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BSIM3v3 to EKV2.6 Model Parameter Extraction and Optimisation using LM Algorithm on 0.18μ Technology node

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***Abstract*—The industry standard BSIM3v3 and BSIM4.0 have been replaced by BSIM6.0 compact MOSFET model for deep submicron technology node. The BSIM6.0 is next generation, defacto industry standard model for bulk MOSFET. This model is charge based which is continuous from weak to strong inversion of operation. The core of analytical and physical BSIM6 model[3] is charge, with drain current equation expressed in form of source(q_s) and drain charge(q_d). This model has all its governing equations continuous and can be used to develop design methodology using IC based approach. But its method of computing q_s and q_d is complicated which is different from Vittoz traditional charge calculation method. The continuous interpolation equation of drain current as adopted by EKV2.6 although is empirical but its compact expression is preferred by analog designer to get intuitive design guidance. BSIM6 is a combined effort by BSIM and EKV modeling groups based on charge based continuous equations. Although EKV2.6 model is not valid for deep submicron process as it only includes submicron short channel effects like velocity saturation(VS), vertical field mobility reduction(VFMR), Drain induced barrier lowering(DIBL), channel length modulation(CLM) etc. But it still offers some benefits to have first cut design methodology because of its much simplified analytical equations. The inversion coefficient(IC) has found extensive acceptance in designer community as it offers enhanced design elegance in EKV then more complicated BSIM model. This paper discuses first step in analog design process by extracted core EKV2.6 intrinsic model parameters from industry standard BSIM3v3 model on 0.18μ technology node. The 0.18μ technology is chosen as it is still more common technology node in analog circuit design. The model parameters are extracted for different bins and optimisation is done using nonlinear optimisation LM algorithm. The optimised EKV2.6 parameters are validated with current-voltage(I-V), intrinsic voltage gain(A_{vi}) and Early voltage circuit parameter(V_A) with BSIM3v3 model.**

***Keywords*—EKV2.6, BSIM3v3, specific current I_S, optimisation, LM algorithm**

I. INTRODUCTION

TLSI The aggressive shrinking of transistor size has complicated IC design due to increased influence of second order effects. The physical device models have to accept drastic changes in the modeling strategy to meet the need of reliable, accurate and computationally fast models which are compatible with SPICE[1]. Around ninety percent of model parameters are empirically fitted to achieve accuracy in the modeling equations which makes it unsuitable for first-cut design. Thus as a first step analog designer prefers to have simplified model which may not to very accurate but it helps in providing design intuition and structured design methodology. Among all standard compact models like BSIM, EKV, HiSIM and PSP the computational high intensive BSIM3v3 model complicates the design procedure as it does not provide simplified analytical equation for pre-SPICE guidance[2]. The EKV model provides the facility for pre-SPICE design guidance using inversion coefficient(IC) based approach. The version 2.6 EKV model is much simplified and helps in analytical analysis with minimum trial and error simulation[6], [7]. It has reduced set of model parameters(eg., for DC analysis only 9 physical, 2 temperature and 3 fitting parameter) and it uses inversion factor as one of the design parameter. Whereas version 3 of EKV model is charge based model valid upto $65\mathrm{nm}$ with significant increase in number of model parameters. The MOSFET model parameter extraction is also an important activity of modeling group. Thus model should not only be accurate and fast, it must also offer easier method of extraction. The extraction of model parameters depends on the complexity of model and how model parameter are interrelated among themselves. Since EKV2.6 model have all its parameter hierarchically linked with each other therefore its extraction procedure is systematic and less time consuming. In present work EKV2.6 model parameter is extracted to show the capability of this model to design analog circuits.

Section-II of this paper gives list of key EKV2.6 model parameters, Section-III shows hierarchical procedure of extracting EKV model parameters, Section-IV covers optimization of model parameters using LM algorithm, Section-V on MATLAB optimization tool and finally in Section-VI result are discussed, followed by Appendix in which all current-voltage(I-V) curves using extracted EKV model are verified using BSIM3v3 model.

II. EKV2.6 MODEL PARAMETERS

There are set of 13 core intrinsic parameter of EKV2.6 model as listed in Table I[5] which include process related parameters, basic model parameters, important short channel effects of VS, VFMR, DIBL, CLM, impact ionization coefficient, reverse short channel effect(RSCE) and temperature dependent parameters. These parameters are defined within lower and upper physical range which can be used during extraction and optimization for different channel length and width.

