Analog Design Tool based on the ACM model

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ABSTRACT

This paper presents MOSVIEW, a CAD tool for transistor-level analog design, which is based on the Advanced Compact MOSFET (ACM) model, derived from physics. MOSVIEW allows designers to size and bias the MOS transistor for a given set of specifications. A friendly graphical interface provides MOSVIEW users with a distinctive set of curves from which the design space is readily identified. MOSVIEW allows the designer to easily visualize solutions to his/her design and also optimize circuit performance. Design examples demonstrate the applicability of MOSVIEW as a powerful learning tool.

I. INTRODUCTION

To comply with the increasing complexity of chips and the trend to include sensors and communication interfaces inside them, most integrated circuits will have analog components in the near future [1]. The multiplicity of performance specifications, the dependence of circuit behavior on technology variations, the diversity of element sizes and shapes make the analog design problem difficult. The natural difficulties of analog design are worsened by the lack of good device models implemented in circuit simulators and by the fact that most modern electrical engineering curricula do not provide adequate preparation for analog design.

Circuit topology and transistor bias current and dimensions are basic factors that determine the performance of an analog circuit. Frequency response, voltage gain, output voltage swing, power dissipation, slew rate, and silicon area are some of the performance metrics of analog circuits. The transistor-level design problem that we deal with in this paper consists of determining bias currents, channel widths and channel lengths such that the specifications are met. The sizing method presented here, like those in [3], [4], is based on the transconductance efficiency g_m/I_D.

To assist designers with the use of our methodology, we developed MOSVIEW. The current version of MOSVIEW is based on the ACM model, which is fully derived from physics and can be applied to any CMOS process. Using the ACM model, the performance of MOS circuits can be written in terms of bias currents and channel width and length. A valuable characteristic of MOSVIEW is its graphical interface, described by a plane that exhibits the channel length as the abscissa and the intrinsic low-frequency gain as the ordinate. Families of curves of constant performance (transition frequency, saturation voltage, noise corner frequency, etc) can be plotted and the region denominated design space is identified as that which meets the input specifications. With MOSVIEW, designers can easily analyze design tradeoffs and develop an intuition about transistor sizing for analog circuits. In addition, MOSVIEW can guide the designer to the solution to the problem thus reducing time-consuming simulations.

Section II presents the interpretation of the drain current as the combination of forward and reverse currents. In Section III, we revisit the design of common-source amplifiers. Section IV describes MOSVIEW and illustrates its use for some design examples. Finally, Section V summarizes the contribution of this work.

II. THE DRAIN CURRENT OF MOSFETS

In a long-channel transistor, the drain current, resulting from both the drift and diffusion transport mechanisms, is given in [6], [8], [9] as

$$I_D = I_F - I_R = I(V_G, V_S) - I(V_G, V_D) \quad (1a)$$

$$I_{F(R)} = I_S . i_{f(r)} \quad (1b)$$

$$I_S = \mu C'_{ox} n \phi_t^2 \frac{W}{2L} \quad (1c)$$

where μ is the carrier mobility, ϕ_t is the thermal voltage, C'_{ox} is the gate oxide per unit area, W is the channel width and L is the channel length. n is the slope factor. For the remaining part of the paper, n will be taken as a constant. $I_{F(R)}$ is the forward (reverse) saturation current evaluated at the source (drain) end; $i_{f(r)}$ is the normalized forward (reverse) current or inversion level while I_S is the specific current or normalization current [5], [6]. Equation (1a) emphasizes the source-drain symmetry of the MOSFET [5]-[8], i.e. if the drain and source ends of an integrated transistor are interchanged, the drain current changes direction but its value remains the same.

Fig. 1 illustrates the definitions of the forward and reverse components of the drain current. Note that there is a region, usually called the saturation region, where the drain current is almost independent of V_D. This means that, in the saturation region, $I(V_G, V_S) >> I(V_G, V_D)$. Therefore, $I(V_G, V_S)$ can be interpreted as the drain current in forward saturation.

