

Qucs

A Report

Verilog-A implementation of the EKV v2.6 long and short
channel MOSFET models

Mike Brinson

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Introduction

This report presents the background to the Qucs implementation of the EKV 2.6 long and short channel MOSFET models. During 2007 the Qucs development team employed the EKV v2.6 MOSFET model as a test case while developing the Qucs non-linear equation defined devices (EDD)¹. More recently complete implementations of the long and short channel EKV v2.6 models have been developed using the Qucs Verilog-A compact device modelling route. This work forms part of the Verilog-A compact device modelling standardisation initiative². The EKV v2.6 MOSFET model is a physics based model which has been placed in the public domain by its developers. It is ideal for analogue circuit simulation of submicron CMOS circuits. Since the models introduction and development between 1997 and 1999 it has been widely used in industry and by academic circuit design groups. Today the EKV v2.6 model is available with most of the major commercial simulators and a growing number of GPL simulators. The Verilog-A code for the Qucs ADMS³ compiled version of the EKV v2.6 model is given in an appendix to this report.

Effects modelled

The EKV v2.6 MOSFET model includes the following effects:

- Basic geometrical and process related features dependent on oxide thickness, junction depth, effective channel length and width
- Effects of doping profile
- Modelling of weak, moderate and strong inversion behaviour
- Modelling of mobility effects due to vertical and lateral fields, velocity saturation
- Short channel effects including channel-length modulation, source and drain charge-sharing and reverse channel effect

¹An example EDD macromodel of the short channel EKV 2.6 model can be found at <http://qucs.sourceforge.net/>.

²Stefan Jahn, Mike Brinson, Michael Margraf, Hélène Parrutte, Bertrand Ardouin, Paolo Nenzi and Laurent Lemaitre, GNU Simulators Supporting Verilog-A Compact Model Standardization, MOS-AK Meeting, Premstaetten, 2007, http://www.mos-ak.org/premstaetten/papers/MOS-AK_QUCS_ngspice_ADMS.pdf

³Lemaitre L. and GU B., ADMS - a fully customizable Verilog-AMS compiler approach, MOS-AK Meeting, Montreux. Available from http://www.mos-ak.org/montreux/posters/17_Lemaitre_MOS-AK06.pdf

- Modelling of substrate current due to impact ionization
- Thermal and flicker noise
- First order non-quasistatic model for the transconductances
- Short-distance geometry and bias dependent device matching

The Qucs implementation of the short channel EKV v2.6 model includes nearly all the features listed above⁴. A simpler long channel version of the model is also available for those simulations that do not require short channel effects. Both nMOS and pMOS devices have been implemented. No attempt is made in this report to describe the physics of the EKV v2.6 model. Readers who are interested in learning more about the background to the model, its physics and function should consult the following references:

- Matthias Bucher *et. al.*, The EPFL-EKV MOSFET Model Equations for Simulation, Electronics Laboratories, Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, Model Version 2.6, Revision II, July 1998.
- Władysław Grabiński *et. al.* Advanced compact modelling of the deep sub-micron technologies, Journal of Telecommunications and Information Technology, 3-4/2000, pp. 31-42.
- Matthias Bucher *et. al.*, A MOS transistor model for mixed analog-digital circuit design and simulation, pp. 49-96, Design of systems on a chip - Devices and Components, KLUWER Academic Publishers, 2004.
- Trond Ytterdal *et. al.*, Chapter 7: The EKV model, pp. 209-220, Device Modeling for Analog and RF CMOS Circuit Design, John Wiley & Sons, Ltd, 2003.
- Patrick Mawet, Low-power circuits and beyond: a designer's perspective on the EKV model and its usage, MOS-AK meeting, Montreux, 2006, http://www.mos-ak.org/montreux/posters/09_Mawet_MOS-AK06.pdf
- Christian C. Enz and Eric A. Vittoz, Charge-based MOS transistor Modeling - The EKV model for low-power and RF IC design, John Wiley & Sons, Ltd, 2006.

⁴This first release of the Qucs implementation of the EKV v2.6 MOSFET model does not include the first-order non-quasistatic model for transconductances.

The Qucs long channel EKV v2.6 model

A basic DC model for the long channel nMOS EKV v2.6 model is given at the EKV Compact MOSFET model website⁵. Unfortunately, this model is only of limited practical use due to its restricted modelling features⁶. It does however, provide a very good introduction to compact device modelling using the Verilog-A hardware description language. Readers who are unfamiliar with the Verilog-A hardware description language should consult the following references:

- Accellera, Verilog-AMS Language Reference Manual, Version 2.2, 2004, Available from <http://www.accellera.org>.
- Kenneth S. Kundert and Olaf Zinke, The Designer's Guide to Verilog-AMS, Kluwer Academic Publishers, 2004.
- Dan Fitzpatrick and Ira Miller, Analog Behavioral Modeling with the Verilog-A Language, Kluwer Academic Publishers, 1998.
- Coram G. J., How to (and how not to) write a compact model in Verilog-A, 2004, IEEE International Behavioural modeling and Simulation Conference (BMAS2004), pp. 97-106.

The equivalent circuit of the Qucs EKV long channel n type MOSFET model is shown in Fig. 1. In this model the inner section, enclosed with the red dotted box, represents the fundamental intrinsic EKV v2.6 elements. The remaining components model extrinsic elements which represent the physical components connecting the intrinsic MOSFET model to its external signal pins. In the Qucs implementation of the EKV v2.6 long channel MOSFET model the drain to source DC current I_{ds} is represented by the equations listed in a later section of the report, capacitors C_{gdi} , C_{gsi} , C_{dbi} and C_{sbi} are intrinsic components derived from the charge-based EKV equations, capacitors C_{gdo} , C_{gso} and C_{gbo} represent external overlap elements, the two diodes model the drain to channel and source to channel junctions (including diode capacitance) and resistors R_{Deff} and R_{Seff} model series connection resistors in the drain and source signal paths respectively.

Long channel model parameters (LEVEL = 1)

Name	Symbol	Description	Unit	Default nMOS	Default pMOS
LEVEL		Model selector		1	1
L	L	length parameter	m	$10e-6$	$10e-6$

⁵See <http://legwww.epfl.ch/ekv/verilog-a/> for the Verilog-A code.

⁶No dynamic, noise or temperature effects.

Name	Symbol	Description	Unit	Default nMOS	Default pMOS
W	<i>W</i>	width parameter	<i>m</i>	$10e-6$	$10e-6$
Np	<i>Np</i>	parallel multiple device number		1	1
Ns	<i>Ns</i>	series multiple device number		1	1
Cox	<i>Cox</i>	gate oxide capacitance per unit area	F/m^2	$3.4e-3$	$3.4e-3$
Xj	<i>Xj</i>	metallurgical junction length	<i>m</i>	$0.15e-6$	$0.15e-6$
Dw	<i>Dw</i>	channel width correction	<i>m</i>	$-0.02e-6$	$-0.02e-6$
Dl	<i>Dl</i>	channel length correction	<i>m</i>	$-0.05e-6$	$-0.05e-6$
Vto	<i>Vto</i>	long channel threshold voltage	<i>V</i>	0.5	-0.55
Gamma	<i>Gamma</i>	body effect parameter	\sqrt{V}	0.7	0.69
Phi	<i>Phi</i>	bulk Fermi potential	<i>V</i>	0.5	0.87
Kp	<i>Kp</i>	transconductance parameter	A/V^2	$50e-6$	$20e-6$
Theta	<i>Theta</i>	mobility reduction coefficient	$1/V$	$50e-3$	$50e-3$
Tcv	<i>Tcv</i>	threshold voltage temperature coefficient	V/K	$1.5e-3$	$-1.4e-3$
Hdif	<i>Hdif</i>	heavily doped diffusion length	<i>m</i>	$0.9e-6$	$0.9e-6$
Rsh	<i>Rsh</i>	drain-source diffusion sheet resistance	$\Omega/square$	510	510
Rsc	<i>Rsc</i>	source contact resistance	Ω	0.0	0.0
Rdc	<i>Rdc</i>	drain contact resistance	Ω	0.0	0.0
Cgso	<i>Cgso</i>	gate to source overlay capacitance	<i>F</i>	$1.5e-10$	$1.5e-10$
Cgdo	<i>Cgdo</i>	gate to drain overlay capacitance	<i>F</i>	$1.5e-10$	$1.5e-10$
Cgbo	<i>Cgbo</i>	gate to bulk overlay capacitance	<i>F</i>	$4e-10$	$4e-10$
N	<i>N</i>	diode emission coefficient		1.0	1.0
Is	<i>Is</i>	leakage current	<i>A</i>	$1e-1$	$1e-14$
Bv	<i>Bv</i>	reverse breakdown voltage	<i>V</i>	100	100
Ibv	<i>Ibv</i>	current at Bv	<i>A</i>	$1e-3$	$1e-3$
Vj	<i>Vj</i>	junction potential	<i>V</i>	1.0	1.0
Cj0	<i>Cj0</i>	zero bias depletion capacitance	<i>F</i>	$1e-12$	$1e-12$
M	<i>M</i>	grading coefficient		0.5	0.5
Area	<i>Area</i>	relative area		1.0	1.0
Fc	<i>Fc</i>	forward-bias depletion capacitance coefficient		0.5	0.5
Tt	<i>Tt</i>	transit time	<i>s</i>	$0.1e-9$	$0.1e-9$
Xti	<i>Xti</i>	saturation current temperature exponent		3.0	3.0
Kf	<i>Kf</i>	flicker noise coefficient		$1e-27$	$1e-28$
Af	<i>Af</i>	flicker noise exponent		1.0	1.0
Tnom	<i>Tnom</i>	parameter measurement temperature	$^{\circ}C$	26.85	26.85
Temp	<i>Temp</i>	device temperature	$^{\circ}C$	26.85	26.85

Fundamental long channel DC model equations (LEVEL = 1)

$$\begin{aligned}
<22> \quad & Vg = V(Gate) - V(Bulk) \\
<23> \quad & Vs = V(Source) - V(Bulk) \\
<24> \quad & Vd = V(Drain) - V(Bulk) \\
<33> \quad & VGprime = Vg - Vto + Phi + Gamma \cdot \sqrt{Phi} \\
<34> \quad & Vp = VGprime - Phi - Gamma \cdot \left(\sqrt{VGprime + \left[\frac{Gamma}{2} \right]^2} - \frac{Gamma}{2} \right) \\
<39> \quad & n = 1 + \frac{Gamma}{2 \cdot \sqrt{Vp + Phi} + 4 \cdot Vt} \\
<58, 64> \quad & \beta = Kp \cdot \frac{W}{L} \cdot \frac{1}{1 + Theta \cdot Vp} \\
<44> \quad & X1 = \frac{Vp - Vs}{Vt} \quad If = \left[\ln \left\{ 1 + \limexp \left(\frac{X1}{2} \right) \right\} \right]^2
\end{aligned}$$

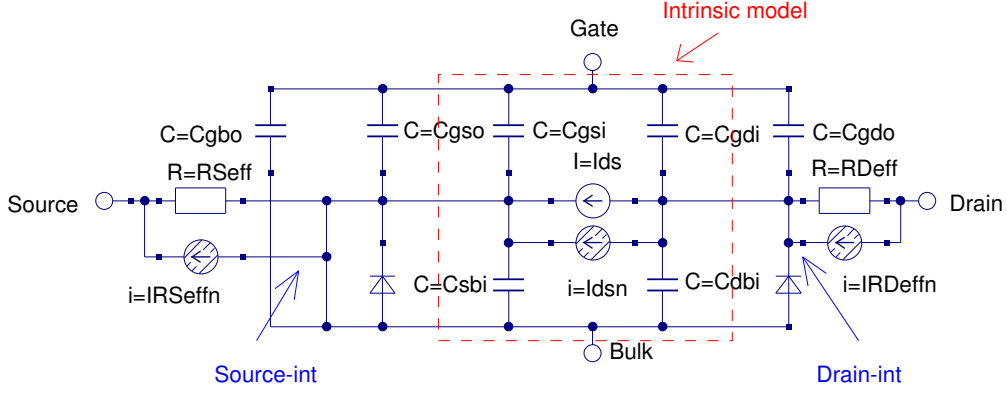


Figure 1: Equivalent circuit for the Qucs EKV v2.6 long channel nMOS model

$$\begin{aligned}
 <57> \quad X2 = \frac{Vp - Vd}{Vt} \quad Ir = \left[\ln \left\{ 1 + \limexp \left(\frac{X2}{2} \right) \right\} \right]^2 \\
 <65> \quad Ispecific = 2 \cdot n \cdot \beta \cdot Vt^2 \\
 <66> \quad Ids = Ispecific \cdot (If - Ir)
 \end{aligned}$$

Where VG_{prime} is the effective gate voltage, Vp is the pinch-off voltage, n is the slope factor, β is a transconductance parameter, $Ispecific$ is the specific current, If is the forward current, Ir is the reverse current, Vt is the thermal voltage at the device temperature, and Ids is the drain to source current. EKV v2.6 equation numbers are given in “< >” brackets at the left-hand side of each equation. Typical plots of Ids against Vds for both the nMOS and pMOS long channel devices are given in Figure 2.

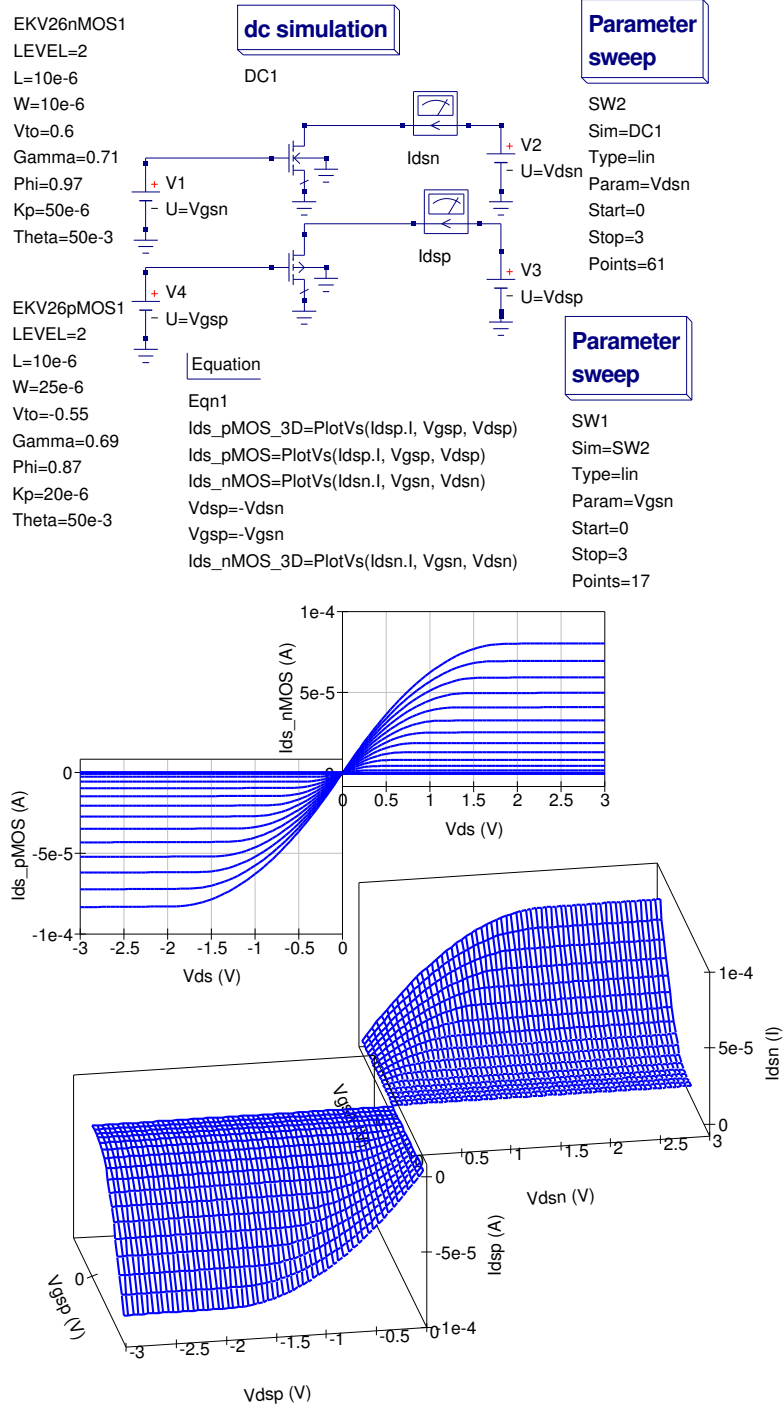


Figure 2: I_{ds} versus V_{ds} plots for the Qucs EKV v2.6 long channel nMOS and pMOS models

Testing model performance

Implementing advanced component models like the EKV v2.6 MOSFET model is a complex process, involving the translation of a set of equations into the Verilog-A hardware design language, conversion of the Verilog-A code into C++ code via the ADMS compiler, and finally compiling and linking the model code with the main body of Qucs code. At all stages in the process accuracy becomes an important issue. This section of the Qucs EKV v2.6 report introduces a number of test simulations which were used during the model development cycle to check the performance of the Qucs EKV v2.6 implementation. The tests also demonstrate how a circuit simulator can be used to extract model parameters. The values of which help to confirm correct model operation.