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TABLE I
EXTRACTED EKV PARAMETERS FOR 0.18μ TECH. NODE

NAME	LOWER	UPPER
DL (m)(Channel length correction)	$-0.175\,e^{-06}$	$-0.175\,e^{-06}$
COX (Fm^{-1})(Gate oxide capacitance)	–	–
GAMMA ($\mathrm{V}^{1/2}$)(Body effect factor)	0	2
PHI (V)(Bulk Fermi potential)	0.3	2
KP (AV^{-2})(Transconductance parameter)	$10e^{-06}$	–
E0 (Vm^{-1})(Mobility reduction coefficient)	$25e^{+06}$	–
VTO (V)(Nominal threshold voltage)	0	2
Q0 ($\mathrm{A\ sm}^{-2}$)(RSCE peak charge density)	0	–
LK (m)(RSCE characteristic length)	$0.05e^{-06}$	$2e^{-06}$
LETA (Short channel effect coefficient)	0	2
WETA (Narrow channel effect coefficient)	0	2
UCRIT (Vm^{-1})(Longitudinal critical field)	$1e^{+06}$	$25e^{+06}$
LAMBDA (Depletion length coefficient)	0	3
IBA (m^{-1})(First impact ionization coefficient)	0	$5e^{+08}$
IBB (Vm^{-1})(Second impact ionization coefficient)	$1.8e^{+08}$	$4.0e^{+08}$
IBN (Saturation voltage factor for impact ionization)	0.4	1
TCV (VK^{-1})(Threshold voltage temp coefficient)	0	–
BEX (Mobility temperature exponent)	0	−3
UCEX (Longitudinal critical field temp exponent)	0	3

III. HIERARCHICAL METHOD OF EXTRACTING EKV2.6 MODEL PARAMETERS

The flowchart of complete extraction method is shown in Fig. 10 given in Appendix-I . The different bins file of 0.18μ technology as given in Table II will be used for model parameters extraction.

Since EKV parameters are interrelated thus it is necessary to maintain the hierarchy in extraction procedure. The transistor characteristics are generated using HSPICE simulator which generates an output files and array of data points. These points are used subsequently in extraction procedure by curve fitting the simulated curves data points with EKV model equations. The first step is initialization where process related information is mapped directly from BSIM to EKV model as discussed below

TABLE II
DIFFERENT SETS OF CHANNEL DIMENSION

BIN NAME	**LMIN**(μm)	**LMAX**(μm)	**WMIN**(μm)	**WMAX**(μm)
NMOS 1	10.00	20.001	10.00	100.001
NMOS 2	1.20	10.00	10.00	100.001
NMOS 3	0.50	1.20	10.00	100.001
NMOS 4	0.18	0.50	10.00	100.001
NMOS 5	10.00	20.001	1.20	10.00
NMOS 6	1.20	10.00	1.20	10.00
NMOS 7	0.50	1.20	1.20	10.00
NMOS 8	0.18	0.50	1.20	10.00
NMOS 9	10.00	20.001	0.50	1.20
NMOS 10	1.20	10.00	0.50	1.20
NMOS 11	0.50	1.20	0.50	1.20
NMOS 12	0.18	0.50	0.50	1.20
NMOS 13	10.00	20.001	0.22	0.50
NMOS 14	1.20	10.00	0.22	0.50
NMOS 15	0.50	1.20	0.22	0.50
NMOS 16	0.18	0.50	0.22	0.50

A. *Initialization*

The technology information is the first step for the conversion which requires transistor dimensions(W_{MIN}, L_{MIN}) and supply voltages. The mapping of process parameters like TOX, $NSUB$, XJ and DW form BSIM3.3 to EKV2.6 is done followed by calculation of initial values of parameters DL, GAMMA, PHI, KP, UCRIT, E0, IBB and IBA.

B. *Extraction of specific current(I_S)*

First step in extraction is to determine specific current which must be extracted for each transistor geometry. The I_S is extracted from the slope of the square root of the drain current as a function of the source voltage as given below in (1) whose plot is shown in Fig. 1.

$$I_S = \left[2U_T(d\sqrt{I_D}/dV_S)_{max}\right]^2 \tag{1}$$

Since the slope is not constant we take maximum slope as **-173**m**A/V**. Thus I_S obtained using (1) is **81**μA. The strong inversion saturation is ensured by setting $V_D = V_G = V_{DD}$ for NMOS transistor.