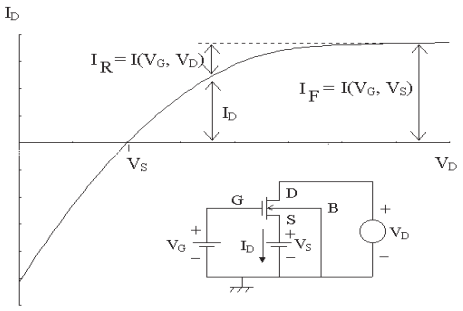

Fig. 1. Output characteristic of a long-channel NMOS transistor for constant V_S and V_G.

The expression relating the normalized components of the current and applied voltages is given in [6], [8] as

$$\frac{V_G - V_T}{n\phi_t} - \frac{V_{S(D)}}{\phi_t} = \sqrt{1+i_{f(r)}} - 2 + \ln\left(\sqrt{1+i_{f(r)}} - 1\right) \qquad (2)$$

The voltages in expression (2) are referred to the substrate. It is worthwhile noting the asymptotic cases of expression (2). In strong inversion at both drain and source ends, the inversion levels are much greater than one and expression (2) reduces to the conventional dependence of the current on the squared voltage. On the other hand, in the so-called weak inversion region, the inversion level is less than one and the current varies exponentially with the applied voltages.

III. THE COMMON-SOURCE AMPLIFIER

In this section, we present a design methodology for integrated MOS amplifiers using the ACM model. The design procedure accounts for the specifications of capacitive load (C_L), gain-bandwidth product (GB), DC voltage gain (A_{VO}) and voltage swing. This methodology allows the designer to choose the bias current and transistor dimensions from closed expressions. The design approach proposed here, which has been applied to the design of common-source amplifiers, can be extended to more complex topologies such as differential and operational amplifiers.

A. Voltage gain and bandwidth

In order to provide the readers with some insight into the design of a simple analog circuit, let us consider the common-source amplifier depicted in Fig. 2. The maximum voltage gain achievable with a single transistor is limited by its source-to-drain conductance g_{ds}, which is approximately proportional to the ratio of the drain current to the channel length, i. e., $g_{ds}=I_D/V_E L$. Here, V_E is the Early voltage per unit length, which in this work is supposed to be dependent on technology and independent of both current and L. Thus, A_{vo}, the absolute value of the low-frequency voltage gain of the common source amplifier shown in Fig. 2 can be written as

$$A_{vo} = \frac{g_m}{g_{ds}} = \frac{g_m}{I_D} V_E L \qquad (3)$$

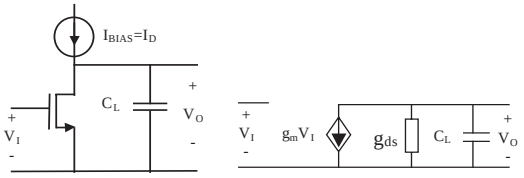

Fig. 2. Common-source amplifier and simplified small-signal model.

In the ideal common-source amplifier shown in Fig. 2, the transconductance required for a gain-bandwidth equal to GB is

$$g_m = 2\pi GB C_L \qquad (4)$$

In the derivation that follows, we assume that the transconductance is fixed and given by (4). The effect of the drain parasitic capacitance can be absorbed by the load capacitance.

For the purpose of developing our CAD tool, we have assumed that the MOSFET intrinsic cutoff frequency f_T must be greater than four times the value of the gain-bandwidth product to avoid non-quasi-static effects [9].

According to the ACM model [6], [8] one can calculate the transconductance of MOSFETs operating in the saturation regime from

$$\frac{n\phi_t g_m}{I_D} = \frac{2}{1 + \sqrt{1 + i_f}} \qquad (5)$$

In (5), $i_f=I_D/I_S$. The transconductance-to-current ratio of the MOSFET given by (5) is a universal relationship, valid for any technology, dimensions and temperature. The transconductance g_m depends on both the drain current I_D and the normalized drain current [5], [6] or inversion level i_f at source. The voltage gain A_{VO} as a function of the channel length is readily calculated from (3) and (5)

$$A_{V0} = \frac{V_E L}{n\phi_t} \frac{2}{\sqrt{1+i_f} + 1} \qquad (6)$$

Using the results of [12], the dependence of the voltage gain on both channel-length and cutoff frequency is written as

$$A_{V0} = \frac{V_E L}{n\phi_t} \frac{1}{1 + \frac{\pi L^2}{2\mu\phi_t} f_T} \qquad (7)$$

B. Design space

Let us now plot the normalized voltage gain in terms of the normalized channel-length. We have chosen the minimal channel-length (L_{min}) of the technology as the normalization length and the DC voltage gain ($V_E L_{min}/n\phi_t$) of a minimal-length transistor operating

deep in weak inversion (i_f<<1) as the normalization gain, as in [12].

