.19E-04	-6.54E-04	3.34E-04
-3.0	-1.0		-5.838E-04	-5.982E-04	1.45E-05	-5.84E-04	-6.68E-04	8.38E-05
-3.0	-3.0		-8.573E-04	-1.033E-03	1.75E-04	-8.57E-04	-1.15E-03	2.95E-04
-3.0	-5.0		-9.607E-04	-1.286E-03	3.25E-04	-9.61E-04	-1.43E-03	4.68E-04
-4.0	-1.0		-8.772E-04	-8.767E-04	4.90E-07	-8.77E-04	-9.76E-04	9.84E-05
-4.0	-3.0		-1.553E-03	-1.786E-03	2.33E-04	-1.55E-03	-1.99E-03	4.34E-04
-4.0	-5.0		-1.742E-03	-2.127E-03	3.86E-04	-1.74E-03	-2.36E-03	6.22E-04
-5.0	-1.0		-1.122E-03	-1.099E-03	2.37E-05	-1.12E-03	-1.22E-03	9.83E-05
-5.0	-3.0		-2.283E-03	-2.543E-03	2.61E-04	-2.28E-03	-2.83E-03	5.43E-04
-5.0	-5.0		-2.620E-03	-3.097E-03	4.77E-04	-2.62E-03	-3.44E-03	8.21E-04
				AVG Error	1.70E-04		AVG Error	2.86E-04
				SD Error	1.51E-04		SD Error	2.44E-04

UnOptimized and Optimized data using Average Error Current method for 57.6x1.6 um PMOS FET.

W = 57.6um & L = 1.6 um			Using the optimized values of Vt = -0.84 V and M = 0.9			Using the default values of Vt = -0.84 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=-0.84V and M = 0.9	Error Factor Meas. Vs Sim. (SMU- Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=- 0.84V and M = 1	Error Factor Meas. Vs Sim. (SMU- Sim)
			Die #3			Die #3		
			(A)	(A)		(A)	(A)	
0.0	-1.0		9.820E-12	-1.525E-12	1.13E-11	9.82E-12	-1.63E-12	1.14E-11
0.0	-3.0		-1.684E-11	-4.543E-12	1.23E-11	-1.68E-11	-4.65E-12	1.22E-11
0.0	-5.0		-1.616E-11	-1.132E-11	4.84E-12	-1.62E-11	-1.18E-11	4.38E-12
-1.0	-1.0		-6.732E-07	-1.942E-05	1.87E-05	-6.73E-07	-2.35E-05	2.28E-05
-1.0	-3.0		-1.245E-06	-8.822E-05	8.70E-05	-1.25E-06	-1.01E-04	1.00E-04
-1.0	-5.0		-2.004E-06	-1.910E-04	1.89E-04	-2.00E-06	-2.12E-04	2.10E-04
-2.0	-1.0		-3.298E-04	-4.132E-04	8.33E-05	-3.30E-04	-4.65E-04	1.36E-04
-2.0	-3.0		-4.179E-04	-6.624E-04	2.44E-04	-4.18E-04	-7.44E-04	3.26E-04
-2.0	-5.0		-4.769E-04	-9.237E-04	4.47E-04	-4.77E-04	-1.03E-03	5.49E-04
-3.0	-1.0		-8.951E-04	-9.162E-04	2.11E-05	-8.95E-04	-1.02E-03	1.27E-04
-3.0	-3.0		-1.303E-03	-1.613E-03	3.10E-04	-1.30E-03	-1.80E-03	4.97E-04
-3.0	-5.0		-1.454E-03	-2.019E-03	5.65E-04	-1.45E-03	-2.24E-03	7.90E-04
-4.0	-1.0		-1.358E-03	-1.338E-03	1.97E-05	-1.36E-03	-1.49E-03	1.31E-04
-4.0	-3.0		-2.385E-03	-2.782E-03	3.98E-04	-2.38E-03	-3.10E-03	7.12E-04
-4.0	-5.0		-2.660E-03	-3.342E-03	6.82E-04	-2.66E-03	-3.71E-03	1.05E-03
-5.0	-1.0		-1.741E-03	-1.674E-03	6.74E-05	-1.74E-03	-1.86E-03	1.19E-04
-5.0	-3.0		-3.511E-03	-3.929E-03	4.18E-04	-3.51E-03	-4.37E-03	8.54E-04
-5.0	-5.0		-3.992E-03	-4.864E-03	8.73E-04	-3.99E-03	-5.40E-03	1.41E-03
				AVG Error	2.95E-04		AVG Error	4.69E-04
				SD Error	2.65E-04		SD Error	4.17E-04

UnOptimized and Optimized data using Average Error Current method for 76.8x1.6 um PMOS FET.

