The EKV/ACM compact models for mismatch modeling down to 90nm and for new emergent non-CMOS nanotechnology FETs

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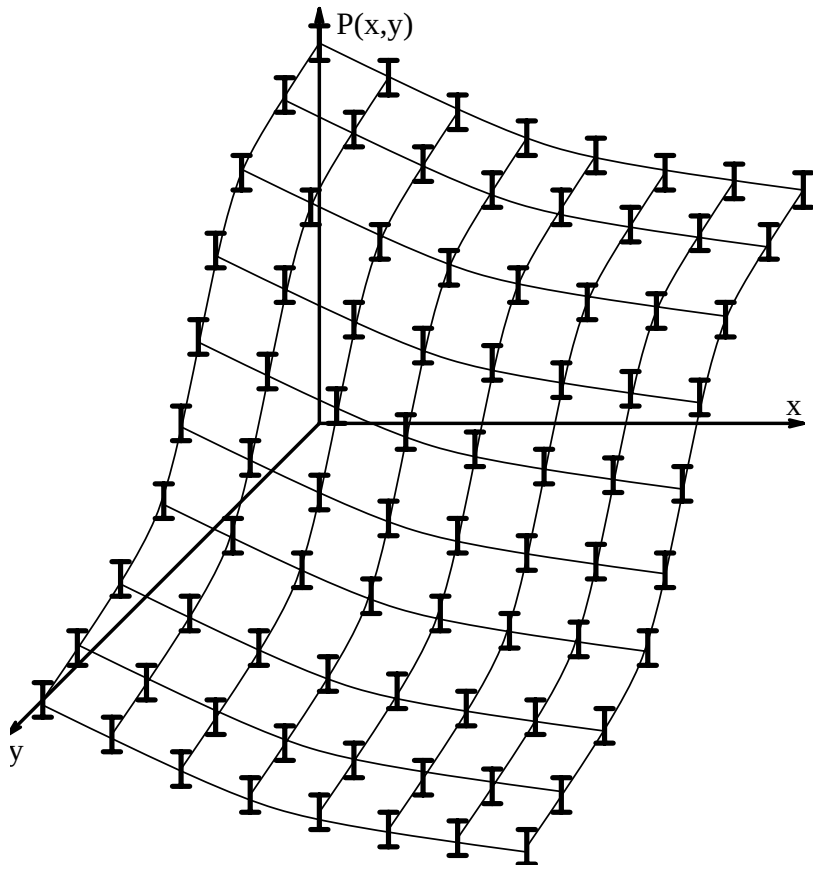
Outline

- Continuous Weak-to-Strong inversion models for mismatch
- Mismatch characterization chip
- Results for 0.35um CMOS
- Results for 90nm CMOS
- Simulating in Cadence-Spectre
- Modelling Pelgrom's Distance Term Efficiently
- Extension of continuous CMOS models to new coming nano-FETs

The Mismatch Behavior



$$\sigma^2(\Delta P) = f_A(W, L) + f_D(D)$$

- $f_A(W, L)$ Small random, transistor size dependent component, 'true' mismatch component
- $f_D(D)$ Gradient surface, transistor distance dependent component, can be eliminated with layout techniques

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Historical Perspective. Mismatch Models in Strong Inversion

$$\sigma^2(\Delta P) = f(W, L) + S_P^2 D^2$$

	$\sigma^2_{(\Delta\beta/\beta)}$	$\sigma^2_{(\Delta V_{T0})}$	$\sigma^2_{(\Delta\theta)}$		$\sigma^2_{(\Delta\gamma)}$
			$\sigma^2_{(\Delta\theta_o)}$	$\sigma^2_{(\Delta\theta_e)}$	
Pelgrom89	✓	✓	–		✓
Bastos98	✓	✓	✓		✓
Serrano99	✓	✓	✓	✓	✓

$$\Delta\theta = \Delta\theta_o + \frac{V_{DS}\big|_{sat}}{V_{GS} - V_T}\Delta\theta_e$$

$$\theta_o = \theta + 2\frac{\mu C_{ox} l_d R_{\square}}{L} \qquad \theta_e = \frac{\mu}{L}\left(\frac{1}{2v_s} - C_{ox} l_d R_{\square}\right)$$

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A Continuous Transistor Model from Weak to Strong Inversion. The ACM Model

$$I_{DS} = I_s(i_f(V_P - V_S) - i_r(V_P - V_D))$$

$$V_P - V_{S(D)} = \phi_t(\sqrt{1 + i_{f(r)}} - 2 + \ln(\sqrt{1 + i_{f(r)}} - 1))$$

$$V_P = \frac{V_G - V_{TO}}{n}$$

$$n = 1 + \frac{\gamma}{2\left(\sqrt{V_G - V_{TO} + 2\phi_F + \gamma\sqrt{2\phi_F} + 1/4\gamma^2} - 1/2\gamma\right)}$$

$$I_S = I_S' n = \mu n C'_{ox}(W/L)\left(\phi_t^2/2\right)$$

- Continuous for all transistor operation regions
- Based on a reduced set of physically meaningful parameters $\{I_S, V_{TO}, \gamma, \phi_F\}$
- Drain/Source symmetric

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Introducing Continuosly Second Order Effects

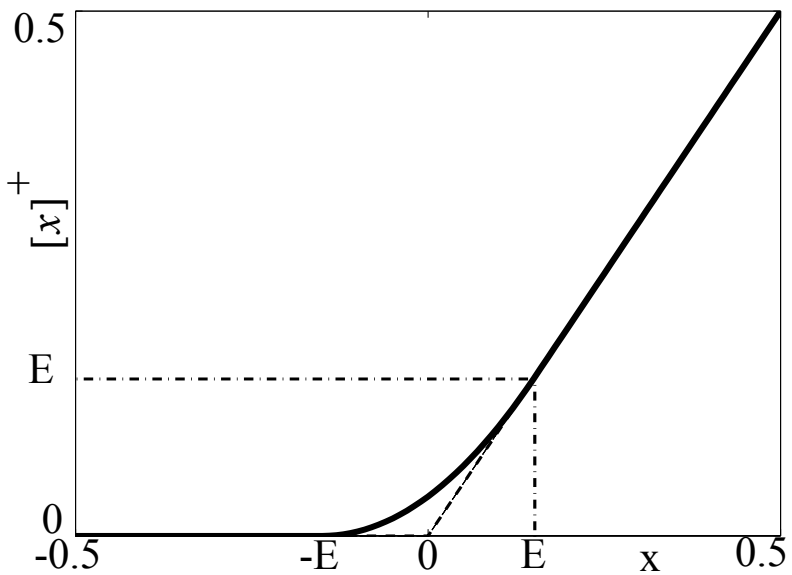
$$I_{DS} = \frac{I_S(i_f - i_r)(1+\lambda(V_D - V_S))}{\left(1+\theta_o[V_P - V_S]^+\right)\left(1+\theta_e V_{DS_{eff}}\right)} \quad ,$$

traditionally,

$V_{DS_{eff}} = V_{DS}$ in ohmic region;

$V_{DS_{eff}} = V_P - V_S$ in saturation.

define smoothed rectification $[\ ]^+$



$$[x]^+ = \begin{cases} 0 \text{ if } x < -E \\ \dfrac{(x+E)^2}{4E} \text{ if } -E < x < E \\ x \text{ if } x > E \end{cases}$$

redefine

$$V_{DS_{eff}} = \left|[V_P - V_S]^+ - [V_P - V_D]^+\right|$$

with $E = 0{,}3\,V_{DS}$

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A Continuous Mismatch Model Valid from Weak to Strong Inversion

$$I_{DS} = \frac{I_S(i_f - i_r)(1+\lambda(V_D - V_S))}{\left(1+\theta_o[V_P - V_S]^+\right)\left(1+\theta_e V_{DS_{eff}}\right)}$$

$$\Downarrow$$

$$\frac{\Delta I_{DS}}{I_{DS}} = \frac{\Delta I_S}{I_S} + \frac{1}{I_{DS}}\frac{\partial I_{DS}}{\partial V_P}\frac{\partial V_P}{\partial V_{T0}}\Delta V_{T0} + \left(\frac{1}{I_{DS}}\frac{\partial I_{DS}}{\partial V_P}\frac{\partial V_P}{\partial n} + \frac{1}{n}\right)\frac{\partial n}{\partial \gamma}\Delta\gamma + \frac{1}{I_{DS}}\frac{\partial I_{DS}}{\partial \theta_o}\Delta\theta_o + \frac{1}{I_{DS}}\frac{\partial I_{DS}}{\partial \theta_e}\Delta\theta_e$$

$$\Downarrow$$

$$\left\{\frac{\Delta I_S}{I_S}, \Delta V_{T0}, \Delta\gamma, \Delta\theta_o, \Delta\theta_e\right\}$$

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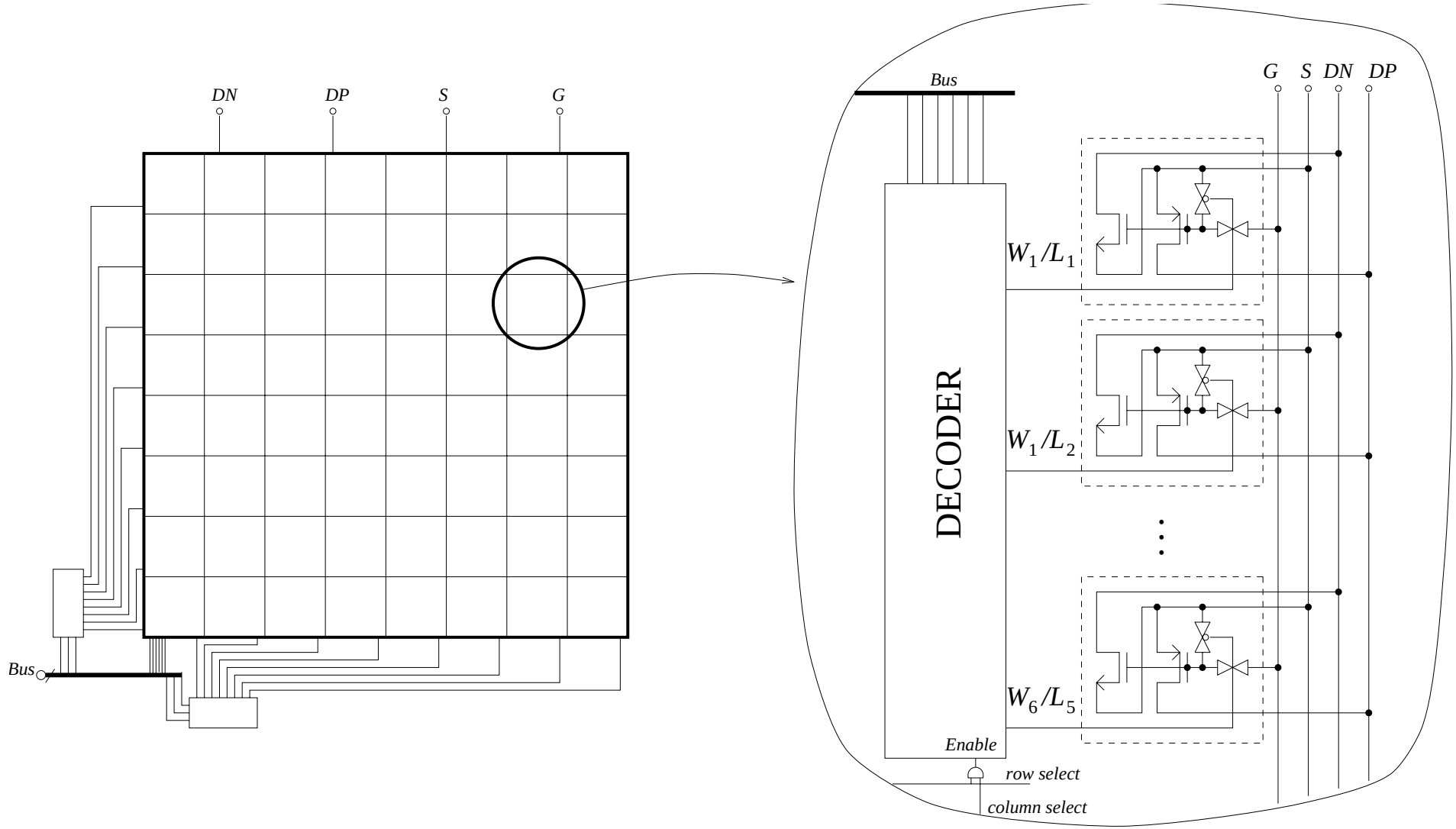
Mismatch Characterization Chip



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Measuring Curves: 7 Measured Curves

- $V_{DS} = 1{,}65\,V$

  Curve 1: $I_{DS}(V_{GS})$, $V_{SB} = 0\,V$, $V_{GS} \in [0, 3{,}3]$

  Curve 2: $I_{DS}(V_{GS})$, $V_{SB} = 1\,V$, $V_{GS} \in [0, 3{,}3]$

- $V_{DS} = 0{,}1\,V$

  Curve 3: $I_{DS}(V_{GS})$, $V_{SB} = 0\,V$, $V_{GS} \in [0, 3{,}3]$

  Curve 4: $I_{DS}(V_{GS})$, $V_{SB} = 1\,V$, $V_{GS} \in [0, 3{,}3]$

- $V_G = 1{,}25\,V_S + \alpha$

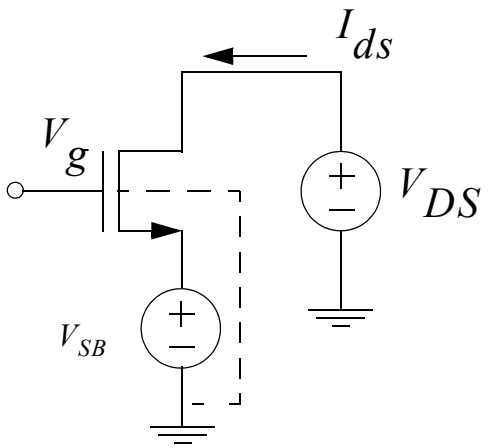
  Curve 5: $I_{DS}(V_S), \alpha = \alpha_1, V_S \in [0, 3{,}3]$

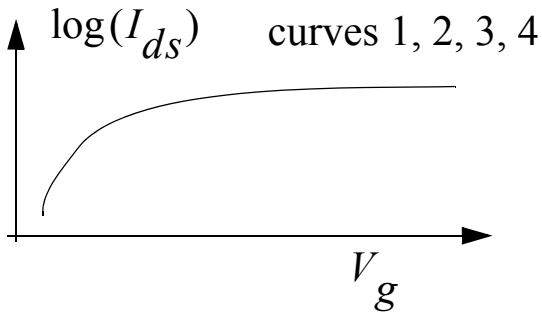
  Curve 6: $I_{DS}(V_S), \alpha = \alpha_2, V_S \in [0, 3{,}3]$

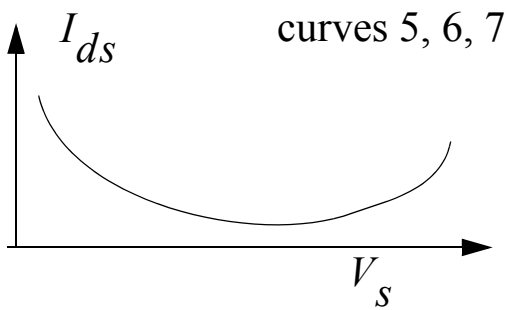
  Curve 7: $I_{DS}(V_S), \alpha = \alpha_3, V_S \in [0, 3{,}3]$

where:

α_1, α_2 and α_3 are values of V_G from curve 1 so that we are in weak, moderate and strong inversion respectively.