Extraction of I_{spec}

When a MOS transistor is operating in the saturation region, reverse current I_r approaches zero and the drain to source current is approximated by

$$I_{ds} = I_{specific} \cdot I_f = I_{specific} \cdot \left[\ln \left\{ 1 + \limexp \left(\frac{V_p - V_s}{2 \cdot V_t} \right) \right\} \right]^2 \quad (1)$$

In saturation $\limexp \left(\frac{V_p - V_s}{2 \cdot V_t} \right) \gg 1$, yielding

$$\sqrt{I_{ds}} = \sqrt{\frac{I_{specific}}{2 \cdot V_t^2}} \cdot (V_p - V_s) \quad (2)$$

Hence

$$\frac{\partial(\sqrt{I_{ds}})}{\partial V_s} = -\sqrt{\frac{I_{specific}}{2 \cdot V_t^2}} = -slope \quad (3)$$

Or

$$I_{specific} = 2 \cdot slope^2 \cdot V_t^2 \quad (4)$$

Figure 3 shows a typical test circuit configuration for measuring and simulating I_{ds} with varying V_s . Qucs post-simulation functions in equation block Eqn1 are used to calculate the value for $I_{specific}$. The value of $I_{specific}$ for the nMOS transistor with the parameters given in Fig. 3 is 3.95e-8 A. Figure 4 illustrates a test circuit for measuring V_p with the transistor in saturation. In this circuit $I_s = I_{specific}$ and the threshold voltage corresponds to V_g when $V_p = 0V$. Notice also that $n = \partial V_g / \partial V_p$. In Fig. 4 Qucs post-simulation processing functions are also used to generate data for V_p , V_{Gprime} and n . The value of the threshold voltage for the device shown in Fig. 4 is 0.6V. At this voltage $n = 1.37$. The two test configurations illustrated in Figs. 3 and 4 go some way to confirming that the Qucs implementation of the EKV v2.6 long channel model is functioning correctly.

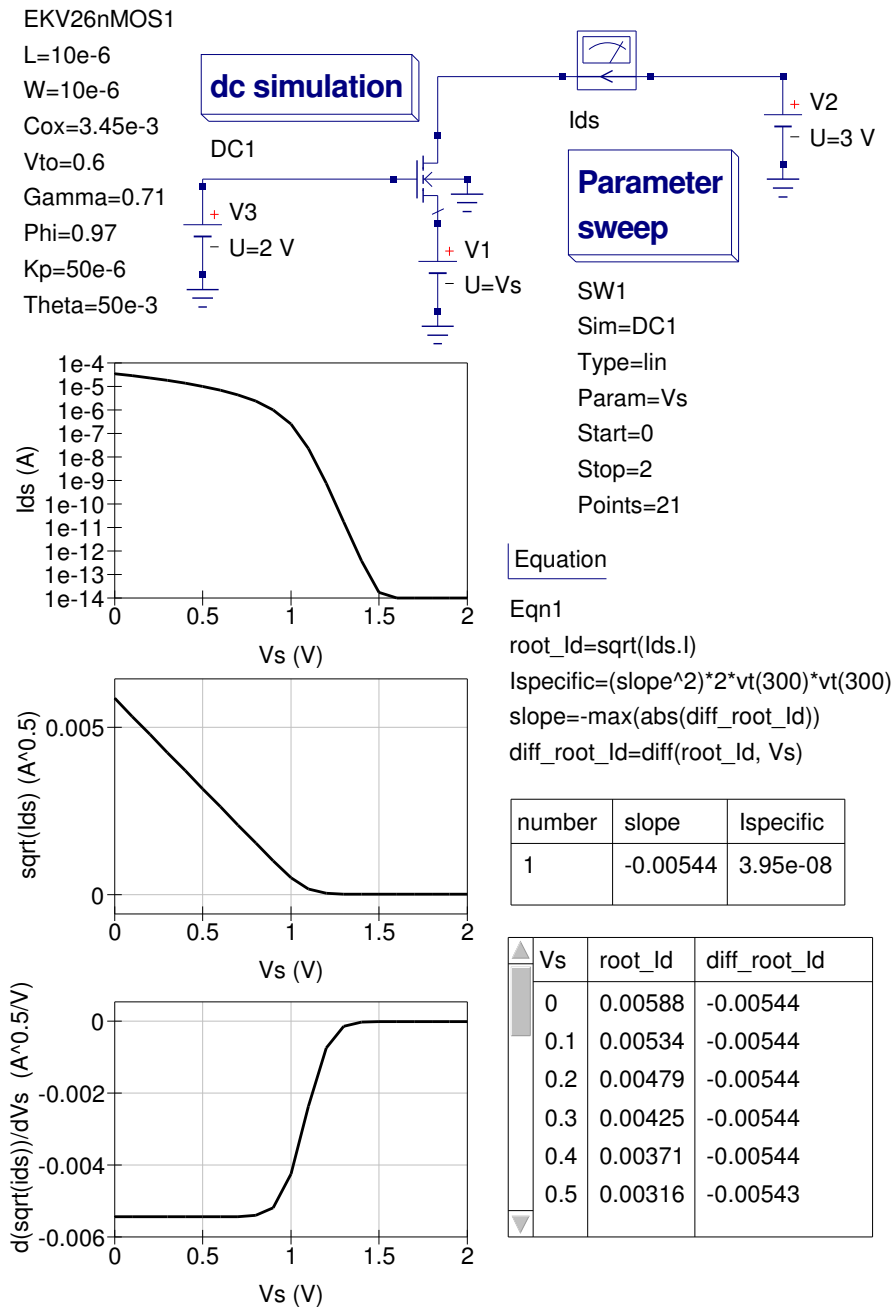


Figure 3: $I_{specific}$ extraction test circuit and post simulation data processing results

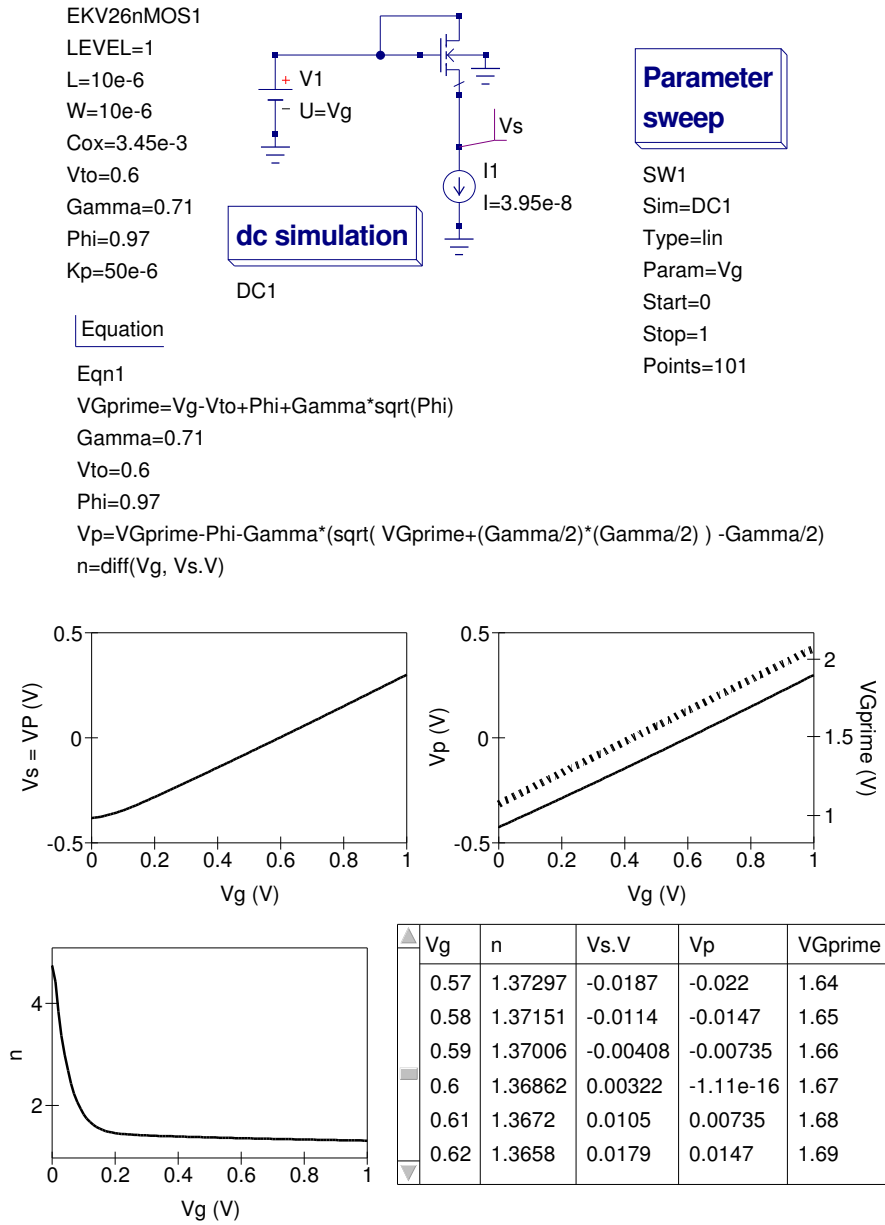


Figure 4: V_p extraction test circuit and post simulation data processing results

Extraction of model intrinsic capacitance

The Qucs implementation of the EKV v2.6 MOSFET model uses the charge-based model for transcapacitances. This model ensures charge-conservation during transient analysis. Both the long channel and short channel versions employ the quasi-static charge-based model. The EKV v2.6 charge equations for the long channel intrinsic device are:

$$nq = 1 + \frac{Gamma}{2 \cdot \sqrt{Vp + Phi + 1e - 6}} \quad (5)$$

$$Xf = \sqrt{\frac{1}{4} + If} \quad (6)$$

$$Xr = \sqrt{\frac{1}{4} + Ir} \quad (7)$$

$$qD = -nq \cdot \left\{ \frac{4}{15} \cdot \frac{3 \cdot Xr^3 + 6 \cdot Xr^2 \cdot Xf + 4 \cdot Xr \cdot Xf^2 + 2 \cdot Xf^3}{(Xf + Xr)^2} - \frac{1}{2} \right\} \quad (8)$$

$$qS = -nq \cdot \left\{ \frac{4}{15} \cdot \frac{3 \cdot Xf^3 + 6 \cdot Xf^2 \cdot Xr + 4 \cdot Xf \cdot Xr^2 + 2 \cdot Xr^3}{(Xf + Xr)^2} - \frac{1}{2} \right\} \quad (9)$$

$$qI = qS + qD = -nq \cdot \left\{ \frac{4}{3} \cdot \frac{3 \cdot Xf^3 + Xr \cdot Xf + Xr^2}{Xf + Xr} - 1 \right\} \quad (10)$$

$$qB = -Gamma \cdot \sqrt{Vp + Phi + 1e - 6} \cdot \frac{1}{Vt} - \left(\frac{nq - 1}{nq} \right) \cdot qI \quad \forall (VGprime > 0) \quad (11)$$

$$qB = -VGprime \cdot \frac{1}{Vt} \quad \forall (VGprime \leq 0) \quad (12)$$

$$qG = -qI - qB \quad (13)$$

$$COX = Cox \cdot Np \cdot Weff \cdot Ns \cdot Leff \quad (14)$$

$$Q(I, B, D, S, G) = COX \cdot Vt \cdot q(I, B, D, S, G) \quad (15)$$

The first release of the Qucs EKV v2.6 MOSFET model assumes that the gate and bulk charge is partitioned between the drain and source in equal ratio⁷. Fifty per-cent charge portioning yields the following I_{ds} current contributions:

$$I(Gate, Source_int) < +0.5 \cdot p_n_MOS \cdot ddt(QG) \quad (16)$$

$$I(Gate, Drain_int) < +0.5 \cdot p_n_MOS \cdot ddt(QG) \quad (17)$$

$$I(Source_int, Bulk) < +0.5 \cdot p_n_MOS \cdot ddt(QB) \quad (18)$$

$$I(drain_int, Bulk) < +0.5 \cdot p_n_MOS \cdot ddt(QB) \quad (19)$$

Where $p_n_MOS = 1$ for nMOS devices or -1 for pMOS devices. Charge associated with the extrinsic overlap capacitors, $Cgs0$, $Cgd0$ and $Cgb0$, is represented in the Qucs EKV v2.6 implementation by the following equations:

$$Qgs0 = Cgs0 \cdot W_{eff} \cdot Np \cdot (VG - VS) \quad (20)$$

$$Qgd0 = Cgd0 \cdot W_{eff} \cdot Np \cdot (VG - VD) \quad (21)$$

$$Qgb0 = Cgb0 \cdot L_{eff} \cdot Np \cdot VB \quad (22)$$

The drain to bulk and source to bulk diodes also introduce additional components in the extrinsic capacitance model. The default value of $CJ0$ being set at 300fF. Analysis of the y-parameters⁸ for the EKV v2.6 equivalent circuit shown in the test circuit illustrated in Fig. 5 yields

$$y_{11} = \frac{j \cdot \omega \cdot Cg}{1 + \omega^2 \cdot (Rgn \cdot Cg)^2} \quad (23)$$

Or

$$y_{11} \cong \omega^2 \cdot Rg \cdot Cg^2 + j \cdot \omega \cdot Cg, \quad \text{when } \omega \cdot Rg \cdot Cg \ll 1. \quad (24)$$

⁷For an example of this type of charge partitioning see F. Pregaldiny et. al., An analytic quantum model for the surface potential of deep-submicron MOSFETS, 10th International Conference, MIXDES 2003, Lodz, Poland, 26-28 June 2003.

⁸A more detailed anlysis of the EKV v2.6 y-parameters can be found in F. Krummenacher *et. al.*, HF MOSET MODEL parameter extraction, European Project No. 25710, Deliverable D2.3, July 28, 2000.

