

The g_m/I_D Methodology,
A Sizing Tool for Low-voltage
Analog CMOS Circuits

ANALOG CIRCUITS AND SIGNAL PROCESSING SERIES

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The g_m/I_D Methodology, A Sizing Tool for Low-voltage Analog CMOS Circuits

The Semi-empirical and Compact
Model Approaches

By

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Springer

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Additional material to this book can be downloaded from <http://extra.springer.com>.

ISBN 978-0-387-47100-6 e-ISBN 978-0-387-47101-3
DOI 10.1007/978-0-387-47101-3
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2009940107

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*to Denise
and
to my parents
Oscar Jespers
and Mia Carpentier*

Foreword

IC designers appraise currently transistors sizes while having to fulfill simultaneously a large number of objectives like a prescribed gain-bandwidth product, minimal power consumption, minimal area, low-voltage design, dynamic range, non-linear distortion, etc. Making appropriate decisions is not always obvious. How to meet gain-bandwidth specifications while minimizing power consumption of an Op. Amp without area penalty? Should moderate inversion be preferred to strong inversion? Is sizing an art or a mixture of design experience and repeated simulations? Or is it a constrained multivariate optimization problem? Optimization algorithms are attractive without doubt but they require translating not always well-defined concepts into mathematical expressions. The interactions amid semiconductor physics and systems are not always easy to implement.

The objective of the book is to devise a methodology enabling to fix currents and transistors widths of CMOS analog circuits so as to meet specifications such as gain-bandwidth while optimizing attributes like low power and small area. A special attention is given to low-voltage circuits. The sizing method takes advantage of the g_m/I_D ratio and makes use of either ‘semi-empirical’ data or compact models. The ‘semi-empirical’ approach utilizes large look-up tables derived from physical measurements carried out on real transistors or advanced models. The compact model approach offers the possibility to make use of analytic expressions. Unfortunately when it comes to real transistors, especially sub-micron devices, this isn’t true anymore. Other means are necessary to keep track of high order effects without the risk to loose the inherent simplicity of compact models. Bias dependent instead of constant parameters offer the possibility to extend the validity of a model like the E.K.V. model.

In the first chapter, the Intrinsic Gain Stage, is sized making use of the classical strong and weak inversion large signal models of MOS transistors. This leaves open the moderate inversion region, a region that offers the best compromises generally as far as power consumption and sizes. To be able to size circuits in moderate inversion, we need a reliable large signal MOS model. The Charge Sheet Model that is considered in Chapter 2 is an invaluable tool for understanding the mechanisms governing current in MOS transistors, but it is not fitted for real transistors for it relies on the gradual channel approximation and makes use of mathematical expressions that are too complicated. The MATLAB tools that are available under

'extras.springer.com' overcome the mathematical aspects and offer the possibility to perform 'ideal experiments'. Some of the abstract aspects of the Charge Sheet Model moreover are bridged in Chapter 3 by the introduction of a graphical representation of the drain current that combines physical aspects and practical circuits.

The E.K.V. basic model discussed in Chapter 4, offers clearly more flexibility. It is an approximation of the Charge Sheet Model and a forerunner of what is viewed nowadays as compact Surface Potential Models. The model paves the way towards analytical expressions not only for the drain current but also for the terminal voltages whatsoever the mode of operation of the transistor, whether saturated or not. Unfortunately, the simple E.K.V. model is a gradual channel model like the Charge Sheet Model, unfit thus for real transistors, in particular short channel device.

The fact that drain currents predicted by the E.K.V. compact model look so similar to real drain currents opens the question whether the model could not be extended to real devices. In Chapter 5, we show that currents very close to real drain currents can be predicted when the parameters of the E.K.V. model vary with bias, even with 100 nm devices. The explanation may be the quasi-one-dimensional nature of the channel opposed to the two-dimensional space charge below the inversion layer. As a result, gradual channel conditions prevail in the inversion layer any longer than in the space charge when the gate length is shrinking. An algorithm is proposed to acquire the model parameters.

The Intrinsic Gain Stage is reconsidered in Chapter 6 in the light of the variable parameters compact model. Currents and transistor width obtained by means of the compact model reproduce very closely the values obtained by means of the 'semi-empirical' method. A series of examples considering a low-frequency and a one GHz gain-bandwidth product I.G.S. are described.

The remaining Chapters 7 and 8 extend the method respectively to the common-gate stage and to the basic Miller Op. Amp. The latter illustrates how to meet both, specifications and attributes. Specifications concern the gain-bandwidth product and phase margin, attributes low power and area. These determine optimal regions in the 2D sizing space defined by the first and second stages of the Miller Op. Amp. A MATLAB file compares design strategies.