W = 76.8um & L = 1.6 um			Using the optimized values of Vt = -0.84 V and M = 0.9			Using the default values of Vt = -0.84 V and M = 1		
Vgs (V)	Vds (V)		Ids Measured with dual SMUs	Ids Simulated w/ Vt=- 0.84V and M = 0.9	Error Factor Meas. Vs Sim. (SMU- Sim)	Ids Measured with dual SMUs	Ids Simulated w/ Vt=- 0.84V and M = 1	Error Factor Meas. Vs Sim. (SMU- Sim)
			Die #3			Die #3		
			(A)	(A)		(A)	(A)	
0.0	-1.0		-2.866E-11	-1.525E-12	2.71E-11	-2.87E-11	-1.63E-12	2.70E-11
0.0	-3.0		-1.383E-10	-4.550E-12	1.34E-10	-1.38E-10	-4.66E-12	1.34E-10
0.0	-5.0		-3.167E-10	-1.305E-11	3.04E-10	-3.17E-10	-1.37E-11	3.03E-10
-1.0	-1.0		-6.930E-07	-2.661E-05	2.59E-05	-6.93E-07	-3.22E-05	3.15E-05
-1.0	-3.0		-1.333E-06	-1.205E-04	1.19E-04	-1.33E-06	-1.38E-04	1.37E-04
-1.0	-5.0		-2.186E-06	-2.607E-04	2.58E-04	-2.19E-06	-2.90E-04	2.87E-04
-2.0	-1.0		-4.252E-04	-5.608E-04	1.36E-04	-4.25E-04	-6.32E-04	2.06E-04
-2.0	-3.0		-5.403E-04	-9.053E-04	3.65E-04	-5.40E-04	-1.02E-03	4.76E-04
-2.0	-5.0		-6.181E-04	-1.264E-03	6.46E-04	-6.18E-04	-1.40E-03	7.86E-04
-3.0	-1.0		-1.147E-03	-1.235E-03	8.71E-05	-1.15E-03	-1.38E-03	2.30E-04
-3.0	-3.0		-1.687E-03	-2.195E-03	5.08E-04	-1.69E-03	-2.45E-03	7.63E-04
-3.0	-5.0		-1.885E-03	-2.757E-03	8.72E-04	-1.89E-03	-3.06E-03	1.18E-03
-4.0	-1.0		-1.691E-03	-1.800E-03	1.08E-04	-1.69E-03	-2.00E-03	3.11E-04
-4.0	-3.0		-3.080E-03	-3.783E-03	7.03E-04	-3.08E-03	-4.21E-03	1.13E-03
-4.0	-5.0		-3.444E-03	-4.564E-03	1.12E-03	-3.44E-03	-5.07E-03	1.63E-03
-5.0	-1.0		-2.107E-03	-2.249E-03	1.42E-04	-2.11E-03	-2.50E-03	3.92E-04
-5.0	-3.0		-4.516E-03	-5.317E-03	8.01E-04	-4.52E-03	-5.91E-03	1.39E-03
-5.0	-5.0		-5.152E-03	-6.643E-03	1.49E-03	-5.15E-03	-7.38E-03	2.23E-03
				AVG Error	4.92E-04		AVG Error	7.45E-04
				SD Error	4.38E-04		SD Error	6.42E-04

