Comparative Analysis of SOI/SOS MOSFET SPICE Models with Account for Radiation Effects

Konstantin O. Petrosyants[1,2], Igor A. Kharitonov[1], Lev M. Sambursky[1,2]

[1] Moscow Institute of Electronics and Mathematics of National Research University "Higher School of Economics" // Moscow, Russia

[2] Institute for Design Problems in Microelectronics, Russian Academy of Sciences // Zelenograd, Moscow, Russia

eande@miem.edu.ru

2014 12th MOS-AK ESSDERC/ESSCIRC Workshop, September 26, 2014 Venice

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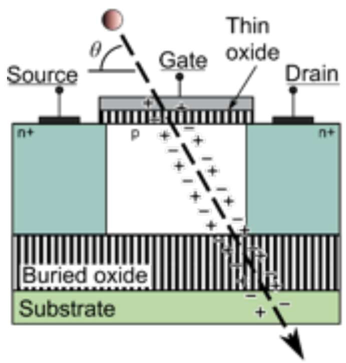
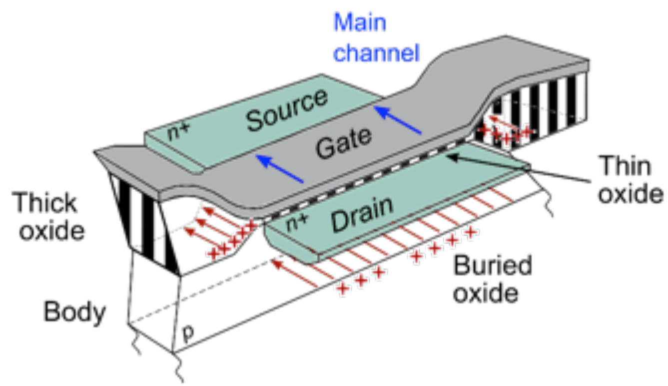
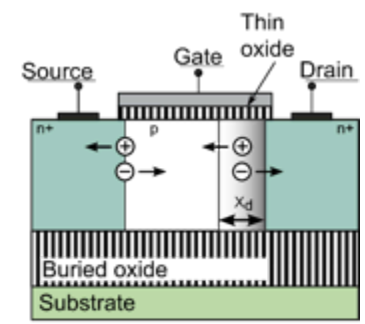
Types of Radiation Effects to Be Considered in Models of SOI/SOS MOSFETs

SOI/SOS MOSFET structure

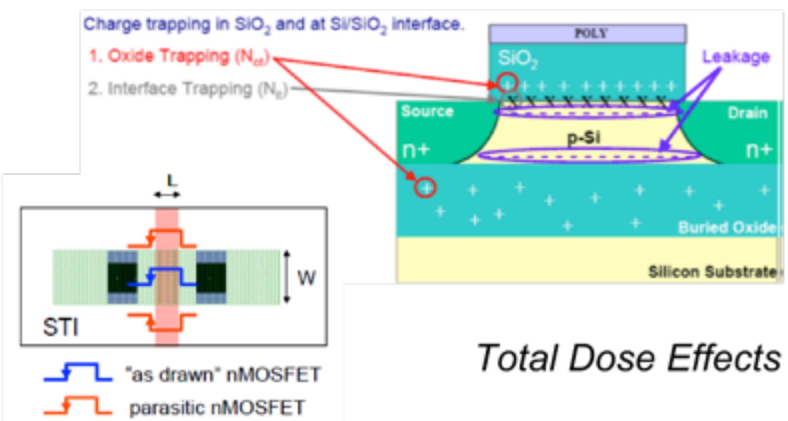


Single events





Pulse radiation



Total Dose Effects

In modern MOSFETs sidewall and back channel leakage currents dominate

Tendencies in CMOS Devices Radiation Hardness

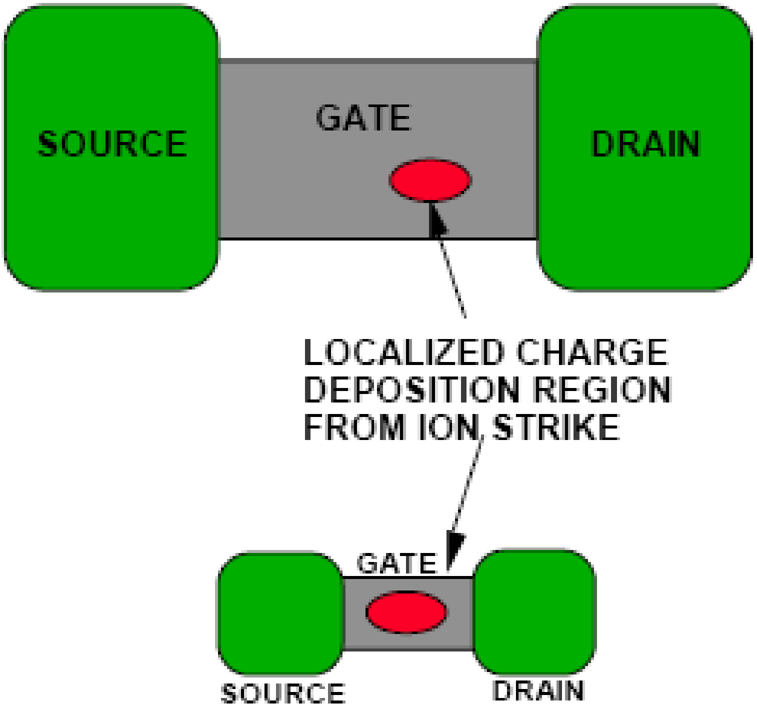
With devices scaling caused by progress in semiconductor technologies, MOSFETs become:

- more sensitive to radiation pulse,
- more sensitive to single high energetic particles,
- less sensitive to total irradiation dose

OLDER DEVICES

LOCALIZED DAMAGE REGION << GATE AREA

LARGE NUMBERS OF IONS MUST STRIKE GATE TO CAUSE TOTAL DOSE DAMAGE



SCALED DEVICES

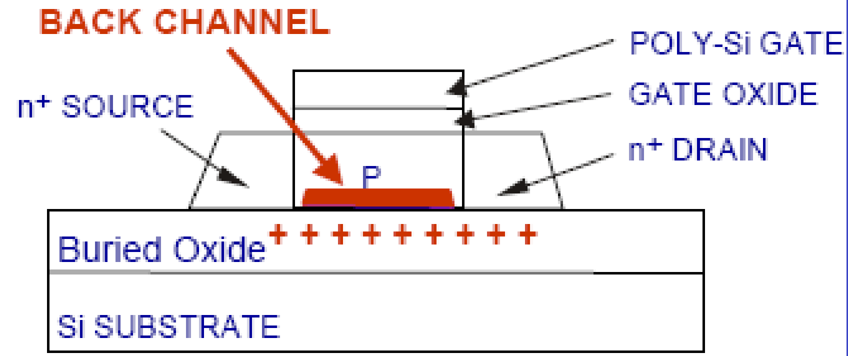
LOCALIZED DAMAGE REGION ≅ GATE AREA

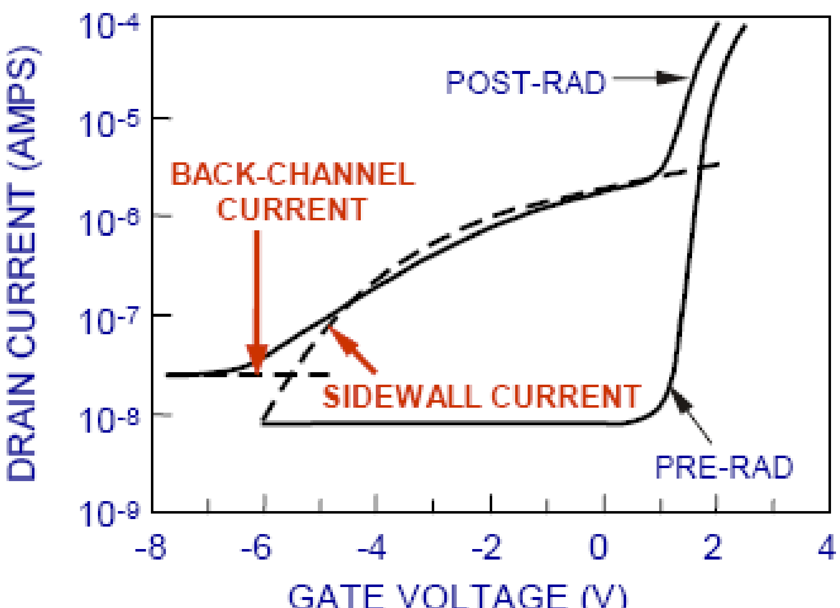
SINGLE ION STRIKING GATE CAN CAUSE TOTAL DOSE FAILURE

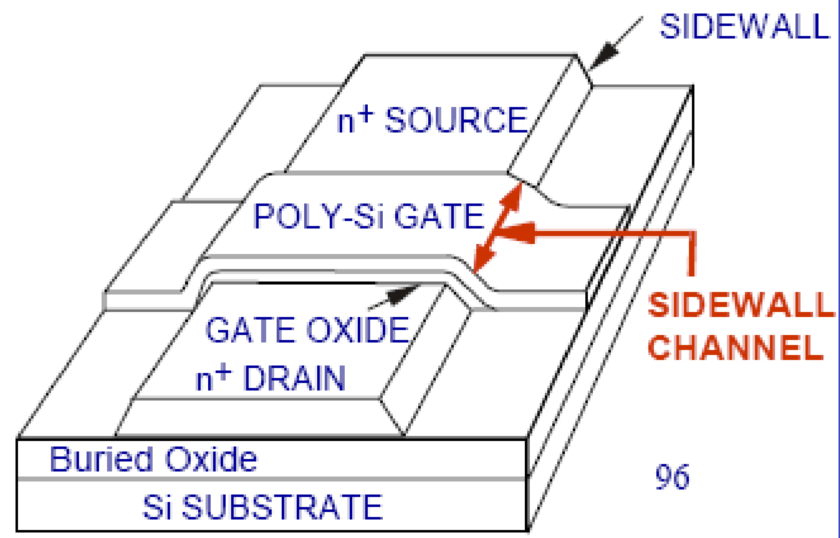
SOI/SOS MOSFET Structures

SOI Advantages:
1. **Total Isolation**
2. **SEU Immune**
3. **High Speed**
4. **Low Power**
5. **Latchup Eliminated**

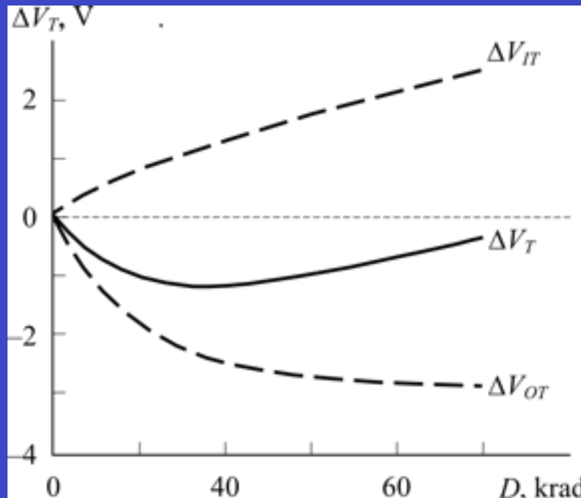
New SOI Total Dose Leakage Paths:
1. **Back Channel Leakage**
2. **Sidewall Leakage**



