R.L. Oliveira Pinto, F. Maloberti: "**X ray and blue print: tools for mosfet analog circuit design addressing short-channel effects**"; Proc. of the 2004 International Symposium on Circuits and Systems, ISCAS 2004, Vol. 5, 23-26 May 2004, pp. 277-280.

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X RAY AND BLUE PRINT: TOOLS FOR MOSFET ANALOG CIRCUIT DESIGN ADDRESSING SHORT-CHANNEL EFFECTS

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ABSTRACT

An automatic engine built in the Java language designs transistors in few and easy steps. The results come from a combination of parameter extraction and simple analytical models that address the short-channel effects by referring them to the Early voltage. The outcome is precise output conductance, thermal noise coefficient and thermal noise from a friendly graphical user interface. Design and simulations of common-source amplifiers show the efficiency of the automation.

1. INTRODUCTION

Automation of analog circuits has been a hot topic for the past few years [1, 2], yet the analog designers still rely basically on circuit simulators and layout editors to accomplish their goals. There are solutions for complete sizing of MOSFET circuits, however, requiring manual modeling for further automation [3]. Circuit level design tools hide their methods from the analog designers who prefer to use their own design procedures [1]. Here we propose automation at transistor level by providing access to precise values of the main parameters of an amplifier to be used at the circuit level design.

Two design tools implemented in Java aid the designer to size MOSFET's for analog circuits. The first tool, which is called X Ray, extracts amplifier parameters mainly based on the inversion level [4, 5, 6, 7]. The second tool, which is called Blue Print, combines the data points from X Ray and analytical expressions [8] to size the transistors.

This paper describes the tools and the basis of the automation [8] as well as presents designs and simulation results to validate the method.

2. X RAY

X Ray is a program that extracts the Early voltage V_A , thermal noise coefficient γ , and thermal noise i_d^2 based on a given range of inversion level i_f , drain-to-source-voltage V_{DS} and channel length L , for a specific technology, temperature T and channel

type (N or P). The correct values of Early voltage are fundamental to design DC gain. Also, good prediction of the thermal noise is important to properly reduce its value in any amplifier design.

The main parameter extracted is the Early voltage for each point of each drain current because it reflects all the short channel effects modeled in the mobility and channel length [8], as equations (1) to (3) demonstrate. Equation (1) is the drain current I_D for hand design purposes. It is function of the gate-to-source voltage V_{GS} and drain-to-source voltage V_{DS} working with a constant Early voltage. V_{DSsat} is V_{DS} in the saturation point. μ is the mobility, C'_{ox} is the oxide capacitance per unit area, and V_T is the threshold voltage. The geometry is given by the channel width W and length L . Equation (2) is a simplified model of I_D for simulation purposes where μ and L are replaced by μ_{EFF} and L_{EFF} , respectively effective mobility and length, both containing short-channel effects. From (1) and (2) it is straightforward to find (3) and see that it is possible to refer the short-channel effects of μ_{EFF} and L_{EFF} to V_A .

$$I_D = \frac{C'_{ox}}{2} \frac{W}{L} (V_{GS} - V_T)^2 \left(\frac{V_{DS} - V_A}{V_{DSsat} - V_A} \right) \quad (1)$$

$$I_D = \left(\frac{\mu_{EFF}}{L_{EFF}} \right) \frac{C'_{ox}}{2} W (V_{GS} - V_T)^2 \quad (2)$$

$$\frac{\mu_{eff}}{L_{eff}} = \frac{\mu}{L} \left(\frac{V_{DS} - V_A}{V_{DSsat} - V_A} \right) \quad (3)$$

The designer can work directly with points of V_A during the hand design instead of complicated models of μ_{EFF} and L_{EFF} , however, the problem now is how to determine the space of extraction of V_A that is applicable to as many designs as possible. The Early voltage depends on i_f , V_{DS} , L and T [9]. The inversion level and drain-to-source voltage have practical physical limits that naturally establish a space of extraction: i_f between 1 and 1000, which means from weak to strong inversion, and V_{DS} between 0V and the maximum voltage supply. We can normalize the channel length by the minimum length L_{MIN} and define a maximum normalized length for a particular design, for instance L/L_{MIN} equals to 9. The temperature is kept fixed. Once the points of V_A are extracted they can be stored and used for several designs because i_f is

R. L. Oliveira Pinto is sponsored by CAPES, research agency of the Brazilian Ministries of Science and Technology and Education.

independent of geometry [4], and VA is not a function of the channel width W [9].