Repeatability Data for 38.4x1.6 um NMOS FET

W = 38.4um & L = 1.6 um						Worst case	% Worst case
		6/17/2004	6/17/2004	6/18/2004	6/18/2004	Variation (A)	Variation / Avg I
		Day 1	Day 1	Day 2	Day 2		
Vgs (V)	Vds (V)	Test 1	Test 2	Test 1	Test 2		
		Die #3	Die #3	Die #3	Die #3		
		(A)	(A)	(A)	(A)		
0	1.0	8.660E-11	4.438E-11	1.356E-11	3.436E-11	7.304E-11	163.309%
0	3.0	2.960E-11	3.296E-11	3.494E-11	5.258E-11	2.298E-11	61.247%
0	5.0	9.990E-11	3.604E-11	6.702E-11	9.120E-11	6.386E-11	86.837%
1.0	1.0	2.715E-04	2.715E-04	2.715E-04	2.715E-04	4E-08	0.015%
1.0	3.0	3.178E-04	3.176E-04	3.176E-04	3.180E-04	4.4E-07	0.138%
1.0	5.0	3.548E-04	3.547E-04	3.547E-04	3.548E-04	1.6E-07	0.045%
2.0	1.0	1.526E-03	1.527E-03	1.527E-03	1.528E-03	1.8E-06	0.118%
2.0	3.0	1.763E-03	1.764E-03	1.765E-03	1.765E-03	2E-06	0.113%
2.0	5.0	1.872E-03	1.873E-03	1.874E-03	1.875E-03	2.4E-06	0.128%
3.0	1.0	2.742E-03	2.742E-03	2.744E-03	2.746E-03	4.60E-06	0.168%
3.0	3.0	3.608E-03	3.608E-03	3.612E-03	3.614E-03	6.6E-06	0.183%
3.0	5.0	3.766E-03	3.766E-03	3.771E-03	3.773E-03	7E-06	0.186%
4.0	1.0	3.706E-03	3.705E-03	3.708E-03	3.711E-03	6E-06	0.162%
4.0	3.0	5.595E-03	5.597E-03	5.598E-03	5.602E-03	7E-06	0.125%
4.0	5.0	5.803E-03	5.802E-03	5.804E-03	5.807E-03	4.8E-06	0.083%
5.0	1.0	4.497E-03	4.497E-03	4.502E-03	4.505E-03	7.8E-06	0.173%
5.0	3.0	7.603E-03	7.602E-03	7.609E-03	7.612E-03	1.06E-05	0.139%
5.0	5.0	7.892E-03	7.892E-03	7.898E-03	7.903E-03	1.08E-05	0.137%
						Avg error	0.128%

Repeatability Data for 76.8x1.6 um NMOS FET

W = 76.8um & L = 1.6 um						Worst case	% Worst case
		6/17/2004	6/17/2004	6/18/2004	6/18/2004	Variation (A)	Variation / Avg I
		Day 1	Day 1	Day 2	Day 2		
Vgs (V)	Vds (V)	Test 1	Test 2	Test 1	Test 2		
		Die #3	Die #3	Die #3	Die #3		
		(A)	(A)	(A)	(A)		
0	1.0	2.326E-04	2.329E-04	2.276E-04	2.340E-04	6.36E-06	2.744%
0	3.0	2.852E-04	2.858E-04	2.800E-04	2.870E-04	6.96E-06	2.446%
0	5.0	3.296E-04	3.304E-04	3.239E-04	3.314E-04	7.56E-06	2.299%
1.0	1.0	2.222E-03	2.223E-03	2.222E-03	2.230E-03	8.8E-06	0.396%
1.0	3.0	2.636E-03	2.637E-03	2.635E-03	2.646E-03	1.04E-05	0.394%
1.0	5.0	2.835E-03	2.836E-03	2.834E-03	2.846E-03	1.2E-05	0.423%
2.0	1.0	4.530E-03	4.530E-03	4.538E-03	4.546E-03	1.66E-05	0.366%
2.0	3.0	6.061E-03	6.061E-03	6.068E-03	6.080E-03	1.84E-05	0.303%
2.0	5.0	6.379E-03	6.379E-03	6.386E-03	6.399E-03	2.04E-05	0.319%
3.0	1.0	6.399E-03	6.399E-03	6.416E-03	6.426E-03	2.76E-05	0.431%
3.0	3.0	9.840E-03	9.840E-03	9.860E-03	9.876E-03	3.54E-05	0.359%
3.0	5.0	1.028E-02	1.027E-02	1.029E-02	1.030E-02	3E-05	0.292%
4.0	1.0	7.928E-03	7.927E-03	7.950E-03	7.959E-03	3.16E-05	0.398%
4.0	3.0	1.368E-02	1.368E-02	1.370E-02	1.372E-02	3.6E-05	0.263%
4.0	5.0	1.429E-02	1.428E-02	1.430E-02	1.433E-02	4.2E-05	0.294%
5.0	1.0	9.206E-03	9.204E-03	9.232E-03	9.243E-03	3.9E-05	0.423%
5.0	3.0	1.732E-02	1.732E-02	1.735E-02	1.737E-02	5.20E-05	0.300%
5.0	5.0	1.831E-02	1.830E-02	1.834E-02	1.836E-02	5.8E-05	0.316%
						Avg error	0.352%