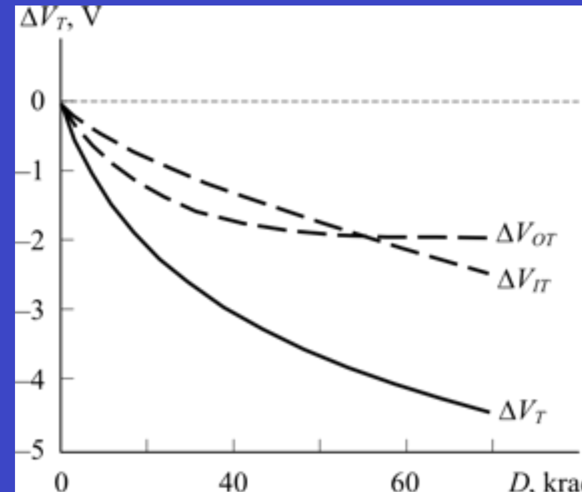




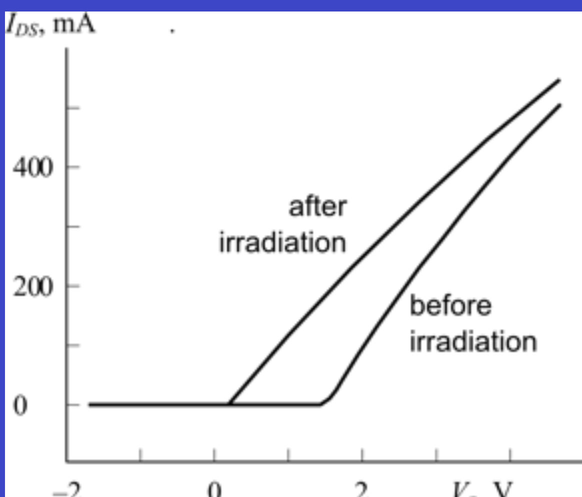
MOSFET Parameter Degradation under Irradiation Conditions (Total Dose Effects)



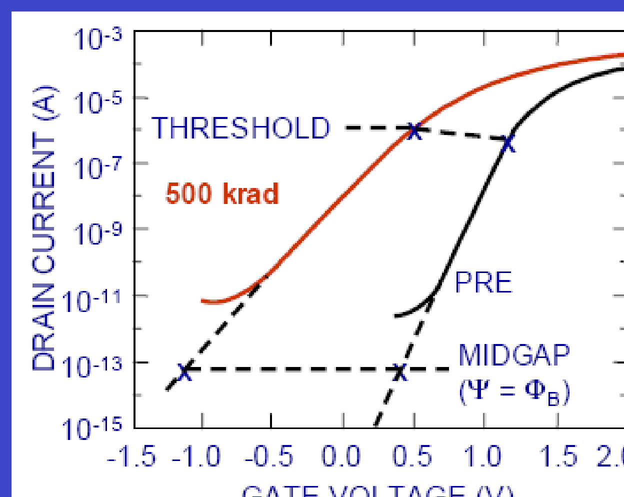
Threshold voltage: NMOS



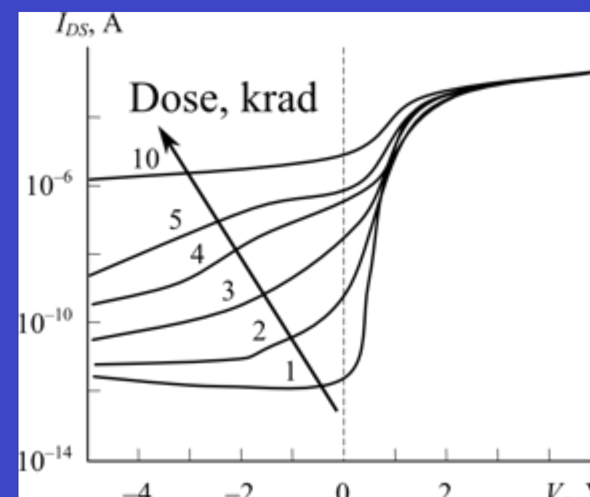
Threshold voltage: PMOS



Mobility



Subthreshold slope



Leakage current

SOI/SOS MOSFET Models with Account for Radiation Effects: State of Art

1. P. Pavan, R. H. Tu, E. R. Minami, G. Lum, P. K. Ko, C. Hu A complete radiation reliability software simulator // IEEE Trans. on Nuclear Science. – 1994. – Vol. 41. – P. 2619–2630
   Radiation-induced leakage currents are not considered

2. Petrosjanc K. O., Adonin A. S., Kharitonov I. A., Sicheva M. V. SOI Device Parameter Investigation and Extraction for VLSI Radiation Hardness Modeling with SPICE // Proc. IEEE Intl. Conf. on Microelectronic Test Structures. – 1994. – Vol. 7. – P. 126–129
   Submicron effects are not considered

3. J. Alvarado, E. Boufouss, V. Kilchytska, D. Flandre Compact model for single event transients and total dose effects at high temperatures for partially depleted SOI MOSFETs // Microelectronics Reliability. – 2010. – Vol. 50. – P. 1852–1856
   Radiation-induced static leakage currents are not considered;
   Parameter extraction procedure is not presented

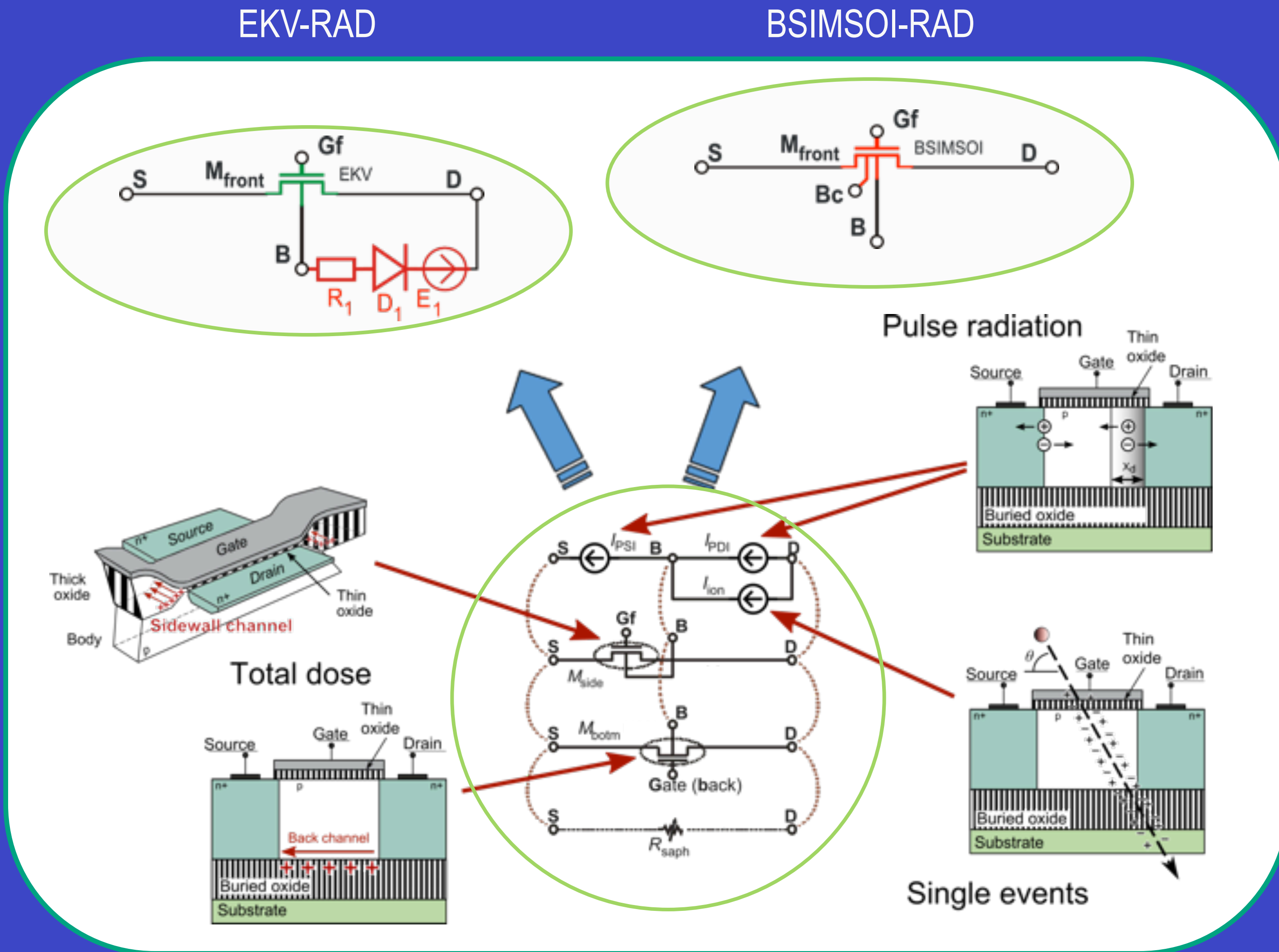
4. Gorbunov M. S. et al. Verilog-A Modeling of Radiation-Induced Mismatch Enhancement //IEEE Trans. on Nuclear Science,. – 2011. – Vol. 58. – No. 3. – P. 785-792
   Parameter extraction procedure is not presented

5. Bu Jianhui, Bi Jinshun, Liu Mengxin, Han Zhengsheng A total dose radiation model for deep submicron PDSOI NMOS // Journal of Semiconductors. – 2011. – Vol. 32. – No 1. – P. 014002-1 – 014002-3
   Applicable to small radiation doses only (uses oversimplified expressions);
   Some types of radiation-induced leakage currents are not considered

Approach for SPICE Models Development for SOI/SOS MOSFET Taking into Account Radiation Effects

Model parameters for V_T, μ, S = *f (D)* are radiation-dependent

Additional circuit components taking into account radiation effects



Core Models

	BSIMSOI	EKV
Semiconductor device	SOI MOSFETs	Bulk-Silicon MOSFETs
Model application	Universal general-purpose model	Low-voltage micro- and nanocurrent analog integrated circuits
Account for submicron effects	+	+
Included in many popular EDA tools	+	+
Number of parameters	Large	Small
Complexity of Parameter Extraction Procedure	+ +	+

Drain Current Equations

BSIMSOI:

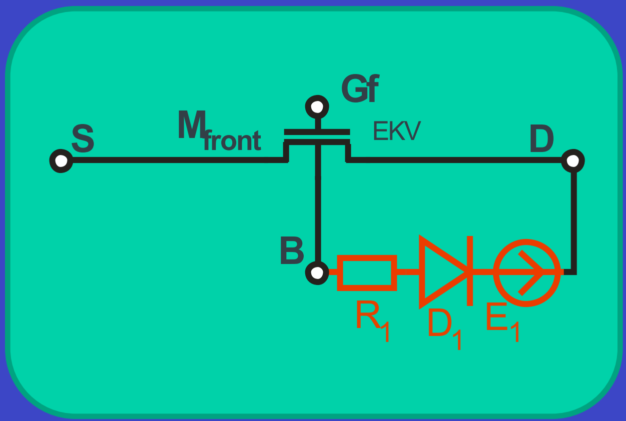
$$I_{DS,MOSFET} = \frac{I_{DS0}}{1 + \dfrac{R_{DS} I_{DS0}}{V_{DSeff}}} \cdot \left(1 + \frac{V_{DS} - V_{DSeff}}{V_A}\right),$$

$$\text{where } I_{DS0} = \frac{\mu_{eff} C_{ox} \dfrac{W_{eff}}{L_{eff}} \cdot V_{gst,eff} \left(1 - A_{bulk} \dfrac{V_{DSeff}}{2\left(V_{gst,eff} + 2\varphi_T\right)}\right) V_{DSeff}}{1 + \dfrac{V_{DSeff}}{E_{sat} L_{eff}}}$$