Hence, $C_g = \text{imag}(y_{11}/\omega)$ and $R_{gn} = \text{real}(y_{11}/(\omega^2 \cdot C_g^2))$, where $\omega = 2 \cdot \pi \cdot f$, and f is the frequency of y-parameter measurement, R_g is a series extrinsic gate resistance and $C_g \cong C_{gs} + C_{gd} + C_{gb}$. With equal partitioning of the intrinsic gate charge C_{gb} approximates to zero and $C_g \cong C_{gs} + C_{gd}$. The data illustrated in Figures 5 and 6 shows two features which are worth commenting on; firstly the values of C_g are very much in line with simple hand calculations (for example in the case of the nMOS device $C_g(\text{max}) = W \cdot L \cdot C_{ox} = 10e-6 * 10e-6 * 3.45e-3 = 3.45e-13\text{F}$) and secondly both sets of simulation data indicate the correct values for the nMOS and pMOS threshold voltages (for example -0.55 V for the pMOS device and 0.6 V for the nMOS device), reinforcing confidence in the EKV v2.6 model implementation.

Extraction of extrinsic diode capacitance and drain resistance

The extrinsic section of the EKV v2.6 model includes diodes which in turn are modelled by conventional DC characteristics and parallel capacitance. This capacitance is represented by depletion layer capacitance in the diode reverse bias region of operation. In the diode forward bias section of the I-V characteristic diffusion capacitance dominates. Figure 7 illustrates a test circuit that allows the diode capacitance to be extracted as a function of V_{ds} . In Fig. 7 the nMOS device is turned off and the drain to bulk diode reverse biased. Simple analysis indicates that

$$y_{11} \cong \omega^2 \cdot R_{Def f} \cdot C_d^2 + j \cdot \omega \cdot C_d, \quad \text{when } \omega \cdot R_{Def f} \cdot C_d \ll 1. \quad (25)$$

Hence, $C_d = \text{imag}(y_{11}/\omega)$ and $R_{def f} = \text{real}(y_{11}/(\omega^2 \cdot C_d^2))$, where $\omega = 2 \cdot \pi \cdot f$, f is the frequency of y-parameter measurement, and C_d is the diode capacitance. The data shown in Fig. 7 indicate good agreement with the expected values for C_d and $R_{Def f}$; which are expected to be $C_d = 300\text{fF}$ at $V_{ds}=0\text{V}$, and $R_{def f} = 46\Omega$.

Simulating EKV v2.6 MOSFET noise

The EKV v2.6 intrinsic device noise is modelled by a noise current source connected between the internal drain and source terminals. The noise current source I_{dsn} , see Fig. 1, is composed of a thermal noise component and a flicker noise component. The Power Spectral Density (S_{PSD}) of these components are given by:

$$S_{PSD} = S_{thermal} + S_{flicker} \quad (26)$$

Where

- Thermal noise

$$S_{thermal} = 4 \cdot k \cdot T \cdot \beta \cdot |qI| \quad (27)$$

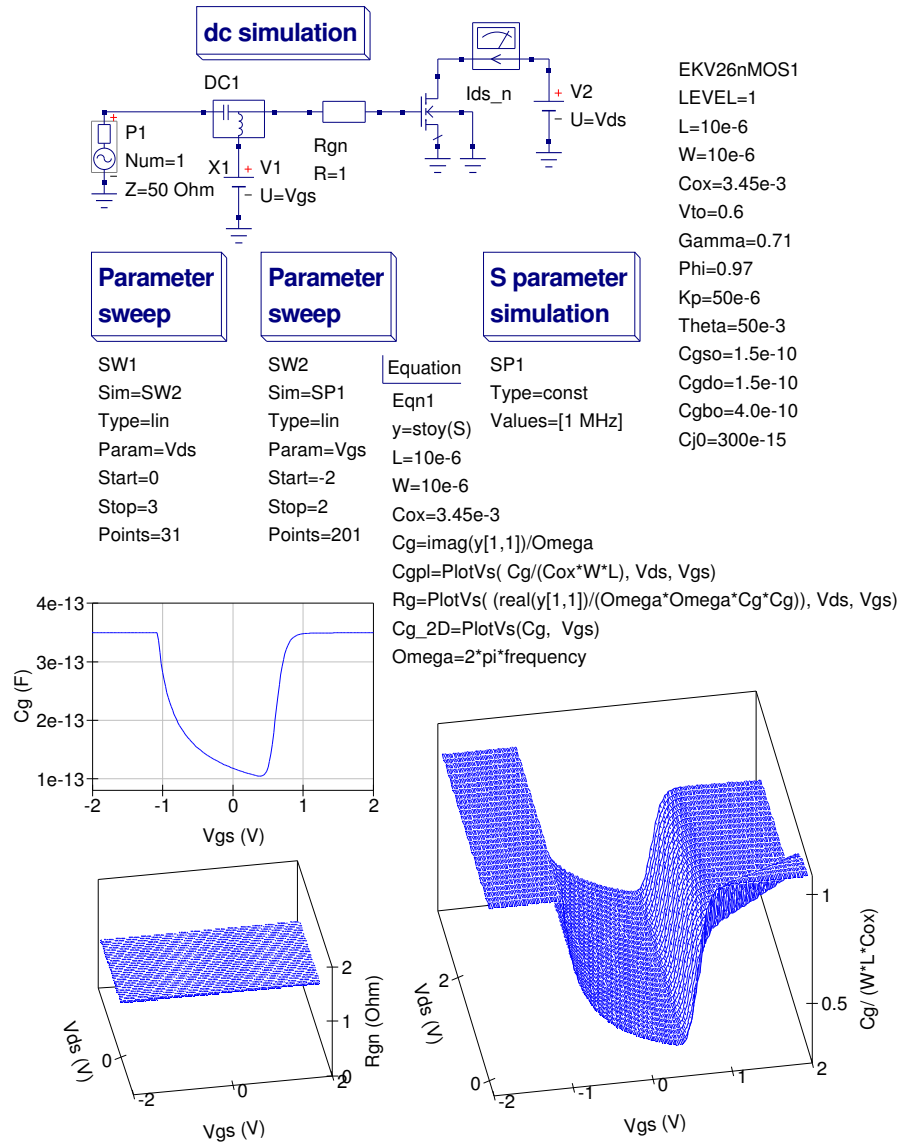


Figure 5: y_{11} test circuit and values of C_g for the long channel EKV v2.6 nMOS model

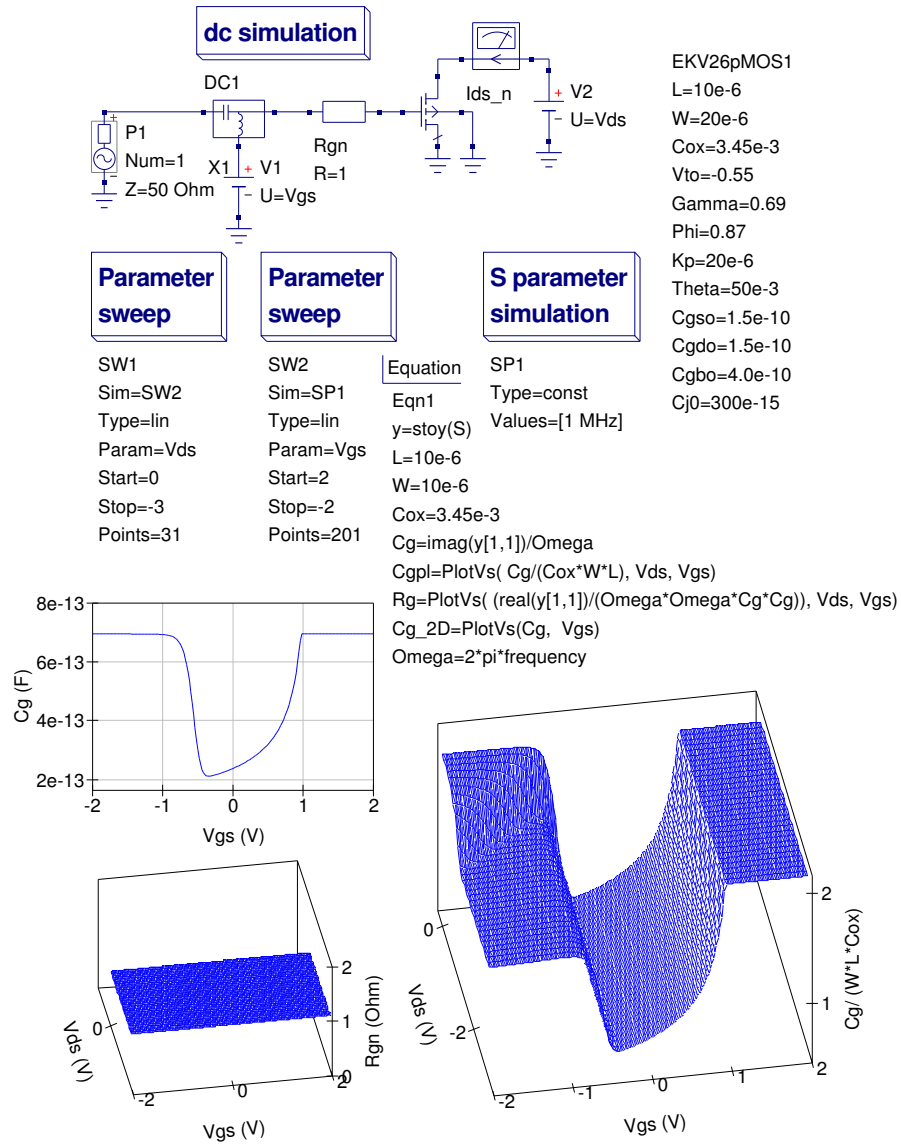


Figure 6: y_{11} test circuit and values of C_g for the long channel EKV v2.6 pMOS model

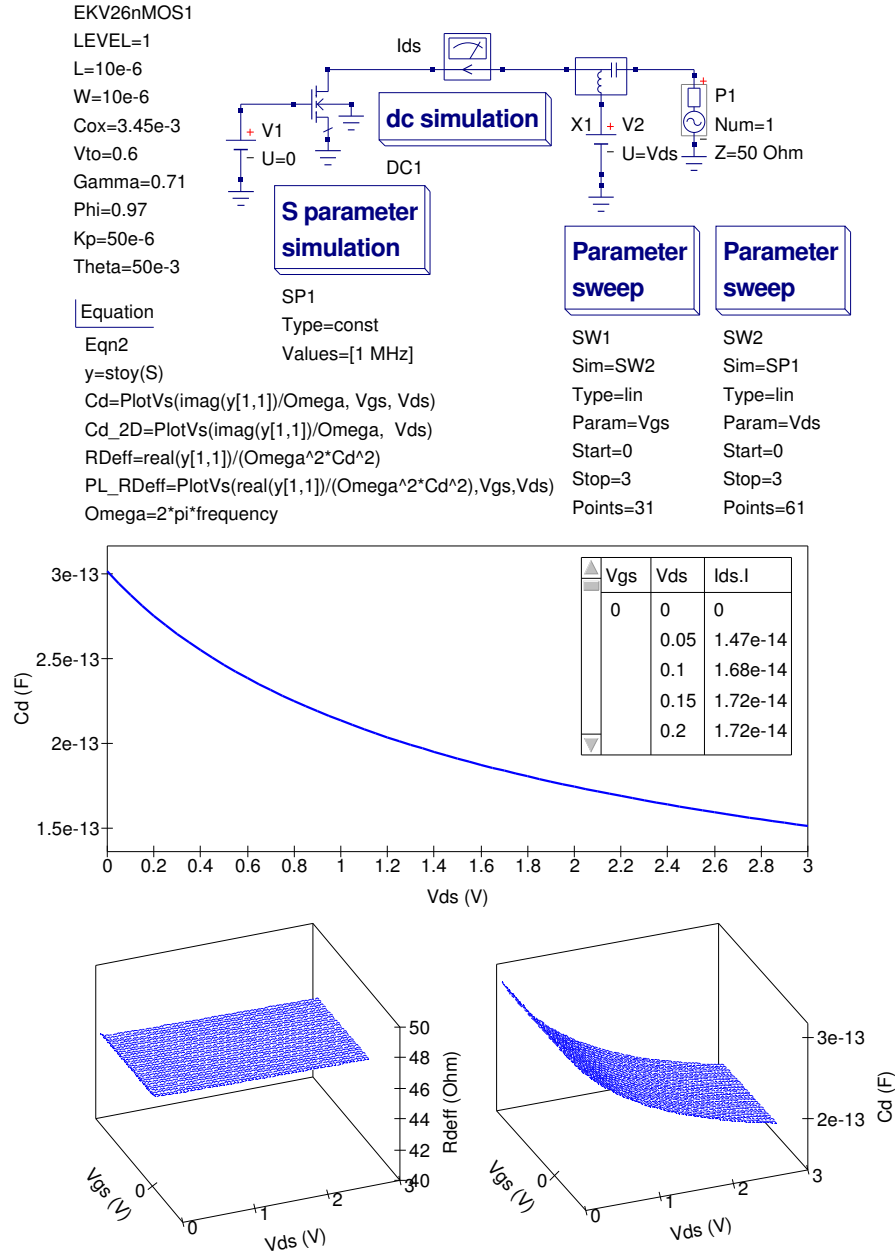


Figure 7: Test circuit for extracting EKV v2.6 extrinsic diode capacitance

- Flicker noise

$$S_{flicker} = \frac{KF \cdot g_{mg}^2}{Np \cdot Weff \cdot Ns \cdot Leff \cdot Cox \cdot f^{Af}}, \quad (28)$$

$$g_{mg} = \frac{\partial I_{ds}}{\partial V_{gs}} = \beta \cdot Vt \cdot \left(\sqrt{\frac{4 \cdot If}{I_{specific}} + 1} - \sqrt{\frac{4 \cdot Ir}{I_{specific}} + 1} \right) \quad (29)$$

Where β is a transconductance factor, $qI = qD + qS$, and the other symbols are defined in the EKV v2.6 long channel parameter list or have their usual meaning. Noise has been implemented in both the Qucs long channel and short channel EKV v2.6 models. In addition to the intrinsic device noise the Qucs EKV v2.6 model includes the thermal noise components for both extrinsic resistors $RDeff$ and $RSeff$. Figure 8 presents a typical noise test circuit and simulated noise currents. In Figure 8 four nMOS devices are biased under different DC conditions and their noise current simulated for a range of W values between 1e-6 m and 100e-6 m. The first three devices include both thermal and flicker noise components ($KF = 1e-27$) while the fourth device has it's flicker component set to zero. The resulting current noise curves clearly demonstrate the effect of summing intrinsic thermal and flicker components on the overall performance of the EKV v2.6 noise model.

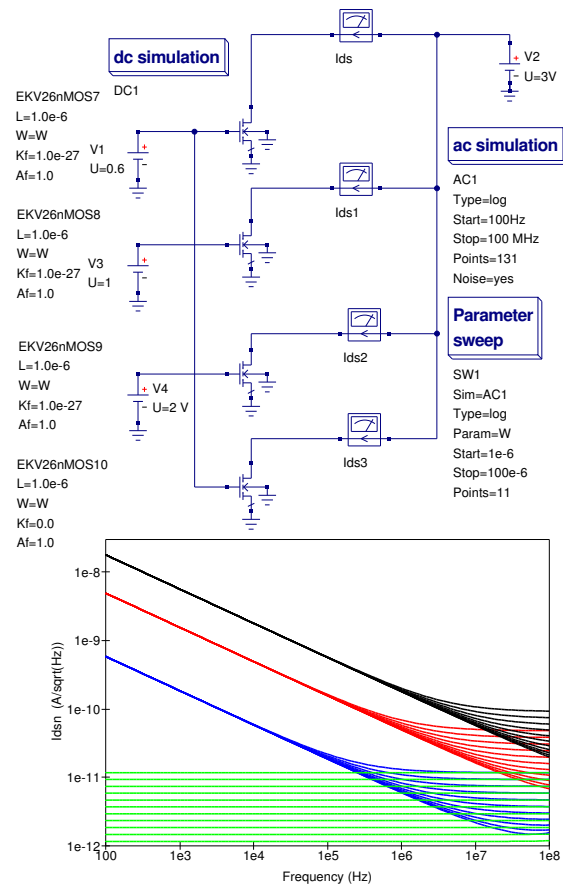


Figure 8: Test circuit for simulating EKV v2.6 noise: I_{ds} in blue curve, I_{ds1} in red curve, I_{ds2} in black curve and I_{ds3} in green curve

The Qucs short channel EKV v2.6 model

The Qucs implementation of the short short channel EKV v2.6 MOSFET model contains all the features implemented in the long channel version of the model plus a number of characteristics specific to short channel operation. However, the short channel version of the model does not use parameter *Theta*. Parameter LEVEL set to 2 selects the short channel model. Both pMOS and nMOS versions of the model are available for both long and short channel implementations. The entire short channel EKV v2.6 MOSFET model is described by roughly 94 equations. Readers who are interested in the mathematics of the model should consult “The EPFL-EKV MOSFET Model Equations for Simulation” publication cited in previous text. Appendix A lists the complete Verilog-A code for the first release of the Qucs EKV v2.6 MOSFET models. Additional Verilog-A code has been added to the model equation code to (1) allow interchange of the drain and source terminals, and (2) select nMOS or pMOS devices.