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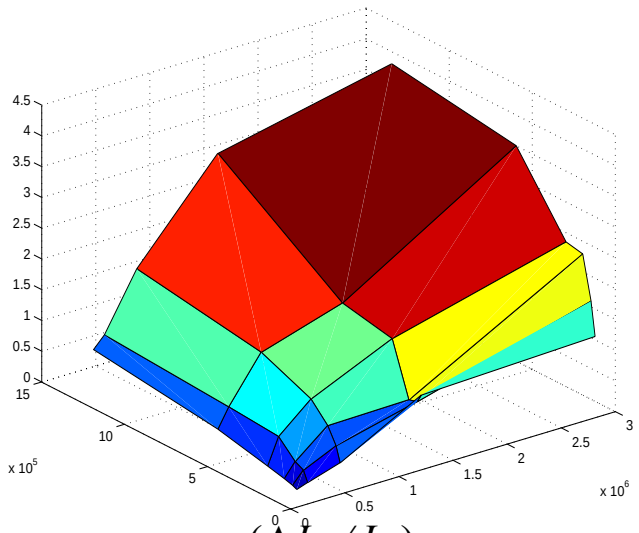
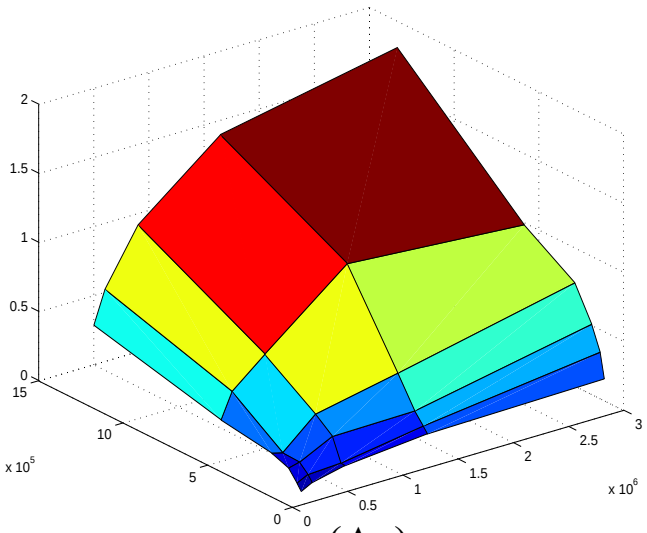
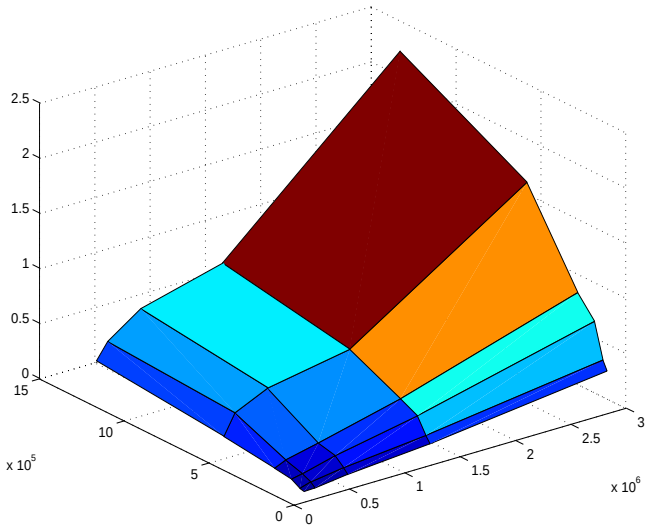
Computing Statistics



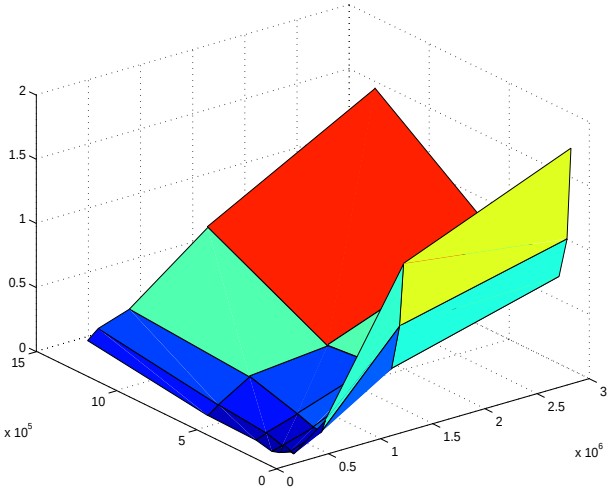
$\sigma(\Delta I_S/I_S)$



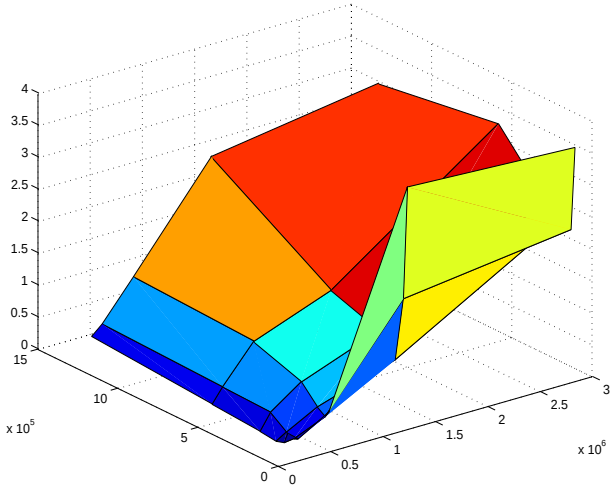
$\sigma(\Delta\gamma)$



$\sigma(\Delta V_{T0})$



$\sigma(\Delta\theta_e)$



$\sigma(\Delta\theta_o)$

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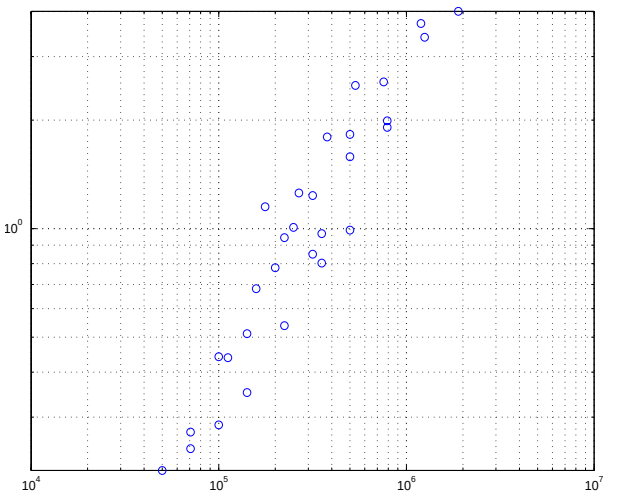
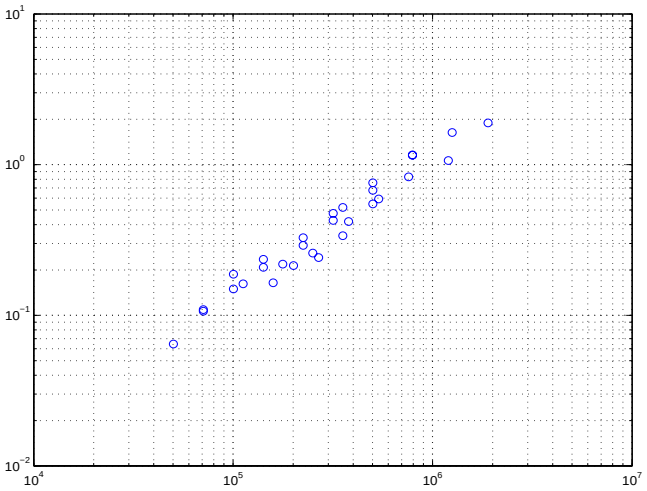
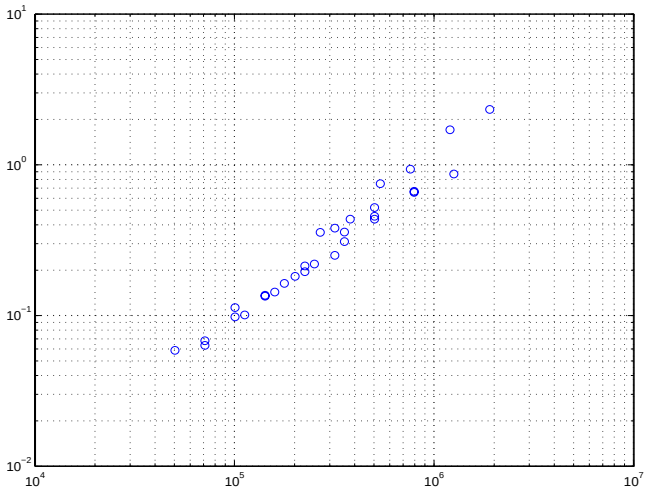
Computing Statistics



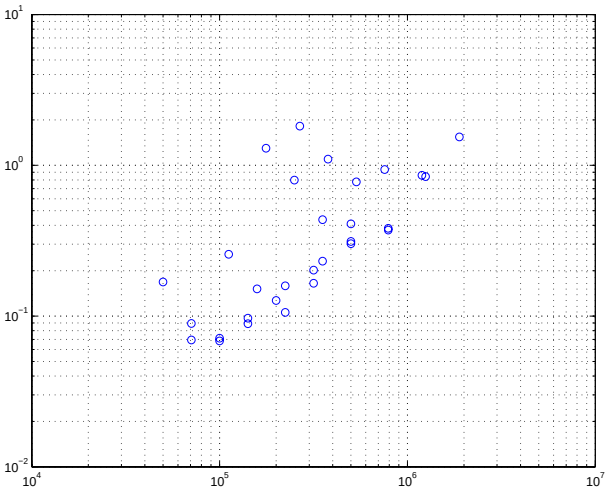
$\sigma(\Delta I_S/I_S)$ $1/(\sqrt{WL})$



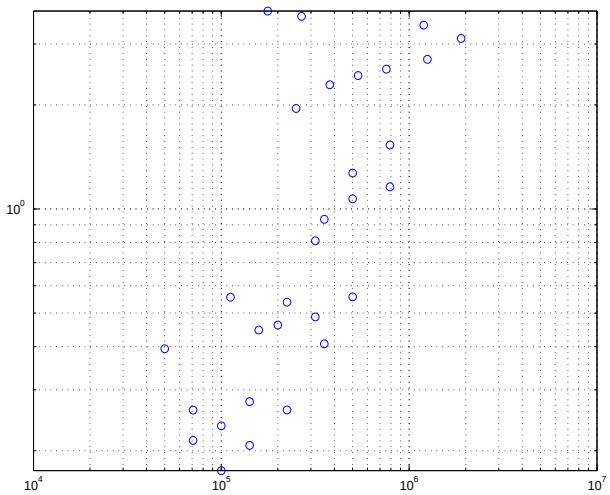
$\sigma(\Delta\gamma)$ $1/(\sqrt{WL})$



$\sigma(\Delta V_{T0})$ $1/(\sqrt{WL})$



$\sigma(\Delta\theta_e)$ $1/(\sqrt{WL})$



$\sigma(\Delta\theta_o)$ $1/(\sqrt{WL})$

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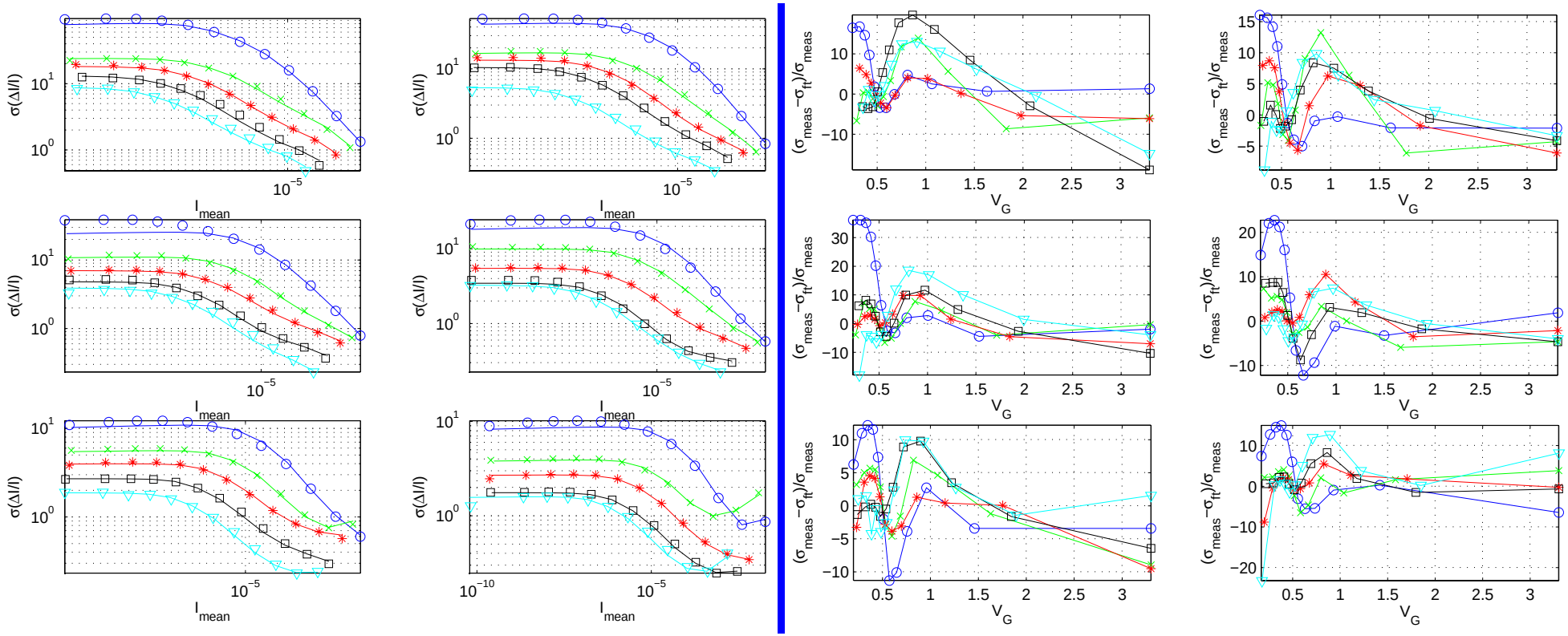
Predicting $\sigma(\Delta I/I)$ of measured curves and errors $(\sigma(\Delta I/I)_{meas} - \sigma(\Delta I/I)_{pred})/\sigma(\Delta I/I)_{meas}$