EKV:

$$I_D = I_S (i_f - i_r) = I_S \left[\ln^2\left(1 + \exp\left(\frac{VP - V_S}{2\varphi_t}\right)\right) - \ln^2\left(1 + \exp\left(\frac{VP - V_D}{2\varphi_t}\right)\right)\right]$$

Account for Floating Body Effects in EKV-RAD



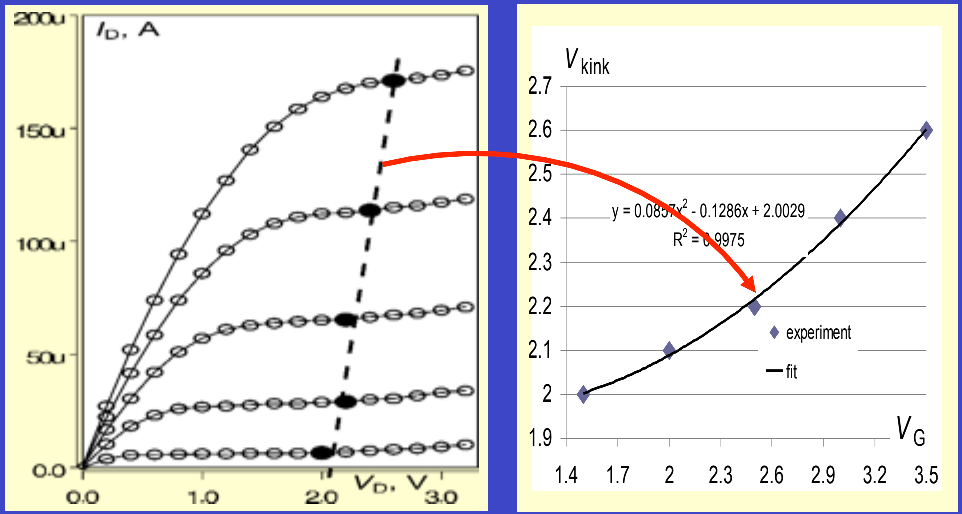
Dependency of E1 on the gate bias:

$$E_1(V_{GS}) = V_{dd} - \underbrace{\left(p_1 + p_2 \cdot V_{GS} + p_3 \cdot V_{GS}^2\right)}_{Vkink}$$

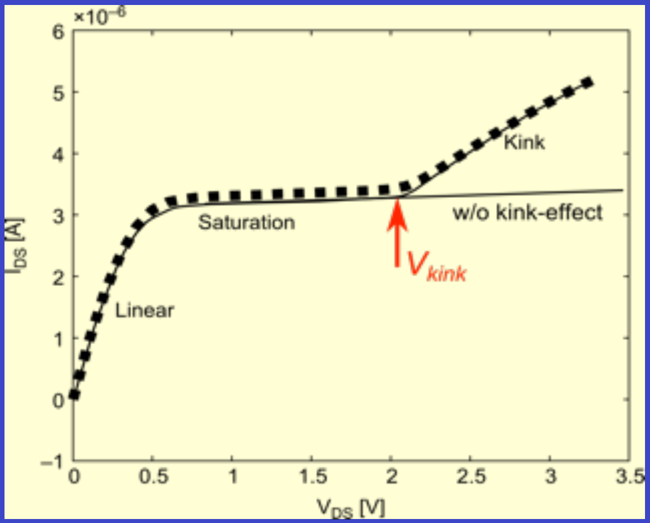
R1 is described by function:

$$R1 = R + \max R \cdot \frac{1}{2} \cdot \left(1 + \tanh\left[\delta\left(-V_{GS} + DV\right)\right]\right)$$

SOS n-MOSFET W/L = 1.2/5 µm (Peregrine)

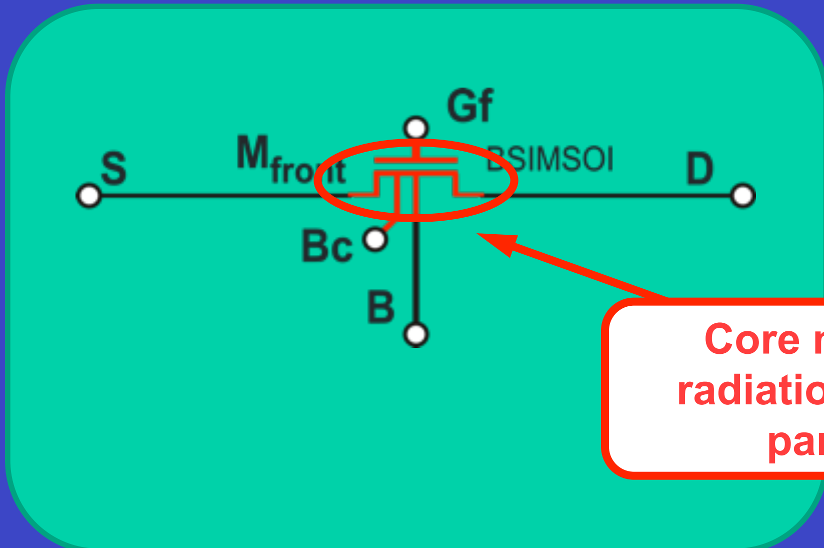


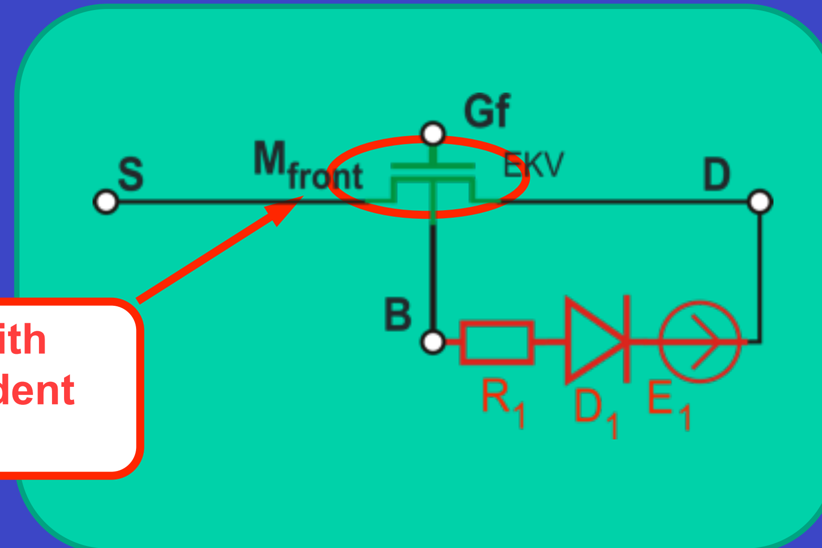
Approach to determine $E_1(V_{GS})$ factors



Measured vs. simulated output curves for SOS MOSFET

Account for Radiation Effects



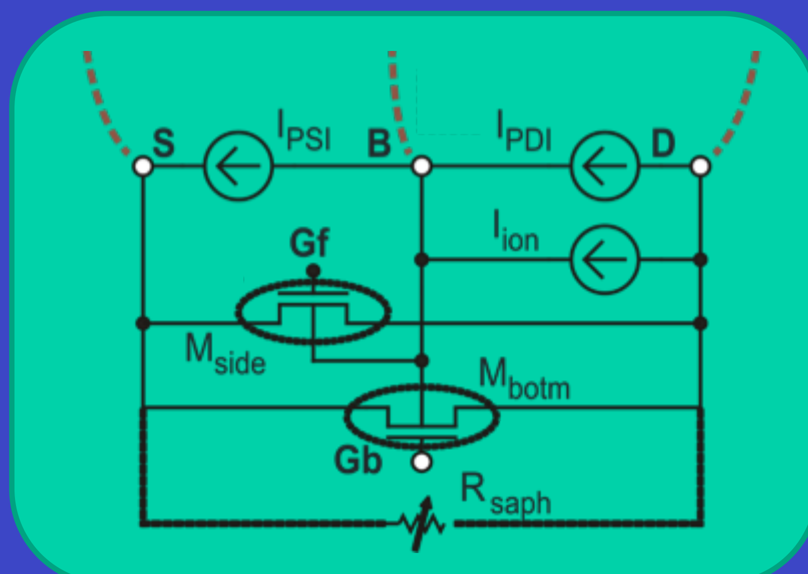


Core models with radiation-dependent parameters

$$VTH0,..,U0,UA,..,VOFF,CIT = f\left(D\right)$$

$$VTO,GAMMA,KP,E0 = f\left(D\right)$$

Additional circuit fragment to account for radiation-induced currents (<u>equal for both models</u>)

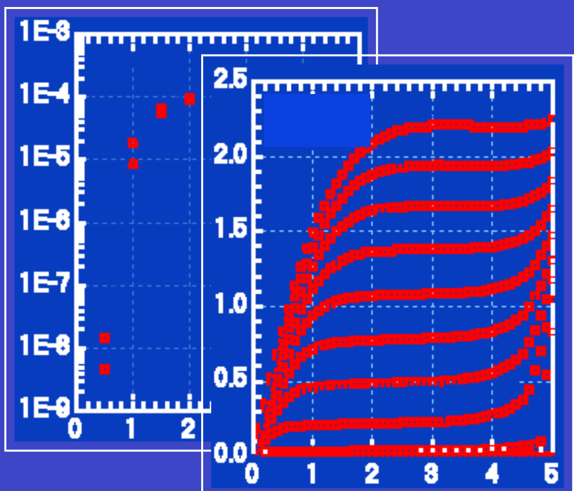


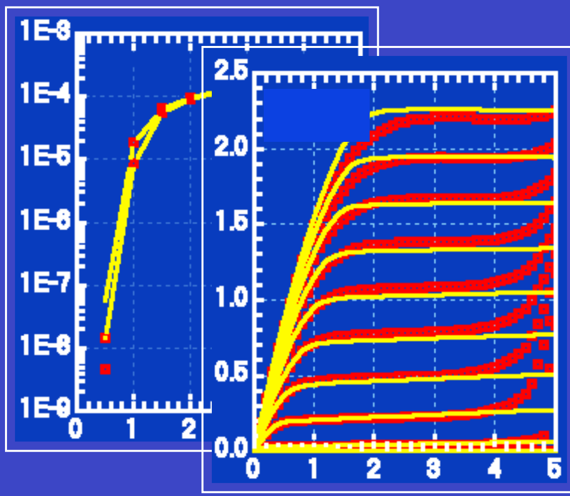
Strategy for Model Parameter Extraction with Account for Radiation Effects

1. **The full set of macromodel parameters is extracted for unirradiated devices**
2. **Among all the model parameters for MOSFET sub-components a limited number of radiation dependent parameters is selected, related to threshold voltage, mobility, subthreshold slope;**
   - **For a given set of radiation doses these parameters are extracted**
3. **Dependencies of radiation parameters on dose are approximated to a known physical function**

Model Parameter Extraction Procedure for Unirradiated Devices

Measurement Results → **IC-CAP + AdMOS tool** → **Data for Model Library**





Standard Extraction Flow

Models: BSIMSOI, EKV

(Full set of model parameters)