I want to express my gratitude to Piet Wambacq for the opportunity he gave me to check the validity of the variable parameter E.K.V. model on a 90 nm technology developed by IMEC. I am also very thankful Prof. Gilbert Declerck, former President CEO and Ludo Deferm, executive vice-president of IMEC, who gave me permission to publish the results and the data listed under the 'extras.springer.com'.

My sincere thanks go to Prof. Fernando Silveira who published in 1996 the first paper illustrating the potential of the g_m/I_D methodology. I want to thank him as well as Prof. A. Vladimirescu for the very detailed comments and suggestions they made of the first chapters. I also want to associate Prof. D. Flandre to my thanks owing to our long-term collaboration at the Microelectronics lab of the Université Catholique de Louvain.

Though the specific current put to use in the book is the one defined in the E.K.V. model, I owe much to two research groups. I am indebted to Prof. Eric Vittoz for the

E.K.V. model, and to Prof. Carlos Galup-Montoro and Marcio C. Schneider for the A.C.M. model. I thank the supporters of the two models for motivating discussions and in particular the opportunity Prof. Montoro and Schneider gave me to visit them at the Federal University of Santa Catarina, Brasil.

Tervuren, July 2009

P. Jaspers

Contents

| | | |
|----------|---|----|
| 1 | Sizing the Intrinsic Gain Stage | 1 |
| 1.1 | The Intrinsic Gain Stage | 1 |
| 1.2 | The Intrinsic Gain Stage Frequency Response | 1 |
| 1.3 | Sizing the Intrinsic Gain Stage | 3 |
| 1.3.1 | Sizing the I.G.S. with the Quadratic Model | 4 |
| 1.3.2 | Sizing the I.G.S. by Means of the Weak Inversion Model | 4 |
| 1.3.3 | Sizing the I.G.S. in the Moderate Inversion Region | 5 |
| 1.4 | The g_m/I_D Sizing Methodology | 7 |
| 1.5 | Conclusions | 8 |
| 2 | The Charge Sheet Model Revisited | 11 |
| 2.1 | Why the Charge Sheet Model? | 11 |
| 2.2 | The Generic Drain Current Equation | 11 |
| 2.3 | The Charge Sheet Model <i>Drain Current Equation</i> | 13 |
| 2.4 | Common Source Characteristics | 15 |
| 2.4.1 | The $I_D(V_D)$ Characteristics | 15 |
| 2.4.2 | The $I_D(V_G)$ Characteristic of the Saturated Transistor | 17 |
| 2.4.3 | Drift and Diffusion Contributions to the Drain Current | 18 |
| 2.5 | Weak Inversion Approximation of the Charge Sheet Model | 18 |
| 2.6 | The g_m/I_D Ratio in the Common Source Configuration | 20 |
| 2.7 | Common Gate Characteristics of the Saturated Transistor | 23 |
| 2.8 | A Few Concluding Remarks Concerning the C.S.M. | 24 |
| 3 | Graphical Interpretation of the Charge Sheet Model | 25 |
| 3.1 | A Graphical Representation of I_D | 25 |
| 3.2 | More on the V_T Curve | 28 |
| 3.3 | Two Approximate Representations of V_T | 29 |
| 3.3.1 | The ‘Linear’ Surface Potential Approximation | 29 |
| 3.3.2 | The ‘Linear’ Threshold Voltage V_T Approximation | 31 |
| 3.4 | A Few Examples Illustrating the Use of the Graphical Construction | 32 |
| 3.4.1 | The MOS Diode | 32 |

| | | |
|----------|---|-----------|
| 3.4.2 | The MOS Source Follower | 32 |
| 3.4.3 | The CMOS Inverter | 33 |
| 3.4.4 | Small Signal Transconductances | 34 |
| 3.4.5 | CMOS Transmission Gates | 35 |
| 3.4.6 | How to Implement Quasi-linear Resistors with MOS Transistors | 36 |
| 3.4.7 | Source-Bootstrapping | 37 |
| 3.5 | A Closer Look to the Pinch-Off Region | 38 |
| 3.6 | Conclusion | 39 |
| 4 | Compact Modeling | 41 |
| 4.1 | The Basic Compact Model | 41 |
| 4.2 | The E.K.V. Model | 42 |
| 4.2.1 | The $V_T(V)$ Characteristic | 42 |
| 4.2.2 | The Drain Current | 45 |
| 4.2.3 | The Equations of the Basic E.K.V. Model | 46 |
| 4.2.4 | Graphical Interpretation of the E.K.V. Model | 47 |
| 4.3 | The Common Source Characteristics $I_D(V_G)$ | 48 |
| 4.4 | Strong and Weak Inversion Asymptotic Approximations Derived from the Compact Model | 50 |
| 4.5 | Checking the Compact Model Against the C.S.M. | 50 |
| 4.5.1 | The Acquisition Algorithm (MATLAB Identif3.m) | 50 |
| 4.5.2 | Verification | 52 |
| 4.6 | Evaluation of g_m/I_D | 54 |
| 4.7 | Sizing the Intrinsic Gain Stage by Means of the E.K.V. Model | 55 |
| 4.8 | The Common-Gate g_{ms}/I_D Ratio | 57 |
| 4.9 | An Earlier Compact Model | 58 |
| 4.10 | Modeling Mobility Degradation | 59 |
| 4.10.1 | The Impact of Mobility Degradation on the Drain Current | 59 |
| 4.10.2 | The Impact of Mobility Degradation on the g_m/I_D Ratio | 64 |
| 4.10.3 | Sizing the Intrinsic Gain Stage in the Presence of Mobility Degradation | 65 |
| 4.11 | Conclusion | 66 |
| 5 | The Real Transistor | 67 |
| 5.1 | Short Channel Effects | 67 |
| 5.2 | Checking the Validity of the Compact Model when its Parameters vary with the Source and Drain Voltages | 69 |
| 5.2.1 | E.K.V Parameter Identification (MATLAB IdentifDemo.m) | 70 |
| 5.2.2 | How to Introduce Mobility Degradation? | 73 |
| 5.2.3 | Drain Current Reconstruction | 75 |