Short channel model parameters (LEVEL = 2)

Name	Symbol	Description	Unit	Default nMOS	Default pMOS
LEVEL		Model selector		2	2
L	<i>L</i>	length parameter	<i>m</i>	$10e-6$	$10e-6$
W	<i>W</i>	width parameter	<i>m</i>	$10e-6$	$10e-6$
Np	<i>Np</i>	parallel multiple device number		1	1
Ns	<i>Ns</i>	series multiple device number		1	1
Cox	<i>Cox</i>	gate oxide capacitance per unit area	<i>F/m²</i>	$3.4e-3$	$3.4e-3$
Xj	<i>Xj</i>	metallurgical junction length	<i>m</i>	$0.15e-6$	$0.15e-6$
Dw	<i>Dw</i>	channel width correction	<i>m</i>	$-0.02e-6$	$-0.02e-6$
Dl	<i>Dl</i>	channel length correction	<i>m</i>	$-0.05e-6$	$-0.05e-6$
Vto	<i>Vto</i>	long channel threshold voltage	<i>V</i>	0.5	-0.55
Gamma	<i>Gamma</i>	body effect parameter	\sqrt{V}	0.7	0.69
Phi	<i>Phi</i>	bulk Fermi potential	<i>V</i>	0.5	0.87
Kp	<i>Kp</i>	transconductance parameter	<i>A/V²</i>	$50e-6$	$20e-6$
EO	<i>EO</i>	mobility reduction coefficient	<i>V/m</i>	$88e-6$	$51e-6$
Ucrit	<i>Ucrit</i>	longitudinal critical field	<i>V/m</i>	$4.5e-6$	$18e-6$
Lambda	<i>Lambda</i>	depletion length coefficient		0.23	1.1
Weta	<i>Weta</i>	narrow channel effect coefficient		0.05	0.0
Leta	<i>eta</i>	short channel effect coefficient		0.28	0.45
Q0	<i>Q0</i>	reverse short channel effect peak charge density		$280e-6$	$200e-6$
Lk	<i>Lk</i>	reverse short channel effect characteristic length	<i>m</i>	$0.5e-6$	$0.6e-6$
Tcv	<i>Tcv</i>	threshold voltage temperature coefficient	<i>V/K</i>	$1.5e-3$	$-1.4e-3$
Bex	<i>Bex</i>	mobility temperature coefficient		-1.5	-1.4
Ucex	<i>Ucex</i>	longitudinal critical field temperature exponent		1.7	2.0
Ibbt	<i>Ibbt</i>	temperature coefficient for Ibb	<i>1/K</i>	0.0	0.0
Hdif	<i>Hdif</i>	heavily doped diffusion length	<i>m</i>	$0.9e-6$	$0.9e-6$
Rsh	<i>Rsh</i>	drain-source diffusion sheet resistance	Ω/square	510	510
Rsc	<i>Rsc</i>	source contact resistance	Ω	0.0	0.0
Rdc	<i>Rdc</i>	drain contact resistance	Ω	0.0	0.0
Cgso	<i>Cgso</i>	gate to source overlay capacitance	<i>F</i>	$1.5e-10$	$1.5e-10$
Cgdo	<i>Cgdo</i>	gate to drain overlay capacitance	<i>F</i>	$1.5e-10$	$1.5e-10$
Cgbo	<i>Cgbo</i>	gate to bulk overlay capacitance	<i>F</i>	$4e-10$	$4e-10$
N	<i>N</i>	diode emission coefficient		1.0	1.0
Is	<i>Is</i>	leakage current	<i>A</i>	$1e-1$	$1e-14$

Name	Symbol	Description	Unit	Default nMOS	Default pMOS
Bv	<i>Bv</i>	reverse breakdown voltage	<i>V</i>	100	100
Ibv	<i>Ibv</i>	current at Bv	<i>A</i>	$1e-3$	$1e-3$
Vj	<i>Vj</i>	junction potential	<i>V</i>	1.0	1.0
Cj0	<i>Cj0</i>	zero bias depletion capacitance	<i>F</i>	$1e-12$	$1e-12$
M	<i>M</i>	grading coefficient		0.5	0.5
Area	<i>Area</i>	relative area		1.0	1.0
Fc	<i>Fc</i>	forward-bias depletion capacitance coefficient		0.5	0.5
Tt	<i>Tt</i>	transit time	<i>s</i>	$0.1e-9$	$0.1e-9$
Xti	<i>Xti</i>	saturation current temperature exponent		3.0	3.0
Kf	<i>Kf</i>	flicker noise coefficient		$1e-27$	$1e-28$
Af	<i>Af</i>	flicker noise exponent		1.0	1.0
Avto	<i>Avto</i>	area related threshold mismatch parameter		0	0
Akp	<i>Akp</i>	area related gain mismatch parameter		0	0
Agamma	<i>Agamma</i>	area related body effect mismatch parameter		0	0
Iba	<i>Iba</i>	first impact ionization coefficient	$1/m$	$2e8$	0.0
Ibb	<i>Ibb</i>	second impact ionization coefficient	V/m	$3.5e8$	$3.5e8$
Ibn	<i>Ibn</i>	saturation voltage factor for impact ionization		1.0	1.0
Tnom	<i>Tnom</i>	parameter measurement temperature	$^{\circ}C$	26.85	26.85
Temp	<i>Temp</i>	device temperature	$^{\circ}C$	26.85	26.85

Simulating short channel charge sharing effects

A simple test circuit for demonstrating the effects of charge sharing is given in Figure 9. With charge sharing disabled, by setting Weta and Leta to zero, the magnitude and slope of the I_{ds} vs. V_{ds} curve shows a marked difference to that where charge sharing is enabled. One point to note with this test: charge sharing in short channel devices significantly reduces the device output resistance which could have, of course, important consequences on circuit performance.

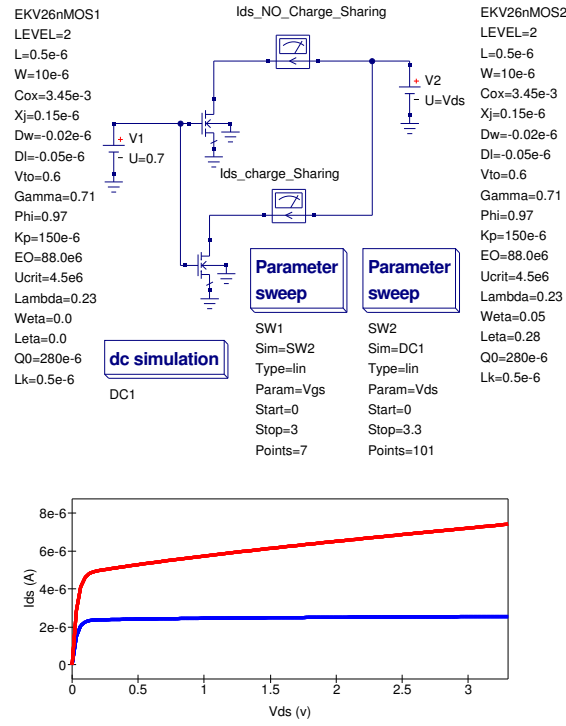


Figure 9: Test circuit for simulating EKV v2.6 charge sharing effects in short channel devices: I_{ds} blue curve; NO charge sharing ($Weta = 0.0$, $Leta = 0.0$), I_{ds} red curve; charge sharing ($Weta = 0.05$, $Leta = 0.28$)

End note

This report outlines some of the background to the Qucs implementation of the EKV v2.6 MOSFET model. A series of test results demonstrate a range of results that have been achieved with this new Qucs compact device model. Although the test results give data similar to what is expected in all cases it must be stressed that this is the first release of this MOSFET model and as such it will probably contain bugs. A great deal of work has gone into providing this new Qucs model. However, all the effort has been worthwhile because for the first time Qucs now has a submicron MOSFET model. Please use the model and report bugs to the Qucs development team. Much work still remains to be done in the development of MOSFET models for Qucs. In future releases both bug fixes and new models are likely to feature strongly. Once again I would like to thank Stefan Jahn and Władysław Grabiński (of MOS-AK) for their encouragement and support during the period I have been working on developing the Qucs implementation of the EKV v2.6 model and writing this report.

Qucs Verilog-A code for the EKV v2.6 MOSFET model

nMOS: EKV equation numbers are given on the right-hand side of code lines

```
//  Qucs EPFL-EKV 2.6 nMOS model:
//
//  The structure and theoretical background to the EKV 2.6
//  Verilog-a model is presented in the Qucs EPFL-EKV 2.6 report.
//  Typical parameters are for 0.5um CMOS (C) EPLFL-LEG 1999.
//  Geometry range: Short channel  $W \geq 0.8\mu\text{m}$ ,  $L \geq 0.5\mu\text{m}$ 
//                  Long channel  $W \geq 2\mu\text{m}$ ,  $L \geq 2\mu\text{m}$ 
//  Voltage range:  $|V_{gb}| < 3.3\text{V}$ ,  $|V_{db}| < 3.3\text{V}$ ,  $|V_{sb}| < 2\text{V}$ 
//
//  This is free software; you can redistribute it and/or modify
//  it under the terms of the GNU General Public License as published by
//  the Free Software Foundation; either version 2, or (at your option)
//  any later version.
//
//  Copyright (C), Mike Brinson, mbrin72043@yahoo.co.uk, May 2008.
//
#include "disciplines.vams"
#include "constants.vams"

//
module EKV26nMOS (Drain, Gate, Source, Bulk);
  inout Drain, Gate, Source, Bulk;
  electrical Drain, Gate, Source, Bulk;
// Internal nodes
  electrical Drain_int, Source_int;
  define attr(txt) (*txt*)
// Device dimension parameters
```

```

parameter real LEVEL = 1 from [1 : 2]
    'attr(info="long_1,_short_2");
parameter real L = 0.5e-6 from [0.0 : inf]
    'attr(info="length_parameter" unit = "m" );
parameter real W = 10e-6 from [0.0 : inf]
    'attr(info="Width_parameter" unit = "m");
parameter real Np = 1.0 from [1.0 : inf]
    'attr(info="parallel_multiple_device_number");
parameter real Ns = 1.0 from [1.0 : inf]
    'attr(info="series_multiple_device_number");
// Process parameters
parameter real Cox = 3.45e-3 from [0 : inf]
    'attr(info="gate_oxide_capacitance_per_unit_area" unit = "F/m**2" );
parameter real Xj = 0.15e-6 from [0.01e-6 : 1.0e-6]
    'attr(info="metallurgical_junction_depth" unit = "m");
parameter real Dw = -0.02e-6 from [-inf : 0.0]
    'attr(info="channel_width_correction" unit = "m");
parameter real Dl = -0.05e-6 from [-inf : 0.0]
    'attr(info="channel_length_correction" unit = "m");
// Basic intrinsic model parameters
parameter real Vto = 0.6 from [1e-6 : 2.0]
    'attr(info="long_channel_threshold_voltage" unit="V" );
parameter real Gamma = 0.71 from [0.0 : 2.0]
    'attr(info="body_effect_parameter" unit="V**(1/2)");
parameter real Phi = 0.97 from [0.3 : 2.0]
    'attr(info="bulk_Fermi_potential" unit="V");
parameter real Kp = 150e-6 from [10e-6 : inf]
    'attr(info="transconductance_parameter" unit = "A/V**2");
parameter real Theta = 50e-3 from [0.0 : inf]
    'attr(info="mobility_reduction_coefficient" unit = "1/V");
parameter real EO = 88.0e6 from [1.0e6 : inf]
    'attr(info="mobility_coefficient" unit="V/m");
parameter real Ucrit = 4.5e6 from [2.0e6 : 25.0e6]
    'attr(info="longitudinal_critical_field" unit="V/m");
// Channel length and charge sharing parameters
parameter real Lambda = 0.23 from [0.1 : inf]
    'attr(info="depletion_length_coefficient");
parameter real Weta = 0.05 from [0.0 : inf]
    'attr(info="narrow-channel_effect_coefficient");
parameter real Leta = 0.28 from [0.0 : inf]
    'attr(info="longitudinal_critical_field");
// Reverse short channel effect parameters
parameter real Q0 = 280e-6 from [0.0 : inf]
    'attr(info="reverse_short_channel_charge_density" unit="A*s/m**2");
parameter real Lk = 0.5e-6 from [0.0 : inf]
    'attr(info="characteristic_length" unit="m");
// Intrinsic model temperature parameters
parameter real Tcv = 1.5e-3
    'attr(info="threshold_voltage_temperature_coefficient" unit="V/K");
parameter real Bex = -1.5
    'attr(info="mobility_temperature_coefficient");
parameter real Ucx = 1.7
    'attr(info="Longitudinal_critical_field_temperature_exponent");
parameter real Ibbt = 0.0
    'attr(info="Ibb_temperature_coefficient" unit="1/K");
// Series resistance calculation parameters
parameter real Hdif = 0.9e-6 from [0.0 : inf]
    'attr(info="heavily_doped_diffusion_length" unit = "m");
parameter real Rsh = 510.0 from [0.0 : inf]
    'attr(info="drain/source_diffusion_sheet_resistance" unit="Ohm/square");
parameter real Rsc = 0.0 from [0.0 : inf]
    'attr(info="source_contact_resistance" unit="Ohm");