VTH0, K1, K2, U0, UA, UB, …

↓

Full (global) optimization

Problem reduction →

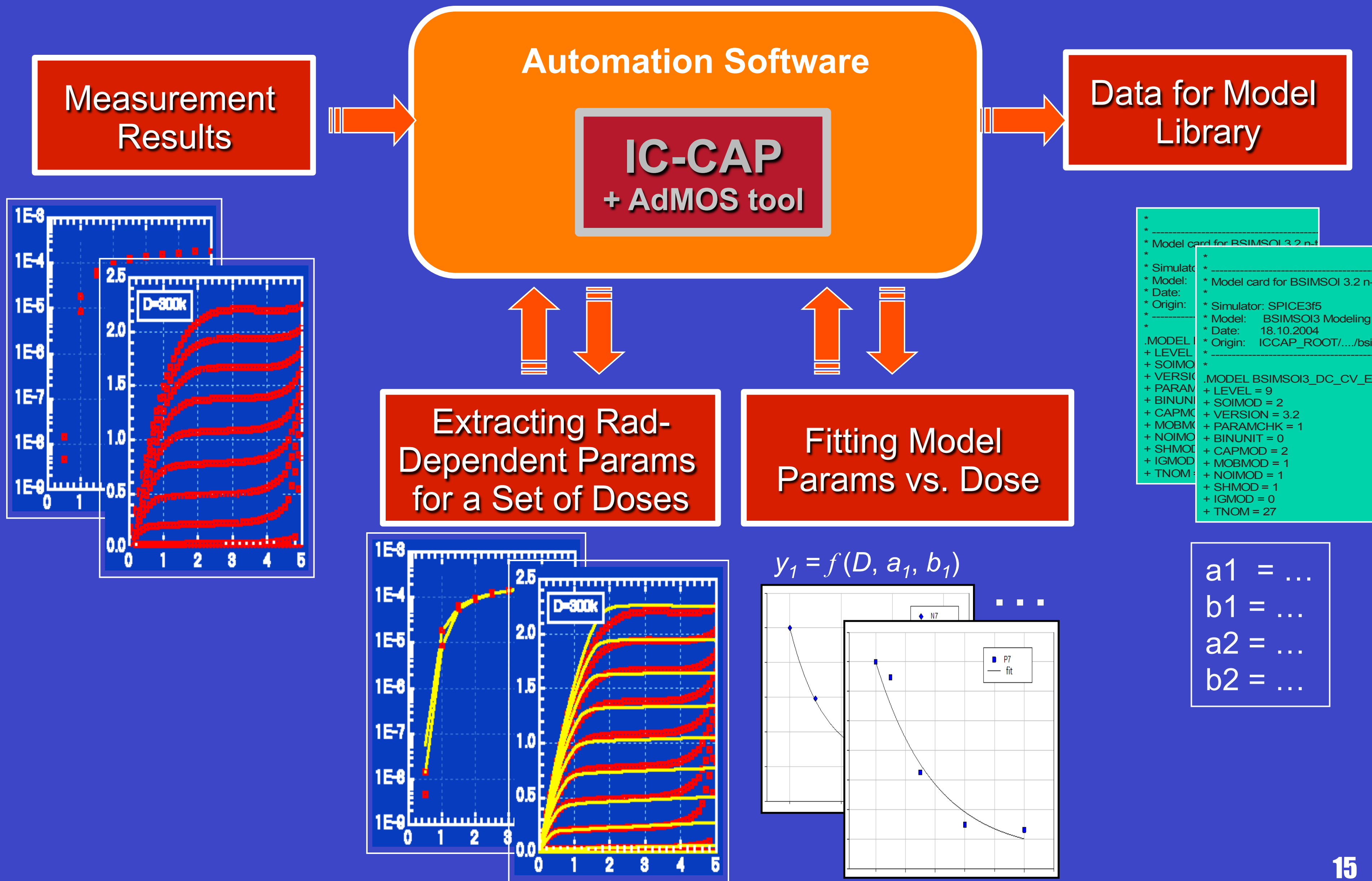
(Groups of related model parameters)

VTH0, K1, K2, … ↓ local optimization

U0, UA, UB, … ↓ local optimization

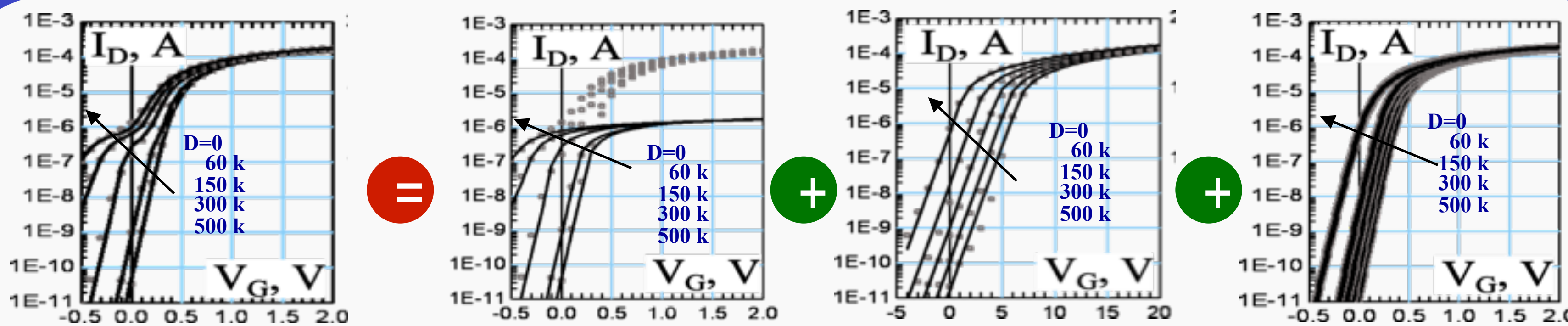
. . .

Procedure for Model Parameter Extraction with Account for Radiation Effects



Additional Details of Macromodel Parameter Extraction Procedure for Irradiated SOI/SOS MOSFETs

Simulated vs. measured transfer curves for SOI MOSFET with $L / W = 0.25 / 8$ µm BSIMSOI-RAD



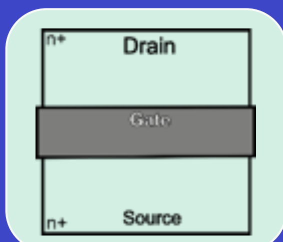
Full macromodel
Maximum simulation error: 7-15%

Parasitic sidewall transistor M_{side}

Parasitic back transistor M_{back}

Main front transistor M_{front}

All components active

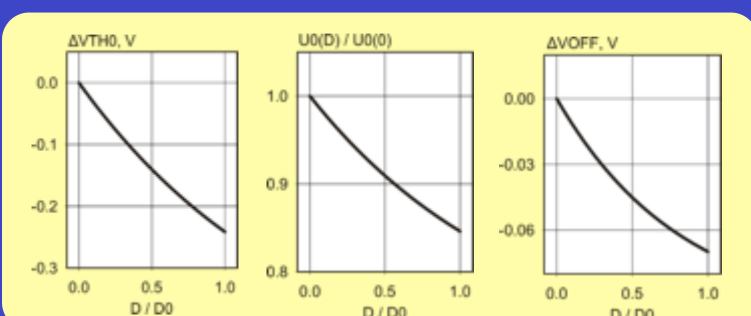


Front and back components blocked

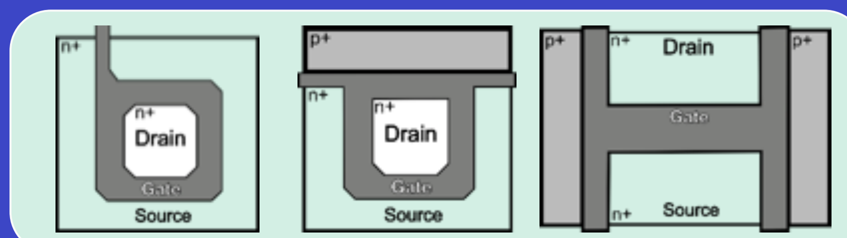
Front component blocked

Back component blocked

Linear (I-type) test structure



Dose dependencies for front model

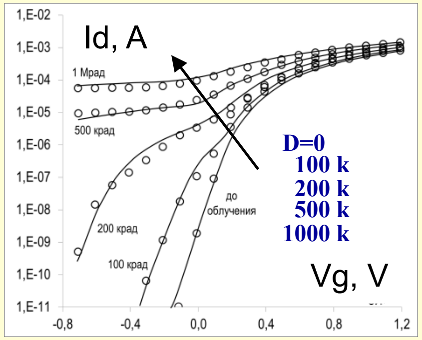


Radiation-hardened (O-, R-, H-type) test structures

Special test structures are necessary!

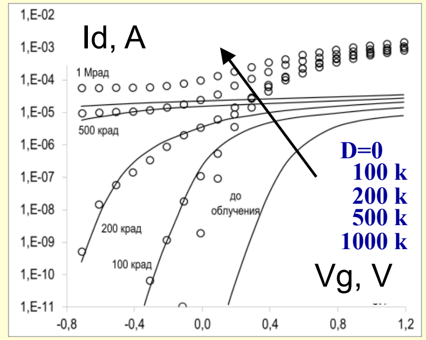
Measured and Simulated I-V Characteristics

(on the example of EKV-RAD)



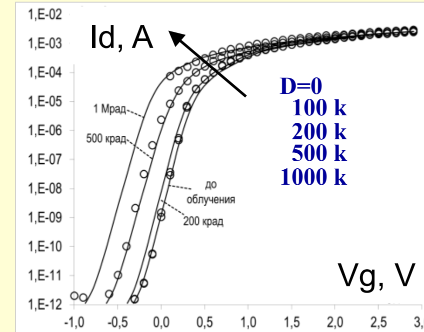
Full macromodel

=



Parasitic sidewall transistor M_{side}

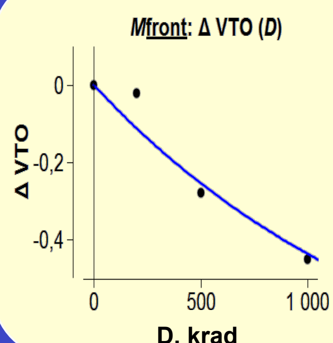
+

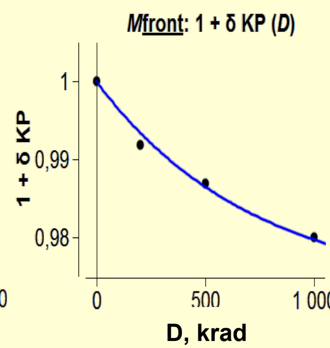


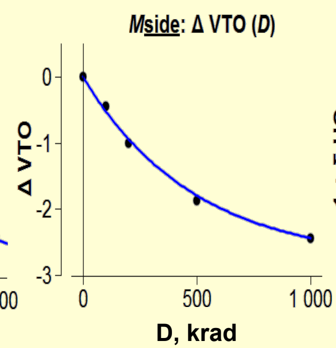
Main front transistor M_{front}

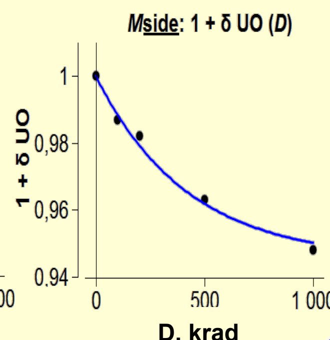
Simulated and measured SOI MOSFET transfer IV-curves (*L / W* = 0.13 / 8 μm)