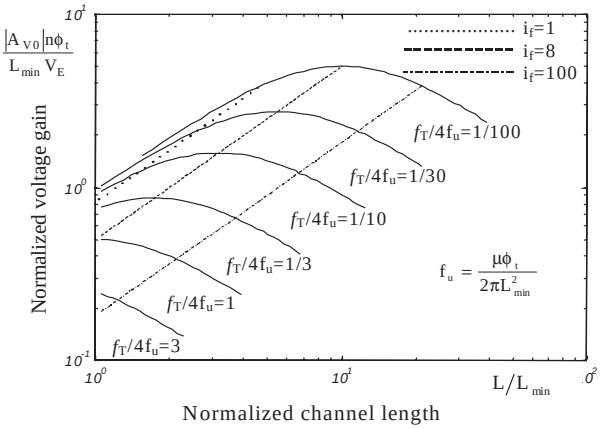

Fig. 3. Voltage gain versus channel length, with either the inversion level or transition frequency as parameter.

Now we use Fig. 3 to discuss the design of a single-stage amplifier. Assume the specifications for the voltage gain and gain-bandwidth product to be A_{VO} and GB. The MOSFET transition frequency is chosen, at least, four times greater than GB. Therefore, a single-stage amplifier that meets the specs is realizable if the curve f_T=4GB in Fig. 3 intersects the horizontal line corresponding to the desired gain A_{VO} for L>L_{min}. Obviously, if we choose simultaneously high gain (horizontal lines in the uppermost part of the plane) and high GB (constant f_T curves in the bottom part of the plane) the single-stage solution may not exist.

IV. MOSVIEW

MOSVIEW [10], [11] is a graphical tool for transistor-level design that allows rapid exploration of the design space. With MOSVIEW, designers can analyze design tradeoffs and develop an intuition about transistor sizing for analog integrated circuits.

A. Specifications for transistor-level design

In MOSVIEW, the normalized channel length is the abscissa while the intrinsic gain is the ordinate. We will illustrate the use of MOSVIEW as a design tool for two sets of input specifications. In some traditional design approaches, the design space is not fully explored because the channel length and the inversion level are fixed (e. g.: channel length L = 2 L_{min} or 3 L_{min}, gate voltage overdrive V_{GS}-V_T = 200mV).

In order to determine the design space, a set of technological parameters and a set of specifications for each case must be provided. The relevant technological parameters that should be given are the minimum channel length (L_{min}), the oxide capacitance per unit area (C'_{ox}), the slope factor (n), the threshold voltage (V_T), the carrier mobility (μ_0), and the Early voltage per unit length (V_E).

B. Design space for elementary building blocks

The current version of MOSVIEW handles a common-source amplifier, classified in four cases according to the input specifications. In this paper, two elementary circuit designs will be shown, namely:

B.1 Amplifier I: The specifications are a fixed transconductance (g_m), a range of intrinsic cutoff frequencies (f_{Tmin}, f_{Tmax}) and a minimum value for the voltage gain (A_{Vmin}). In Fig. 4, g_m = 4μA/V, f_{Tmin} = 1MHz, f_{Tmax} = 10MHz, and A_{Vmin} = 1000. The ascending straight line represents the maximum allowable gain versus channel length for the specified technological parameters. The bottommost curve shows the variation of the gain in terms of the channel length for f_T= f_{Tmax} while the uppermost curve corresponds to f_T= f_{Tmin}. The white region represents the design space, i. e., the region for which the specs are met.

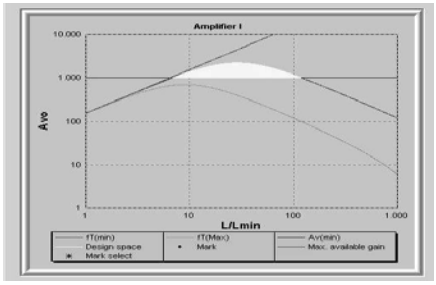

Fig. 4. Design space for amplifier I.