$$\sigma^2\left(\frac{\Delta I_{DS}}{I_{DS}}\right) = \sigma^2_{I_S} + \left(\frac{1}{I_{DS}}\frac{\partial I_{DS}}{\partial V_{TO}}\right)^2 \sigma^2_{V_{T0}} + \left(\frac{1}{I_{DS}}\frac{\partial I_{DS}}{\partial \gamma}\right)^2 \sigma^2_{\gamma} + \left(\frac{1}{I_{DS}}\frac{\partial I_{DS}}{\partial \theta_o}\right)^2 \sigma^2_{\theta_o} + \left(\frac{1}{I_{DS}}\frac{\partial I_{DS}}{\partial \theta_e}\right)^2 \sigma^2_{\theta_e} + \text{correlation}$$



Curve 1. $V_{DS} = 1{,}65V \quad V_S = 0V$

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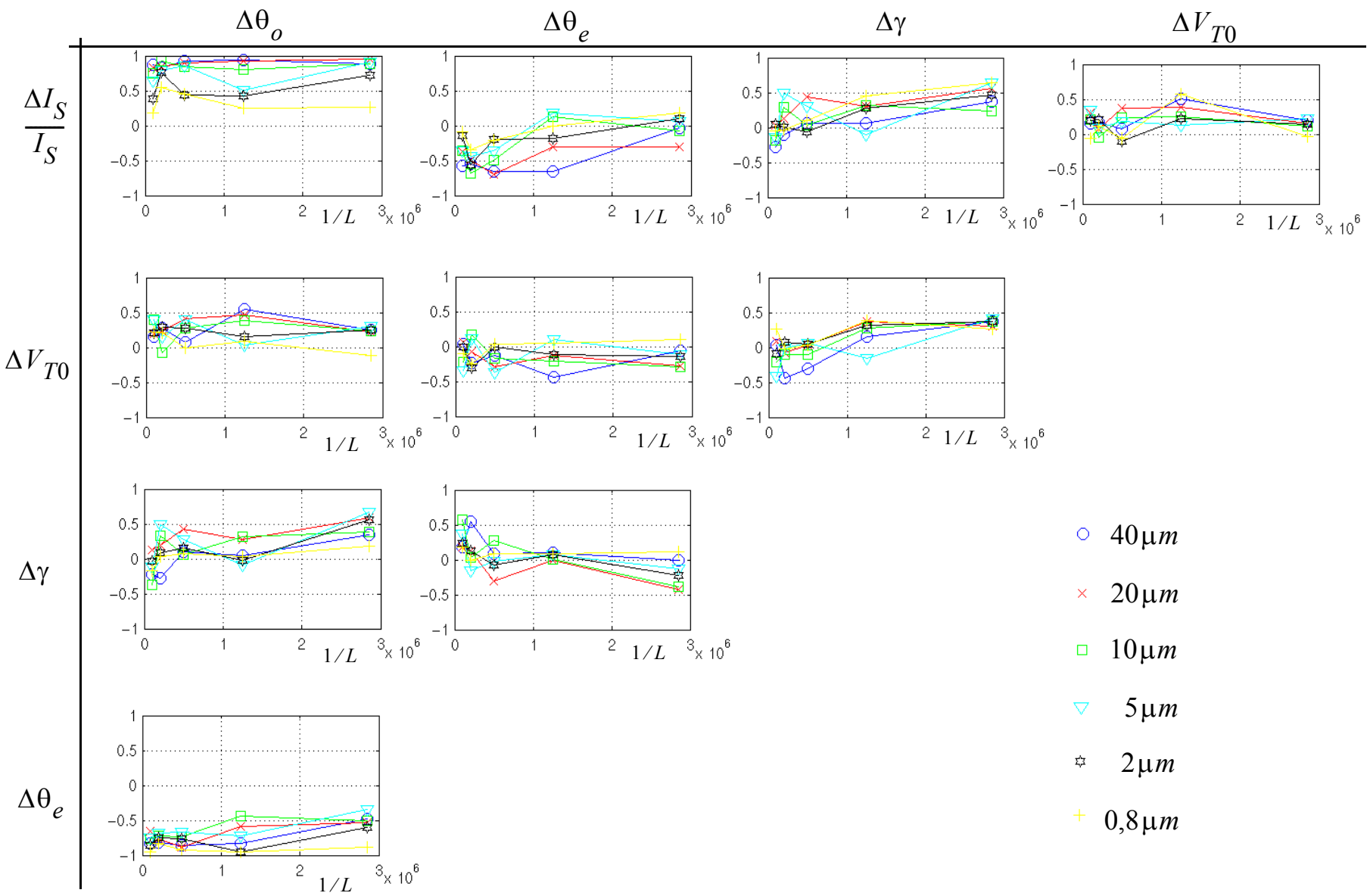
Correlations



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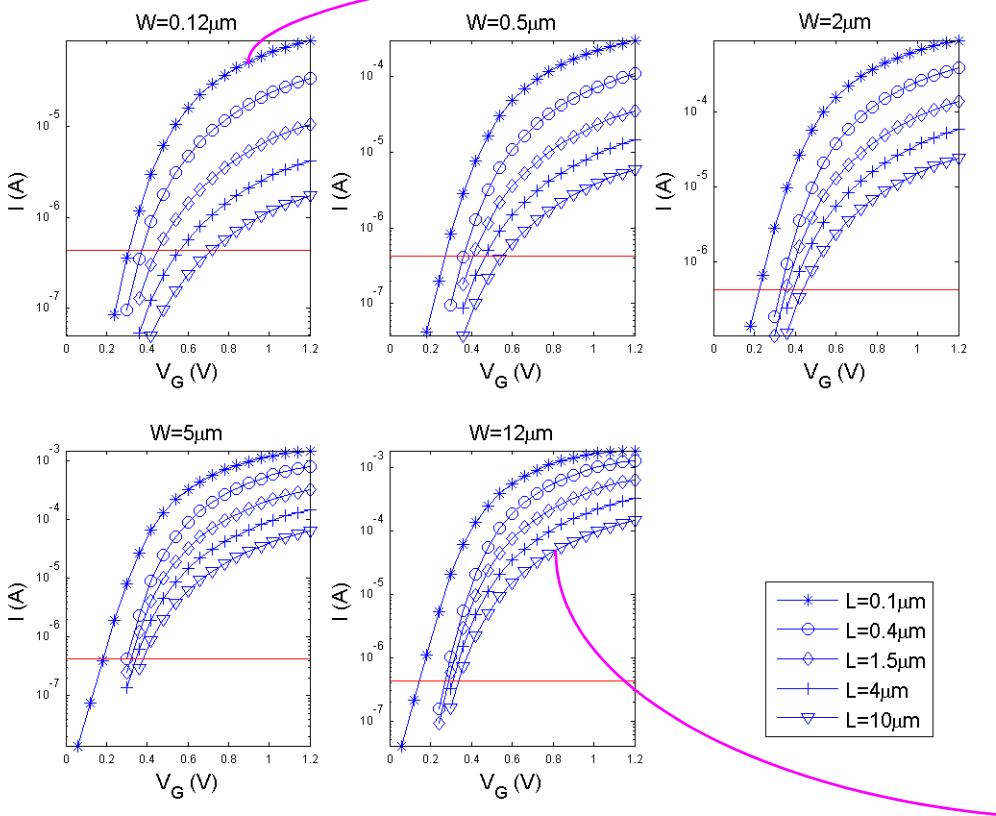
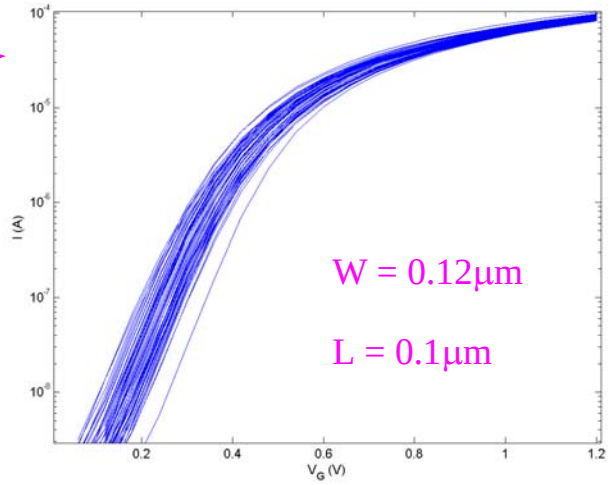
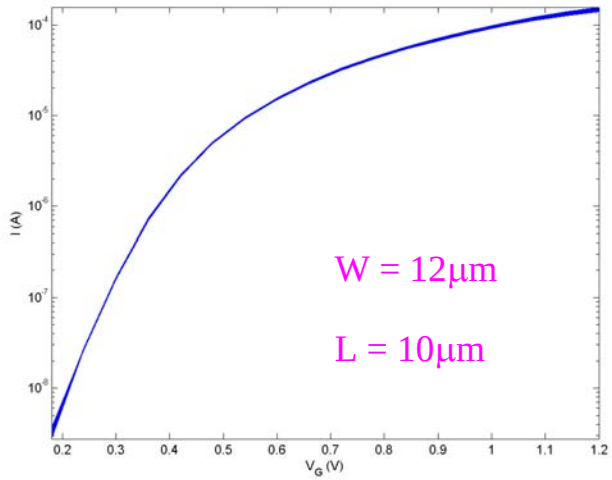
Mismatch Measurements

Nominal Measured Curves







CMOS Transistors

90nm process

25 different sizes

64 devices each size

Measured Curves with Mismatch

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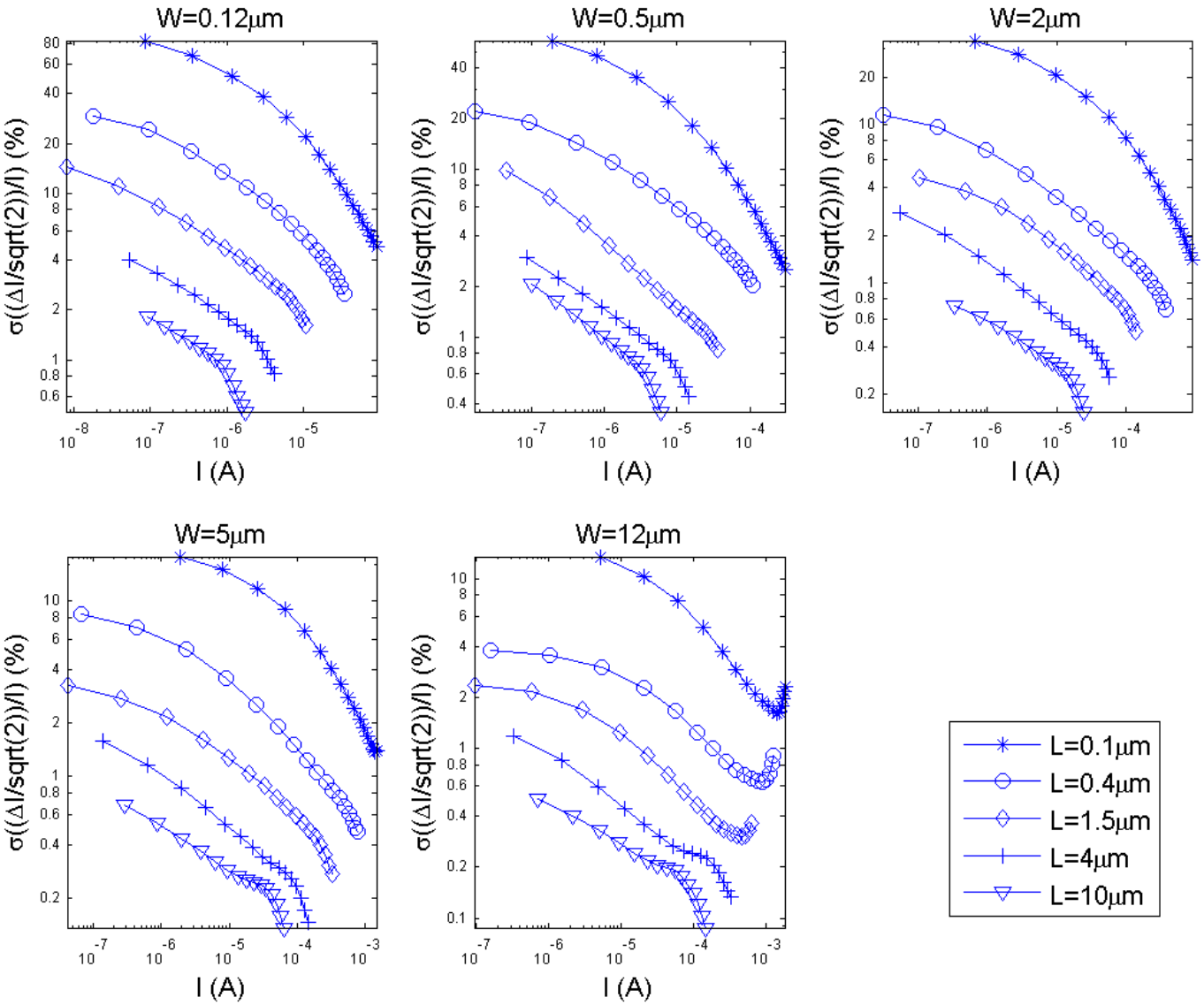
Mismatch Measurements