For design purposes, all the transistors that have the same i_f can share the same set of curves. The geometry is adjusted according to the drain current needed by using equations (4) and (5) [4], where I_s is the normalization current, n is the slope factor, and ϕ_t is the thermal voltage.

$$i_f = \frac{I_D}{I_s} \quad (4) \quad I_s = n C'_{ox} \frac{\phi_t^2 W}{2 L} \quad (5)$$

Figure 1 presents the X Ray user interface showing its input and output areas.

The input area accepts steps of normalized channel length, as well as steps of inversion level. The minimum length for normalization has its respective field. V_{DS} receives a maximum range and resolution. The button "Load Model" opens a file chooser dialog box to assign a Spice transistor model to the system. An input field receives the temperature, and a radio button selects the channel type. Because i_f is independent of geometry, the system has a single transistor width as input.

Figure 1. X Ray Graphical User Interface

An internal simulation module generates a Spice file and runs a simulator whose result is a set of drain currents for each channel length and inversion level for a given range of drain-to-source voltage. The set of VA's extracted will reflect the short channel effects of the mosfet model and simulator used. The current implementation of X Ray runs Spectre, however, it could be any other Spice-like simulator in any platform that has the Java virtual machine installed.

The output area presents the results in sets of curves where each set is for one i_f . Figure 1 shows VA0 that is the Early voltage for $i_f=1$ where VA is in the y axis and V_{DS} is in the x axis. Each curve is for one step of L/L_{MIN} .

The thermal noise coefficient and thermal noise presented by X Ray follow expressions (6) and (7) [8], where q is the electronic charge and Δf is the bandwidth. The short-channel effects for γ and i_d^2 are taken into account by assigning VA for each i_f and V_{DS} in (6) and (7). Likewise γ and i_d^2 , the intrinsic

cut-off frequency f_T that accounts short-channel effects also comes from a mixture of an analytical model, equation (8) [8], and data points of VA.

$$\gamma_{sat} = \frac{1}{3} \left(2 + \frac{1}{i_f} - \frac{\sqrt{1+i_f}}{i_f} \right) \left(\frac{V_{DS} - VA}{V_{DSsat} - VA} \right) \quad (6)$$

$$\frac{i_d^2}{8qI_s\Delta f} = \gamma(\sqrt{1+i_f} - 1) \quad (7)$$

$$f_T = \frac{\phi_t}{2\pi L^2} 2(\sqrt{1+i_f} - 1) \left(\frac{V_{DS} - VA}{V_{DSsat} - VA} \right) \quad (8)$$

For the hand design, the user can pick VA, γ and f_T from the graphics for a given i_f , V_{DS} and L [8]. Graphics for i_d^2 are also available, however, requiring adjustments according to the width needed. Another option is to size the transistor by means of Blue Print, as shown in the next section.

3. BLUE PRINT

Blue Print is an experimental calculator attached to X Ray that presents all the trade-offs involving a single transistor design by imitating the hand calculation process. Table 1 shows the expressions implemented by Blue Print, where some are analytical equations [4] while others are data points provided by X Ray. In both cases the variables involved are the ones required to design MOSFET amplifiers: the gate transconductance g_m , and the output resistance r_o , besides the ones already mentioned for noise, geometry, current, intrinsic cut-off frequency, and Early voltage. The analytical models used here work continuously from weak to strong inversion, hence, easy to be implemented for calculation purposes once there is no need of any interpolation function. The Blue Print graphical user interface shows only the design variables and hides the constants n , C'_{ox} , ϕ_t . Figure 2 shows the interface, where each row represents a variable and each column one of the relations from Table 1.

The numbers given by Blue Print will be tailored for the simulator, technology and transistor model used by X Ray, even though the design equations [4] are different from the model used by the simulator. This approach is based on the assumption that the long channel transistor models should have similar behavior, both the ones that use any interpolation function to fill the gap between weak and strong inversion and those that work continuously, being the Early voltage the only parameter needed to be extracted in order to address short-channel effects for each particular model.