| | | |
|----------|--|------------|
| 5.3 | Compact Model Parameters Versus Bias and Gate Length | 76 |
| 5.3.1 | The Influence of the Gate Length on the Model Parameters | 76 |
| 5.3.2 | The Influence of Bias Conditions on the Parameters | 78 |
| 5.4 | Reconstructing $I_D(V_{DS})$ Characteristic | 82 |
| 5.5 | Evaluation of g_x/I_D Ratios | 84 |
| 5.5.1 | The g_m/I_D Ratio | 85 |
| 5.5.2 | The g_d/I_D Ratio | 88 |
| 5.6 | Conclusions | 91 |
| 6 | The Real Intrinsic Gain Stage | 93 |
| 6.1 | The Dependence on Bias Conditions of the g_m/I_D and g_d/I_D Ratios (MATLAB fig061.m) | 93 |
| 6.2 | Sizing the I.G.S with 'Semi-empirical' Data | 94 |
| 6.2.1 | Sizing the I.G.S Loaded by a Constant Total Capacitance | 95 |
| 6.2.2 | Introduction of Extrinsic Capacitances | 99 |
| 6.2.3 | Sizing the I.G.S Loaded by a Constant Load Capacitance | 103 |
| 6.3 | Model Driven Sizing of the I.G.S. | 104 |
| 6.3.1 | Sizing W and ID (MATLAB fig612.m) | 104 |
| 6.3.2 | Evaluation of the Intrinsic Gain (MATLAB fig613.m) | 106 |
| 6.3.3 | An Alternative Method to Evaluate the Gain (MATLAB fig615.m) | 107 |
| 6.3.4 | A Simplified Sizing Procedure | 110 |
| 6.4 | Slew-Rate Considerations | 111 |
| 6.5 | Conclusions | 112 |
| 7 | The Common-Gate Configuration | 113 |
| 7.1 | Drain Current Versus Source-to-Substrate Voltage (Matlab fig071.m) | 113 |
| 7.2 | The Cascoded Intrinsic Gain Stage | 115 |
| 7.2.1 | Sizing the Cascode (Matlab fig074.m) | 115 |
| 7.2.2 | Gain Evaluation of the Cascode (MATLAB fig075.m) | 117 |
| 7.2.3 | The Poles of the Cascode Circuit (MATLAB fig075.m) | 118 |
| 8 | Sizing the Miller Op. Amp. | 121 |
| 8.1 | Introductory Considerations | 121 |
| 8.2 | The Miller Op. Amp. | 121 |
| 8.2.1 | Analysis of the Miller Operational Amplifier | 122 |
| 8.2.2 | Pole Splitting | 123 |
| 8.2.3 | The Impact of the Current Mirror | 126 |
| 8.2.4 | Poles and Zeros | 127 |