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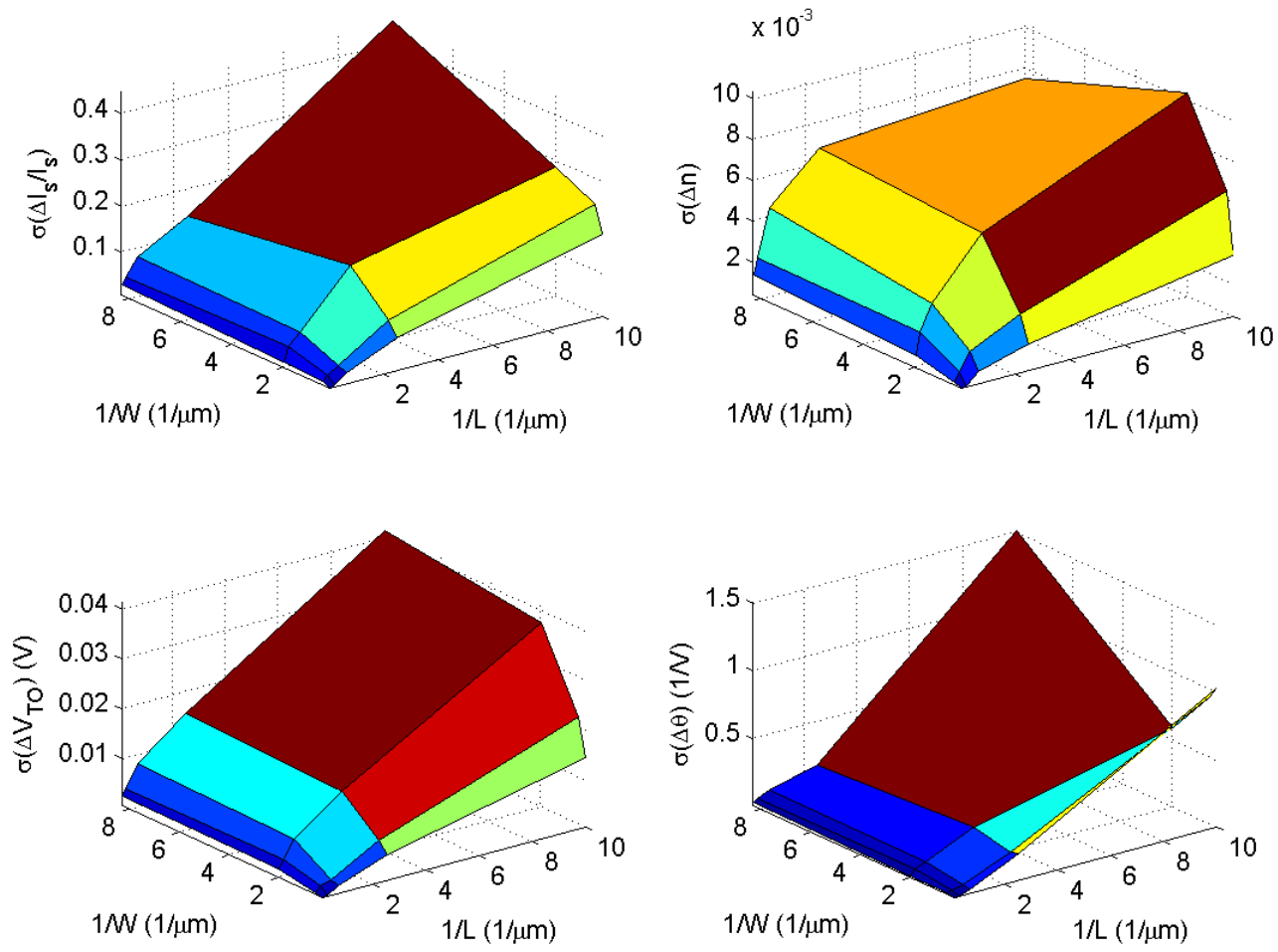
Extracted Mismatch Parameters

Standard NMOS transistors 90nm process



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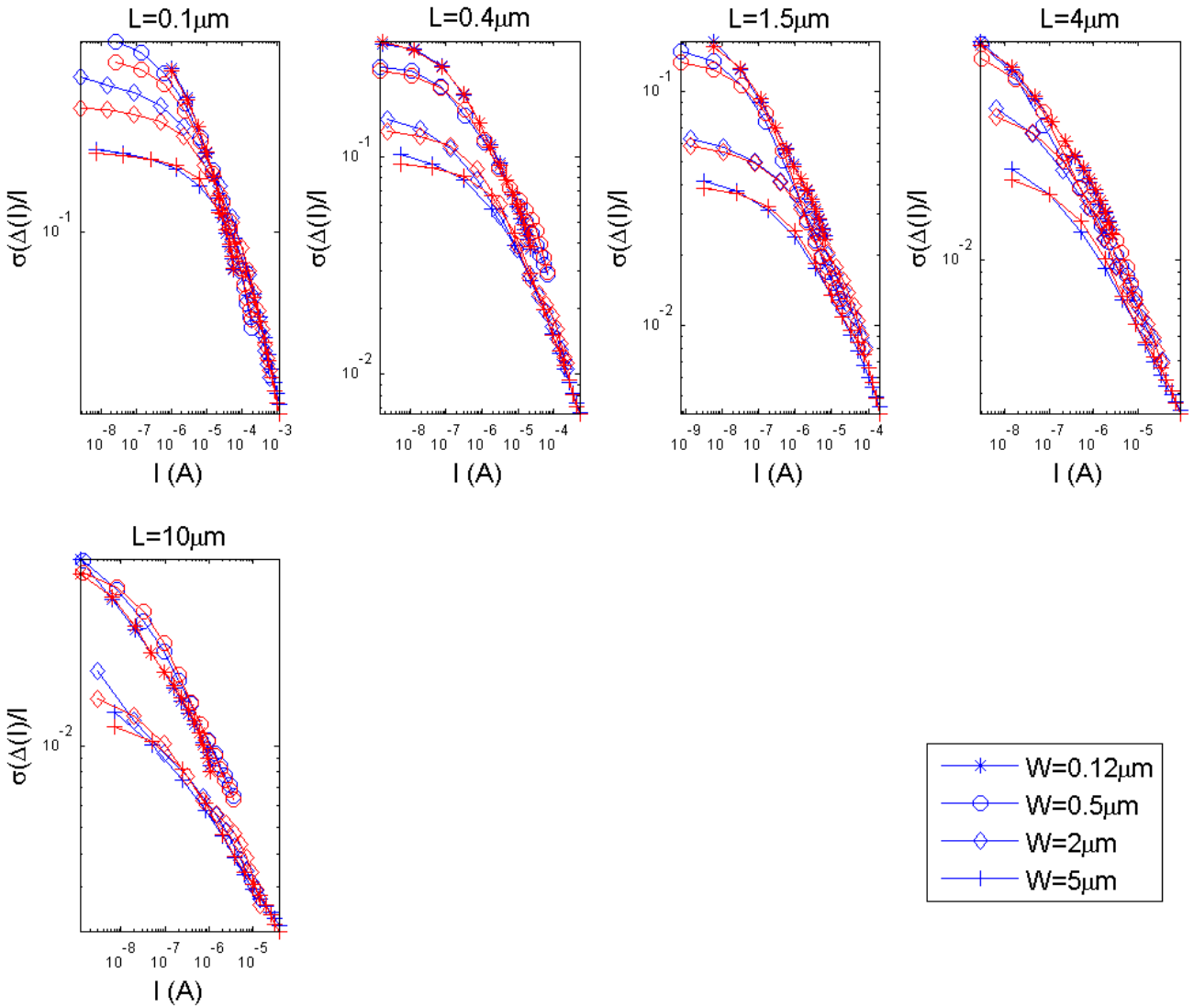
Measured vs. Predicted Current Mismatch

Standard NMOS transistors 90nm process



measured

predicted

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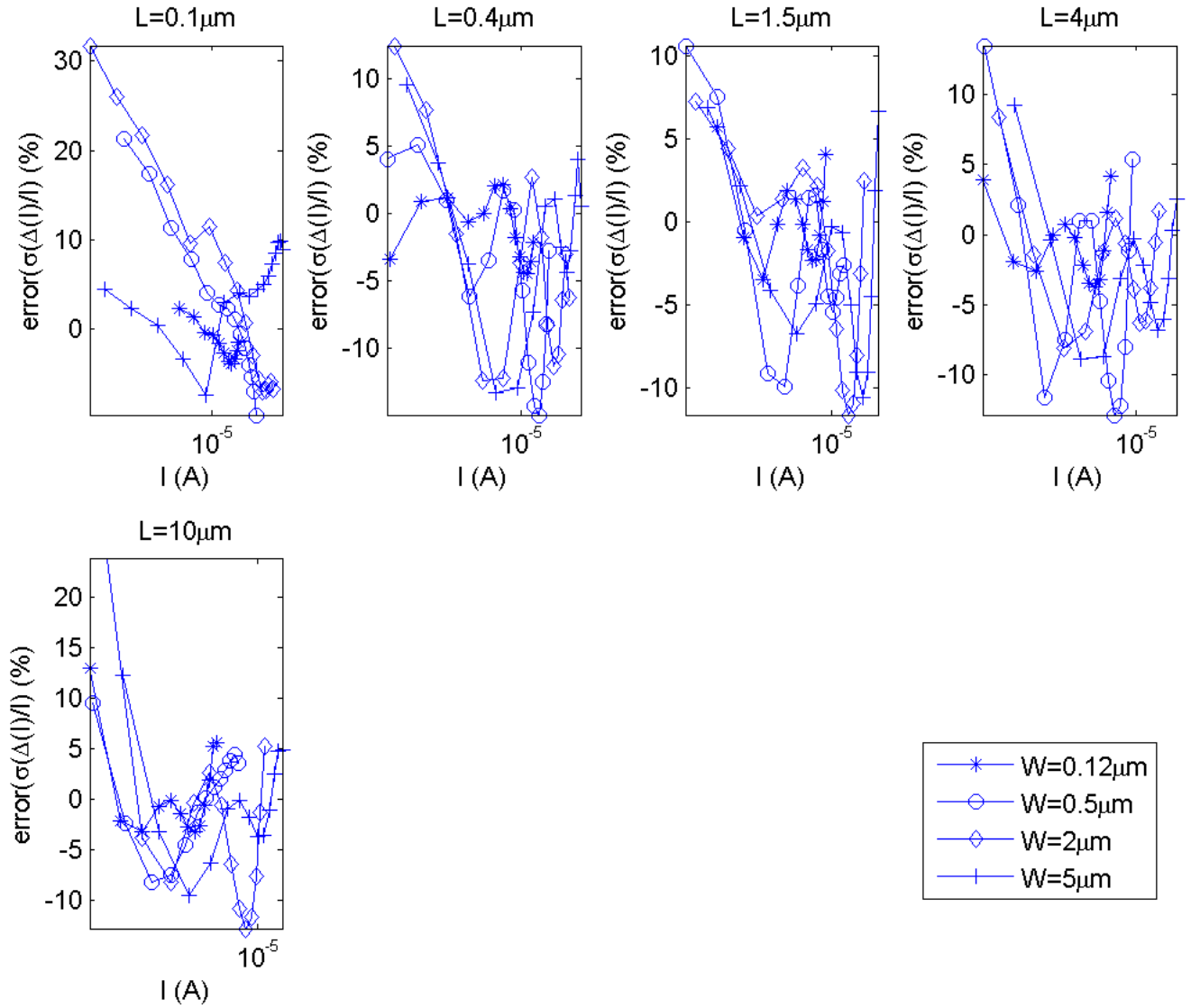
Error in Current Mismatch Prediction

Standard NMOS transistors 90nm process



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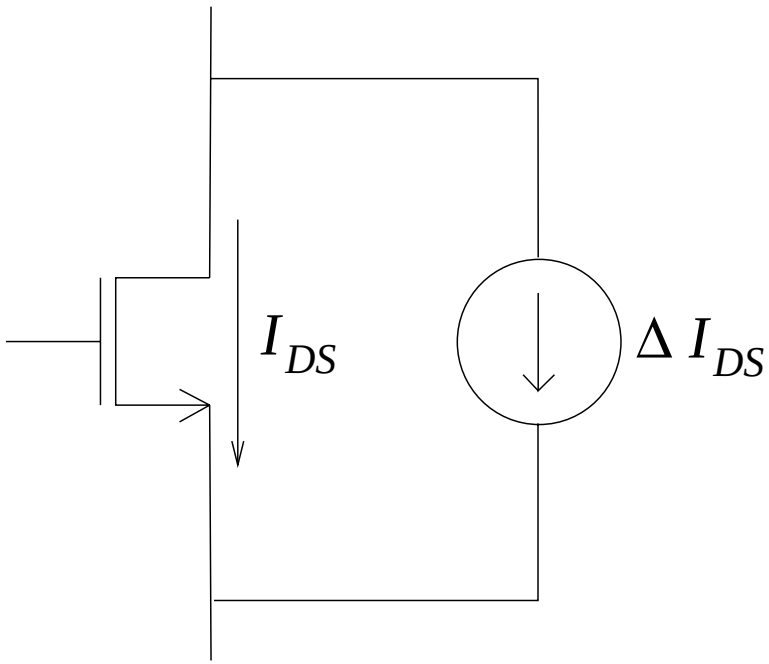
Spectre Mismatch Model Implementation

- Our intention is to create a model of a MOS transistor that fits with the results of the model.
- This model has been implemented in AHDL (Analog Hardware Description Language) and can be used in Simulator Spectre
- The model implementation is based on a current in parallel with a spectre library transistor that emulates the mismatch behavour.