To design a transistor the user enters the desired value in the respective field and pushes one of the buttons in that row. If only one variable is left in that column, this variable is immediately determined. If one single variable is left in any other column as well, this one is also automatically calculated. This process continues until either more than one variable is left or all parameters are determined. One major advantage in the Blue Print is the fact that the numbers can be entered in any sequence, therefore providing to the designer freedom to choose what are the main parameters for that particular design, i.e.,

there is no preset design procedure. For instance, in the relation between V_{DSsat} and i_f , the designer can either enter first V_{DSsat} and then i_f or vice versa, the first one entered determines the other one. The designs are stored in the draft area under the calculator. Once the design is finished the user can reset the calculator and start another design.

The system supports several instances of both X Ray and Blue Print opened simultaneously, hence, allowing on the same screen the design of many transistors of N and P channels. This is a desirable feature while designing several transistors.

Table 1. Equations implemented in the Blue Print

Index	Expressions	Relations
1	$\frac{n\phi_s g_m}{I_D} = \frac{2}{1 + \sqrt{1 + i_f}}$	g_m, I_D, i_f
2	$i_f = \frac{I_D}{nC_{ox} \frac{\phi_s^2}{2} \frac{W}{L}}$	I_D, i_f, W, L
3 (data points)	$f_T = f(i_f, V_{DS}, L)$	i_f, L, f_T, V_{DS}
4	$\frac{V_{DSsat}}{\phi_s} = (\sqrt{1 + i_f} - 1) + 4$	i_f, V_{DSsat}
5 (data points)	$VA = f(i_f, V_{DS}, L)$	i_f, L, V_{DS}, VA
6	$r_o = \frac{VA}{I_D}$	I_D, VA, r_o
7 (data points)	$\gamma = f(i_f, V_{DS}, L)$	i_f, L, V_{DS}, γ
8 (data points)	$i_d^2 = f(i_f, V_{DS}, L, W)$	i_f, W, L, V_{DS}, i_d^2

Figure 2. Blue Print Graphical User Interface

To access the data points the tool performs a simple linear interpolation between the points in the available range of values. If a certain value is out of range an error message is given. The precision, of course, will depend on the resolution of the points. This is why it is called Blue Print.

One can notice that depending on the sequence we can find more than one result for a certain parameter. It is also possible a different arrangement for the equations. For multiple results Blue Print takes the first one found. A better equation arrangement is a subject for another kind of study. The difficulties and constraints of a transistor level design, though, are clearly seen. The knowledge gained with this tool can help to create engines for circuit level design in the future.

In short, Blue Print automatically performs the hand calculation design that would require manipulation of several equations and manual reading of graphics.

4. DESIGNS AND SIMULATION RESULTS

This section compares results from X Ray / Blue Print with simulations using BSIM 3v3 of a common-source amplifier as the one seen in Figure 3. The technology used was TSMC25, $L_{MIN}=0.3 \mu m$, run T21Q (MM_NON-EPI). We extracted the parameters for both N and P channels using i_f equals 1, 30, 100, 300 and 1000, L/L_{MIN} equals 1, 1.2, 1.4, 1.6, 1.8, 2, 3, 4, 5, 6, 7, 8 and 9, V_{DS} from 0 to 3V with 0.3V step, width equals 1 μm , the minimum technology length and temperature of 300K.

Figure 3. Common-Source (CS) Amplifier

Table 2 shows a design of a common source amplifier to compare the values given by Blue Print and the ones found in the simulations regarding the DC gain A_{vo} of the amplifier. The Blue Print column presents the steps used for the design, actually the ones input in the calculator, and the respective results. The first transistor designed was the NMOS, with i_f , W and L/L_{MIN} arbitrarily chosen. The V_{DS} , required in this method [8], is half of the voltage supply, V_{DD} to V_{SS} , of 1.5V. Among several other parameters, we primarily focus on g_m , and VA once they are directly related to the gain, as equations (9) and (10) [8] show, and I_D because it is needed to design the PMOS. W and VA are the main parameters for the P transistor, whose design also requires V_{DS} [8].

$$A_{vo} = \frac{g_{m1}}{g_{o1} + g_{o2}} \quad (9)$$

$$A_{vo} = \frac{1}{\phi_s n} \left(\frac{2}{\sqrt{1 + i_{f1}} + 1} \right) \left(\frac{1}{1/VA_1 + 1/VA_2} \right) \quad (10)$$

The design and simulations values agree fairly well. The Early voltages given by the simulations are very close to the ones provided by Blue Print, proving that the information of VA of a 1 μm width transistor can be used for any width. The theoretical and simulated DC gains are, respectively, 25 and 37. Overall, the numbers quickly provided by Blue Print matched the ones found in the simulations.