Repeatability Data for 38.4x1.6um PMOS FET

W = 38.4um & L = 1.6 um						Worst case	% Worst case
		6/17/2004	6/17/2004	6/18/2004	6/18/2004	Variation (A)	Variation / Avg I
		Day 1	Day 1	Day 2	Day 2		
Vgs (V)	Vds (V)	Test 1	Test 2	Test 1	Test 2		
		Die #3	Die #3	Die #3	Die #3		
		(A)	(A)	(A)	(A)		
0.0	-1.0	-1.542E-11	-3.840E-11	-5.03E-11	-3.134E-11	3.488E-11	-87.021%
0.0	-3.0	-1.768E-11	-3.484E-11	1.940E-12	-8.040E-12	3.29E-11	-187.253%
0.0	-5.0	-3.204E-11	-1.906E-11	-3.948E-11	-5.862E-11	3.956E-11	-106.059%
-1.0	-1.0	-4.972E-07	-4.996E-07	-4.925E-07	-4.924E-07	7.28E-09	-1.469%
-1.0	-3.0	-9.509E-07	-9.520E-07	-9.456E-07	-9.442E-07	7.86E-09	-0.829%
-1.0	-5.0	-1.536E-06	-1.542E-06	-1.528E-06	-1.529E-06	1.34E-08	-0.874%
-2.0	-1.0	-2.170E-04	-2.169E-04	-2.172E-04	-2.171E-04	3.4E-07	-0.157%
-2.0	-3.0	-2.770E-04	-2.768E-04	-2.774E-04	-2.775E-04	6.8E-07	-0.245%
-2.0	-5.0	-3.171E-04	-3.169E-04	-3.177E-04	-3.177E-04	8E-07	-0.252%
-3.0	-1.0	-5.740E-04	-5.722E-04	-5.734E-04	-5.736E-04	1.78E-06	-0.310%
-3.0	-3.0	-8.448E-04	-8.429E-04	-8.463E-04	-8.457E-04	3.38E-06	-0.400%
-3.0	-5.0	-9.483E-04	-9.462E-04	-9.496E-04	-9.492E-04	3.34E-06	-0.352%
-4.0	-1.0	-8.631E-04	-8.632E-04	-8.655E-04	-8.634E-04	2.4E-06	-0.278%
-4.0	-3.0	-1.517E-03	-1.514E-03	-1.512E-03	-1.510E-03	6.6E-06	-0.436%
-4.0	-5.0	-1.703E-03	-1.700E-03	-1.694E-03	-1.695E-03	8.6E-06	-0.506%
-5.0	-1.0	-1.111E-03	-1.109E-03	-1.114E-03	-1.113E-03	4.8E-06	-0.432%
-5.0	-3.0	-2.209E-03	-2.200E-03	-2.210E-03	-2.203E-03	9.8E-06	-0.444%
-5.0	-5.0	-2.513E-03	-2.509E-03	-2.513E-03	-2.511E-03	4.8E-06	-0.191%
						Avg error	-0.478%