B.2 Amplifier II: The specifications given are a fixed transconductance (g_m), a range of intrinsic cutoff frequencies (f_{Tmin}, f_{Tmax}) and a minimum DC currrent. In Fig. 5, g_m = 4μA/V, f_{Tmin} = 1MHz, f_{Tmax} = 10MHz, and I_{Dmin}=200nA.

All graphs were plotted using the same technological parameters - L_{min} = 1μm, C'_{ox} = 2fF/μm^2, n = 1.25, μ_0 = 500·10^{8}μm^2/Vs, V_E = 5V/μm, and ϕ_t = 25.9 mV.

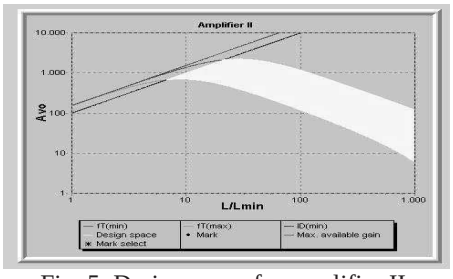

Fig. 5. Design space for amplifier II.

C. Design example

Assume the common-source amplifier shown in Fig. 2. If the gain-bandwidth product GB = 25MHz and the load capacitance C_L = 1pF, then g_m = 157μA/V.

Using as specifications g_m = 157μA/V, f_{Tmin} = 100MHz, f_{Tmax} = 1000MHz and A_{VO} = 100 and considering as technological parameters L_{min} = 1μm, C'_{ox} = 2fF/μm^2, n = 1.25, μ_0 = 500cm^2/Vs, V_E = 5V/μm, and ϕ_t = 25.9 mV, the design space is shown in Fig. 6. Some designs within (1, 2, and 4) and outside of (3 and 5) the design space were selected. Table I shows the characteristics of the transistors for each selected marker. It can be observed that marker 3 does not meet the gain spec, while marker 5 meets neither the gain spec nor the frequency spec. The maximum intrinsic gain is for the transistor with the lowest transition frequency f_T. On the other hand, the minimum area is associated with the maximum cutoff frequency. Finally, the minimum current consumption is achieved with the lowest inversion level.

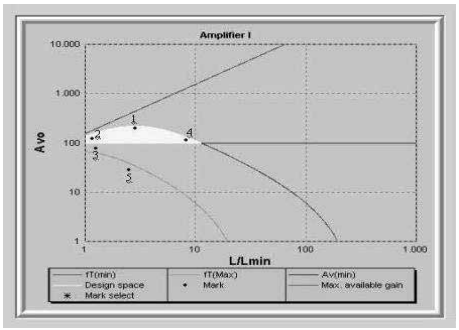

Fig. 6. Design space exploration

Table I
Calculated parameters for the amplifier of the design example.

Spec /Marker	**1**	**2**	**3**	**4**	**5**
L [um]	2.85	1.15	1.25	8.25	2.50
A_{VO}	197	121	***77***	113	***28***
i_f	10.7	2.75	14	430	550
W [um]	72	76	27	26	7.5
WL [um^2]	205.2	87.4	33.7	214.5	18.7
f_T [MHz]	120	280	730	115	***1330***
V_{DSsat} [mV]	165	130	180	620	690
g_m/I_D [1/V]	13.9	20.8	12.4	2.74	2.25
I_D [μA]	11.3	7.53	12.7	57.3	69.7

V. SUMMARY

We introduced MOSVIEW, a CAD tool for transistor-level design that features the following characteristics: (i) it is built-up from a physics-based model; (ii) it allows users to visualize the design space for single-stage amplifiers; (iii) users are able to visualize the "sensitivity" of specifications to design parameters; (iv) the friendly graphical interface allows designers to make quick decisions based on an overall picture of the possible tradeoffs; (v) the velocity saturation effect through the modification of the transconductance in accordance with [13]; (vi) specifications of noise corner frequency and matching; (vii) the four cases of input specifications of amplifiers described in MOSVIEW [10], [11] include most of the usual specifications of elementary analog building blocks. Finally, analog designers are invited to visit the web site of MOSVIEW [11] and try out some design specs for common-source amplifiers.

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