Maximum error: 7-15%







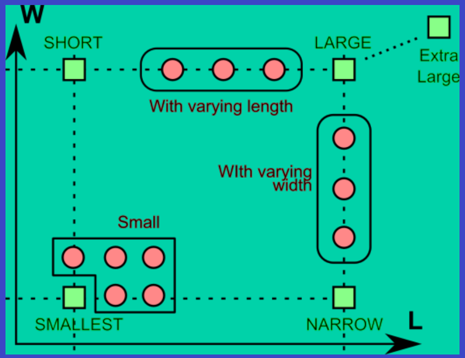


Main and parasitic model parameters dependencies on dose

Number of Macromodel Parameters

Parameters group	BSIMSOI-RAD	EKV-RAD
1. Core model parameters (without account for radiation effects)	180 (BSIMSOI v3.2)	30 (EKV v2.64)
2. Additional parameters: • for floating-body effects • for parasitic transistors (M_{side}, M_{botm})	— 32	8 32
3. Radiation-dependent parameters: • for the core model • for parasitic transistors (M_{side}, M_{botm}) models • approximation coefficients for all radiation-dependent parameters	10 8 36	4 8 24

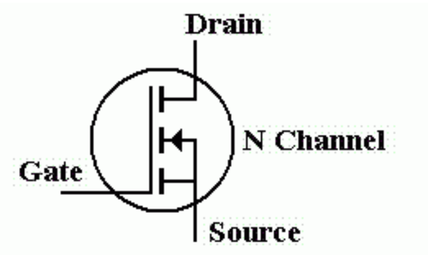
Time Assessment of Parameter Extraction Procedure



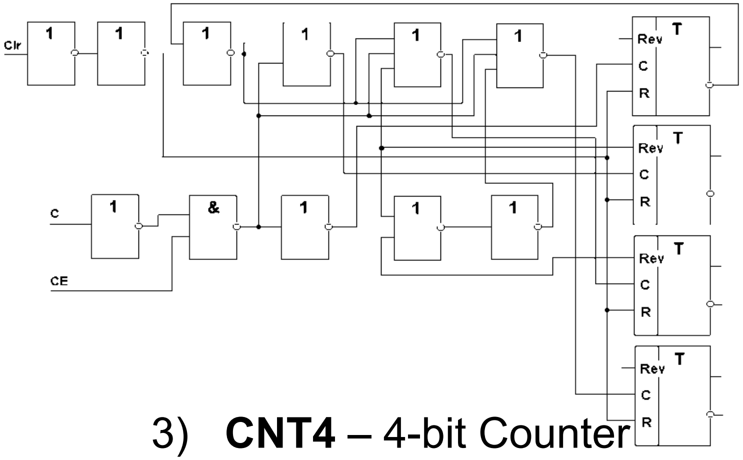
Time, minutes;
16 test MOSFETs of different size;
6 radiation doses;
Intel i5-2430M 2.4 GHz, 4 GB RAM

Semi-automatic procedure stages	BSIMSOI-RAD	EKV-RAD
1. **Extraction of model parameters for unirradiated transistors :**		
• for parasitic transistors (M_{side}, M_{botm})	16	16
• for the core model	40	15
2. **Extraction of radiation-dependent parameters only (6 radiation doses):**		
• for parasitic transistors (M_{side}, M_{botm})	10 * 6 = 60	10 * 6 = 60
• for the core model	8 * 6 = 48	5 * 6 = 30
3. Approximation of the table function for parameters dependency on dose:	2	2
TOTAL: • semi-automatic method	166 min.	123 min.
• with manual data exchange	448 min.	393 min.

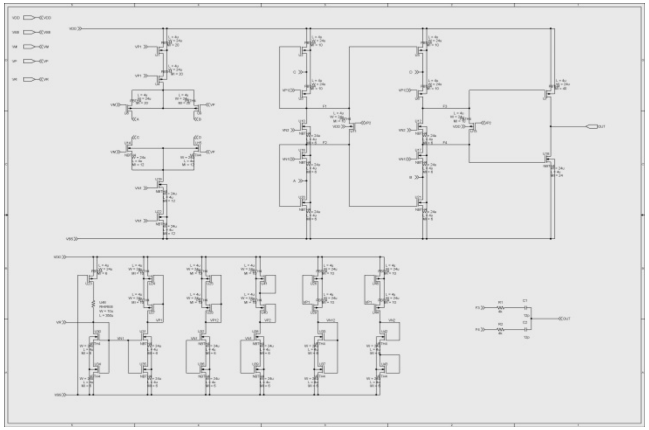
SOI/SOS CMOS Circuits under Test



1) Single MOSFET



3) **CNT4** – 4-bit Counter (250 MOSFETs)



2) **OA** – Operational Amplifier (45 MOSFETs)

Intel i5-2430M 2.4 GHz, 4 GB RAM; HSpice A-2008.03

Time Assessment of Circuit Simulation

Intel i5-2430M 2.4 GHz, 4 GB RAM; HSpice A-2008.03

CPU Time, seconds

Model Variant	***Std. BSIMSOI***	***Std. EKV***	**BSIMSOI-RAD**		**EKV-RAD**	
Dose, rad	**0**	**0**	**0**	**$1 \cdot 10^6$**	**0**	**$1 \cdot 10^6$**
IV curves, 1 MOSFET *(10000 pts.)*	2.33	1.76	2.63	2.50	2.12	2.20
OA frequency response *(45 MOSFETs, 800 pts.)*	3.32	2.88	3.68	3.87	3.16	3.20
CNT4 transient *(250 MOSFETs, 1800 pts.)*	34.6	10.4	46.5	44.4	20.4	21.5

The results obtained from these tests are the following:

a) with the use of full variants of both macromodels, simulation time is longer by 10-100% than with core models only (depending on a circuit).
b) with the use of the EKV-RAD macromodel, simulation time is shorter by 15-50% than with BSIMSOI-RAD macromodel (depending on a circuit),

Circuit Simulation Time Increase Using EKV-RAD and BSIMSOI-RAD in Comparison with the Original Versions

Model Variant	***BSIMSOI-RAD ref. to BSIMSOI***	***EKV-RAD ref. to EKV***
Dose, rad	**0**	**0**
IV curves, 1 MOSFET *(10000 pts.)*	+ 13%	+ 20%
OA frequency response *(45 MOSFETs, 800 pts.)*	+ 11%	+ 10%
CNT4 transient *(250 MOSFETs, 1800 pts.)*	+ 34%	+ 96%

- When using full macromodels, simulation time (with dose D=0) increases as compared to the corresponding standard models.
- This fact is reasonably explained by complication of the equivalent circuits (3 transistors instead of 1 in the standard models; additional circuit components) and introduction of additional analytical functions describing radiation-dependent parameters.
- Simulation time increase for EKV-RAD is relatively larger than for BSIMSOI-RAD because EKV-RAD has less parameters

Circuit Simulation Time Decrease Using EKV-RAD with Reference to BSIMSOI-RAD

Dose, rad	**$1 \cdot 10^5$**	**$1 \cdot 10^6$**
IV curves, 1 MOSFET *(10000 pts.)*	19%	12%
OA frequency response *(45 MOSFETs, 800 pts.)*	14%	17%
CNT4 transient *(250 MOSFETs, 1800 pts.)*	56%	52%

Conclusion

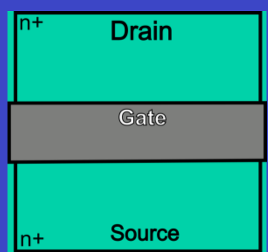
1. The versions of BSIMSOI and EKV models taking into account radiation effects for SOI/SOS MOSFETs were developed using two methods:
    - Introduction of additional mathematical equations for radiation-dependent model parameters
    - Connection of additional elements to equivalent circuits of basic models
2. Models with account for radiation effects are more complex and provide relatively longer circuit simulation time:
    - for BSIMSOI-RAD: from 10 to 35% (depending on circuit type)
    - for EKV-RAD: from 10 to 100% (depending on circuit type)
3. For SOI/SOS CMOS circuit simulation, EKV-RAD model is preferable, because it has a smaller set of parameters and provides:
    - shorter parameter extraction time (~25%),
    - shorter circuit simulation time (10–50% depending on circuit type)
4. All models were included in circuit simulators: HSpice, Spectre, Eldo

Thank you for attention!

XXX 2.3. Procedure for MOSFET Characteristic Measurement

Standard Procedure Features

- Goal: to obtain a single set of curves for the set of devices with diff. size
- Linear transistor test structures:

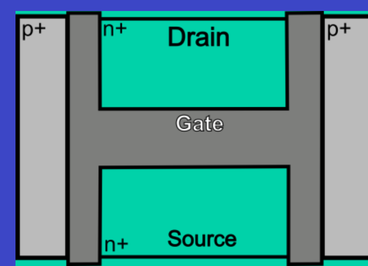


I-type

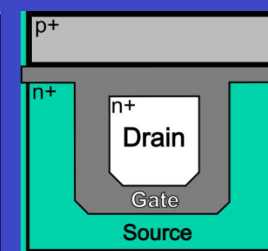
- Standard electrical curves:
  - Id-Vg
  - Id-Vd
  - Diodes (p-n-junctions)
  - Parasitic BJT

Modified Procedure Features

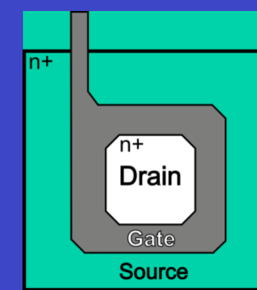
- Goal: to obtain the standard set of electrical curves for every macromodel component
- Rad-hard transistor test structures:



H-type



R-type



O-type

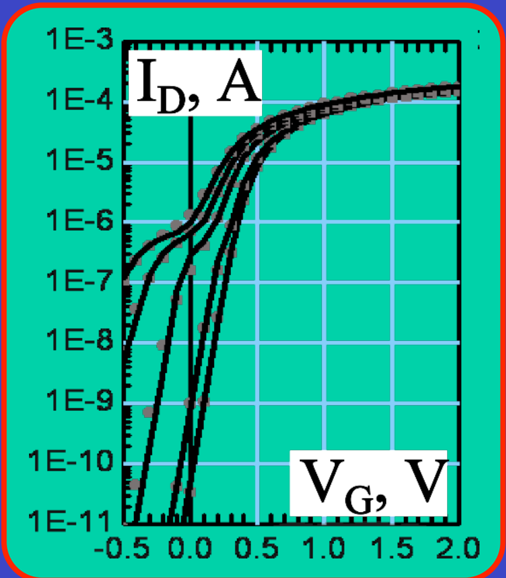
- Sequence of operations:

1. Full measurement of unirradiated device
2. Shortened measurement of every interface (front, bottom, sidewall) for every single dose to separate leakage currents later

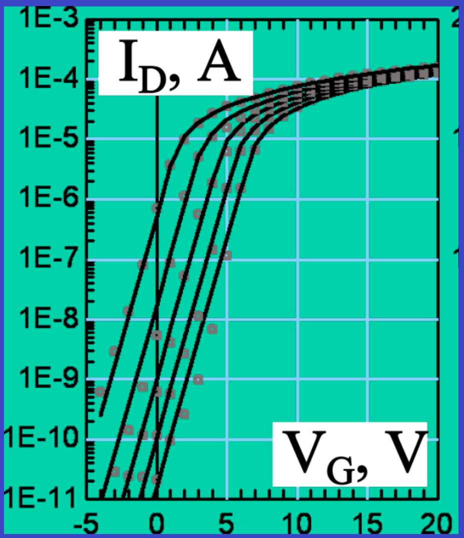
- Use of automation of curve measurement and data processing to reduce time of operation, human error and risk of device damage