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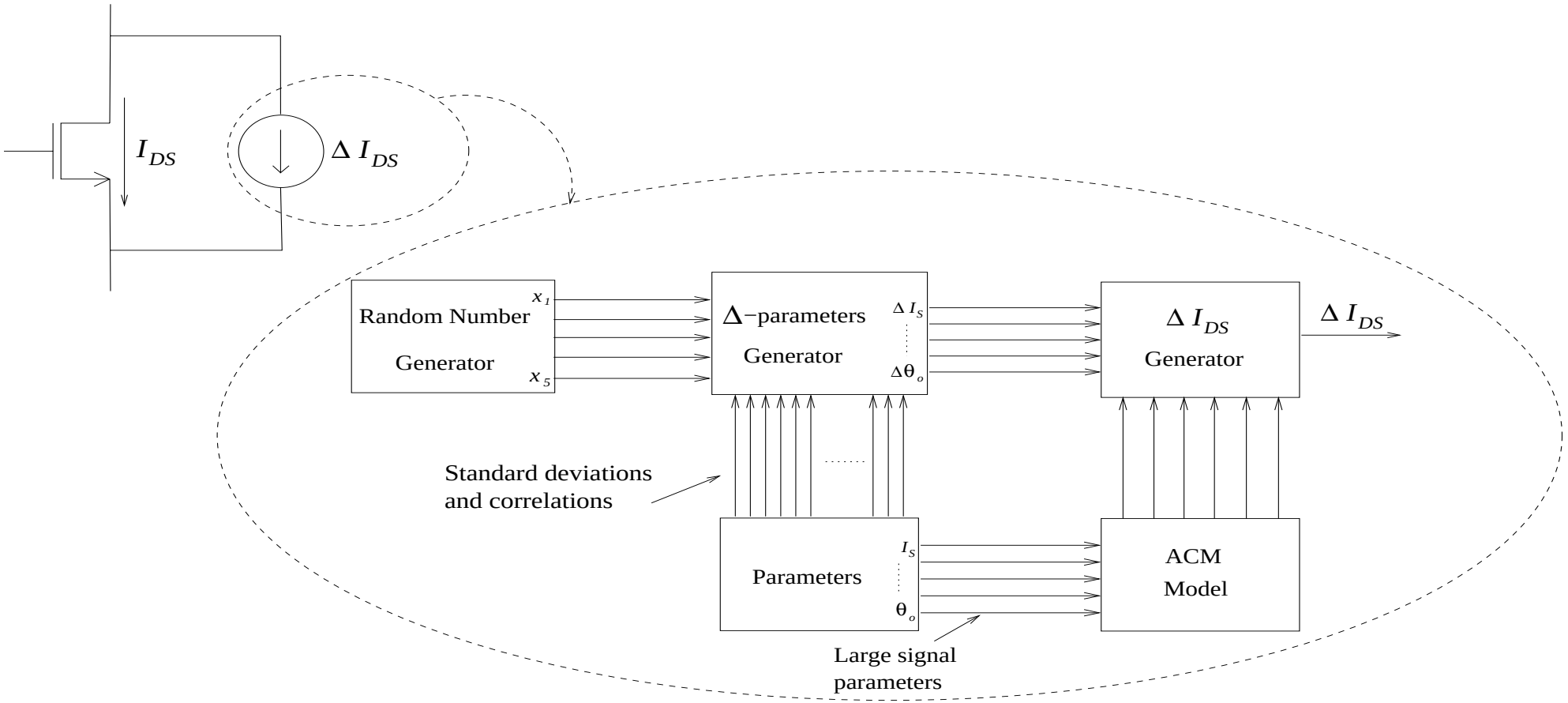

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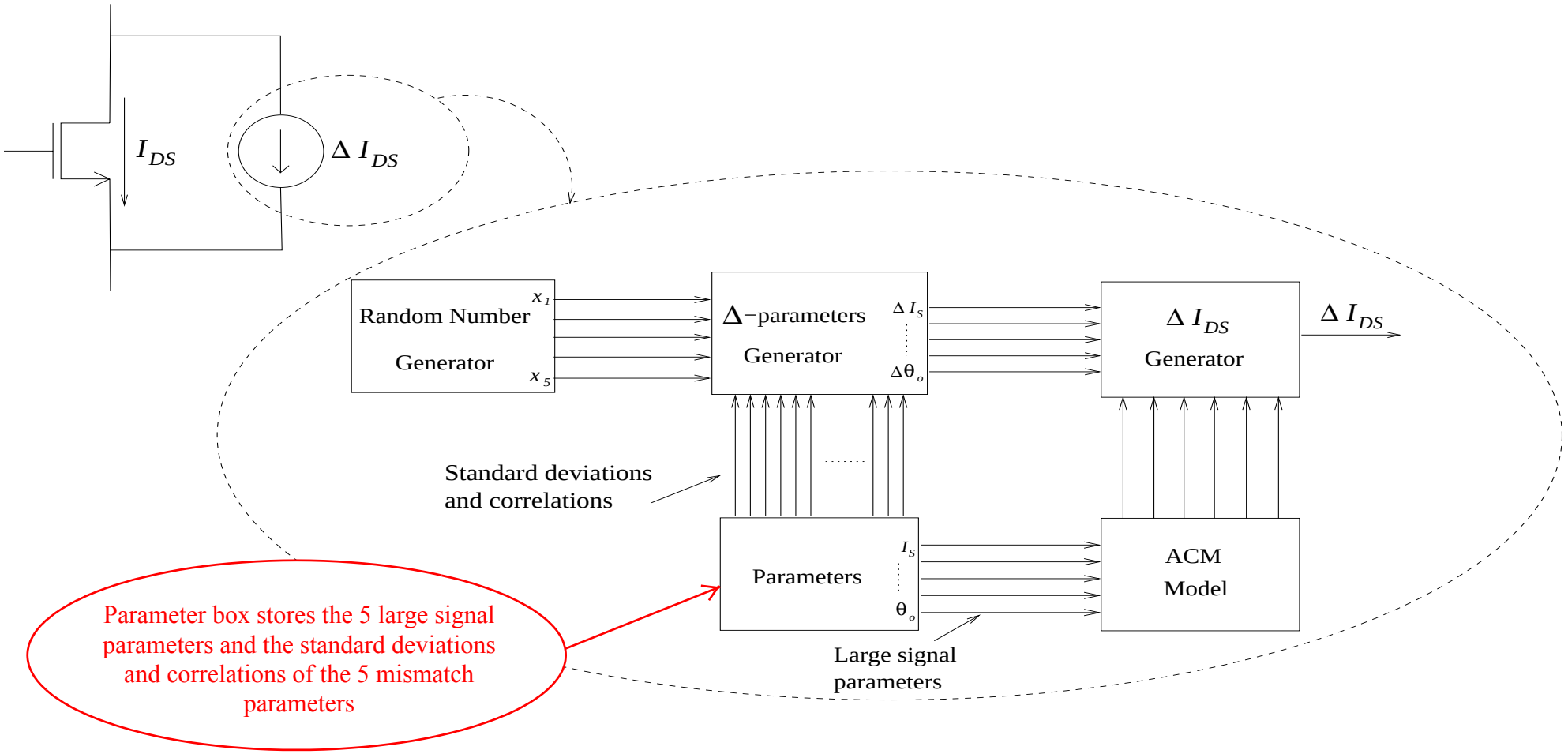
Spectre Mismatch Model Implementation



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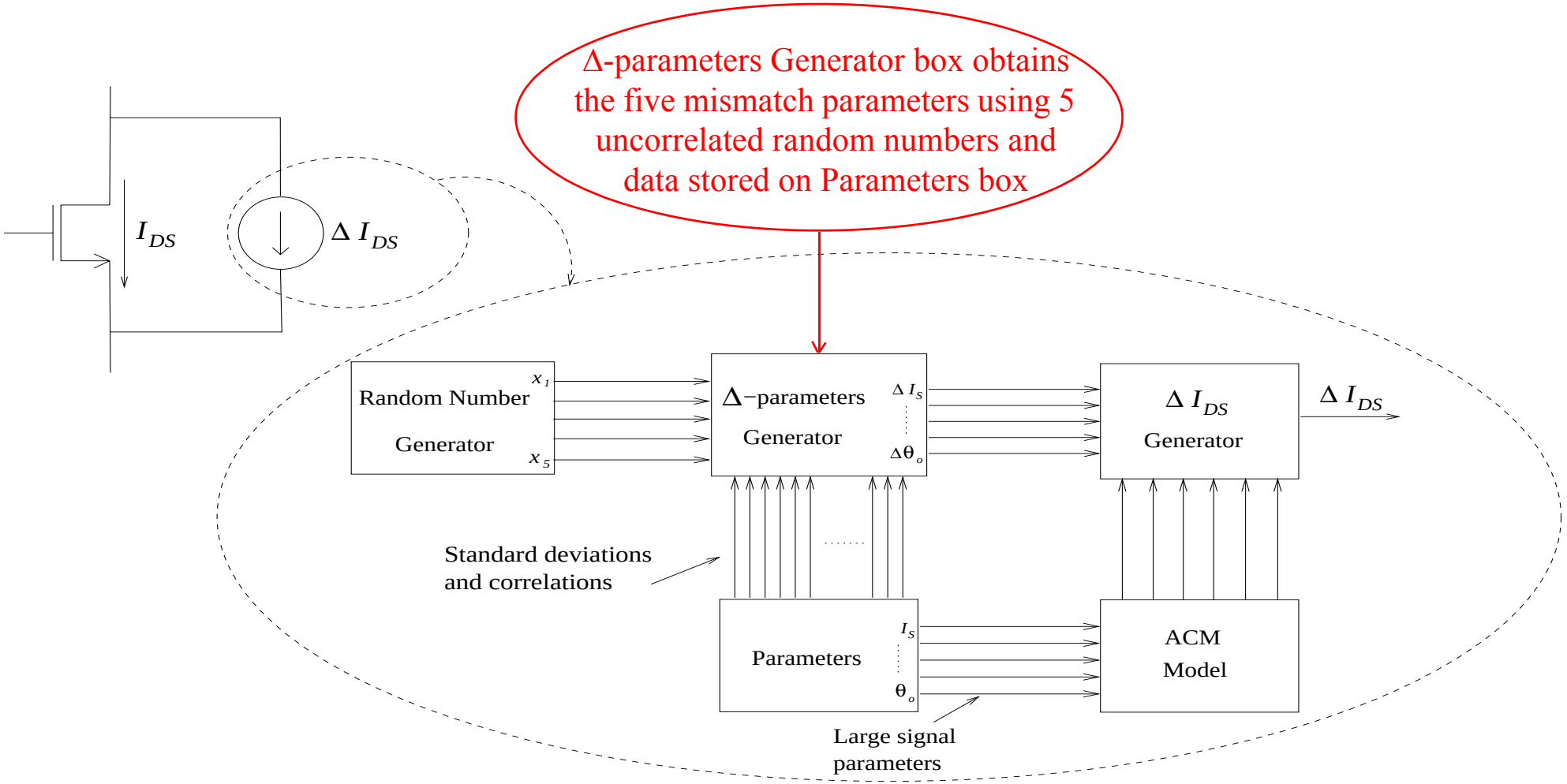

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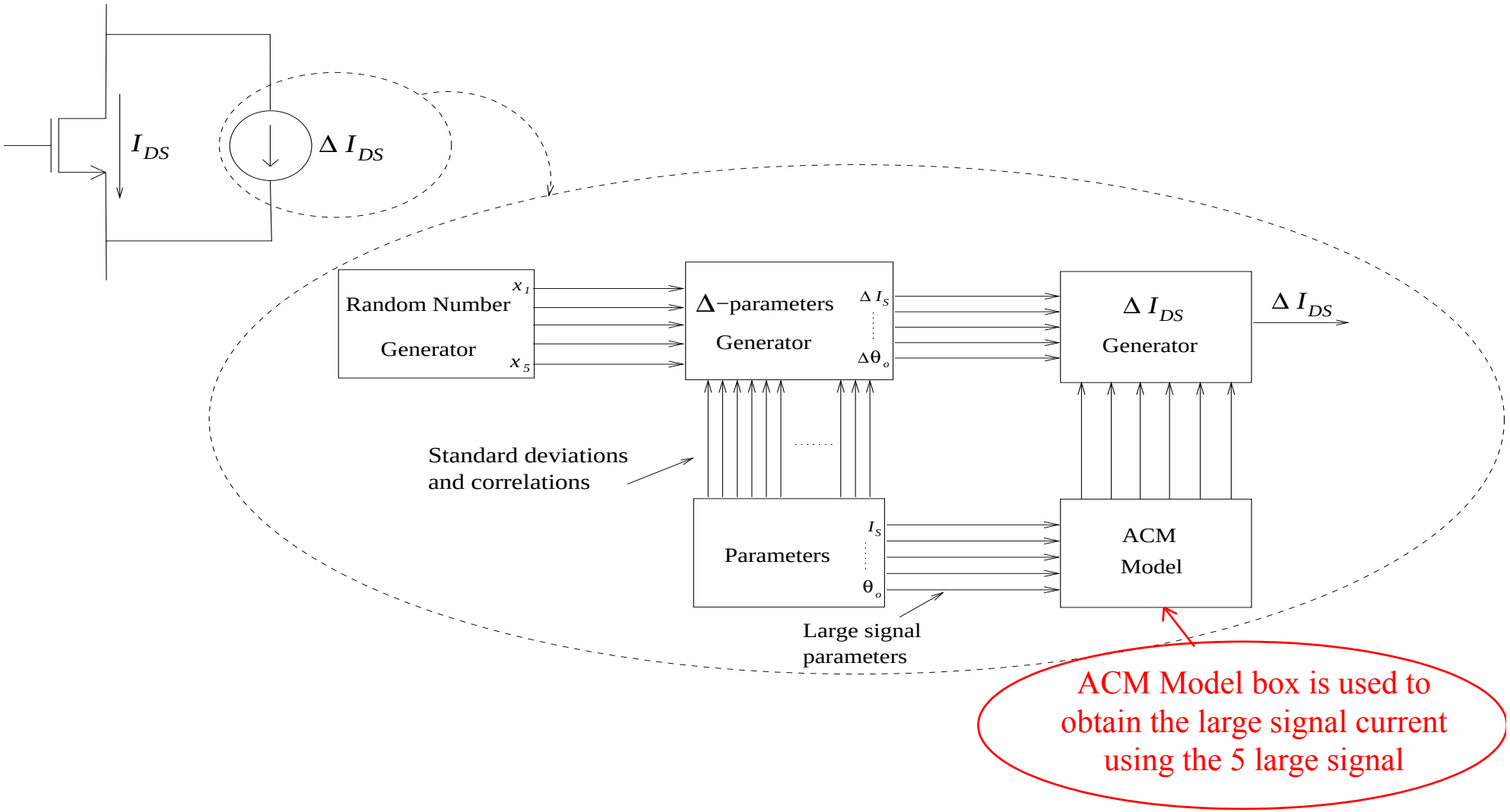