C. *Extraction of parameters VTO, GAMMA and PHI*

The intrinsic parameters VTO, GAMMA and PHI are determined by fitting the simulated curves $V_P = f(V_G)$ for the WL transistor to the simplified equation given below

VTO is determined as a particular value of V_G corresponding to the point where $V_P = 0$. GAMMA and PHI are extracted by curve fitting (2) to the simulated characteristics.

$$V_P = \begin{cases} V_G' - PHI - GAMMA\left(\sqrt{V_G' + \left(\frac{GAMMA}{2}\right)^2} - \frac{GAMMA}{2}\right) & \text{for } V_G' > 0 \\ -PHI & \text{for } V_G' \leq 0 \end{cases} \tag{2}$$

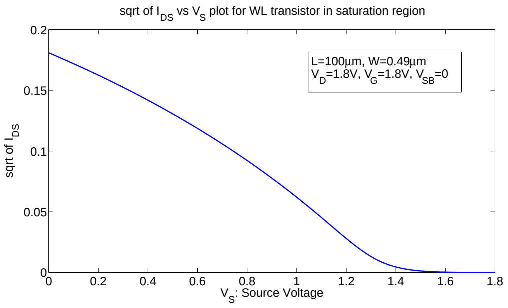

Fig. 1. $\sqrt{I_{DS}}$ vs V_S plot for long channel NMOS transistor

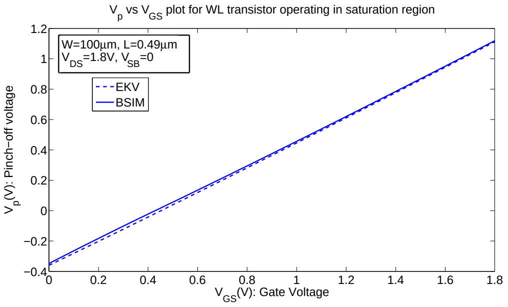

Fig. 2. V_p vs V_{GS} measured and fitted plot using EKV2.6 model equations

V_P vs V_G characteristic for NMOS and its curve fitting with EKV2.6 model obtained as shown in Fig. 2 Extracted value of **VTO** corresponding to the $V_P = 0$ is **0.471V**.The curve fitting is done by fixing the value of VTO and changing the value of GAMMA and PHI to get the best fit. The extracted value of **VT0, GAMMA** and **PHI** are **0.471V, 0.632**$\sqrt{V}$ and **1.67V** respectively.

D. Extraction of parameters LETA and WETA

The parameter LETA is extracted using the simulated $V_P = f(V_G)$ curves for WS(Wide/Short) transistors, while the parameter WETA is extracted from $V_P = f(V_G)$ curves for NL(Narrow/Long) transistors. The plot of (2) taking the effect of LETA and WETA is shown in Fig. 3 and Fig. 4 respectively. The extracted value of short and narrow channel effect coefficient after curve fitting (2) with simulated characteristics using BSIM3v3 is **LETA=0.272** and **WETA=15.2**.