Repeatability Data for 76.8x1.6um PMOS FET

W = 76.8um & L = 1.62 um						Worst case	% Worst case
		6/17/2004	6/17/2004	6/18/2004	6/18/2004	Variation (A)	Variation / Avg I
		Day 1	Day 1	Day 2	Day 2		
Vgs (V)	Vds (V)	Test 1	Test 2	Test 1	Test 2		
		Die #3	Die #3	Die #3	Die #3		
		(A)	(A)	(A)	(A)		
0.0	-1.0	-5.846E-11	-4.190E-11	-1.080E-11	-8.018E-11	6.938E-11	-145.040%
0.0	-3.0	-1.595E-10	-1.813E-10	-1.228E-10	-1.640E-10	5.848E-11	-37.273%
0.0	-5.0	-3.101E-10	-3.714E-10	-3.090E-10	-3.300E-10	6.238E-11	-18.895%
-1.0	-1.0	-7.027E-07	-7.052E-07	-7.077E-07	-7.357E-07	3.302E-08	-4.632%
-1.0	-3.0	-1.360E-06	-1.366E-06	-1.372E-06	-1.367E-06	1.22E-08	-0.893%
-1.0	-5.0	-2.229E-06	-2.235E-06	-2.245E-06	-2.234E-06	1.6E-08	-0.716%
-2.0	-1.0	-4.207E-04	-4.209E-04	-4.226E-04	-4.225E-04	1.88E-06	-0.446%
-2.0	-3.0	-5.371E-04	-5.368E-04	-5.389E-04	-5.390E-04	2.2E-06	-0.409%
-2.0	-5.0	-6.154E-04	-6.154E-04	-6.171E-04	-6.174E-04	2.02E-06	-0.328%
-3.0	-1.0	-1.116E-03	-1.118E-03	-1.125E-03	-1.129E-03	1.3E-05	-1.158%
-3.0	-3.0	-1.671E-03	-1.671E-03	-1.682E-03	-1.683E-03	1.2E-05	-0.716%
-3.0	-5.0	-1.873E-03	-1.871E-03	-1.883E-03	-1.882E-03	1.18E-05	-0.629%
-4.0	-1.0	-1.615E-03	-1.616E-03	-1.622E-03	-1.634E-03	1.88E-05	-1.159%
-4.0	-3.0	-3.048E-03	-3.047E-03	-3.064E-03	-3.066E-03	1.9E-05	-0.622%
-4.0	-5.0	-3.414E-03	-3.415E-03	-3.432E-03	-3.435E-03	2.06E-05	-0.602%
-5.0	-1.0	-2.033E-03	-2.027E-03	-2.035E-03	-2.039E-03	1.26E-05	-0.620%
-5.0	-3.0	-4.443E-03	-4.441E-03	-4.461E-03	-4.472E-03	3.12E-05	-0.700%
-5.0	-5.0	-5.091E-03	-5.089E-03	-5.113E-03	-5.121E-03	3.24E-05	-0.635%
						Avg error	-0.951%

Alpha0 calculation.

Vin (V)	Vout (V)			Error Calculation	
	Measured Data	Simulated Data		A0	alpha0)
	Die#1	A0	alpha0	Abs (meas- sim)/sim	Abs (meas- sim)/sim
0	0.030	1.152	1.128	0.974	0.973
0.5	0.481	1.165	1.140	0.587	0.578
1	0.993	1.275	1.260	0.221	0.212
1.5	1.489	1.595	1.590	0.066	0.064
2	2.000	2.058	2.056	0.028	0.027
2.5	2.498	2.530	2.529	0.013	0.012
3	2.987	3.000	3.000	0.004	0.004
3.5	3.465	3.468	3.468	0.001	0.001
4	3.969	3.927	3.928	0.011	0.010
4.5	4.465	4.336	4.342	0.030	0.028
5	4.961	4.605	4.619	0.077	0.074
		Average Error		18.29%	18.04%

Beta0 calculation.