ACM Model box is used to obtain the large signal current using the 5 large signal

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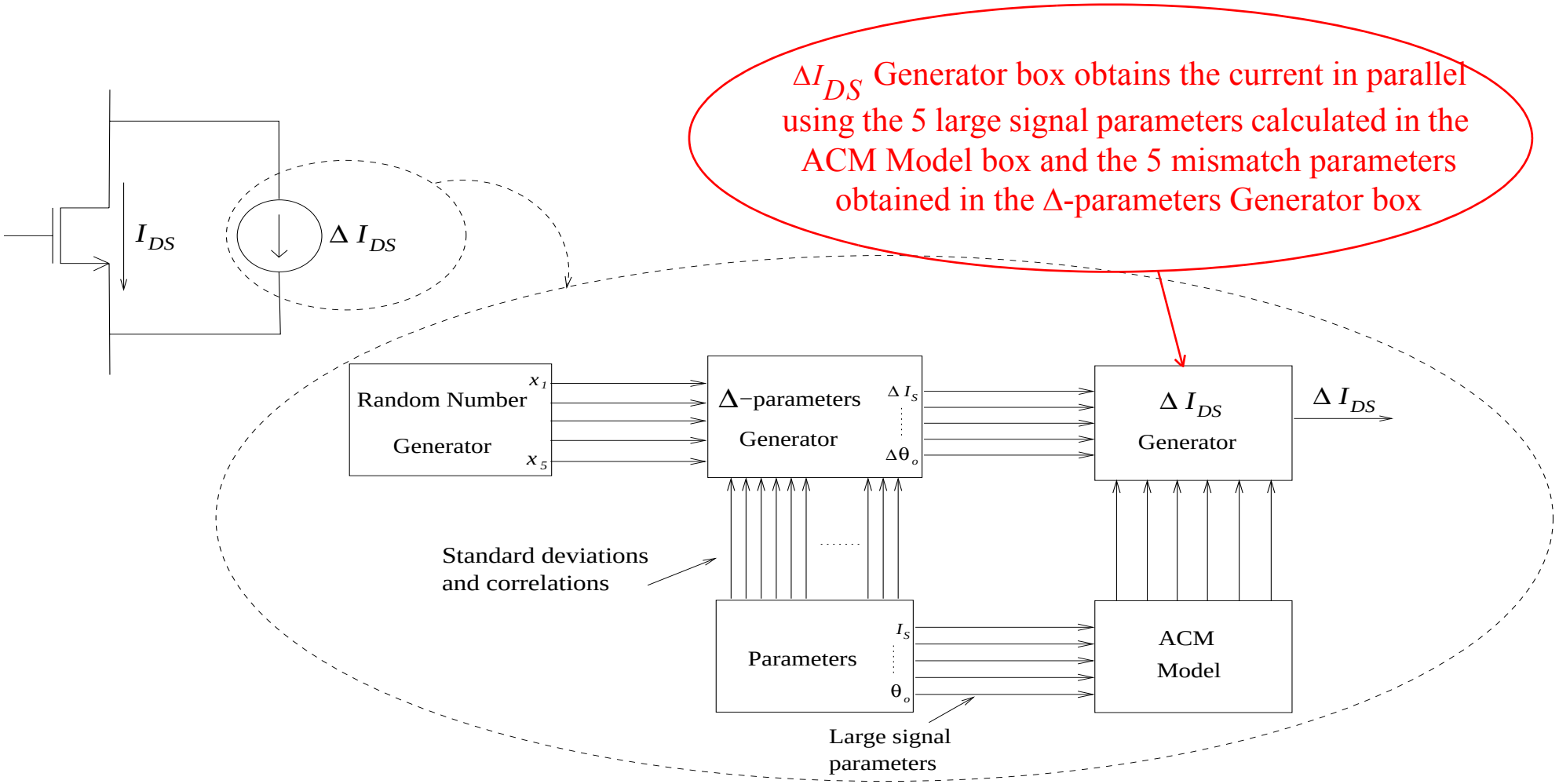

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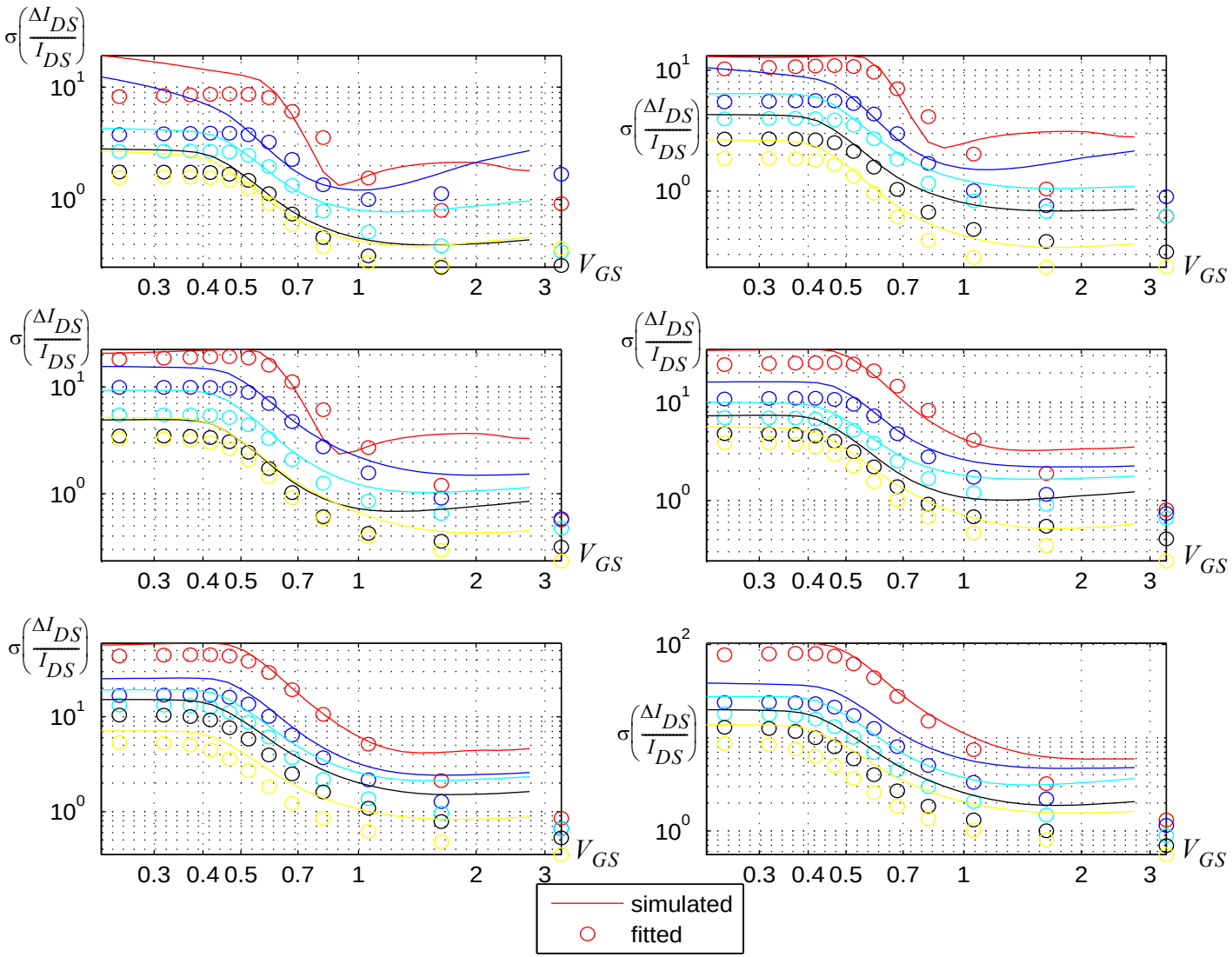
Spectre Mismatch Model Implementation



Comparisson between simulated and fitted data for curve 1 and all transistor sizes

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Outline

- Continuous Weak-to-Strong inversion models for mismatch
- Mismatch characterization chip
- Results for 0.35um CMOS
- Results for 90nm CMOS
- Simulating in Cadence-Spectre
- Modelling Pelgrom's Distance Term Efficiently
- Extension of continuous CMOS models to new coming nano-FETs

Pelgrom JSSC-89

$$\sigma^2(\Delta P) = \frac{A_P^2}{WL} + S_P^2 D^2$$

size dependent term
distance independent

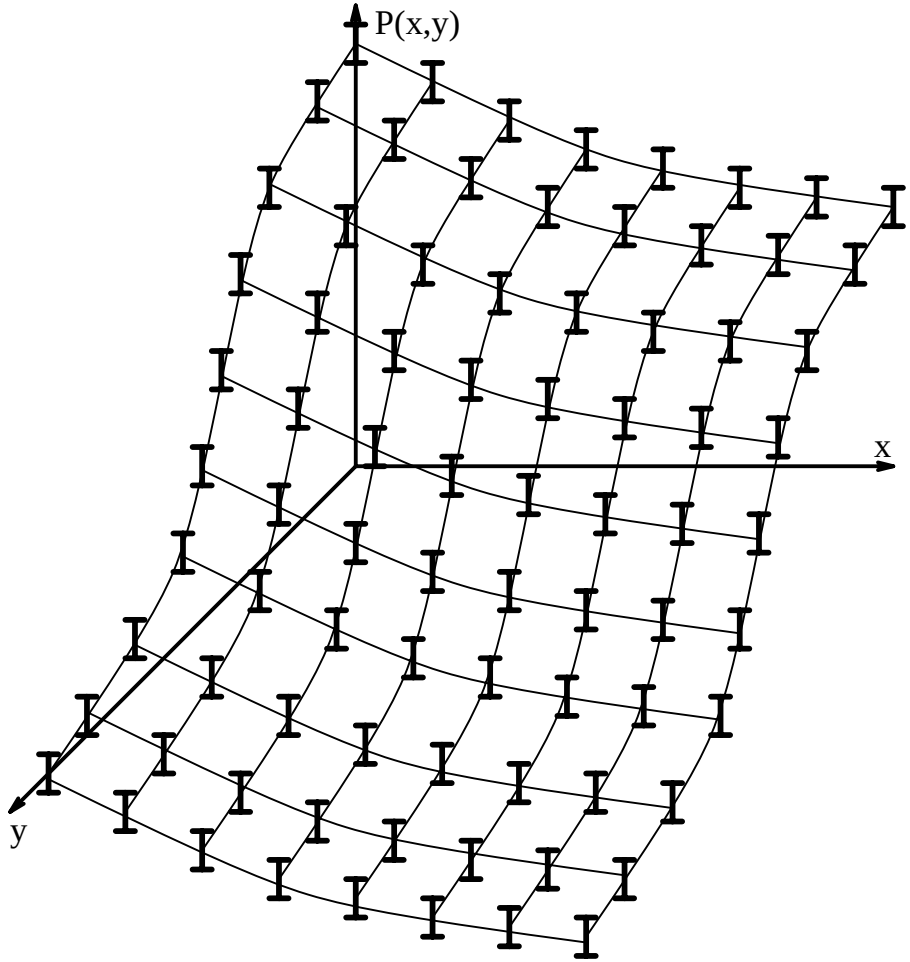
(lot of literature)

distance dependent term
size independent

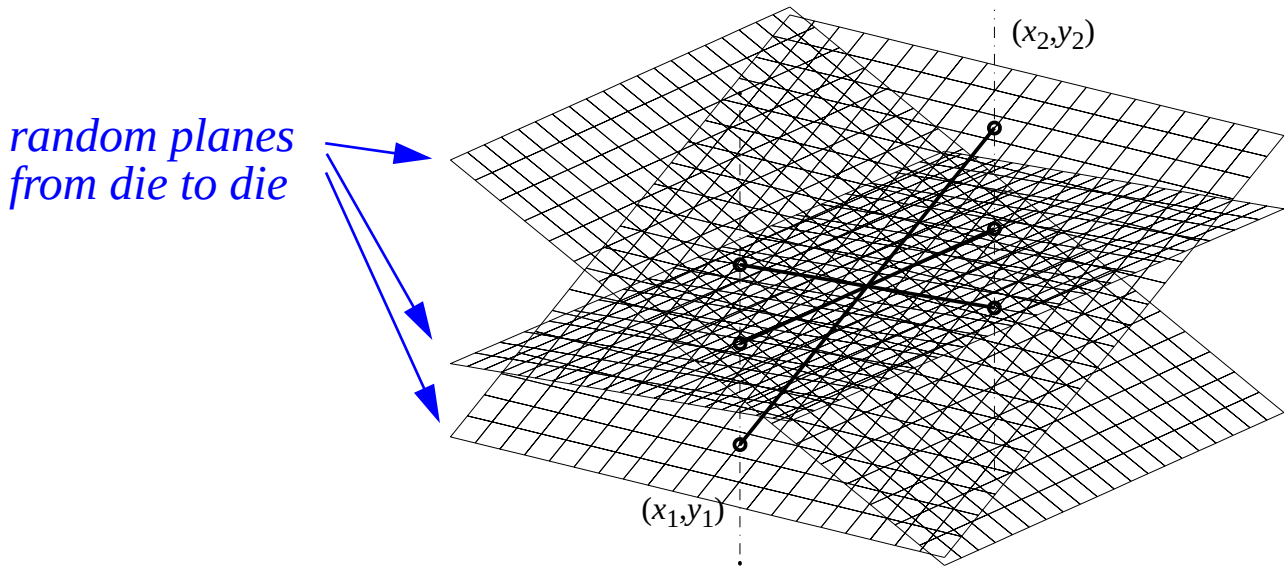
(little literature)

$$\sigma^2(\Delta P) = \frac{A_P^2}{WL} + S_P^2 D^2$$

By analyzing the mathematical derivation



Gradient Component



$$P(x, y) = Ax + By + C$$

random numbers *die average*

Generate random numbers A and B

$$P(x, y) = Ax + By + C$$

Generate random numbers A and B

$$P(x, y) = Ax + By + C$$

$$\downarrow$$

Gradient-induced mismatch

$$\Delta P_{grad_ij} = A(x_i - x_j) + B(y_i - y_j)$$

Generate random numbers A and B

$$P(x, y) = Ax + By + C$$

↓

Gradient-induced mismatch

$$\Delta P_{grad_ij} = A(x_i - x_j) + B(y_i - y_j)$$

↓

Statistics over many planes

$$\sigma^2(\Delta P_{grad_ij}) = \sigma^2(A)(x_i - x_j)^2 + \sigma^2(B)(y_i - y_j)^2$$