Access to the short-channel effects of the thermal noise that are usually evaluated only during the simulations is desirable during the hand calculation design [8]. Table 3 compares the design and simulation of the CS amplifier for several voltage supplies. We chose this criterion due to the influence of V_{DS} on VA , and the correlation of VA with the thermal noise, as seen in equations (6) and (7) [8]. The parameters needed to calculate the noise are those given by Equation (11), which takes into

account the short-channel effects based on data points of i_{d1}^2 , i_{d2}^2 , and VA_1 , this last one to model those effects in g_{m1} [8]. Equation (11) also keeps the V_{DSsat} , which is normally ignored while calculating the influence of VA , because it presented better results for the noise.

The design for the NMOS was based on i_f equals 300, W of 12.525 μm , minimum length, and the steps of V_{DS} presented in Table 3. The g_m for the NMOS is 2.51mA/V, whose i_{d1}^2 and VA_1 are the ones seen in Table 3. The PMOS design also used i_f of 300, I_D equals 7.76 A, this one from the NMOS design, minimum length, and the same steps of V_{DS} . The final width for the PMOS was 35 μm and the values for i_{d2}^2 are also found in Table 3.

Table 2. CS Amplifier Design and Simulations for A_{vo}

Blue Print		Simulations	
N	P	N	P
Steps: 1: $i_f=30$ 2: $W=50 \mu m$ 3: $L=0.42 \mu m$ 4: $V_{DS}=0.75V$ Results: $g_m=2.0mA/V$ $I_D=221 A$ $VA=-3.64V$	Steps: 5: $i_f=30$ 6: $I_D=221 A$ 7: $L=0.42 \mu m$ 8: $V_{DS}=0.75V$ Results: $W=136 \mu m$ $VA=-10.7V$	$i_f=32.8$ $W=50.025 \mu m$ $L=0.45 \mu m$ $V_{DS}=0.51V$ $g_m=2.81mA/V$ $I_D=227.2 A$ $VA=-3.95V$	$i_f=32.8$ $I_D=227.2 A$ $L=0.45 \mu m$ $V_{DS}=0.99V$ $W=140 \mu m$ $VA=-13.44V$

Table 3. Noise: Blue Print X Simulations.

	Blue Print			Eq. (11)	Simul.
V_{DS} (V)	i_{d1}^2 $\left(\frac{A^2}{Hz}\right)$	i_{d2}^2 $\left(\frac{A^2}{Hz}\right)$	VA_1 (V)	$\sqrt{V_{Nin}^2}$ $\left(\frac{nV}{\sqrt{Hz}}\right)$	$\sqrt{V_{Nin}^2}$ $\left(\frac{nV}{\sqrt{Hz}}\right)$
0.9	3.68e-23	3.70E-23	-5.77	3.232	3.193
1.2	3.80e-23	3.68E-23	-6.75	3.155	3.172
1.5	3.91e-23	3.70E-23	-7.24	3.089	3.137
1.8	4.03e-23	3.73E-23	-7.46	3.028	3.115
2.1	4.16e-23	3.76E-23	-7.55	2.968	3.099
2.4	4.28e-23	3.79E-23	-7.56	2.907	3.089

Figure 4. Noise for several values of V_{DS} .

$$V_{N,in}^2 = (i_{d1}^2 + i_{d2}^2) \frac{1}{\left(g_{m1} \left(\frac{V_{DS1} - VA_1}{V_{DSsat1} - VA_1} \right)\right)^2} \quad (11)$$

Calculations and simulations, again, are very close. Figure 4 shows the graphics of the noise for each V_{DS} presented in Table

3. The thermal noise using the long channel model would be 2.865nV/ $\sqrt{Hz}$. The design model for the thermal noise with the short-channel effects is more precise than the long channel one.

5. CONCLUSIONS

This paper has presented an alternative approach to address short-channel effects for analog design by mixing analytical expression with data points. Short-channel effects were referred to the Early voltage. An engine for extraction of the Early voltage based in a well defined design space and calculation of thermal noise coefficient and thermal noise, as well as a tool for transistor level design were successfully implemented and tested. Theoretical and simulated results were compared and showed very good agreement, therefore, confirming the efficiency of the design method. The results presented here, for transistor level design, can be used as basis to build circuit level design tools.

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