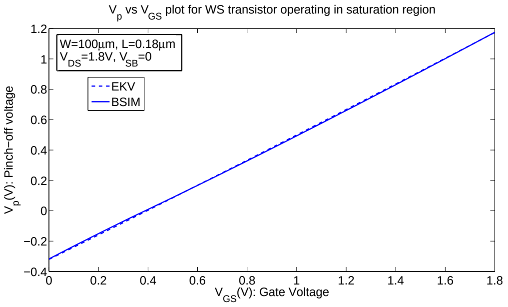

Fig. 3. V_p vs V_{GS} characteristics of short channel NMOS device

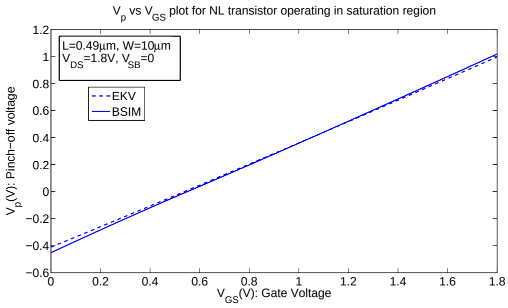

Fig. 4. V_p vs V_{GS} characteristics of narrow channel NMOS device

E. Extraction of parameters KP and E0

Using the simplified drain current equation, the Transconductance parameter(KP) and Mobility reduction coefficient(E0) are extracted by fitting the curves $I_{DS} = f(V_{GS})$ for a WL transistor operating in the linear region($V_{DS} = 50mV$) for different source to bulk voltages V_{SB}. The figure in Appendix gives the results obtained after fitting the simulated curves with the drain current equation of EKV2.6 model in linear region. The extracted value of **KP=383**$\times 10^{-6}\,\mathrm{A/V^2}$ and **E0=62**$\times 10^{6}\ \mathrm{V/m}$ is obtained by this method.

F. Extraction of parameters UCRIT and LAMBDA

The Longitudinal critical field parameter UCRIT and Channel length modulation parameter LAMBDA are extracted using the complete set of EKV2.6 model equations and the simulated characteristics for $I_D = f(V_D)$ and $I_D = f(V_G)$. The, initial values of UCRIT, LAMBDA are estimated by fitting $I_D = f(V_D)$ curves simulated for WS transistor in strong inversion. The parameter LAMBDA is fixed to its initial value, and the parameter UCRIT is extracted by fitting $I_D = f(V_G)$ curves simulated for WS transistors operating in saturation. The UCRIT value is then fixed to this extracted value, and the parameter LAMBDA is extracted by fitting again $I_D = f(V_D)$ curves simulated for WS transistor in strong inversion Fitted and simulated plot is shown in Fig. fig:nch4a of Appendix. The extracted value obtained by this method are **UCRIT=4.65**$\times 10^{6}\ \mathrm{V/m}$ and **LAMBDA=0.255**.

G. Extraction of parameters IBA, IBN and IBB

The parameters that model the substrate current are extracted from $I_D = f(V_G)$ curves simulated for the WL transistor operating in saturation region. Simulated plot for BSIM and fitted plot EKV2.6 using the equation of I_{DB} is shown in Fig. 5. The values of the parameter obtained are **IBA=450**$\times 10^{6}\ \mathrm{m^{-1}}$, **IBN=0.9** and **IBB=300**$\times 10^{6}\ \mathrm{V/m}$.

H. Extraction of parameters TCV, BEX and UCEX

The temperature parameters such as Threshold voltage temperature coefficient TCV, mobility temperature coefficient

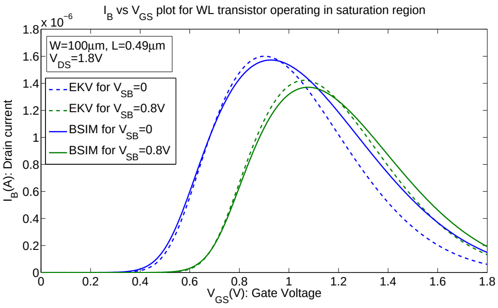

Fig. 5. I_B vs V_G characteristics of long channel NMOS device in saturation region of operation

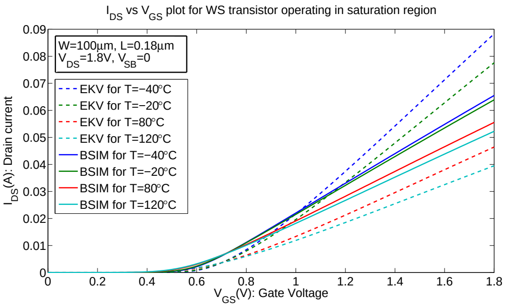

Fig. 8. I_{DS} vs V_{GS} characteristics of short channel NMOS device in saturation region of operation

BEX, and longitudinal critical field temperature exponent UCEX are extracted by fitting the simulated curves for temperatures $-40°C$, $-20°C$, $80°C$ and $120°C$ in the following order:

- TCV from $V_P = f(V_G)$ for a WL transistor,
- BEX from $I_D = f(V_G)$ for a WL transistor operating in the linear region,
- and UCEX from $I_D = f(V_G)$ for WS transistor operating in saturation.

Since TCV is related to VT0, BEX is related to KP and UCEX is related to UCRIT for dependency on temperature. The simulated and fitted plots are shown in Fig. 6, Fig. 7 and Fig. 8 The extracted values of the parameter using this method are **TCV=0.641**$\times 10^{-3}$ V/K, **BEX=-0.912** and **UCEX=0.184**.