Generate random numbers A and B

$$P(x, y) = Ax + By + C$$

Gradient-induced mismatch

$$\Delta P_{grad_ij} = A(x_i - x_j) + B(y_i - y_j)$$

Statistics over many planes

$$\sigma^2(\Delta P_{grad_ij}) = \sigma^2(A)(x_i - x_j)^2 + \sigma^2(B)(y_i - y_j)^2$$

no preferred directions: $\sigma(A) = \sigma(B)$

$$\sigma^2(\Delta P_{grad_ij}) = \sigma^2(A)[(x_i - x_j)^2 + (y_i - y_j)^2] = \sigma^2(A)D_{ij}^2$$

Generate random numbers A and B

$$P(x, y) = Ax + By + C$$

Gradient-induced mismatch

$$\Delta P_{grad_ij} = A(x_i - x_j) + B(y_i - y_j)$$

Statistics over many planes

$$\sigma^2(\Delta P_{grad_ij}) = \sigma^2(A)(x_i - x_j)^2 + \sigma^2(B)(y_i - y_j)^2$$

no preferred directions: $\sigma(A) = \sigma(B)$

$$\sigma^2(\Delta P_{grad_ij}) = \sigma^2(A)[(x_i - x_j)^2 + (y_i - y_j)^2] = \sigma^2(A)D_{ij}^2$$

$$\sigma^2(\Delta P_{ij}) = \frac{A_P^2}{WL} + S_P^2 D_{ij}^2$$

$$S_P = \sigma(A) = \sigma(B)$$

Mismatch Modelling in a CAD Tool

$$P_i = P_{mean} + \Delta P_{global} + \Delta P_{rand_i} + \Delta P_{grad_i}$$

Technology Average

Corner (common for whole die)

Size-dependent mismatch (2-10 random numbers per transistor)

Gradient-induced mismatch (2 random numbers per die) need layout coordinates

Outline

- Continuous Weak-to-Strong inversion models for mismatch
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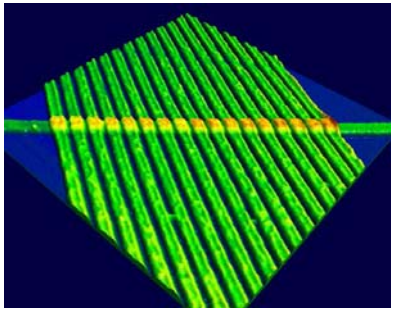
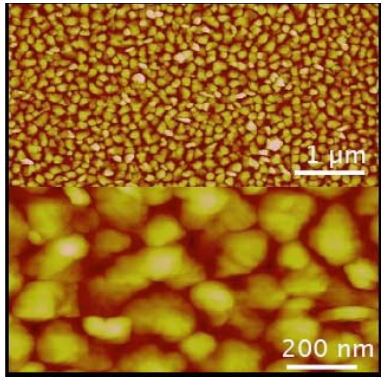
Motivations: Why?

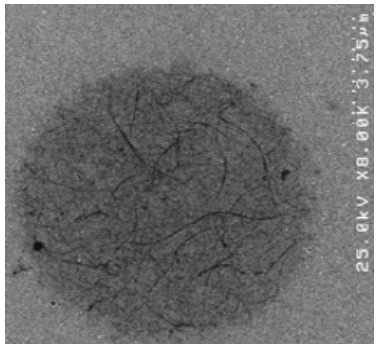
- New nano devices are rapidly appearing offering new functionality and memory capabilities



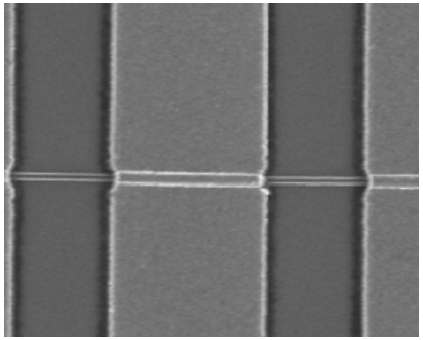
17 memristors in a row. The wires in this image are 50nm about 150 atoms, wide. J. J. Yang, HP Labs



NOMFET



OG-CNFET



ZnO-MemoryFET

- Parallely, new circuits and architectures should be devised exploiting new capabilities
- Models are needed to simulate architectures and circuits
- Physical modelling is a slow, complex and sophisticated process
- Fitting new devices to a compact CMOS model has the advantage that circuit simulators are available allowing quick design and simulation of new architectures
- Hybrid nano-CMOS arquitectures can be easily simulated

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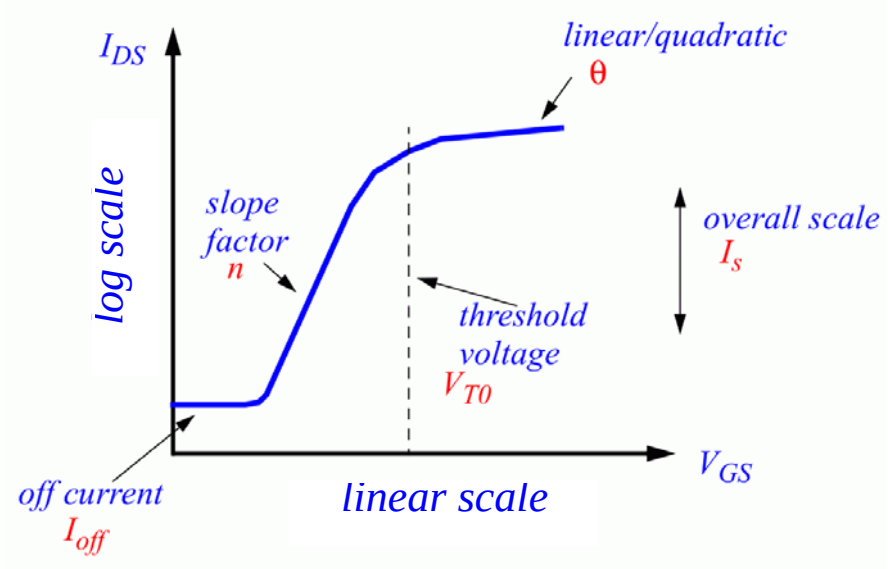
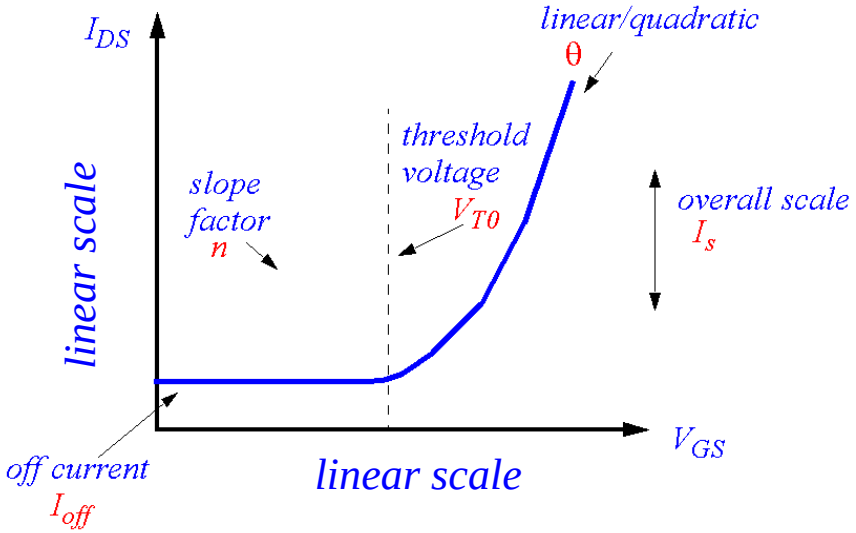
EKV Compact Model [Enz et al. 1995]





I_{DS}	$\dfrac{I_F - I_R}{1 + \theta(V_P - min(V_D, V_S))} + I_{off}$
I_F	$I_s i_f(V_P, V_S)$
I_R	$I_s i_r(V_P, V_D)$
V_P	$\dfrac{V_G - V_{TO}}{n}$
$i_{f(r)}$	$\left[\ln\left(1 + \exp\left[\dfrac{V_P - V_{S(D)}}{2U_t}\right]\right)\right]^2$

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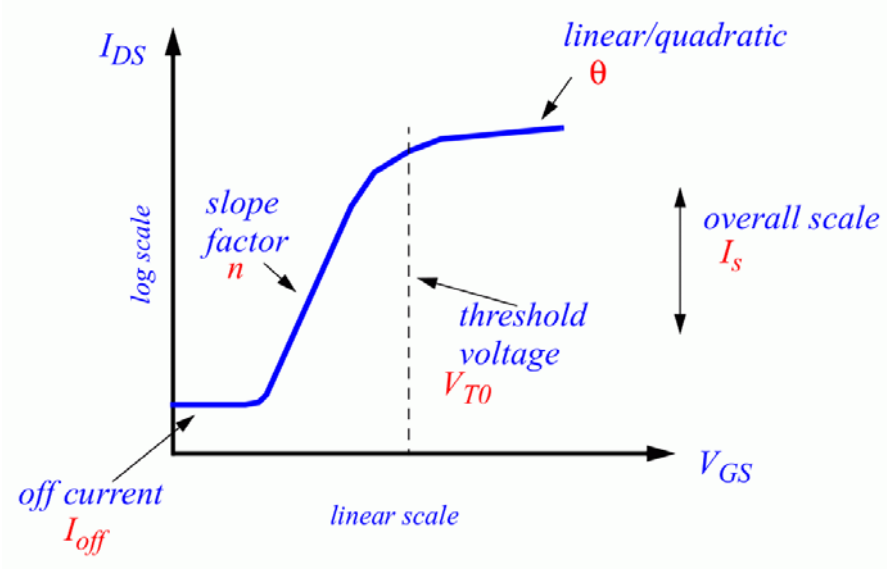
ACM Compact Model [Cunha et al., 1995]



I_{DS}	$\dfrac{I_F - I_R}{1 + \theta(V_P - min(V_D, V_S))} + I_{off}$
I_F	$I_s i_f(V_P, V_S)$
I_R	$I_s i_r(V_P, V_D)$
V_P	$\dfrac{V_G - V_{TO}}{n}$
$i_{f(r)}$	$q'^2_{is(d)} + 2q'_{is(d)}$
$V_P - V_{S(D)}$	$\phi_t((q'_{is(d)} - 1) + \ln q'_{is(d)})$

Other compact models could have been used [Iñiguez et al., 1995]