| | | |
|----------------|--|------------|
| 8.3 | Sizing the Miller Operational Amplifier (MATLAB OpAmp.m) | 129 |
| 8.3.1 | Sizing a Low-voltage Miller Op. Amp. | 130 |
| 8.3.2 | Sizing a High-Frequency Low-Power Miller Op. Amp. | 140 |
| 8.4 | Conclusion | 142 |
| Annex 1 | How to Utilize the Data available under ‘extras.springer.com’ ... | 143 |
| A1.1 | Global Variables | 143 |
| A1.2 | An Example Making Use of the ‘Semi-empirical’ Data: The Evaluation of Drain Currents and g_m/I_D Ratio Matrices (MATLAB A12.m) | 144 |
| A1.3 | An Example Making Use of the E.K.V Global Variables: The Elaboration of an ID(VGS) Characteristic (Matlab A13.m)..... | 146 |
| Annex 2 | The ‘MATLAB’ Toolbox | 149 |
| A2.1 | Charge Sheet Model Files | 149 |
| A2.1.1 | The pMat(T,N,tox) Function | 149 |
| A2.1.2 | The surfpot(p,V,VG) Function | 150 |
| A2.1.3 | The IDsh(p,VS,VD,VG) Function | 151 |
| A2.2 | Compact Model Files | 151 |
| A2.2.1 | The Identif 3(Nb,tox,VFB,T) Function | 151 |
| A2.2.2 | The invq(z) Function | 152 |
| A2.2.3 | The ComS(VGS,VDS,VS,lg) Function | 152 |
| A2.3 | Other Functions | 152 |
| A2.3.1 | The jctCap(L,W,R,V) Function..... | 152 |
| A2.3.2 | The Gss(x,H) Function | 153 |
| Annex 3 | Temperature and Mismatch, from C.S.M. to E.K.V. | 155 |
| A3.1 | The Influence of the Temperature on the Drain Current (MATLAB A31.m) | 155 |
| A3.2 | The Influence of the Temperature on g_m/I_D (Matlab A32.m)..... | 156 |
| A3.3 | Temperature Dependence of E.K.V Parameters (MATLAB A33.m) | 158 |
| A3.4 | The Impact of Technological Mismatches on the Drain Current (Matlab A34.m)..... | 159 |
| A3.5 | Mismatch and E.K.V Parameters (MATLAB A35.m) | 161 |
| Annex 4 | E.K.V. Intrinsic Capacitance Model | 163 |
| | Bibliography | 167 |
| | Index | 169 |

Notations

| | |
|---------------------|---|
| A, A_{DC}, A_{AC} | voltage gain, DC and AC voltage gain |
| A.C.M. | Advanced Compact Model |
| C.L.M. | Channel Length Modulation |
| C.S.M. | Charge Sheet Model |
| C | capacitor value |
| C'_{ox} | gate oxide capacitance per unit area |
| C_{GB} | gate-to-substrate capacitance |
| C_{GD} | gate-to-drain capacitance |
| C_{GS} | gate-to-source capacitance |
| C_J | junction capacitance |
| C_{Jsw} | peripheral side-wall junction capacitance |
| C_{Jswg} | gate side-wall junction capacitance |
| C_m | Miller capacitance |
| CMOS | Complementary MOS |
| D | diffusion constant |
| D.I.B.L. | Drain Induced Barrier Lowering |
| E.K.V. | Enz, Krumenacher and Vittoz compact model |
| G.V.O. | Gate Voltage Overdrive voltage |
| g_d | output conductance |
| g_m | gate transconductance |
| g_{mb} | bulk transconductance |
| g_{ms} | source transconductance |
| i, i_F, i_R | normalized drain current, forward and reverse i |
| I.G.S. | Intrinsic Gain Stage |
| I_D | DC drain current |
| I_{Du} | unary DC drain current ($W = L$) |
| I_S | specific current |
| I_{Su} | unary specific current ($W = L$) |
| I_{Suo} | weak inversion unary specific current |
| L | gate length |
| N | impurity concentration |
| n | slope factor |

| | |
|------------------|---|
| $PolyN, PolyP$ | mobility degradation polyn. of N- and P-channel transistors |
| q, q_F, q_R | normalized mobile charge density, forward and reverse q |
| q_S, q_D | normalized mobile charge density at the source and drain |
| Q'_B | bulk charge density |
| Q'_i , | mobile charge density |
| Q'_t , | total charge density |
| R.H.P. | Right Half Plane zero |
| S_{VT_0} | threshold voltage sensitivity factor with respect to V_{DS} |
| ThN, ThP | mobility degradation function of N- and P-channel transistors |
| U_T | thermal voltage kT/q |
| V, I, v, i | large and small signal voltage or current |
| V_A | <i>Early voltage</i> |
| V_S, V_G, V_D | source, gate and drain voltage with respect to substrate |
| V_{GS}, V_{DS} | gate and drain voltage with respect to the source |
| V_P, V_{PS} | pinch-off voltage with respect to the substrate or the source |
| v_{sat} | saturation velocity of mobile carriers |
| V_T | threshold voltage with respect to the substrate |
| V_{T_0} | threshold voltage with respect to the source |
| W | gate width |
| W.I, M.I, S.I | weak, moderate and strong inversion |
| β | $\mu C'_{ox} W/L$ of MOS transistor |
| γ | gamma of SPICE program |
| μ | mobility |
| μ_o | low-field mobility |
| ψ_S | surface potential |
| ω | angular frequency ($2\pi f$) |
| ω_c | angular cut-off frequency ($2\pi f_c$) |
| ω_T | angular transition frequency ($2\pi f_T$) |