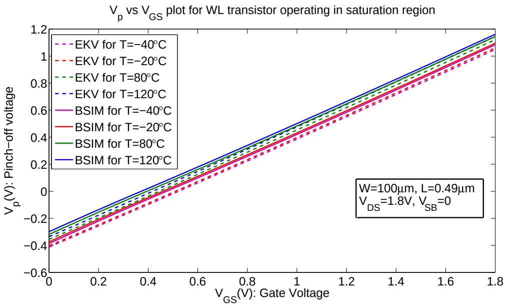

Fig. 6. V_P vs V_{GS} characteristics of long channel NMOS device in saturation region of operation

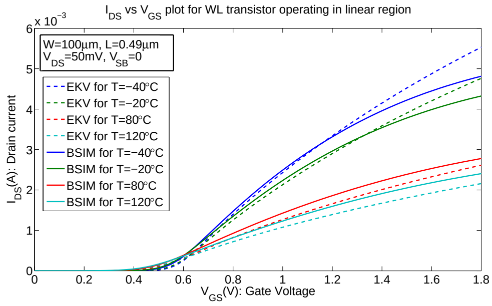

Fig. 7. I_{DS} vs V_{GS} characteristics of long channel NMOS device in linear region of operation

IV. OPTIMISATION USING LM ALGORITHM

A common problem in simulating MOS circuits is the specification of model parameters. Typical extraction procedures determine parameters sequentially and neglect there interactions. As a result, the fit of the model to measured data may be less than optimum [10], [11]. For better curve fitting there is a need of an optimisation technique. The parameter obtained using this optimisation technique relate to a specific device but we need to obtain global parameter which correspond to different device sizes. Thus there is a need for second round of optimisation which would yield global parameters usable for all device dimensions.

The problem of determining the values of a number of interrelated parameters is tackled by focusing on a single design objective to quantify performance and to measure the quality of optimization. This objective is minimized subject to constraints that may limit the selection of parameter values. Among the tentative objectives that characterize the extraction problem, an appropriate measure is the norm of the error vector, f(x). Applying nonlinear least-square minimization method to the objective function f(x), the optimal model parameter vector x* can be estimated [11]. There are many nonlinear least-square optimization algorithms. The algorithm chosen is Levenberg-Marquardt algorithm and MATLAB optimization Tool (optimtool) is selected as a toolbox function. It provides a convenient interface for all optimization routines.

Since EKV model equations are nonlinear function of parameters, we chose Nonlinear curve fitting solver for the optimization. As the algorithm runs, the current iteration field updates and the result window is shown in Figure 9. The setting of the LM tool is given below in Table III Setting of optimizer can also be changed using the MATLAB function optimset. We are using the default values in some of the options field as they produce satisfactory results.

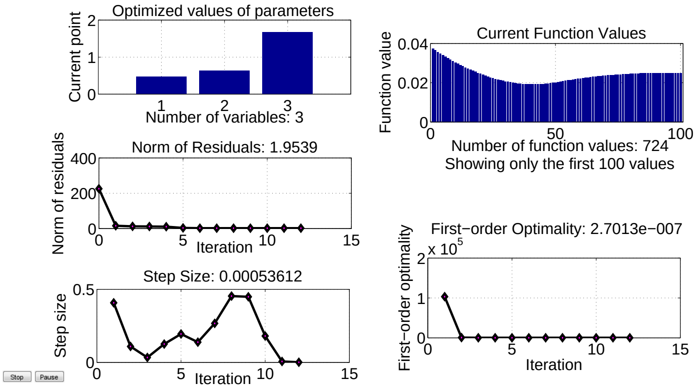

Fig. 9. Result window

Solver	lsqcurvefit - Nonlinear curve fiting
Algorithm	Levenberg-Marquardt
Objective function	@ (function name)
Derivatives	Approximated by solver
Start point	(Initial values of the parameters to be optimized)
X Data	(Measured xdata)
Y Data	(Measured ydata)
Max iterations	Use default:400
Max function evaluations	Use default: 200*number of Variables
X tolerance	Use default: 1e-6
Function tolerance	Use default: 1e-6
Minimum perturbation	Use default: 1e-8
Maximum perturbation	Use default: 0.1
Typical X values	Use default: one(number of Varibles,1)
Scaling	Jacobian
plot functions	Current point and (whatever required)
Output function	(optional)
Level of display	(depends on user)