XXX 3. Example of the Subsystem Application

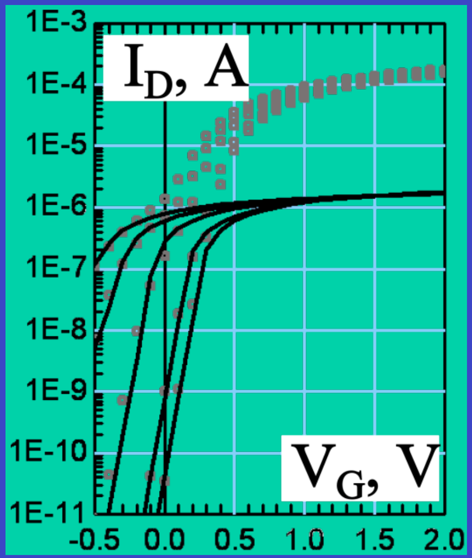
SOI MOSFET
L / W = 0.25 / 8 μm



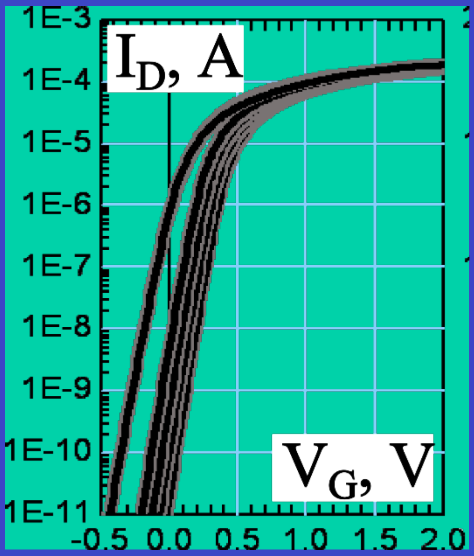
total $M_F + M_{botm} + M_{side}$



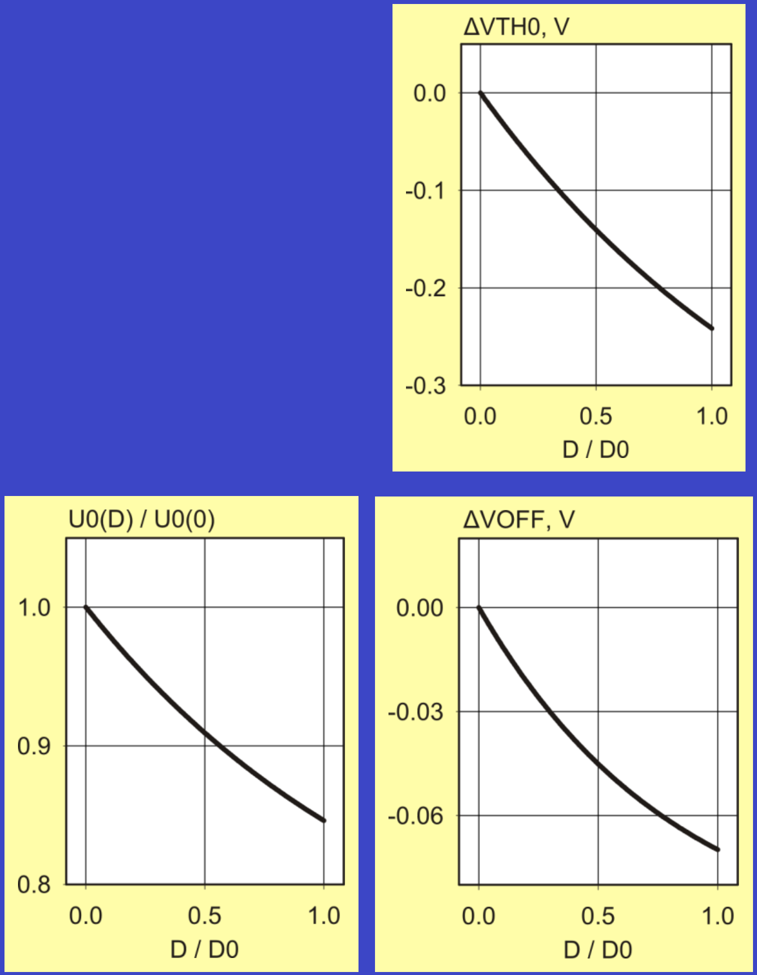
bottom M_{botm}



side M_{side}

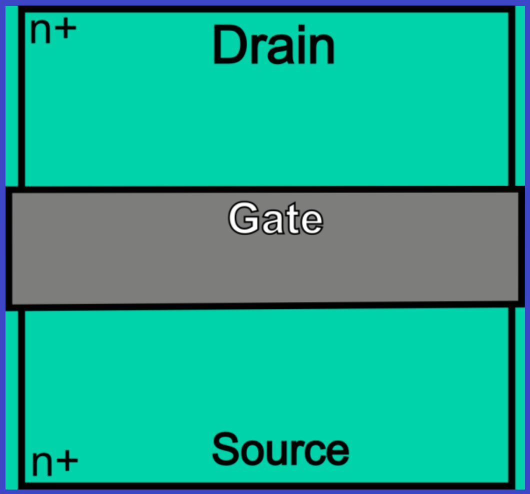


front M_F



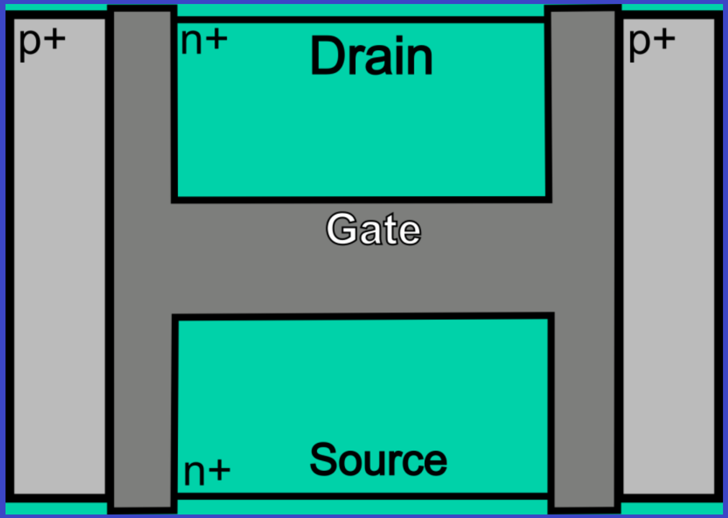
Radiation-dependent parameters vs. *Dose* (example)

XXX 2.4. Test Structures for Electrical Measurement

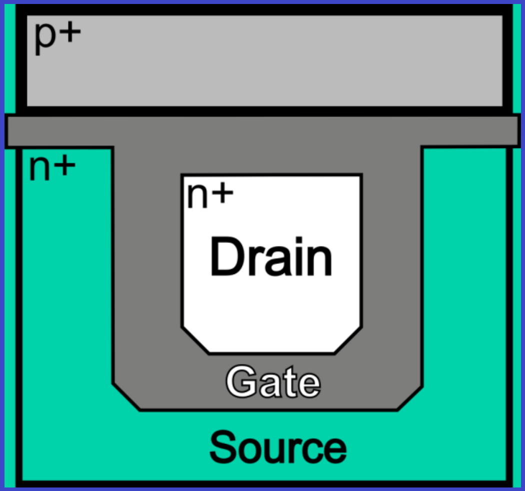


Conventional test structure:
I-type

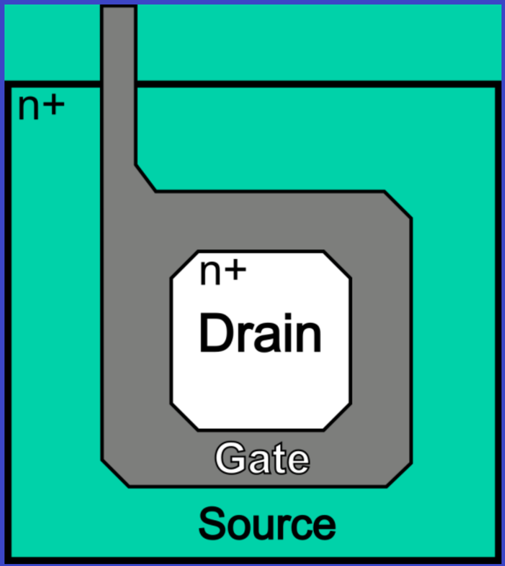
Additional test structures to investigate leakage currents:



H-type

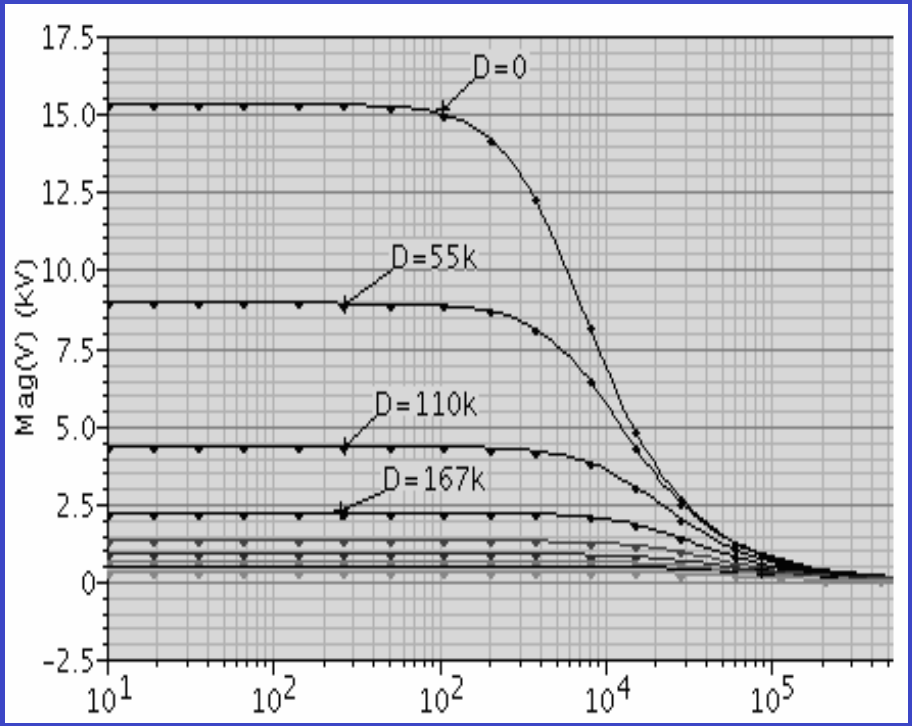


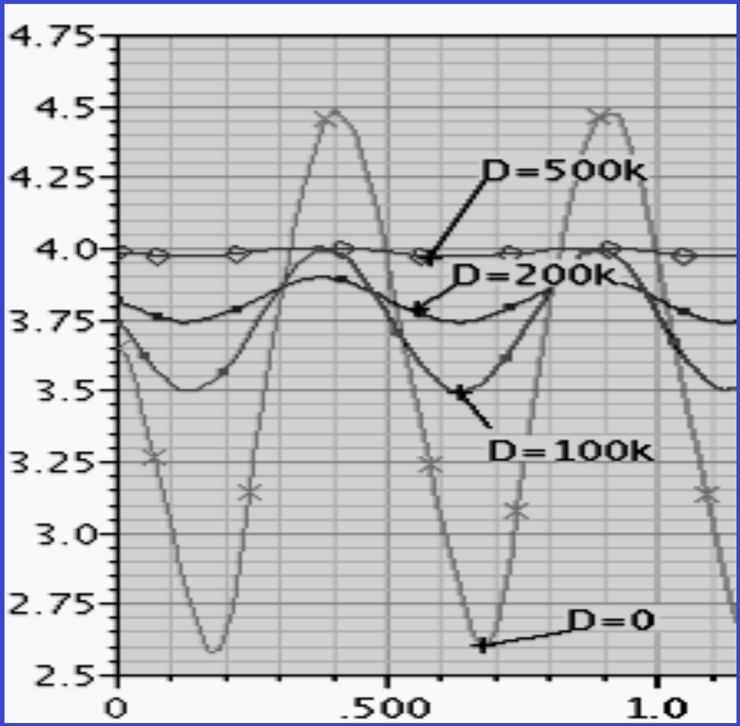
R-type



O-type

MODEL APPLICATION TO OpAmp CIRCUIT SIMULATION

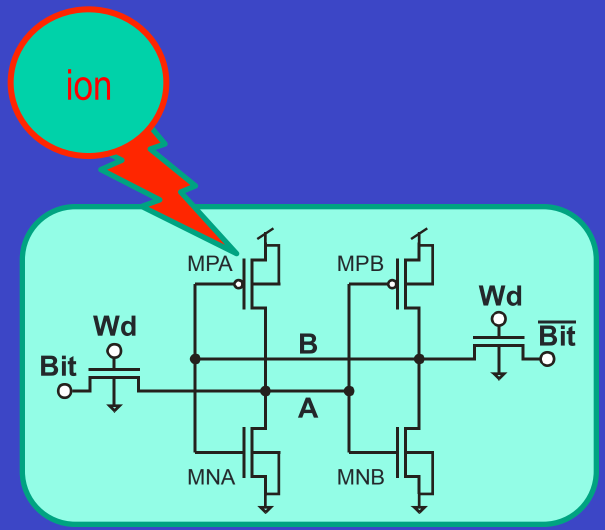




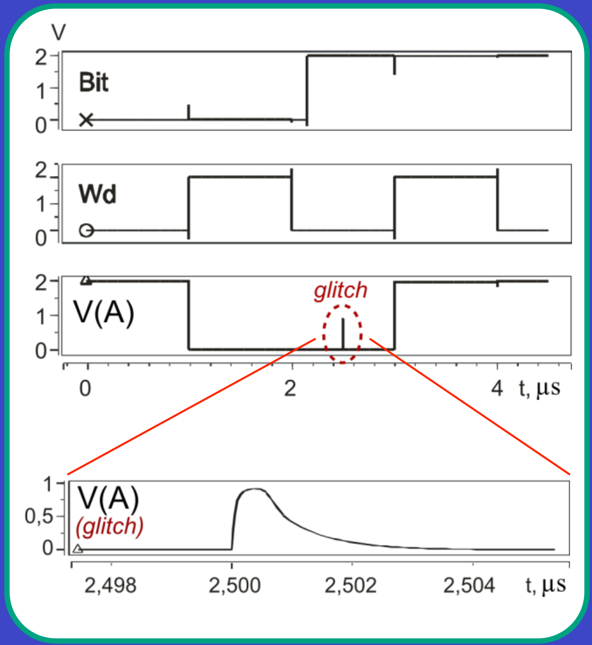
Simulation of frequency (left) and transient response (right)
for OpAmp before and after irradiation to dose in the range 0÷1 Mrad

MODEL APPLICATION TO SRAM CELL

SINGLE EVENT RESPONSE SIMULATION

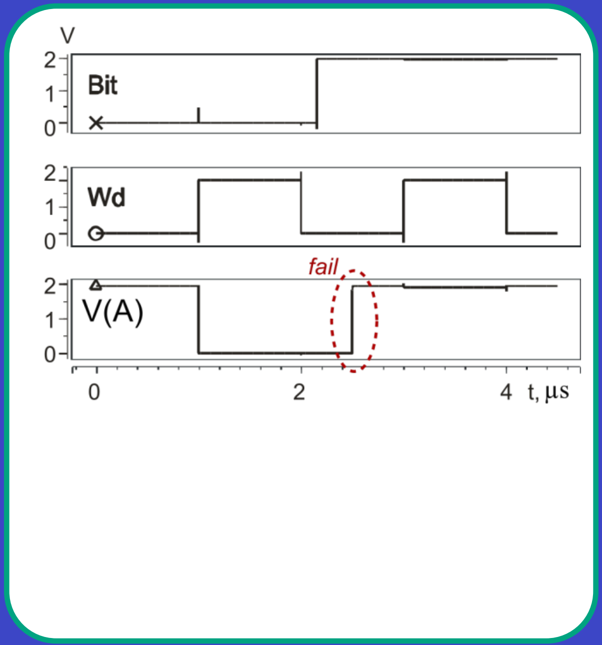


Energetic ion strikes MPA transistor of a memory cell



LET = 18 MeV·cm^{-2}/mg

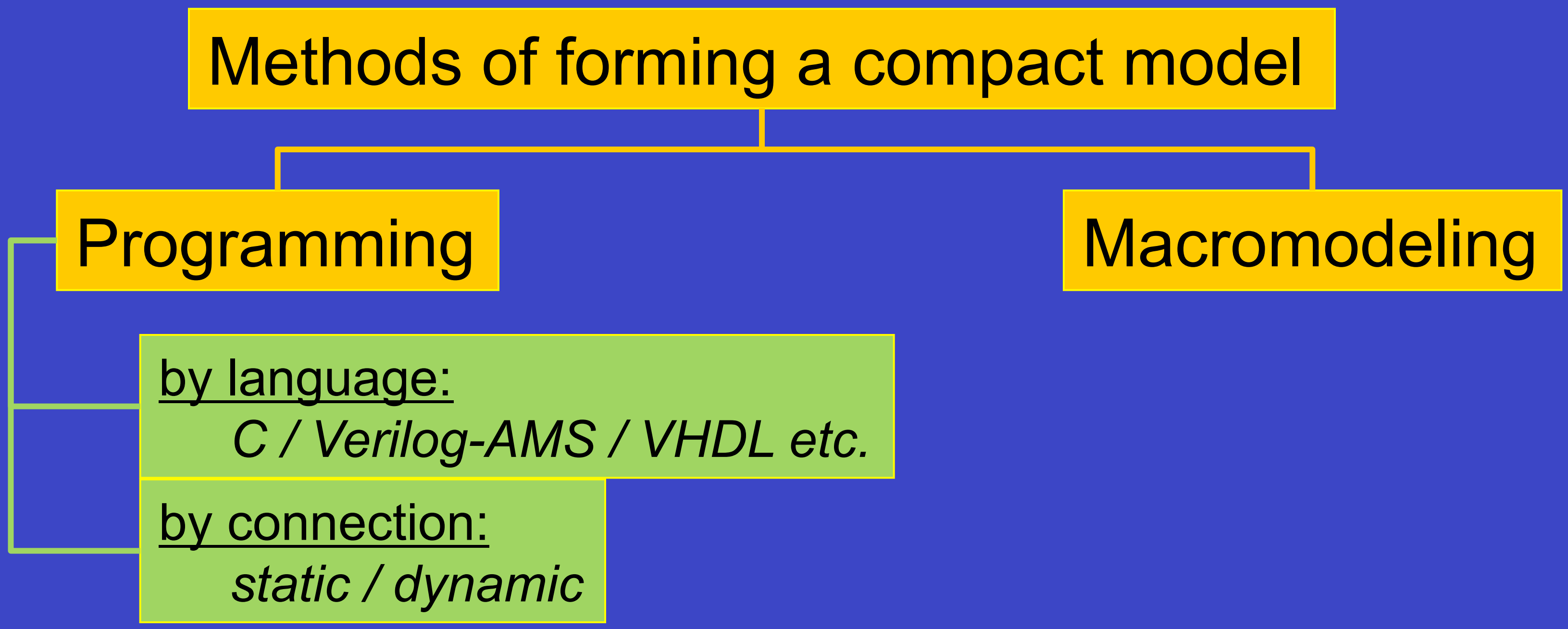
NO FAILURE



LET = 21 MeV·cm^{-2}/mg

FAILURE

Modeling Approaches for Radiation Effects



Executor: programmer
Core model: any one with available source code
Portability: seamless between major simulators

Executor: circuit designer
Core model: any one available in the simulator
Portability: with minimum syntax modifications

Accuracy ???
Extraction ???

SOI/SOS MOSFET Models with Account for Radiation Effects: Experience of Our Group

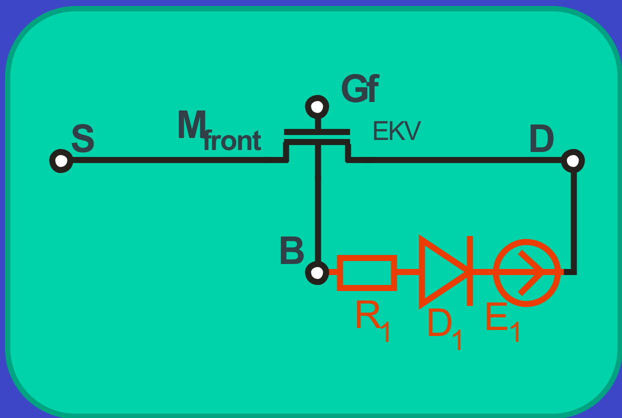
- **WOS and Scopus papers:**

1. Petrosjanc K.O., Kharitonov I.A., “VLSI device parameters extraction for radiation hardness modeling with SPICE,” Proc. 1993 International Conf. on Microelectronic Test Structures, (ICMTS 93) BARCELONA, SPAIN Date: MAR 22-25, 1993, Pages: 9-14
2. Petrosyants, K.O., Kharitonov, I.A., “MIS and bipolar transistor models for LSI circuitry calculations with regard for radiation effects,” Mikroelektronika, 1994, 23 (1) , pp. 21-34
3. Petrosjanc K.O., Adonin A.S., Kharitonov I.A., Sicheva M.V., “SOI Device Parameter Investigation And Extraction for VLSI Radiation Hardness Modeling with SPICE,” Proc. 1994 International Conference on Microelectronic Test Structures Location: SAN DIEGO, CA Date: MAR 22-25, 1994, Pages: 126-129
4. Petrosjanc K.O., Kharitonov I.A., Usov N.N., Adonin A.S., “Device radiation response investigation and SPICE model parameters extraction for VLSI radiation hardness modeling,” Proc. 6th International Symposium on IC Technology, Systems and Applications Location: SINGAPORE, SINGAPORE Date: SEP 06-08, 1995
5. Petrosjanc K. O., Sambursky L. M., Yatmanov A. P. Comparison of Commercial Parameter Extraction Tools for Spice SOI MOSFET Models // Proc. of 5th IEEE East-West Design & Test Intl. Symp. (EWDTS'07), Yerevan, Armenia, Sept. 2007, p. 69–72;
6. Petrosjanc K. O., Kharitonov I. A., Orekhov E. V., Sambursky L. M, et al. A Compact SOI/SOS MOSFET Macromodel Accounting for Radiation Effects // ibid, p. 360;
7. Simulation of Radiation Effects in SOI CMOS Circuits with BSIMSOI-RAD macromodel / Petrosjanc K. O., Kharitonov I. A., Orekhov E. V., Sambursky L.. M, Yatmanov A. P. // Proc. of 7th IEEE East-West Design & Test Intl. Symposium (EWDTS'09), Moscow, Russia, Sept. 2009. – p. 243–246
8. SOI/SOS MOSFET compact macromodel taking into account radiation effects, Petrosyants, K.O., Sambursky, L.M., Kharitonov, I.A., Yatmanov, A.P, Russian Microelectronics; Volume 40, Issue 7, December 2011, Pages 457-462
9. Simulation of total dose influence on analog-digital SOI/SOS CMOS circuits with EKV-RAD macromodel, Petrosyants, K.O., Kharitonov, I.A., Sambursky, L.M., Bogatyrev, V.N., Povarnitcyna, Z.M., Drozdenko, E.S., Proc. of IEEE East-West Design and Test Symposium, EWDTS 2012, Article number 6673145
10. Coupled TCAD-SPICE simulation of parasitic BJT effect on SOI CMOS SRAM SEU, Petrosyants, K.O., Kharitonov, I.A., Popov, D.A., Proceedings of IEEE East-West Design and Test Symposium, EWDTS 2013, pp 312–315
11. Hardware-software subsystem for MOSFETs characteristic measurement and parameter extraction with account for radiation effects, Petrosyants, K.O., Kharitonov, I.A., Sambursky, L.M., Advanced Materials Research, 2013, Vol. 718-720, pp. 750-755

Conclusion CTAPOE

1. Macromodels BSIMSOI-RAD and EKV-RAD for Silicon-on-Insulator/Sapphire (SOI/SOS) MOSFETs are compared by relevant criteria with account for radiation effects.
2. It was shown that while the set of accounted effects is similar and the quantity of core and radiation-dependent parameters is smaller for the EKV-RAD macromodel, it also exhibits a simpler parameter extraction procedure and provides shorter simulation times for various circuits with account for steady-state radiation influence.
3. It is thereby shown that EKV-RAD macromodel is advantageous.