```

```

parameter real Rdc = 0.0 from [0.0 : inf]
    'attr(info="drain_contact_resistance" unit="Ohm");
// Gate overlap capacitances
parameter real Cgso = 1.5e-10 from [0.0 : inf]
    'attr(info="gate_to_source_overlap_capacitance" unit = "F/m");
parameter real Cgdo = 1.5e-10 from [0.0 : inf]
    'attr(info="gate_to_drain_overlap_capacitance" unit= "F/m");
parameter real Cgbo = 4.0e-10 from [0.0 : inf]
    'attr(info="gate_to_bulk_overlap_capacitance" unit= "F/m");
// Impact ionization related parameters
parameter real Iba = 2e8 from [0.0 : inf]
    'attr(info="first_impact_ionization_coefficient" unit = "1/m");
parameter real Ibb = 3.5e8 from [1.0e8 : inf]
    'attr(info="second_impact_ionization_coefficient" unit="V/m");
parameter real Ibn = 1.0 from [0.1 : inf]
    'attr(info="saturation_voltage_factor_for_impact_ionization");
// Flicker noise parameters
parameter real Kf = 1.0e-27 from [0.0 : inf]
    'attr(info="flicker_noise_coefficient");
parameter real Af = 1.0 from [0.0 : inf]
    'attr(info="flicker_noise_exponent" );
// Matching parameters
parameter real Avto = 0.0 from [0.0 : inf]
    'attr(info="area_related_threshold_voltage_mismatch_parameter" unit = "V*m");
parameter real Akp = 0.0 from [0.0 : inf]
    'attr(info="area_related_gain_mismatch_parameter" unit="m");
parameter real Agamma = 0.0 from [0.0 : inf]
    'attr(info="area_related_body_effect_mismatch_parameter" unit="sqrt(V)*m");
// Diode parameters
parameter real N=1.0 from [1e-6:inf]
    'attr(info="emission_coefficient");
parameter real Is=1e-14 from [1e-20:inf]
    'attr(info="saturation_current" unit="A" );
parameter real Bv=100 from [1e-6:inf]
    'attr(info="reverse_breakdown_voltage" unit="V");
parameter real Ibv=1e-3 from [1e-6:inf]
    'attr(info="current_at_reverse_breakdown_voltage" unit="A");
parameter real Vj=1.0 from [1e-6:inf]
    'attr(info="junction_potential" unit="V");
parameter real Cj0=300e-15 from [0:inf]
    'attr(info="zero-bias_junction_capacitance" unit="F");
parameter real M=0.5 from [1e-6:inf]
    'attr(info="grading_coefficient");
parameter real Area=1.0 from [1e-3:inf]
    'attr(info="diode_relative_area");
parameter real Fc=0.5 from [1e-6:inf]
    'attr(info="forward-bias_depletion_capcitanace_coefficient");
parameter real Tt=0.1e-9 from [1e-20:inf]
    'attr(info="transit_time" unit="s" );
parameter real Xti=3.0 from [1e-6:inf]
    'attr(info="saturation_current_temperature_exponent");
// Temperature parameters
parameter real Tnom = 26.85
    'attr(info="parameter_measurement_temperature" unit = "Celsius");
// Local variables
real epsilonSi, epsilonox, Tnomk, T2, Tratio, Vto_T, Ucrit_T, Egnom, Eg, Phi_T;
real Weff, Leff, RDeff, RSeff, con1, con2, Vtoa, Kpa,Kpa_T,Gammaa, C_epsilon, xi;
real nnn, deltaV_RSCE, Vg, Vs, Vd, Vgs, Vgd, Vds, Vdso2, VG, VS, VD;
real VGprime, VP0, VSprime, VDprime, Gamma0, Gammaprime, Vp;
real n, X1, iff, X2, ir, Vc, Vdss, Vdssprime, deltaV, Vip;
real Lc, DeltaL, Lprime, Lmin, Leq, X3, irprime, Beta0, eta;
real Qb0, Beta0prime, nq, Xf, Xr, qD, qS, qI, qB, Beta, Ispecific, Ids, Vib, Idb, Ibb_T;

```



```

real A, B, Vt_T2, Eg_T1, Eg_T2, Vj_T2, Cj0_T2, F1, F2, F3, Is_T2;
real Id1, Id2, Id3, Id4, Is1, Is2, Is3, Is4, V1, V2, Ib_d, Ib_s, Qd, Qs, Qd1, Qd2, Qs1, Qs2;
real qb, qg, qgso, qgdo, qgbo, fourkt, Sthermal, gm, Sflicker, StoDswap, p_nMOS;
//
analog begin
// Equation initialization
p_nMOS = 1.0; // nMOS
A=7.02e-4;
B=1108.0;
epsilonsi = 1.0359e-10; // Eqn 4
epsilonox = 3.453143e-11; // Eqn 5
Tnomk = Tnom+273.15; // Eqn 6
T2=Temperature;
Tratio = T2/Tnomk;
Vto_T = Vto-Tcv*(T2-Tnomk);
Egnom = 1.16-0.000702*Tnomk*Tnomk/(Tnomk+1108);
Eg = 1.16-0.000702*T2*T2/(T2+1108);
Phi_T = Phi*Tratio - 3.0*$vt*ln(Tratio)-Egnom*Tratio+Eg;
Ibb_T = Ibb*(1.0+Ibbt*(T2-Tnomk));
Weff = W + Dw; // Eqn 25
Leff = L + Dl; // Eqn 26
RDeff = ( (Hdif*Rsh)/Weff)/Np + Rdc;
RSeff = ( (Hdif*Rsh)/Weff)/Np + Rsc;
con1 = sqrt(Np*Weff*Ns*Leff);
Vt_T2='P_K*T2/'P_Q;
Eg_T1=Eg-A*Tnomk*Tnomk/(B+Tnomk);
Eg_T2=Eg-A*T2*T2/(B+T2);
Vj_T2=(T2/Tnomk)*Vj-(2*Vt_T2)*ln(pow((T2/Tnomk),1.5))-((T2/Tnomk)*Eg_T1-Eg_T2);
Cj0_T2=Cj0*(1+M*(400e-6*(T2-Tnomk)-(Vj_T2-Vj)/Vj));
F1=(Vj/(1-M))*(1-pow((1-Fc),(1-M)));
F2=pow((1-Fc),(1+M));
F3=1-Fc*(1+M);
Is_T2=Is*pow((T2/Tnomk),(Xti/N))*limexp((-Eg_T1/Vt_T2)*(1-T2/Tnomk));
con2 = (Cox*Ns*Np*Weff*Leff);
fourkt = 4.0*'P_K*T2;
//
if (LEVEL == 2)
begin
Ucrit_T = Ucrit*pow(Tratio, Ucex);
Vtoa = Vto+Avto/con1; // Eqn 27
Kpa = Kp*(1.0+Akp/con1); // Eqn 28
Kpa_T = Kpa*pow(Tratio, Bex); // Eqn 18
Gammaa = Gamma+Agamma/con1; // Eqn 29
C_epsilon = 4.0*pow(22e-3, 2); // Eqn 30
xi = 0.028*(10.0*(Leff/Lk)-1.0); // Eqn 31
nnn = 1.0+0.5*(xi+sqrt(pow(xi,2)+C_epsilon));
deltaV_RSCE = (2.0*Q0/Cox)*(1.0/pow(nnn,2)); // Eqn 32
end
//
// Model branch and node voltages
//
Vg = p_nMOS*V(Gate, Bulk);
Vs = p_nMOS*V(Source, Bulk);
Vd = p_nMOS*V(Drain, Bulk);
VG=Vg; // Eqn 22
if ( (Vd-Vs) >= 0.0)
begin
StoDswap = 1.0;
VS=Vs; // Eqn 23
VD=Vd; // Eqn 24
end

```

```

else
    begin
        StoDswap = -1.0;
        VD=Vs;
        VS=Vd;
    end
if (LEVEL == 2)
    VGprime=VG-Vto_T-deltaV_RSCE+Phi_T+Gamma*sqrt(Phi_T); // Eqn 33 nMOS equation
else
    VGprime=Vg-Vto_T+Phi_T+Gamma*sqrt(Phi_T);

//
if (LEVEL == 2)
    begin
        if (VGprime > 0)
            VP0=VGprime-Phi_T-Gamma*(sqrt(VGprime+(Gamma/2.0)*(Gamma/2.0))
                -(Gamma/2.0)); // Eqn 34
        else
            VP0 = -Phi_T;
        VSprime=0.5*(VS+Phi_T+sqrt(pow((VS+Phi_T),2) + pow((4.0*$vt),2))); // Eqn 35
        VDprime=0.5*(VD+Phi_T+sqrt(pow((VD+Phi_T),2) + pow((4.0*$vt),2))); // Eqn 35
        Gamma0=Gamma*(epsilon/Cox)*((Leta/Leff)*(sqrt(VSprime)+sqrt(VDprime))
            -(3.0*Weta/Weff)*sqrt(VP0+Phi_T)); // Eqn 36
        Gammaprime = 0.5*(Gamma0+sqrt(pow(Gamma0,2) + 0.1*$vt)); // Eqn 37
        if (VGprime > 0.0)
            Vp = VGprime-Phi_T-Gammaprime*(sqrt(VGprime+(Gammaprime/2.0)*
                (Gammaprime/2.0)) - (Gammaprime/2.0)); // Eqn 38
        else
            Vp = -Phi_T;
        n = 1.0 +Gamma/(2.0*sqrt(Vp+Phi_T+4.0*$vt)); // Eqn 39
    end
else
    begin
        if (VGprime > 0)
            Vp=VGprime-Phi_T-Gamma*(sqrt(VGprime+(Gamma/2.0)*(Gamma/2.0))
                -(Gamma/2.0)); // Eqn 34
        else
            Vp = -Phi_T;
        n = 1.0 +Gamma/(2.0*sqrt(Vp+Phi_T+4.0*$vt)); // Eqn 39
    end
//
X1 = (Vp-VS)/$vt;
iff = ln(1.0+limexp(X1/2.0))*ln(1.0+limexp(X1/2.0)); // Eqn 44
X2 = (Vp-Vd)/$vt;
ir = ln(1.0+limexp(X2/2.0))*ln(1.0+limexp(X2/2.0)); // Eqn 57
//
if (LEVEL == 2)
    begin
        Vc = Ucrit_T*Ns*Leff; // Eqn 45
        Vdss = Vc*(sqrt(0.25 + (($vt/(Vc))*sqrt(iff)))-0.5); // Eqn 46;
        Vdssprime = Vc*(sqrt(0.25 + ($vt/Vc)*(sqrt(iff)-0.75*ln(iff)))-0.5)
            +$vt*(ln(Vc/(2.0*$vt)) - 0.6); // Eqn 47
        if (Lambda*(sqrt(iff) > (Vdss/$vt))
            deltaV = 4.0*$vt*sqrt(Lambda*(sqrt(iff) -(Vdss/$vt))
                + (1.0/64.0)); // Eqn 48
        else
            deltaV = 1.0/64.0;
        Vdso2 = (VD-VS)/2.0; // Eqn 49
        Vip = sqrt(pow(Vdss, 2) + pow(deltaV, 2)) - sqrt(pow((Vdso2 - Vdss), 2)
            + pow(deltaV, 2)); // Eqn 50
        Lc = sqrt((epsilon/Cox)*Xj); // Eqn 51
        DeltaL = Lambda*Lc*ln(1.0+((Vdso2-Vip)/(Lc*Ucrit_T))); // Eqn 52
    end

```

```

Lprime = Ns*Leff - DeltaL + ( (Vdso2+Vip)/Ucrit_T); // Eqn 53
Lmin = Ns*Leff/10.0; // Eqn 54
Leq = 0.5*(Lprime + sqrt( pow(Lprime, 2) + pow(Lmin, 2))); // Eqn 55
X3 = (Vp-Vdso2-VS-sqrt( pow(Vdssprime, 2) + pow( deltaV, 2))
      + sqrt( pow( (Vdso2-Vdssprime), 2) + pow(deltaV,2)))/$vt;
irprime = ln(1.0+limexp(X3/2.0))*ln(1.0+limexp(X3/2.0)); // Eqn 56
Beta0 = Kpa_T*(Np*Weff/Leq); // Eqn 58
eta = 0.5; // Eqn 59 - nMOS
Qb0 = Gammaa*sqrt(Phi_T); // Eqn 60;
Beta0prime = Beta0*(1.0 +(Cox/(EO*epsilonsi))*Qb0); // Eqn 61
nq = 1.0 +Gammaa/(2.0*sqrt(Vp+Phi_T+1e-6)); // Eqn 69
end
else
  nq = 1.0 +Gamma/(2.0*sqrt(Vp+Phi_T+1e-6)); // Eqn 69
//
Xf = sqrt(0.25+iff); // Eqn 70
Xr = sqrt(0.25+ir); // Eqn 71
qD = -nq*( (4.0/15.0)*((3.0*pow( Xr,3) + 6.0*pow( Xr, 2)*Xf + 4.0*Xr*pow( Xf, 2)
      + 2.0*pow(Xf, 3))/(pow( (Xf+Xr), 2) ) ) -0.5); // Eqn 72
qS = -nq*( (4.0/15.0)*((3.0*pow( Xf,3) + 6.0*pow( Xf, 2)*Xr + 4.0*Xf*pow( Xr, 2)
      + 2.0*pow(Xr, 3))/(pow( (Xf+Xr), 2) ) ) -0.5); // Eqn 73
qI = -nq*( (4.0/3.0)*((pow(Xf,2)+(Xf*Xr)+pow(Xr,2))/(Xf+Xr)) - 1.0); // Eqn 74
if (LEVEL == 2)
  if (VGprime > 0)
    qB = (-Gammaa*sqrt(Vp+Phi_T+1e-6))*(1.0/$vt) - ( (nq-1.0)/nq)*qI; // Eqn 75
  else
    qB = -VGprime/$vt;
else
  if (VGprime > 0)
    qB = (-Gamma*sqrt(Vp+Phi_T+1e-6))*(1.0/$vt) - ( (nq-1.0)/nq)*qI; // Eqn 75
  else
    qB = -VGprime/$vt;
//
if (LEVEL == 2)
  Beta = Beta0prime/(1.0 + (Cox/ (EO*epsilonsi))*$vt*abs(qB+eta*qI)); // Eqn 62
else
  Beta = Kp*(Weff/Leff)/(1+Theta*Vp);
//
Ispecific = 2.0*n*Beta*pow( $vt, 2); // Eqn 65
//
if (LEVEL == 2)
  begin
    Ids = Ispecific*(iff-irprime); // Eqn 66
    Vib = VD-VS-Ibn*2.0*Vdss; // Eqn 67
    if ( Vib > 0.0)
      Idb = Ids*(Iba/Ibb_T)*Vib*exp( (-Ibb_T*Lc)/Vib); // Eqn 68
    else
      Idb = 0.0;
  end
else
  Ids = Ispecific*(iff-ir); // Eqn 66
//
Sthermal = fourkt*Beta*abs(qI);
gm = Beta*$vt*(sqrt( (4.0* iff/Ispecific) +1.0) - sqrt( (4.0*ir/Ispecific) + 1.0) );
Sflicker = (Kf*gm*gm)/(Np*Weff*Ns*Leff*Cox);
//
qb = con2*$vt*qB;
qg = con2*$vt*(-qI-qB);
qgso = Cgso*Weff*Np*(VG-VS);
qgdo = Cgdo*Weff*Np*(VG-VD);
qgbo = Cgbo*Leff*Np*VG;
// Drain and source diodes