TABLE III
OPTIONS OF LM TOOL USED IN OPTIMIZATION

V. RESULTS

The optimized values for the channel dimensions (LMIN=$0.18\mu m$, LMAX=$0.49\mu m$, WMIN=$10\mu m$, WMAX=$100\mu m$) for NMOS are shown in Table IV

TABLE IV
OPTIMIZED EKV2.6 MODEL PARAMETERS FOR NMOS 4

NAME(UNIT)	LOWER	UPPER	INITIAL	OPTIMIZED
VT0(V)	0	2	0.4	0.471
GAMMA($\sqrt{\mathrm{V}}$)	0	2	0.6	0.632
PHI(V)	0.3	2	1	1.67
LETA	0	2	0.2	0.272
WETA	0	2	13	15.2
LK(m)	0.05×10^{-6}	2×10^{-6}	0.1×10^{-6}	0.0473×10^{-6}
Q0($\mathrm{As/m^2}$)	0	-	150×10^{-5}	158×10^{-5}
KP($\mathrm{A/V^2}$)	10×10^{-6}	-	380×10^{-6}	383×10^{-6}
E0($\mathrm{V/m}$)	61×10^{6}	-	62×10^{6}	62×10^{6}
UCRIT($\mathrm{V/m}$)	1×10^{6}	25×10^{6}	4×10^{6}	4.65×10^{6}
LAMBDA	0	3	0.3	0.255
TCV($\mathrm{V/K}$)	0	-	0.7×10^{-3}	0.641×10^{-3}
BEX	0	-3	-1	-0.912
UCEX	0	3	0.3	0.184
IBA($\mathrm{1/m}$)	0	5×10^{8}	4.5×10^{8}	4.5×10^{8}
IBB($\mathrm{V/m}$)	1.8×10^{8}	4×10^{8}	3×10^{8}	3×10^{8}
IBN	0.4	1	0.9	0.9

The validation of extracted EKV model parameters with BSIM3v3 model is shown in Fig. 11 and Fig. 12 of Appendix. The optimized values for the channel dimensions (LMIN=$0.18\mu m$, LMAX=$0.49\mu m$, WMIN=$10\mu m$, WMAX=$100\mu m$) for PMOS are shown in Table V

VI. CONCLUSION

EKV2.6 model has only 13 core intrinsic model parameters, to analyze dc and small signal model of a circuit. The BSIM3v3 has a large number of model parameters which are correlated, thus this makes the task of extraction procedure lengthy, complex and time consuming. This paper has presented an efficient hierarchical EKV2.6 model parameter extraction method with curve-fitting done using LM optimisation technique. The choice of the optimization algorithm depends on the number of parameters to be optimized. The LM optimization algorithm have converged in less than 10 iterations in most of the group of parameters and gives high accuracy of fitness function. The paper presents a Matlab implementation of the EKV model. Very good accuracy is achieved by using specific expressions for calculating device transconductances plus interpolation functions for calculating the basic model equations. Comparison between the results of the implemented EKV2.6 model and the BSIM3v3 model for a 0.18µm technology node is demonstrated by plotting various characteristics. As very good agreement is observed between the two models, the extracted parameters can be used in future to design analog circuits. The BSIM6.0 to version 2.6 EKV model parameters extraction is not possible since BSIM6.0 model is capable to model the MOSFET in deep submicron node and EKV2.6 model is valid only until 0.18μ technology node. Below this node the EKV3.0 model is applicable which is charge based model and considered to be advanced form of EKV2.6 model.