Account for Floating Body Effects in EKV-RAD



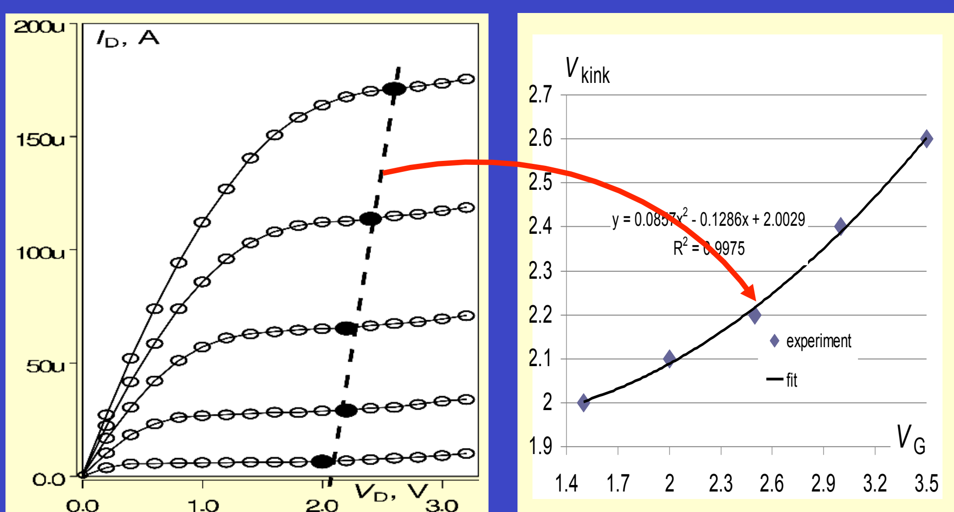
Dependency of E1 on the gate bias:

$$E_1\left(V_{GS}\right) = V_{dd} - \underbrace{\left(p_1 + p_2 \cdot V_{GS} + p_3 \cdot V_{GS}^2\right)}_{Vkink}$$

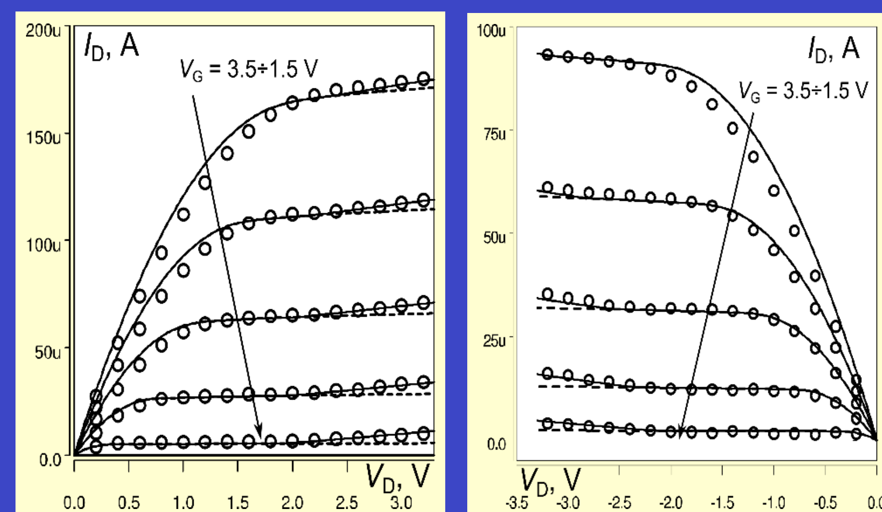
R1 is described by function:

$$R1 = R + \max R \cdot \tfrac{1}{2} \cdot \left(1 + \tanh\left[\delta\left(-V_{GS} + DV\right)\right]\right)$$

SOS n-MOSFET W/L = 2.5/2.5 μm (Peregrine 0.5 μm)

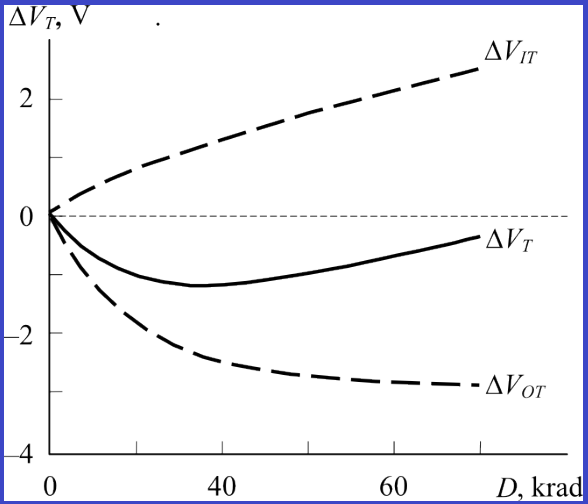


Approach to determine $E_1(V_{GS})$ factors

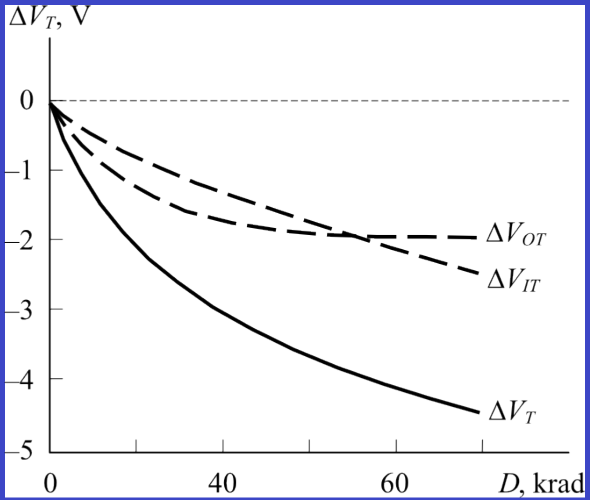


Measured vs. simulated output curves for SOS MOSFET

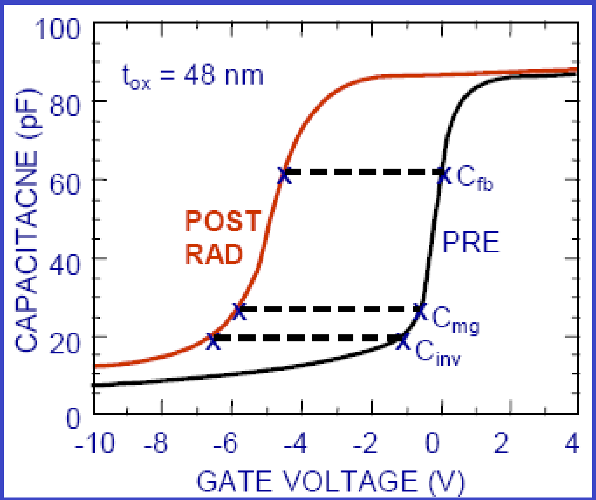
MOSFET Parameter Degradation under Irradiation Conditions (Total Dose Effects)



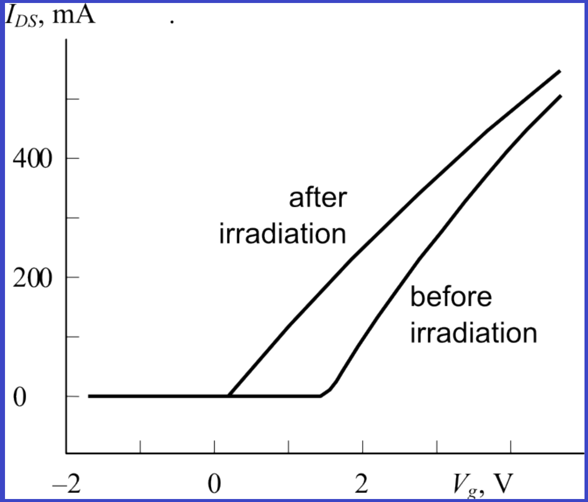
Threshold voltage: NMOS



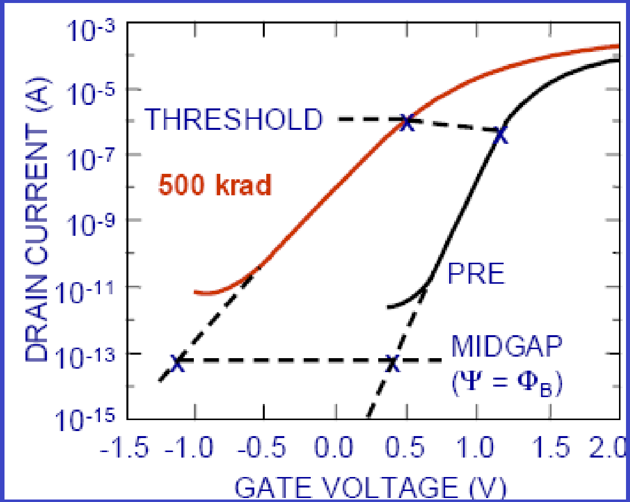
Threshold voltage: PMOS



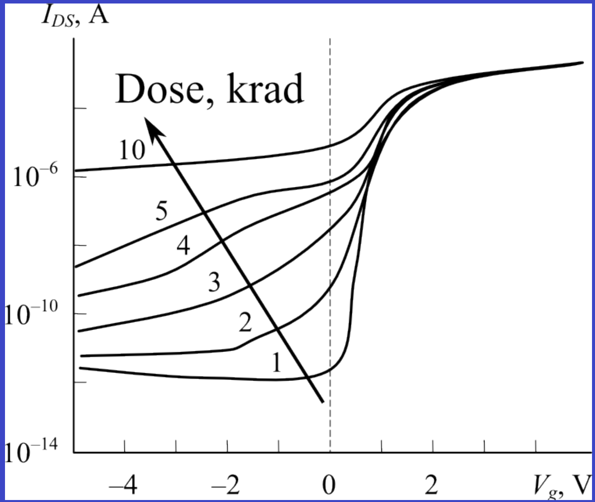
Gate Capacitance



Mobility



Subthreshold slope



Leakage current