Vin (V)	Vout (V)			Error Calculation	
	Measured Data	Simulated Data		(B0=30)	(B0=300)
	Die#1	($\tilde{\alpha}=30$)	($\tilde{\alpha}=300$)	abs(meas- sim)/sim	abs(meas- sim)/sim
0	0.030	1.152	1.152	0.974	0.974
0.5	0.481	1.165	1.165	0.587	0.587
1	0.993	1.275	1.275	0.221	0.221
1.5	1.489	1.595	1.595	0.066	0.066
2	2.000	2.058	2.058	0.028	0.028
2.5	2.498	2.530	2.530	0.013	0.013
3	2.987	3.000	3.000	0.004	0.004
3.5	3.465	3.468	3.468	0.001	0.001
4	3.969	3.927	3.927	0.011	0.011
4.5	4.465	4.336	4.336	0.030	0.030
5	4.961	4.605	4.605	0.077	0.077
		Average Error		18.29%	18.29%

Delta calculation.

Vin (V)	Vout (V)			Error Calculation	
	Measured Data	Simulated Data		delta=0.01	delta=0.001
	Die#1	delta=0.01	delta=0.001	Abs (meas- sim)/sim	Abs (meas- sim)/sim
0	0.030	1.387	1.385	0.978	0.978
0.5	0.481	1.393	1.391	0.655	0.654
1	0.993	1.420	1.418	0.301	0.300
1.5	1.489	1.633	1.630	0.088	0.086
2	2.000	2.074	2.073	0.035	0.035
2.5	2.498	2.538	2.538	0.016	0.016
3	2.987	3.002	3.002	0.005	0.005
3.5	3.465	3.462	3.463	0.001	0.001
4	3.969	3.928	3.929	0.010	0.010
4.5	4.465	4.338	4.339	0.029	0.029
5	4.961	4.703	4.712	0.055	0.053
		Average Error		19.76%	19.70%

Drout calculation.

Vin (V)	Vout (V)				Error Calculation		
	Measured Data	Simulated Data			Drout=0	Drout=0.5	Drout=1
	Die#1	Drout = 0	Drout = 0.5	Drout = 1	Abs (meas- sim)/sim	Abs (meas- sim)/sim	Abs (meas- sim)/sim
0	0.030	1.387	1.382	0.405	0.978	0.978	0.926
0.5	0.481	1.393	1.388	0.569	0.655	0.654	0.154
1	0.993	1.420	1.416	1.029	0.301	0.299	0.035
1.5	1.489	1.633	1.631	1.519	0.088	0.087	0.020
2	2.000	2.074	2.073	2.011	0.035	0.035	0.005
2.5	2.498	2.538	2.538	2.502	0.016	0.016	0.001
3	2.987	3.002	3.002	2.992	0.005	0.005	0.002
3.5	3.465	3.462	3.463	3.484	0.001	0.001	0.006
4	3.969	3.928	3.929	3.968	0.010	0.010	0.000
4.5	4.465	4.338	4.338	4.429	0.029	0.029	0.008
5	4.961	4.703	4.704	4.831	0.055	0.055	0.027
		Average Error			19.76%	19.71%	10.76%

Due to the large discrepancy between the least percentage error value and the default value, this parameter was left unchanged. The D_{sub} value for the NMOS FET was unchanged, which is 1. Figure below shows the change in the output with respect to the input with different D_{sub} values. Table shows the D_{sub} calculations. Since the D_{sub} value at $D_{sub}= 0.4373$ lowers the curve without affecting the output much at the higher voltage values, this value is chosen for the modeling of the PMOS FETs for the 2-18-03 mask set.

Output curve with different D_{sub} values

Dsub calculation for PMOS FETs.

Vin (V)	Vout (V)				Error Calculation		
	Measured Data	Simulated Data			Dsub - 0.2873	Dsub - 0.4373	Dsub - 0.4873
	Die#1	Dsub - 0.2873	Dsub - 0.4373	Dsub - 0.4873	Abs (meas-sim)/sim	Abs (meas-sim)/sim	Abs (meas-sim)/sim
0	0.030	1.387	0.687	0.548	0.978	0.956	0.945
0.5	0.481	1.393	0.763	0.651	0.655	0.369	0.261
1	0.993	1.420	1.090	1.054	0.301	0.089	0.058
1.5	1.489	1.633	1.530	1.521	0.088	0.027	0.021
2	2.000	2.074	2.019	2.013	0.035	0.009	0.006
2.5	2.498	2.538	2.507	2.504	0.016	0.004	0.002
3	2.987	3.002	2.996	2.996	0.005	0.003	0.003
3.5	3.465	3.462	3.482	3.485	0.001	0.005	0.006
4	3.969	3.928	3.969	3.974	0.010	0.000	0.001
4.5	4.465	4.338	4.415	4.432	0.029	0.011	0.008
5	4.961	4.703	4.777	4.788	0.055	0.039	0.036
		Average Error			19.76%	13.75%	12.24%

Nfactor calculation.