```

```

if (StoDswap > 0.0)
  begin
    V1=p_nMOS*V(Bulk, Drain_int);
    V2=p_nMOS*V(Bulk, Source_int);
  end
else
  begin
    V2=p_nMOS*V(Bulk, Drain_int);
    V1=p_nMOS*V(Bulk, Source_int);
  end
  Id1=(V1>-5.0*N*$vt) ? Area*Is_T2*(limexp( V1/(N*Vt_T2) )-1.0) : 0;
  Qd1=(V1<Fc*Vj)? Tt*Id1+Area*(Cj0_T2*Vj_T2/(1-M))*(1-pow((1-V1/Vj_T2),(1-M))):0;
  Id2=(V1<=-5.0*N*$vt) ? -Area*Is_T2 : 0;
  Qd2=(V1>=Fc*Vj)? Tt*Id1+Area*Cj0_T2*(F1+(1/F2)*(F3*(V1-Fc*Vj_T2)+(M/(2.0*Vj_T2))
    *(V1*V1-Fc*Fc*Vj_T2*Vj_T2))):0;
  Id3=(V1 == -Bv) ? -Ibv : 0;
  Id4=(V1<=-Bv) ? -Area*Is_T2*(limexp(-(Bv+V1)/Vt_T2)-1.0+Bv/Vt_T2) : 0;
  Ib_d = Id1+Id2+Id3+Id4;
  Qd = Qd1+Qd2;
  //
  Is1=(V2>-5.0*N*$vt) ? Area*Is_T2*(limexp( V2/(N*Vt_T2) )-1.0) : 0;
  Qs1=(V2<Fc*Vj)? Tt*Is1+Area*(Cj0_T2*Vj_T2/(1-M))*(1-pow((1-V2/Vj_T2),(1-M))):0;
  Is2=(V2<=-5.0*N*$vt) ? -Area*Is_T2 : 0;
  Qs2=(V2>=Fc*Vj)? Tt*Is1+Area*Cj0_T2*(F1+(1/F2)*(F3*(V2-Fc*Vj_T2)+(M/(2.0*Vj_T2))
    *(V2*V2-Fc*Fc*Vj_T2*Vj_T2))):0;
  Is3=(V2 == -Bv) ? -Ibv : 0;
  Is4=(V2<=-Bv) ? -Area*Is_T2*(limexp(-(Bv+V2)/Vt_T2)-1.0+Bv/Vt_T2) : 0;
  Ib_s = Is1+Is2+Is3+Is4;
  Qs = Qs1+Qs2;
  // Current and noise contributions
  if (StoDswap > 0.0)
    begin
      if (RDeff > 0.0)
        I(Drain, Drain_int) <+ V(Drain, Drain_int)/RDeff;
      else
        I(Drain, Drain_int) <+ V(Drain, Drain_int)/1e-7;
      if (RSeff > 0.0)
        I(Source, Source_int) <+ V(Source, Source_int)/RSeff;
      else
        I(Source, Source_int) <+ V(Source, Source_int)/1e-7;
      I(Drain_int, Source_int) <+ p_nMOS*Ids;
      if (LEVEL == 2)
        I(Drain_int, Bulk) <+ p_nMOS*Idb;
        I(Gate, Drain_int) <+ p_nMOS*0.5*ddt(qg);
        I(Gate, Source_int) <+ p_nMOS*0.5*ddt(qg);
        I(Drain_int, Bulk) <+ p_nMOS*0.5*ddt(qb);
        I(Source_int, Bulk) <+ p_nMOS*0.5*ddt(qb);
        I(Gate, Source_int) <+ p_nMOS*ddt(qgso);
        I(Gate, Drain_int) <+ p_nMOS*ddt(qgdo);
        I(Gate, Bulk) <+ p_nMOS*ddt(qgbo);
        I(Bulk, Drain_int) <+ p_nMOS*Ib_d;
        I(Bulk, Drain_int) <+ p_nMOS*ddt(Qd);
        I(Bulk, Source_int) <+ p_nMOS*Ib_s;
        I(Bulk, Source_int) <+ p_nMOS*ddt(Qs);
        I(Drain_int, Source_int) <+ white_noise(Sthermal,"thermal");
        I(Drain_int, Source_int) <+ flicker_noise(Sflicker, Af, "flicker");
        I(Drain, Drain_int) <+ white_noise(fourkt/RDeff, "thermal");
        I(Source, Source_int) <+ white_noise(fourkt/RSeff, "thermal");
      end
    end
  else
    begin
      if (RSeff > 0.0)

```

```

        I(Drain, Drain_int) <+ V(Drain, Drain_int)/RSeff;
    else
        I(Drain, Drain_int) <+ V(Drain, Drain_int)/1e-7;
    if (RDeff > 0.0)
        I(Source, Source_int) <+ V(Source, Source_int)/RDeff;
    else
        I(Source, Source_int) <+ V(Source, Source_int)/1e-7;
I( Source_int, Drain_int) <+ p_nMOS*Ids;
if (LEVEL == 2)
    I(Source_int, Bulk) <+ p_nMOS*Idb;
I( Gate, Source_int) <+ p_nMOS*0.5*ddt(qg);
I( Gate, Drain_int) <+ p_nMOS*0.5*ddt(qg);
I( Source_int, Bulk) <+ p_nMOS*0.5*ddt(qb);
I( Drain_int, Bulk) <+ p_nMOS*0.5*ddt(qb);
I( Gate, Drain_int) <+ p_nMOS*ddt(qgso);
I( Gate, Source_int) <+ p_nMOS*ddt(qgdo);
I( Gate, Bulk) <+ p_nMOS*ddt(qgbo);
I( Bulk, Source_int) <+ p_nMOS*Ib_d;
I( Bulk, Source_int) <+ p_nMOS*ddt(Qd);
I( Bulk, Drain_int) <+ p_nMOS*Ib_s;
I( Bulk, Drain_int) <+ p_nMOS*ddt(Qs);
I( Source_int, Drain_int) <+ white_noise(Sthermal,"thermal");
I( Source_int, Drain_int) <+ flicker_noise(Sflicker, Af, "flicker");
I( Source_int, Source) <+ white_noise(fourkt/RDeff, "thermal");
I( Drain_int, Drain) <+ white_noise(fourkt/RSeff, "thermal");
end
end
endmodule

```

pMOS: EKV equation numbers are given on the right-hand side of code lines

```

//  Qucs EPFL-EKV 2.6 pMOS model:
//
//  The structure and theoretical background to the EKV 2.6
//  Verilog-a model is presented in the Qucs EPL-EKV 2.6 report.
//  Typical parameters are for 0.5um CMOS (C) EPLFL-LEG 1999.
//  Geometry range: Short channel: W>= 0.8um, L >= 0.5um
//                  Long channel: W>= 2um,   L >= 2um
//  Voltage range:  |Vgb| < 3.3V, |Vdb| < 3.3V, |Vsb| < 2V
//
//  This is free software; you can redistribute it and/or modify
//  it under the terms of the GNU General Public License as published by
//  the Free Software Foundation; either version 2, or (at your option)
//  any later version.
//
//  Copyright (C), Mike Brinson, mbrin72043@yahoo.co.uk, May 2008.
//
#include "disciplines.vams"
#include "constants.vams"

//
module EKV26pMOS (Drain, Gate, Source, Bulk);
    inout Drain, Gate, Source, Bulk;
    electrical Drain, Gate, Source, Bulk;
// Internal nodes
    electrical Drain_int, Source_int;
    define attr(txt) (*txt*)

```

```

// Device dimension parameters
parameter real LEVEL = 1 from [1 : 2]
    'attr(info="long_1,short_2")';
parameter real L = 0.5e-6 from [0.0 : inf]
    'attr(info="length_parameter" unit = "m" );
parameter real W = 10e-6 from [0.0 : inf]
    'attr(info="Width_parameter" unit = "m");
parameter real Np = 1.0 from [1.0 : inf]
    'attr(info="parallel_multiple_device_number");
parameter real Ns = 1.0 from [1.0 : inf]
    'attr(info="series_multiple_device_number");
// Process parameters
parameter real Cox = 3.45e-3 from [0 : inf]
    'attr(info="gate_oxide_capacitance_per_unit_area" unit = "F/m**2" );
parameter real Xj = 0.15e-6 from [0.01e-6 : 1.0e-6]
    'attr(info="metallurgical_junction_depth" unit = "m");
parameter real Dw = -0.03e-6 from [-inf : 0.0]
    'attr(info="channel_width_correction" unit = "m");
parameter real Dl = -0.05e-6 from [-inf : 0.0]
    'attr(info="channel_length_correction" unit = "m");
// Basic intrinsic model parameters
parameter real Vto = -0.55 from [-inf : -1e-6]
    'attr(info="long_channel_threshold_voltage" unit="V" );
parameter real Gamma = 0.69 from [0.0 : 2.0]
    'attr(info="body_effect_parameter" unit="V**(1/2)");
parameter real Phi = 0.87 from [0.3 : 2.0]
    'attr(info="bulk_Fermi_potential" unit="V");
parameter real Kp = 35e-6 from [10e-6 : inf]
    'attr(info="transconductance_parameter" unit = "A/V**2");
parameter real Theta = 50e-3 from [0.0 : inf]
    'attr(info="mobility_reduction_coefficient" unit = "1/V");
parameter real EO = 51.0e6 from [1.0e6 : inf]
    'attr(info="mobility_coefficient" unit="V/m");
parameter real Ucrit = 18.0e6 from [2.0e6 : 25.0e6]
    'attr(info="longitudinal_critical_field" unit="V/m");
// Channel length and charge sharing parameters
parameter real Lambda = 1.1 from [0.1 : inf]
    'attr(info="depletion_length_coefficient");
parameter real Weta = 0.0 from [0.0 : inf]
    'attr(info="narrow-channel_effect_coefficient");
parameter real Leta = 0.45 from [0.0 : inf]
    'attr(info="longitudinal_critical_field");
// Reverse short channel effect parameters
parameter real Q0 = 200e-6 from [0.0 : inf]
    'attr(info="reverse_short_channel_charge_density" unit="A*s/m**2");
parameter real Lk = 0.6e-6 from [0.0 : inf]
    'attr(info="characteristic_length" unit="m");
// Intrinsic model temperature parameters
parameter real Tcv = -1.4e-3
    'attr(info="threshold_voltage_temperature_coefficient" unit="V/K");
parameter real Bex = -1.4
    'attr(info="mobility_temperature_coefficient");
parameter real Ucx = 2.0
    'attr(info="Longitudinal_critical_field_temperature_exponent");
parameter real Ibtt = 0.0
    'attr(info="Ibb_temperature_coefficient" unit = "1/K");
// Series resistance calculation parameters
parameter real Hdif = 0.9e-6 from [0.0 : inf]
    'attr(info="heavily_doped_diffusion_length" unit = "m");
parameter real Rsh = 990.0 from [0.0 : inf]
    'attr(info="drain/source_diffusion_sheet_resistance" unit="Ohm/square");
parameter real Rsc = 0.0 from [0.0 : inf]

```

```

        'attr(info="source_contact_resistance" unit="Ohm");
parameter real Rdc = 0.0 from [0.0 : inf]
        'attr(info="drain_contact_resistance" unit="Ohm");
// Gate overlap capacitances
parameter real Cgso = 1.5e-10 from [0.0 : inf]
        'attr(info="gate_to_source_overlap_capacitance" unit = "F/m");
parameter real Cgdo = 1.5e-10 from [0.0 : inf]
        'attr(info="gate_to_drain_overlap_capacitance" unit= "F/m");
parameter real Cgbo = 4.0e-10 from [0.0 : inf]
        'attr(info="gate_to_bulk_overlap_capacitance" unit= "F/m");
// Impact ionization related parameters
parameter real Iba = 0.0 from [0.0 : inf]
        'attr(info="first_impact_ionization_coefficient" unit = "1/m");
parameter real Ibb = 3.0e8 from [1.0e8 : inf]
        'attr(info="second_impact_ionization_coefficient" unit="V/m");
parameter real Ibn = 1.0 from [0.1 : inf]
        'attr(info="saturation_voltage_factor_for_impact_ionization");
// Flicker noise parameters
parameter real Kf = 1.0e-28 from [0.0 : inf]
        'attr(info="flicker_noise_coefficient");
parameter real Af = 1.0 from [0.0 : inf]
        'attr(info="flicker_noise_exponent" );
// Matching parameters
parameter real Avto = 0.0 from [0.0 : inf]
        'attr(info="area_related_threshold_voltage_mismatch_parameter" unit = "V*m");
parameter real Akp = 0.0 from [0.0 : inf]
        'attr(info="area_related_gain_mismatch_parameter" unit="m");
parameter real Agamma = 0.0 from [0.0 : inf]
        'attr(info="area_related_body_effect_mismatch_parameter" unit="sqrt(V)*m");
// Diode parameters
parameter real N=1.0 from [1e-6:inf]
        'attr(info="emission_coefficient");
parameter real Is=1e-14 from [1e-20:inf]
        'attr(info="saturation_current" unit="A" );
parameter real Bv=100 from [1e-6:inf]
        'attr(info="reverse_breakdown_voltage" unit="V");
parameter real Ibv=1e-3 from [1e-6:inf]
        'attr(info="current_at_reverse_breakdown_voltage" unit="A");
parameter real Vj=1.0 from [1e-6:inf]
        'attr(info="junction_potential" unit="V");
parameter real Cj0=300e-15 from [0:inf]
        'attr(info="zero-bias_junction_capacitance" unit="F");
parameter real M=0.5 from [1e-6:inf]
        'attr(info="grading_coefficient");
parameter real Area=1.0 from [1e-3:inf]
        'attr(info="diode_relative_area");
parameter real Fc=0.5 from [1e-6:inf]
        'attr(info="forward-bias_depletion_capcitanace_coefficient");
parameter real Tt=0.1e-9 from [1e-20:inf]
        'attr(info="transit_time" unit="s" );
parameter real Xti=3.0 from [1e-6:inf]
        'attr(info="saturation_current_temperature_exponent");
// Temperature parameters
parameter real Thom = 26.85
        'attr(info="parameter_measurement_temperature" unit = "Celsius");
// Local variables
real epsilonSi, epsilonox, Thomk, T2, Tratio, Vto,T, Ucrit,T, Egnom, Eg, Phi,T;
real Weff, Leff, RDeff, RSeff, con1, con2, Vtoa, Kpa,Kpa,T,Gammaaa, C_epsilon, xi;
real nnn, deltaV_RSCE, Vg, Vs, Vd, Vgs, Vgd, Vds, Vdso2, VG, VS, VD;
real VGprime, VP0, VSprime, VDprime, Gamma0, Gammaprime, Vp;
real n, X1, iff, X2, ir, Vc, Vdss, Vdssprime, deltaV, Vip;
real Lc, DeltaL, Lprime, Lmin, Leq, X3, irprime, Beta0, eta;

```

```

real Qb0, Beta0prime, nq, Xf, Xr, qD, qS, qI, qB, Beta, Ispecific, Ids, Vib, Idb, Ibb_T;
real A, B, Vt_T2, Eg_T1, Eg_T2, Vj_T2, Cj0_T2, F1, F2, F3, Is_T2;
real Id1, Id2, Id3, Id4, Is1, Is2, Is3, Is4, V1, V2, Ib_d, Ib_s, Qd, Qs, Qd1, Qd2, Qs1, Qs2;
real qb, qg, qgso, qgdo, qgbo, fourkt, Sthermal, gm, Sflicker, StoDswap, p_n_MOS;
//
analog begin
// Equation initialization
p_n_MOS = -1.0; // pMOS
A=7.02e-4;
B=1108.0;
epsilonsi = 1.0359e-10; // Eqn 4
epsilonox = 3.453143e-11; // Eqn 5
Tnomk = Tnom+273.15; // Eqn 6
T2=$temperature;
Tratio = T2/Tnomk;
Vto_T = -Vto+Tcv*(T2-Tnomk); // Signs of Vto and Tcv changed for pMOS
Egnom = 1.16-0.000702*Tnomk*Tnomk/(Tnomk+1108);
Eg = 1.16-0.000702*T2*T2/(T2+1108);
Phi_T = Phi*Tratio - 3.0*$vt*ln(Tratio)-Egnom*Tratio+Eg;
Ibb_T = Ibb*(1.0+Ibbt*(T2-Tnomk));
Weff = W + Dw; // Eqn 25
Leff = L + Dl; // Eqn 26
RDeff = ( (Hdif*Rsh)/Weff)/Np + Rdc;
RSeff = ( (Hdif*Rsh)/Weff)/Np + Rsc;
con1 = sqrt(Np*Weff*Ns*Leff);
Vt_T2='P_K*T2/'P_Q;
Eg_T1=Eg-A*Tnomk*Tnomk/(B+Tnomk);
Eg_T2=Eg-A*T2*T2/(B+T2);
Vj_T2=(T2/Tnomk)*Vj-(2*Vt_T2)*ln(pow((T2/Tnomk),1.5))-((T2/Tnomk)*Eg_T1-Eg_T2);
Cj0_T2=Cj0*(1+M*(400e-6*(T2-Tnomk)-(Vj_T2-Vj)/Vj));
F1=(Vj/(1-M))*(1-pow((1-Fc),(1-M)));
F2=pow((1-Fc),(1+M));
F3=1-Fc*(1+M);
Is_T2=Is*pow((T2/Tnomk),(Xti/N))*limexp((-Eg_T1/Vt_T2)*(1-T2/Tnomk));
con2 = (Cox*Ns*Np*Weff*Leff);
fourkt = 4.0*'P_K*T2;
//
if (LEVEL == 2)
begin
Ucrit_T = Ucrit*pow(Tratio, Ucx);
Vtoa = Vto+Avto/con1; // Eqn 27
Kpa = Kp*(1.0+Akp/con1); // Eqn 28
Kpa_T = Kpa*pow(Tratio, Bex); // Eqn 18
Gammaa = Gamma+Agamma/con1; // Eqn 29
C_epsilon = 4.0*pow(22e-3, 2); // Eqn 30
xi = 0.028*(10.0*(Leff/Lk)-1.0); // Eqn 31
nnn = 1.0+0.5*(xi+sqrt(pow(xi,2)+C_epsilon));
deltaV_RSCE = (2.0*Q0/Cox)*(1.0/pow(nnn,2)); // Eqn 32
end
//
// Model branch and node voltages
//

Vg = p_n_MOS*V(Gate, Bulk);
Vs = p_n_MOS*V(Source, Bulk);
Vd = p_n_MOS*V(Drain, Bulk);
VG=Vg; // Eqn 22
if ( (Vd-Vs) >= 0.0)
begin
StoDswap = 1.0;
VS=Vs; // Eqn 23
VD=Vd; // Eqn 24