TABLE V
OPTIMIZED EKV2.6 MODEL PARAMETERS FOR PMOS 4

NAME(UNIT)	LOWER	UPPER	INITIAL	OPTIMIZED
VT0(V)	0	-2	-0.45	-0.465
GAMMA($\sqrt{\mathrm{V}}$)	0	2	0.8	0.878
PHI(V)	0.3	2	2	2.17
LETA	0	2	0.2	0.187
WETA	0	2	10	11.6
LK(m)	0.05×10^{-6}	2×10^{-6}	0.1×10^{-6}	0.0119×10^{-6}
Q0($\mathrm{As/m^2}$)	0	-	900×10^{-5}	889×10^{-5}
KP($\mathrm{A/V^2}$)	10×10^{-6}	-	75×10^{-6}	71.3×10^{-6}
E0($\mathrm{V/m}$)	61×10^{6}	-	62×10^{6}	62×10^{6}
UCRIT($\mathrm{V/m}$)	1×10^{6}	25×10^{6}	25×10^{6}	25×10^{6}
LAMBDA	0	3	1	1.08
TCV($\mathrm{V/K}$)	0	-	-0.9×10^{-3}	-0.946×10^{-3}
BEX	0	-3	-0.8	-0.808
UCEX	0	3	1.2	1.19
IBA($\mathrm{1/m}$)	0	5×10^{8}	0.05×10^{8}	0.05×10^{8}
IBB($\mathrm{V/m}$)	1.8×10^{8}	4×10^{8}	3×10^{8}	$\times10^{8}$
IBN	0.4	1	0.9	0.9

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APPENDIX

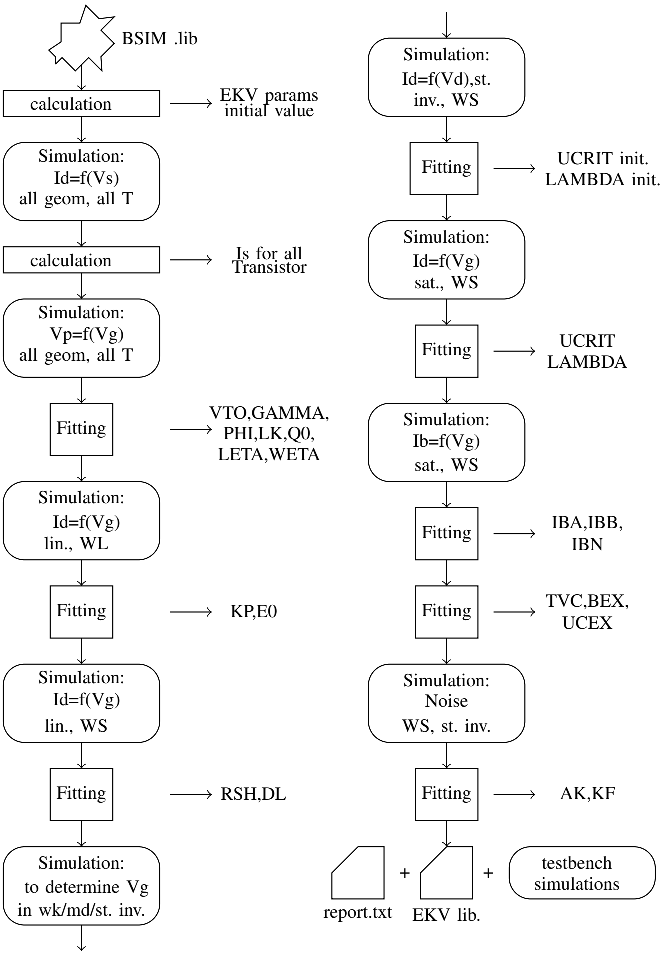
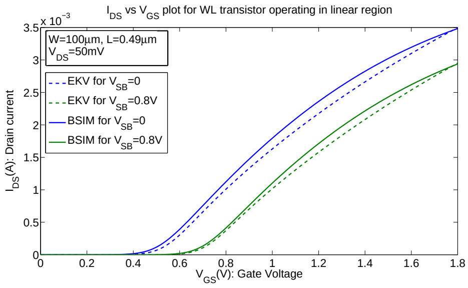
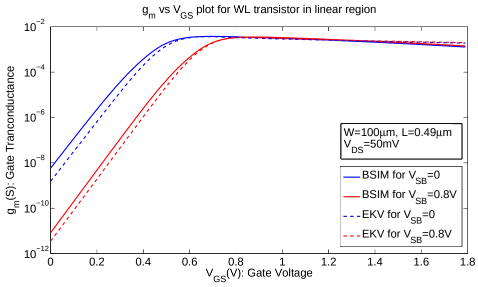


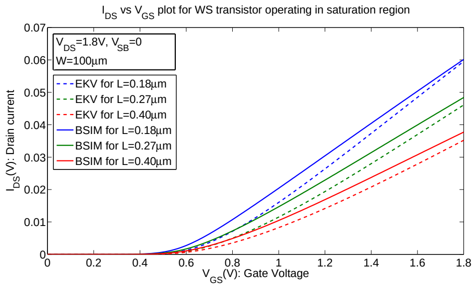
Fig. 10. Flow-chart of BSIM to EKV conversion steps(Source:[9])