Vin (V)	Vout (V)			Error Calculation	
	Measured Data	Simulated Data		NMOS- 0.57404 PMOS - 0.25083	NMOS - 0.03858 PMOS = 0.15974
	Die#1	NMOS- 0.57404 PMOS - 0.25083	NMOS - 0.03858 PMOS = 0.15974	Abs (meas-sim)/sim	Abs (meas-sim)/sim
0	0.030	1.348	1.354	0.978	0.978
0.5	0.481	1.355	1.361	0.645	0.647
1	0.993	1.383	1.389	0.282	0.285
1.5	1.489	1.611	1.613	0.076	0.077
2	2.000	2.064	2.065	0.031	0.032
2.5	2.498	2.526	2.528	0.011	0.012
3	2.987	2.995	2.996	0.003	0.003
3.5	3.465	3.463	3.463	0.001	0.001
4	3.969	3.910	3.910	0.015	0.015
4.5	4.465	4.325	4.323	0.032	0.033
5	4.961	4.716	4.714	0.052	0.052
		Average Error		19.32%	19.40%

PCLM calculation.

Vin (V)		Vout (V)			Error Calculation		
	Measured Data	Simulated Data			PCLM= 1e-9	PCLM = 1e-10	PCLM = 1e-11
	Die#1	PCLM= 1e-9	PCLM = 1e-10	PCLM = 1e-11	abs(meas- sim)/sim	abs(meas- sim)/sim	abs(meas- sim)/sim
0	0.030	1.387	1.387	1.387	0.978	0.978	0.978
0.5	0.481	1.393	1.393	1.393	0.655	0.655	0.655
1	0.993	1.420	1.420	1.420	0.301	0.301	0.301
1.5	1.489	1.633	1.633	1.633	0.088	0.088	0.088
2	2.000	2.074	2.074	2.074	0.035	0.035	0.035
2.5	2.498	2.538	2.538	2.538	0.016	0.016	0.016
3	2.987	3.002	3.002	3.002	0.005	0.005	0.005
3.5	3.465	3.462	3.462	3.462	0.001	0.001	0.001
4	3.969	3.928	3.928	3.928	0.010	0.010	0.010
4.5	4.465	4.338	4.338	4.338	0.029	0.029	0.029
5	4.961	4.703	4.703	4.703	0.055	0.055	0.055
					19.76%	19.76%	19.76%

PSCBE1 and PSCBE2 calculation.

Vin (V)	Vout (V)			Error Calculation	
	Measured Data	Simulated Data		Default	PSCBE1 (NMOS/PMOS)- 1E30 PSCBE2 (NMOS/PMOS)- 0
	Die#1	Default	PSCBE1 (NMOS/PMOS)- 1E30 PSCBE2 (NMOS/PMOS)- 0	Abs (meas-sim)/sim	Abs (meas-sim)/sim
0	0.030	1.152	1.152	0.974	0.974
0.5	0.481	1.165	1.165	0.587	0.587
1	0.993	1.275	1.275	0.221	0.221
1.5	1.489	1.595	1.595	0.066	0.066
2	2.000	2.058	2.058	0.028	0.028
2.5	2.498	2.530	2.530	0.013	0.013
3	2.987	3.000	3.000	0.004	0.004
3.5	3.465	3.468	3.468	0.001	0.001
4	3.969	3.927	3.927	0.011	0.011
4.5	4.465	4.336	4.336	0.030	0.030
5	4.961	4.605	4.605	0.077	0.077
				18.29%	18.29%

u0 (NMOS) calculation.