```



```

        end
    else
        begin
            StoDswap = -1.0;
            VD=Vs;
            VS=Vd;
        end
    if (LEVEL == 2)
        VGprime=VG-Vto_T-deltaV_RSCE+Phi_T+Gamma*sqrt(Phi_T); // Eqn 33 nMOS equation
    else
        VGprime=Vg-Vto_T+Phi_T+Gamma*sqrt(Phi_T);

    if (LEVEL == 2)
        begin
            if (VGprime > 0)
                VP0=VGprime-Phi_T-Gamma*(sqrt(VGprime+(Gamma/2.0)*(Gamma/2.0))-(Gamma/2.0));
            // Eqn 34
            else
                VP0 = -Phi_T;
                VSprime=0.5*(VS+Phi_T+sqrt(pow((VS+Phi_T),2) + pow((4.0*$vt),2))); // Eqn 35
                VDprime=0.5*(VD+Phi_T+sqrt(pow((VD+Phi_T),2) + pow((4.0*$vt),2))); // Eqn 35
                Gamma0=Gamma-(epsilon*si/Cox)*((Leta/Leff)*(sqrt(VSprime)+sqrt(VDprime))
                    -(3.0*Weta/Weff)*sqrt(VP0+Phi_T)); // Eqn 36
                Gammaprime = 0.5*(Gamma0+sqrt(pow(Gamma0,2) + 0.1*$vt)); // Eqn 37
                if (VGprime > 0.0)
                    Vp = VGprime-Phi_T-Gammaprime*(sqrt(VGprime+(Gammaprime/2.0)*(Gammaprime/2.0))
                        - (Gammaprime/2.0)); // Eqn 38
                else
                    Vp = -Phi_T;
                    n = 1.0 +Gamma/(2.0*sqrt(Vp+Phi_T+4.0*$vt)); // Eqn 39
                end
            else
                begin
                    if (VGprime > 0)
                        Vp=VGprime-Phi_T-Gamma*(sqrt(VGprime+(Gamma/2.0)*(Gamma/2.0))-(Gamma/2.0));
                    // Eqn 34
                    else
                        Vp = -Phi_T;
                        n = 1.0 +Gamma/(2.0*sqrt(Vp+Phi_T+4.0*$vt)); // Eqn 39
                    end
                end
            //
            X1 = (Vp-VS)/$vt;
            iff = ln(1.0+limexp(X1/2.0))*ln(1.0+limexp(X1/2.0)); // Eqn 44
            X2 = (Vp-VD)/$vt;
            ir = ln(1.0+limexp(X2/2.0))*ln(1.0+limexp(X2/2.0)); // Eqn 57
            //
            if (LEVEL == 2)
                begin
                    Vc = Ucrit_T*Ns*Leff; // Eqn 45
                    Vdss = Vc*(sqrt(0.25 + (($vt/(Vc))*sqrt(iff))-0.5); // Eqn 46;
                    Vdssprime = Vc*(sqrt(0.25 + ($vt/Vc)*(sqrt(iff)-0.75*ln(iff)) - 0.5)
                        + $vt*(ln(Vc/(2.0*$vt)) - 0.6)); // Eqn 47
                    if (Lambda*(sqrt(iff) > (Vdss/$vt)) )
                        deltaV = 4.0*$vt*sqrt(Lambda*(sqrt(iff) -(Vdss/$vt)) + (1.0/64.0)); // Eqn 48
                    else
                        deltaV = 1.0/64.0;
                    Vdso2 = (VD-VS)/2.0; // Eqn 49
                    Vip = sqrt(pow(Vdss, 2) + pow(deltaV,2)) - sqrt(pow((Vdso2 - Vdss), 2)
                        + pow(deltaV, 2)); // Eqn 50
                    Lc = sqrt((epsilon*si/Cox)*Xj); // Eqn 51
                    DeltaL = Lambda*Lc*ln(1.0+((Vdso2-Vip)/(Lc*Ucrit_T))); // Eqn 52
                    Lprime = Ns*Leff - DeltaL + ((Vdso2+Vip)/Ucrit_T); // Eqn 53
                    Lmin = Ns*Leff/10.0; // Eqn 54
                end
            end
        end
    end

```

```

Leq = 0.5*(Lprime + sqrt( pow(Lprime, 2) + pow(Lmin, 2))); // Eqn 55
X3 = (Vp-Vdso2-VS-sqrt( pow(Vdssprime, 2) + pow( deltaV, 2))
      + sqrt( pow( Vdso2-Vdssprime), 2) + pow(deltaV,2)))/$vt;
irprime = ln(1.0+limexp(X3/2.0))*ln(1.0+limexp(X3/2.0)); // Eqn 56
Beta0 = Kpa_T*(Np*Weff/Leq); // Eqn 58
eta = 0.3333333; // Eqn 59 - pMOS
Qb0 = Gammaa*sqrt(Phi_T); // Eqn 60;
Beta0prime = Beta0*(1.0 +(Cox/(EO*epsilonsi))*Qb0); // Eqn 61
nq = 1.0 +Gammaa/(2.0*sqrt(Vp+Phi_T+1e-6)); // Eqn 69
end
else
nq = 1.0 +Gamma/(2.0*sqrt(Vp+Phi_T+1e-6)); // Eqn 69
//
Xf = sqrt(0.25+iff); // Eqn 70
Xr = sqrt(0.25+ir); // Eqn 71
qD = -nq*( (4.0/15.0)*((3.0*pow( Xr,3) + 6.0*pow( Xr, 2)*Xf + 4.0*Xr*pow( Xf, 2)
+ 2.0*pow(Xf, 3))/(pow( (Xf+Xr), 2) ) ) -0.5); // Eqn 72
qS = -nq*( (4.0/15.0)*((3.0*pow( Xf,3) + 6.0*pow( Xf, 2)*Xr + 4.0*Xf*pow( Xr, 2)
+ 2.0*pow(Xr, 3))/(pow( (Xf+Xr), 2) ) ) -0.5); // Eqn 73
qI = -nq*( (4.0/3.0)*((pow(Xf,2)+(Xf*Xr)+pow(Xr,2))/(Xf+Xr)) - 1.0); // Eqn 74
if (LEVEL == 2)
if (VGprime > 0)
qB = (-Gammaa*sqrt(Vp+Phi_T+1e-6))*(1.0/$vt) - ( (nq-1.0)/nq)*qI; // Eqn 75
else
qB = -VGprime/$vt;
else
if (VGprime > 0)
qB = (-Gamma*sqrt(Vp+Phi_T+1e-6))*(1.0/$vt) - ( (nq-1.0)/nq)*qI; // Eqn 75
else
qB = -VGprime/$vt;
//
if (LEVEL == 2)
Beta = Beta0prime/(1.0 + (Cox/(EO*epsilonsi))*$vt*abs(qB+eta*qI)); // Eqn 62
else
Beta = Kp*(Weff/Leff)/(1+Theta*Vp);
//
Ispecific = 2.0*n*Beta*pow( $vt, 2); // Eqn 65
//
if (LEVEL == 2)
begin
Ids = Ispecific*(iff-irprime); // Eqn 66
Vib = VD-VS-Ibn*2.0*Vdss; // Eqn 67
if ( Vib > 0.0)
Idb = Ids*(Iba/Ibb_T)*Vib*exp( (-Ibb_T*Lc)/Vib); // Eqn 68
else
Idb = 0.0;
end
else
Ids = Ispecific*(iff-ir); // Eqn 66
//
Sthermal = fourkt*Beta*abs(qI);
gm = Beta*$vt*(sqrt( (4.0*iff/Ispecific) +1.0) - sqrt( (4.0*ir/Ispecific) + 1.0) );
Sflicker = (Kf*gm*gm)/(Np*Weff*Ns*Leff*Cox);
//
qb = con2*$vt*qB;
qg = con2*$vt*(-qI-qB);
qgso = Cgso*Weff*Np*(VG-VS);
qgdo = Cgdo*Weff*Np*(VG-VD);
qgbo = Cgbo*Leff*Np*VG;
// Drain and source diodes
if (StoDswap > 0.0)
begin

```

```

        V1=p_nMOS*V(Bulk, Drain_int);
        V2=p_nMOS*V(Bulk, Source_int);
    end
else
    begin
        V2=p_nMOS*V(Bulk, Drain_int);
        V1=p_nMOS*V(Bulk, Source_int);
    end
    Id1= (V1>-5.0*N*$vt) ? Area*Is_T2*(limexp( V1/(N*Vt_T2) )-1.0) : 0;
    Qd1=(V1<Fc*Vj)? Tt*Id1+Area*(Cj0_T2*Vj_T2/(1-M))*(1-pow((1-V1/Vj_T2),(1-M))):0;
    Id2=(V1<=-5.0*N*$vt) ? -Area*Is_T2 : 0;
    Qd2=(V1>=Fc*Vj)? Tt*Id1+Area*Cj0_T2*(F1+(1/F2)*(F3*(V1-Fc*Vj_T2)+(M/(2.0*Vj_T2))
        *(V1*V1-Fc*Fc*Vj_T2*Vj_T2))):0;
    Id3=(V1 == -Bv) ? -Ibv : 0 ;
    Id4=(V1<-Bv) ? -Area*Is_T2*(limexp(-(Bv+V1)/Vt_T2)-1.0+Bv/Vt_T2) : 0;
    Ib_d = Id1+Id2+Id3+Id4;
    Qd = Qd1+Qd2;
    //
    Is1= (V2>-5.0*N*$vt) ? Area*Is_T2*(limexp( V2/(N*Vt_T2) )-1.0) : 0;
    Qs1=(V2<Fc*Vj)? Tt*Is1+Area*(Cj0_T2*Vj_T2/(1-M))*(1-pow((1-V2/Vj_T2),(1-M))):0;
    Is2=(V2<=-5.0*N*$vt) ? -Area*Is_T2 : 0;
    Qs2=(V2>=Fc*Vj)? Tt*Is1+Area*Cj0_T2*(F1+(1/F2)*(F3*(V2-Fc*Vj_T2)+(M/(2.0*Vj_T2))
        *(V2*V2-Fc*Fc*Vj_T2*Vj_T2))):0;
    Is3=(V2 == -Bv) ? -Ibv : 0 ;
    Is4=(V2<-Bv) ? -Area*Is_T2*(limexp(-(Bv+V2)/Vt_T2)-1.0+Bv/Vt_T2) : 0;
    Ib_s = Is1+Is2+Is3+Is4;
    Qs = Qs1+Qs2;
    // Current contributions
    if ( StoDswap > 0.0)
    begin
        if (RDeff > 0.0)
            I(Drain, Drain_int) <+ V(Drain, Drain_int)/RDeff;
        else
            I(Drain, Drain_int) <+ V(Drain, Drain_int)/1e-7;
        if (RSeff > 0.0)
            I(Source, Source_int) <+ V(Source, Source_int)/RSeff;
        else
            I(Source, Source_int) <+ V(Source, Source_int)/1e-7;
        I(Drain_int, Source_int) <+ p_nMOS*Ids;
        if (LEVEL == 2)
            I(Drain_int, Bulk) <+ p_nMOS*Idb;
            I(Gate, Drain_int) <+ p_nMOS*0.5*ddt(qg);
            I(Gate, Source_int) <+ p_nMOS*0.5*ddt(qg);
            I(Drain_int, Bulk) <+ p_nMOS*0.5*ddt(qb);
            I(Source_int, Bulk) <+ p_nMOS*0.5*ddt(qb);
            I(Gate, Source_int) <+ p_nMOS*ddt(qgso);
            I(Gate, Drain_int) <+ p_nMOS*ddt(qgdo);
            I(Gate, Bulk) <+ p_nMOS*ddt(qgbo);
            I(Bulk, Drain_int) <+ p_nMOS*Ib_d;
            I(Bulk, Drain_int) <+ p_nMOS*ddt(Qd);
            I(Bulk, Source_int) <+ p_nMOS*Ib_s;
            I(Bulk, Source_int) <+ p_nMOS*ddt(Qs);
            I(Drain_int, Source_int) <+ white_noise(Sthermal,"thermal");
            I(Drain_int, Source_int) <+ flicker_noise(Sflicker, Af, "flicker");
            I(Drain, Drain_int) <+ white_noise(fourkt/RDeff, "thermal");
            I(Source, Source_int) <+ white_noise(fourkt/RSeff, "thermal");
        end
    end
else
    begin
        if (RSeff > 0.0)
            I(Drain, Drain_int) <+ V(Drain, Drain_int)/RSeff;
        else

```

```

        I(Drain, Drain_int) <+ V(Drain, Drain_int)/1e-7;
    if (RDeff > 0.0)
        I(Source, Source_int) <+ V(Source, Source_int)/RDeff;
    else
        I(Source, Source_int) <+ V(Source, Source_int)/1e-7;
I( Source_int, Drain_int) <+ p_n_MOS*Ids;
if (LEVEL == 2)
    I(Source_int, Bulk) <+ p_n_MOS*Idb;
I( Gate, Source_int) <+ p_n_MOS*0.5*ddt(qg);
I( Gate, Drain_int) <+ p_n_MOS*0.5*ddt(qg);
I( Source_int, Bulk) <+ p_n_MOS*0.5*ddt(qb);
I( Drain_int, Bulk) <+ p_n_MOS*0.5*ddt(qb);
I( Gate, Drain_int) <+ p_n_MOS*ddt(qgso);
I( Gate, Source_int) <+ p_n_MOS*ddt(qgdo);
I( Gate, Bulk) <+ p_n_MOS*ddt(qgbo);
I( Bulk, Source_int) <+ p_n_MOS*Ib_d;
I( Bulk, Source_int) <+ p_n_MOS*ddt(Qd);
I( Bulk, Drain_int) <+ p_n_MOS*Ib_s;
I( Bulk, Drain_int) <+ p_n_MOS*ddt(Qs);
I( Source_int, Drain_int) <+ white_noise(Sthermal,"thermal");
I( Source_int, Drain_int) <+ flicker_noise(Sflicker, Af, "flicker");
I( Source_int, Source) <+ white_noise(fourkt/RDeff, "thermal");
I( Drain_int, Drain) <+ white_noise(fourkt/RSeff, "thermal");
end
end
endmodule

```

Update number one: September 2008

The first version of the Qucs EPFL-EKV v2.6 model provided Qucs users with reasonably complete long and short channel models for nMOS and pMOS devices. In no respect were these models optimized for minimum simulation run time or were they flexible enough to allow users to select the style of charge partitioning employed by the EKV model. Recent work on the Qucs implementation of the EKV v2.6 MOSFET model and the Qucs ADMS/XML interface has resulted in a significant reduction in simulation run time overhead, particularly in transient and small signal analysis. The addition of a SPICE BSIM style partition parameter `Xpart` to the Qucs version of the EKV v2.6 model now allows users to set the style of charge partitioning employed by the EKV model. These notes explain the function of the first EKV v2.6 update and introduce a series of test simulations that demonstrate the effects these changes have on the operation of the Qucs port of the EKV V2.6 model.