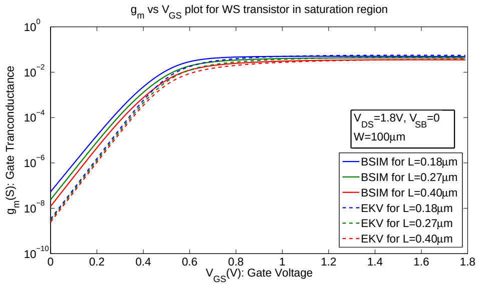
(a) I_{DS} vs V_{GS} characteristics of long channel NMOS device in linear region



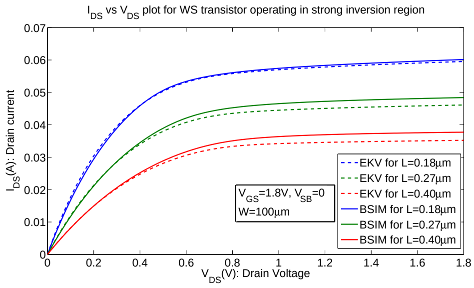
(b) g_m vs V_{GS} characteristics of long channel NMOS device in linear region



(c) I_{DS} vs V_{GS} characteristics of short channel NMOS device in saturation region

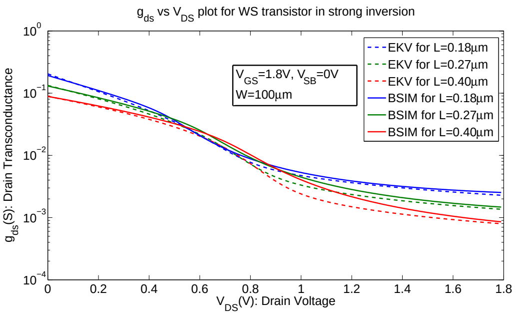


(d) g_m vs V_{GS} characteristics of short channel NMOS device in saturation region

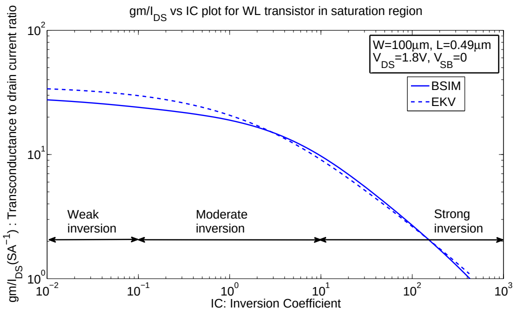


(e) I_{DS} vs V_{DS} characteristics of short channel NMOS device in saturation region

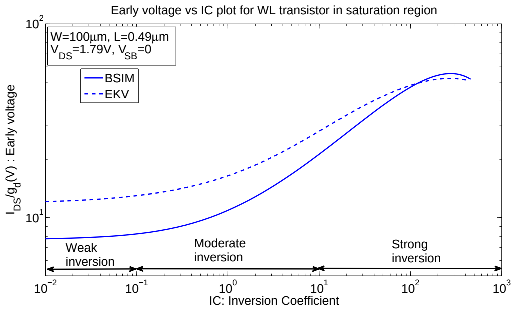
Fig. 11. Various plots for NMOS



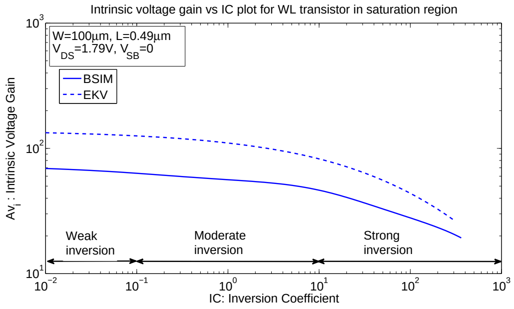
(a) g_d vs V_{DS} characteristics of short channel NMOS device in saturation region



(b) g_m/I_{DS} vs IC characteristics of long channel NMOS device in saturation region



(c) Early voltage vs IC characteristics of long channel NMOS device in saturation region



(d) Intrinsic voltage gain vs IC characteristics of long channel NMOS device in saturation region

Fig. 12. Various plots for NMOS