Vin (V)	Vout (V)					Error Calculation			
	Meas Data	Dsub (PMOS - 0.4373) Simulated Data				u0=620 Default	u0=1000	u0=5000	u0=10000
	Die#1	u0=620 Default	u0-1000	u0-5000	u0-10000	abs(meas-sim)/ sim	abs(meas-sim)/ sim	abs(meas-sim)/ sim	abs(meas-sim)/ sim
0	0.030	0.687	0.537	0.373	0.352	0.956	0.944	0.920	0.915
0.5	0.481	0.763	0.651	0.583	0.570	0.369	0.262	0.175	0.156
1	0.993	1.090	1.054	1.021	1.016	0.089	0.058	0.027	0.022
1.5	1.489	1.530	1.525	1.513	1.505	0.027	0.023	0.016	0.010
2	2.000	2.019	2.014	2.002	1.997	0.009	0.007	0.001	0.002
2.5	2.498	2.507	2.505	2.495	2.490	0.004	0.003	0.001	0.003
3	2.987	2.996	2.995	2.987	2.983	0.003	0.003	0.000	0.001
3.5	3.465	3.482	3.483	3.474	3.472	0.005	0.005	0.003	0.002
4	3.969	3.969	3.970	3.965	3.950	0.000	0.000	0.001	0.005
4.5	4.465	4.415	4.425	4.336	4.263	0.011	0.009	0.030	0.047
5	4.961	4.777	4.737	4.452	4.340	0.039	0.047	0.114	0.143
				Average Error		13.75%	12.37%	11.71%	11.88%

u0 (PMOS) calculation.

Vin (V)	Vout (V)					Error Calculation			
	Meas Data	Dsub (PMOS - 0.4373) Simulated Data				u0=50	u0=100	u0=236 Default	u0=500
	Die#1	u0=50	u0=100	u0=236 (default)	u0=500	Abs (Meas-Sim)/ Sim	Abs (Meas-sim)/ sim	Abs (Meas-sim)/sim	Abs (Meas-sim)/ Sim
0	0.030	0.396	0.468	0.687	1.133	0.924	0.936	0.956	0.974
0.5	0.481	0.589	0.619	0.763	1.141	0.184	0.223	0.369	0.578
1	0.993	1.026	1.040	1.090	1.232	0.032	0.045	0.089	0.194
1.5	1.489	1.512	1.519	1.530	1.546	0.015	0.020	0.027	0.037
2	2.000	2.004	2.010	2.019	2.030	0.002	0.005	0.009	0.015
2.5	2.498	2.496	2.501	2.507	2.516	0.001	0.001	0.004	0.007
3	2.987	2.989	2.992	2.996	3.000	0.001	0.002	0.003	0.004
3.5	3.465	3.478	3.480	3.482	3.483	0.004	0.004	0.005	0.005
4	3.969	3.968	3.969	3.969	3.967	0.000	0.000	0.0001	0.001
4.5	4.465	4.344	4.422	4.415	4.394	0.028	0.010	0.011	0.016
5	4.961	4.437	4.657	4.777	4.808	0.118	0.065	0.039	0.032
				Average Error		11.89%	11.92%	13.75%	16.93%

Saturation Current (IS) calculation.

Vin (V)	Vout (V)			Error Calculation	
	Measured Data	Simulated Data		IS=0	IS= 1E-14
	Die#1	IS=0	IS= 1E-14	$\frac{\text{abs(meas-sim)}}{\text{sim}}$	$\frac{\text{abs(meas-sim)}}{\text{sim}}$
0	0.030	1.152	1.152	0.974	0.974
0.5	0.481	1.165	1.165	0.587	0.587
1	0.993	1.275	1.275	0.221	0.221
1.5	1.489	1.595	1.595	0.066	0.066
2	2.000	2.058	2.058	0.028	0.028
2.5	2.498	2.530	2.530	0.013	0.013
3	2.987	3.000	3.000	0.004	0.004
3.5	3.465	3.468	3.468	0.001	0.001
4	3.969	3.927	3.927	0.011	0.011
4.5	4.465	4.336	4.336	0.030	0.030
5	4.961	4.605	4.605	0.077	0.077
		Average Error		18.29%	18.29%

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