Model initialisation

Readers who have looked through the EKV v2.6 Verilog-A code listed in the previous sections of these notes will probably have been struck by the quantity of calculations involved each time the code is evaluated during simulation. In the case of transient analysis it is calculated at least once per time step, often resulting in many thousands of passes through the code. The more MOS devices included in a circuit the greater the time overhead becomes. Obviously, a sensible approach would be to minimize the amount of calculation by only evaluating once those parts of the EKV model equations which result in constant values during simulation. The Verilog-A hardware description language provides a model initialisation feature which selects those parts of a device model code which are to be evaluated prior to the start of a simulation. The resulting calculated variables are then available for use by other sections of the Verilog-A model code during simulation. In transient and small signal analysis this is particularly important as it significantly reduces simulation calculation time. Verilog-A employs the “at” (`@(initial_step)` or `@(initial_model)`) language construction coupled with a `begin ... end` block to signify the Verilog-A code that is to be evaluated only at model initialisation. Although this technique does greatly improve model simulation speed it does imply significantly more work for the model developer in that the Verilog-A device code has to be split into initialisation and dynamic simulation sections. Readers interested in the detail of how this split can be achieved should compare the latest EKV v2.6 Verilog-A CVS code given at the Qucs Web site with that presented in previous sections of these notes.

Charge partitioning

The MOSFT is a four terminal device with a dynamic performance that requires accurate calculation of the charge at each terminal. Previous notes indicated that the intrinsic channel charge equals the sum of the drain and source charges. However, the exact proportion of intrinsic channel charge that belongs to the drain or to the source is often not known. The assignment of the proportion of the channel charge to the drain and source charges is called charge partitioning. The first release of the Qucs EKV v2.6 model used the 50/50 partitioning scheme where 50% of the channel charge is arbitrarily assigned to both drain and source. It's interesting to note that this partitioning scheme has no physical basis but depends entirely on convenience. A second partitioning scheme, called the 40/60 partitioning, does however, have a strong physical basis⁹. Yet a third charge partitioning is often employed for digital circuit simulation; this is known as the 0/100 partition. The second release of the Qucs EPFL-EKV v2.6 model includes an extra parameter called Xpart which allows users to set the partitioning scheme for dynamic simulation calculations. Xpart default is set at 0.4 which corresponds to the 40/60 partitioning scheme. Figure 10 illustrates a test circuit for determining the S-Parameters of an nMOS device connected as a capacitance. Both the device capacitance and associated series resistance can be extracted from S[1,1]. Qucs equation block Eqn1 gives the equations for extracting these properties. Other equations in Eqn1 show how the extracted capacitance can be represented as a ratio of the basic parallel capacitance given by

$$C_{parallel_plate} = W \cdot L \cdot Cox. \quad (30)$$

Modelling EKV v2.6 charge partitioning using Qucs EDD

Complex simulation results like those shown in Fig 10 suggest the question “How do we check the accuracy of the model being simulated?”. One possible approach is to develop a second model of the same device based on the same physical principles and equations but using a different approach like the Qucs EDD/subcircuit modelling route shown in Fig. 11. It is an EDD/subcircuit model of a long channel EKV v2.6 nMOS device which includes charge partitioning. Figure 12 illustrated the same test circuit as Fig. 10 and the extracted capacitance and resistance values for the EDD model of the long channel nMOS device. A number of features observed from Fig. 10 and Fig. 11 are worth commenting on; firstly that good agreement is recorded between the two sets of results, secondly that the Verilog-A

⁹William Liu, MOSFET models for SPICE simulation, including BSIM3v3 and BSIM4, 2001, Wiley-Interscience publications, ISBN 0-471-39697-4.

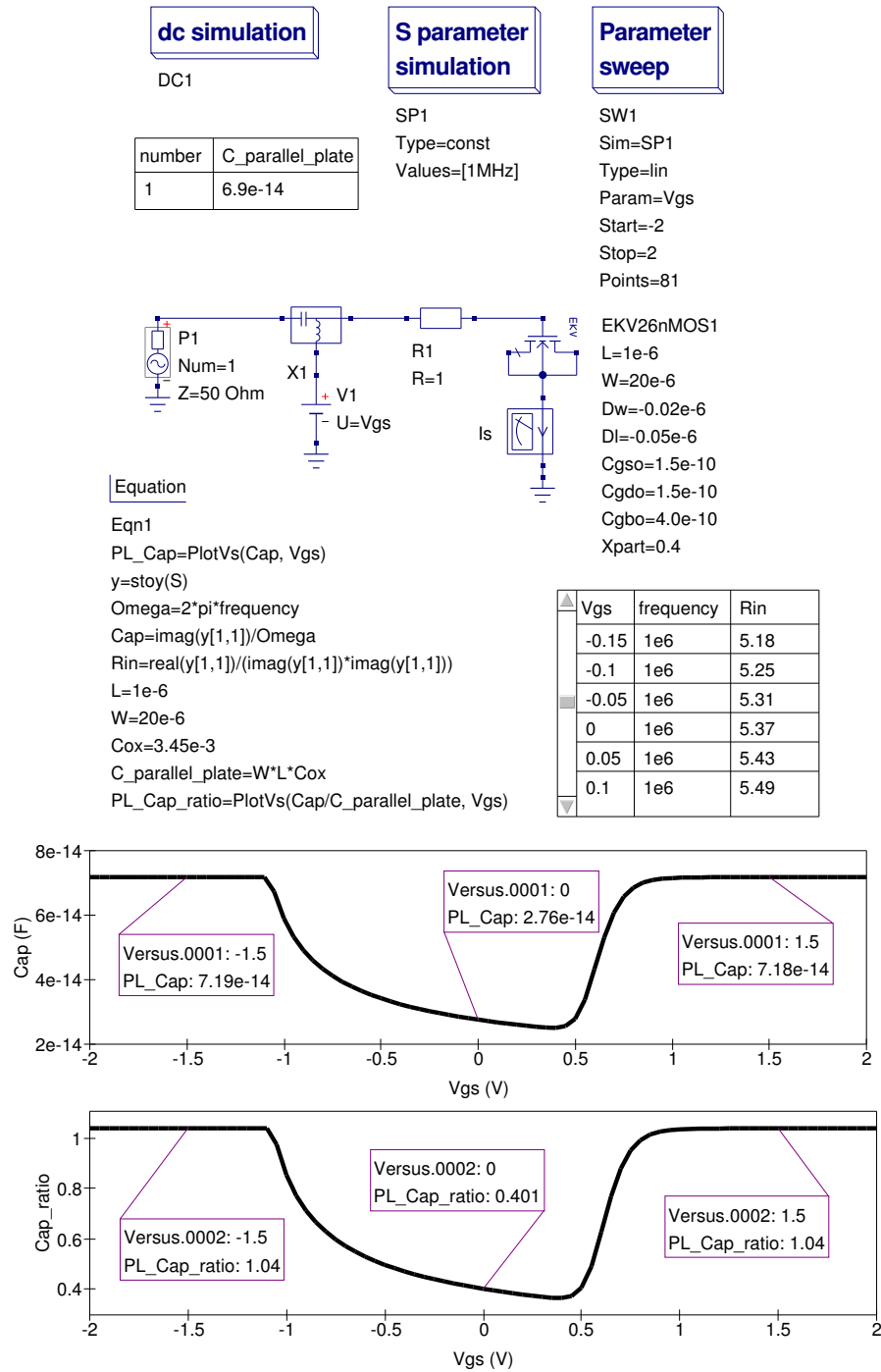


Figure 10: Test circuit for simulating EKV v2.6 charge partitioning effects: Xpart = 0.4 or $QD/QS = 40/60$

model includes both overlap capacitance and drain and gate source resistances. Hence the slight difference in the capacitance ratio and the recorded values of R_{in} above one Ohm for the Verilog-A model.

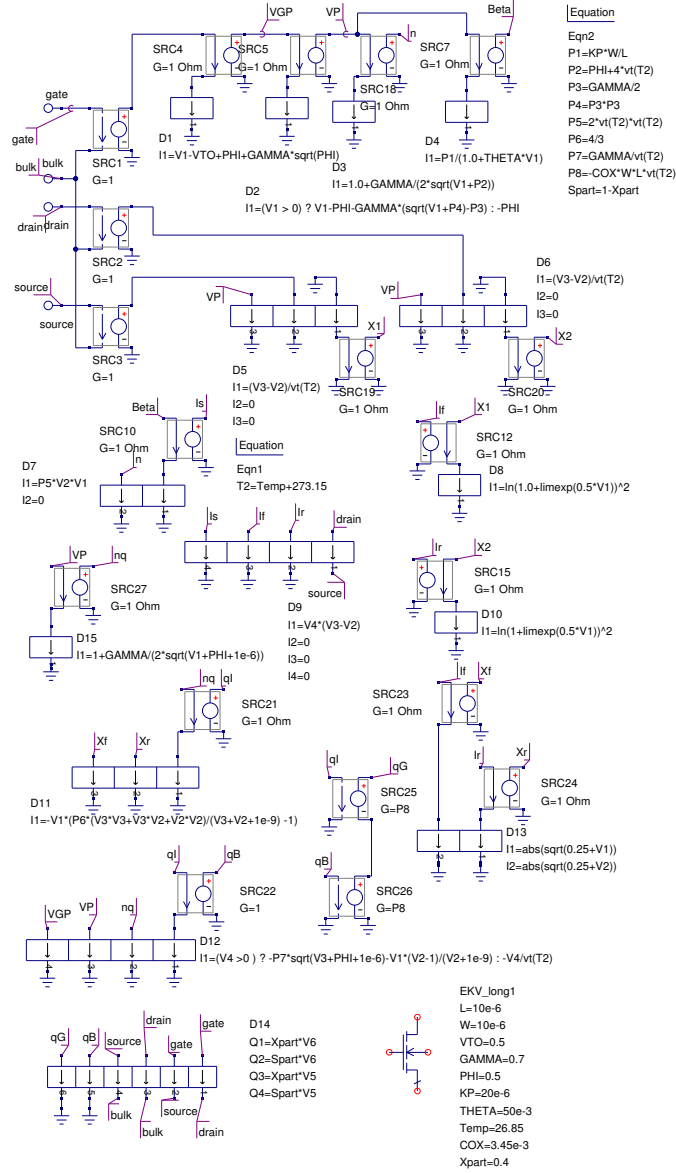
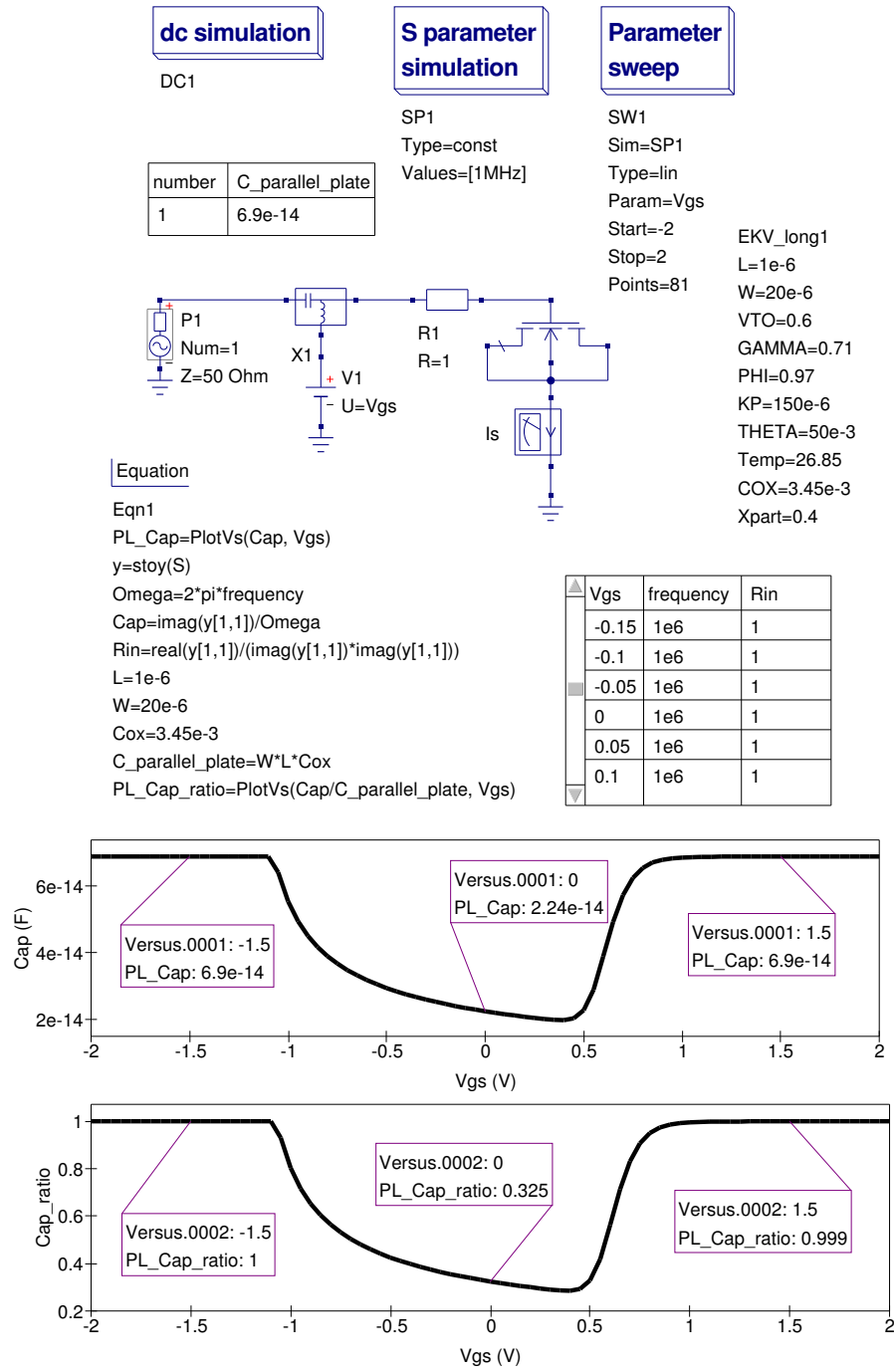


Figure 11: Qucs EDD model for a EKV v2.6 long channel nMOS device with charge partitioning



Versus.0001: -1.5

PL_Cap: 6.9e-14

Versus.0001: 0

PL_Cap: 2.24e-14

Versus.0001: 1.5

PL_Cap: 6.9e-14

Versus.0002: -1.5

PL_Cap_ratio: 1

Versus.0002: 0

PL_Cap_ratio: 0.325

Versus.0002: 1.5

PL_Cap_ratio: 0.999

Figure 12: Test circuit for simulating EKV v2.6 EDD model charge partitioning effects: Xpart = 0.4 or QD/QS = 40/60

End note

The first update of the Qucs EKV v2.6 model provides users with a more optimised model, with improved simulation performance and a more complete charge partitioning scheme. Even with these changes the model is still not complete. The nMOS and pMOS Verilog-A code needs to be unified and a number of optional parameters need to be added to the Qucs implementation of the EKV v2.6 model. The next update of the model is scheduled for the near future, following correction of bug reports sent in by Qucs users. Once again my thanks to Stefan Jahn for all his help and support during the first EKV v2.6 update development phase.