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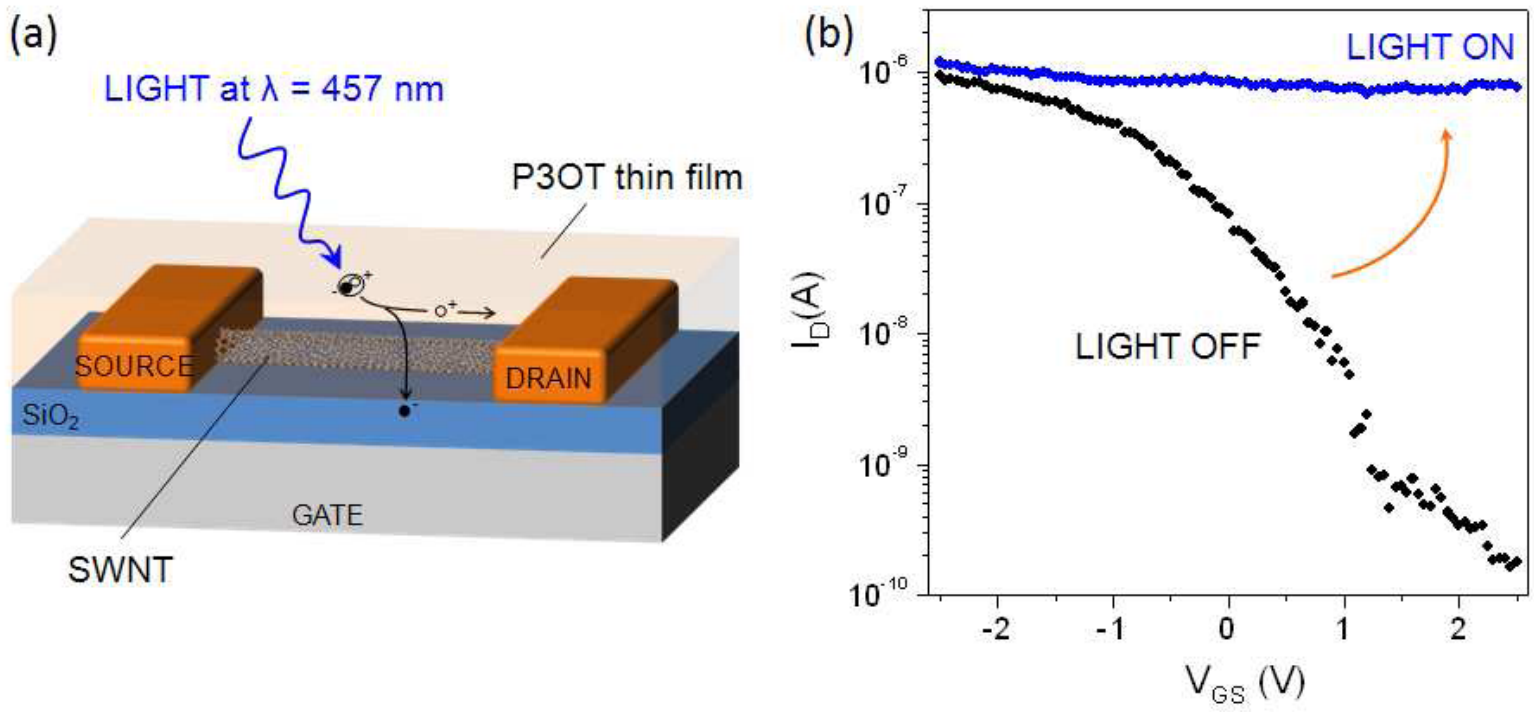
NABAB Nano Devices: OG-CNFET



- OG-CNFET: Optically Gated Carbon Nanotube FET
- P-type Carbon nanotubes single/network coated with photosensitive polymers act as memory devices
- Change in conductance four orders of magnitude upon illumination
- Response to light robust and reversible

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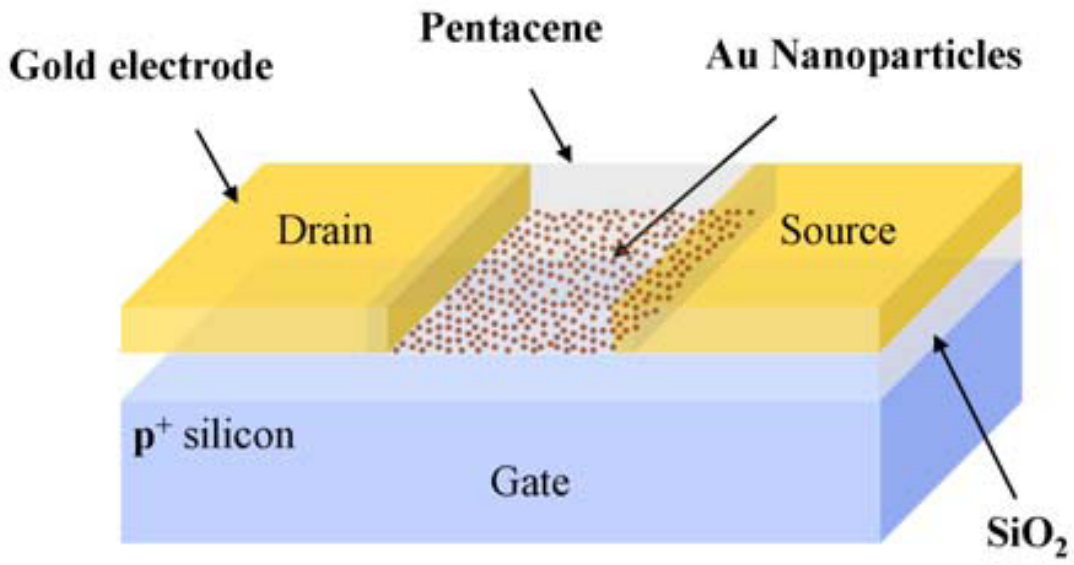
NABAB Nano Devices: NOMFET



- NOMFET: Nano Particle Organic Memory FET Transistor
- Three terminal device
- p^+ common gate/200nm $Si0_2$/gold source-drain electrodes/interelectrode gap 0.2-20μm
- Au nanoparticles deposed on the inter-electrode gap before pentacene deposition
- NPs are afterwards inmobilized using surface chemistry
- Pentacene (organic p-type semiconductor) deposited on top

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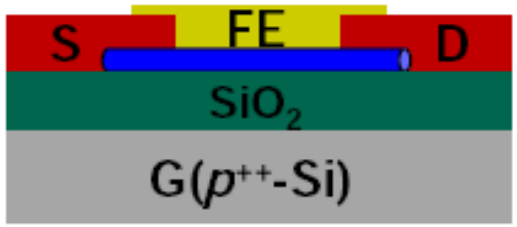
NABAB Nano Devices: ZnO NW memory FETs



- ZnO nanowires dispersed on a $Si0_2$-coated Si substrate

  100nm thick $Si0_2$
- Drain/source metal electrodes grown by photolitography
- Coated with layer of ferroelectric nanoparticles shifts threshold voltage positively or negatively depending on polarization
- Top gate made easy to change the orientation of polarization completely
- Long retention times
- Reversible

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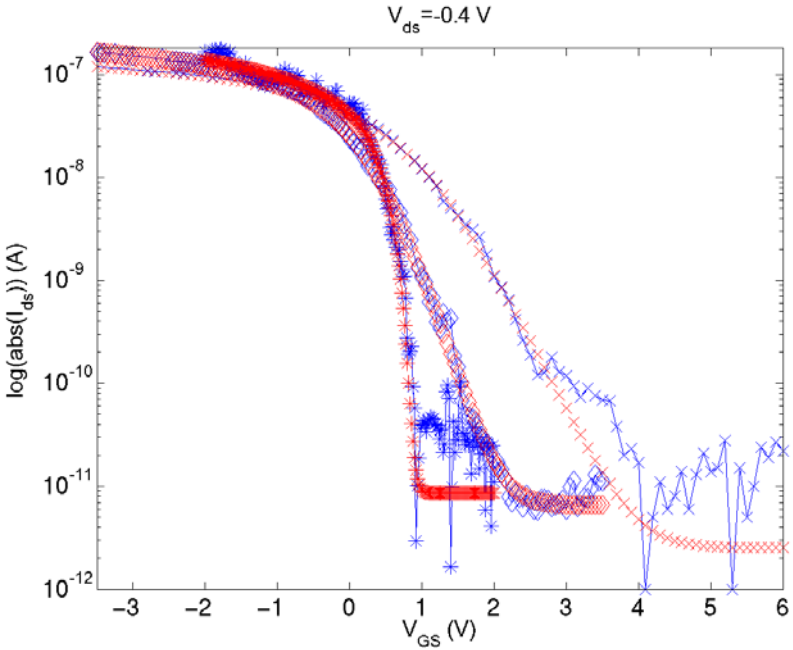
Fitting OG-CNFET to the EKV model. Experimental Results



Different type of channel

Different oxide thickness

Different size

* *Device L_g=200nm, t_{ox}=2nm, single tube:*

I_S=0.4nA n=1.22 V_{TO}=0.7895V θ=1.7530V^{-1} I_{off}=8.7pA

♦ *Device L_g=8000nm, t_{ox}=10nm, network of nanotubes:*

I_S=17.0nA n=7.78 V_{TO}=0.5396V θ=2.2085V^{-1} I_{off}=6.6pA

✕ *Device L_g=8000nm, t_{ox}=20nm, network of nanotubes:*

I_S=28.6nA n=11.82 V_{TO}=1.1904V θ=1.6013V^{-1} I_{off}=2.5pA

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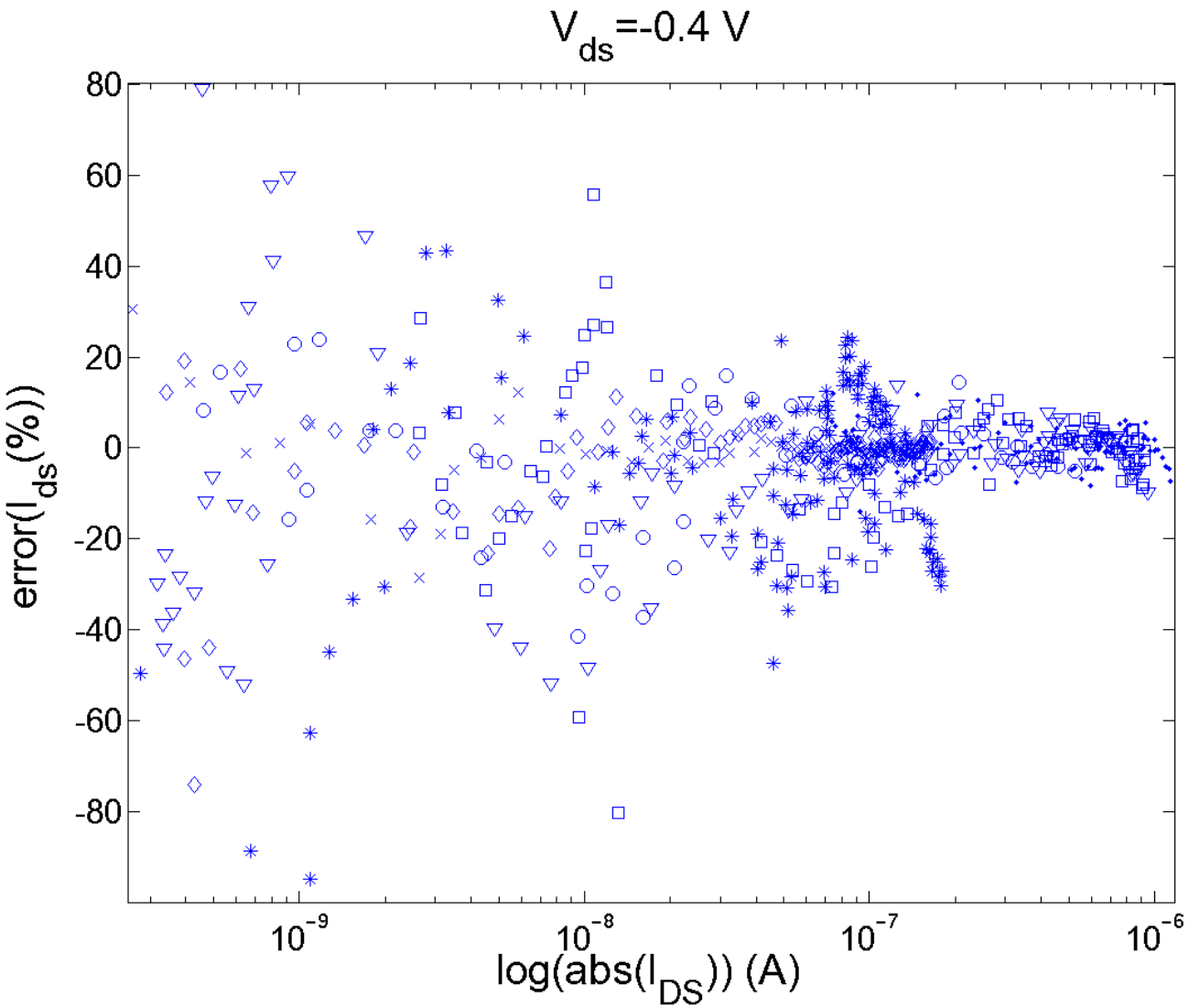

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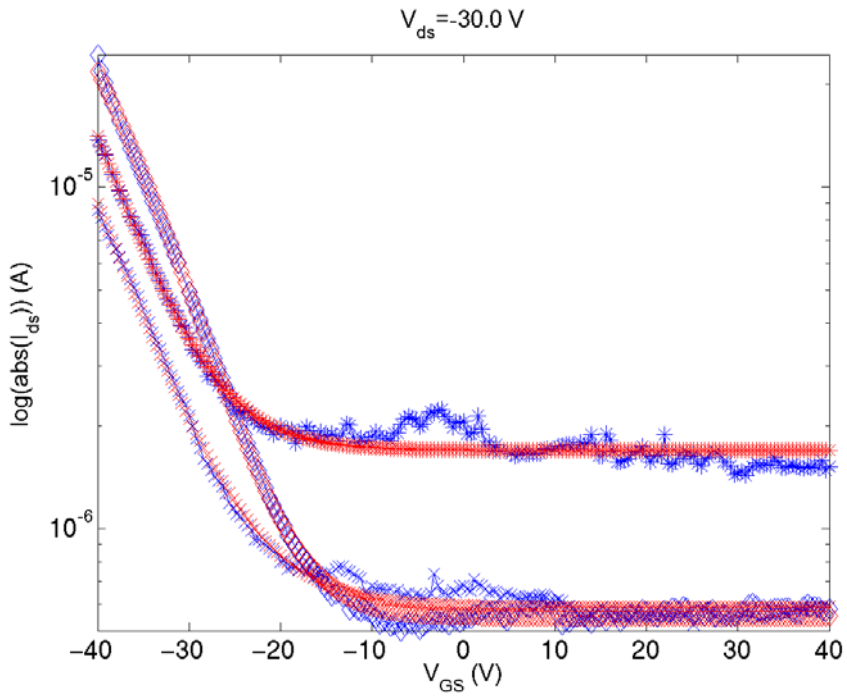
Fitting NOMFET to the EKV model. Experimental Results



Same device

Different programming conditions.

Writing

V_{GS}=-50V for 30 seconds

Erasing

V_{GS}=50V for 30 seconds

* *Device W=1000μm, L=1μm, t_{ox}=200nm, initial:*

I_S=58.6μA n=177 V_{TO}=-44.95V θ=0V^{-1} I_{off}=1.7μA

✕ *Device W=1000μm, L=1μm, t_{ox}=200nm, after writing:*

I_S=65.4μA n=199 V_{TO}=-48.74V θ=0V^{-1} I_{off}=0.6μA

♦ *Device W=1000μm, L=1μm, t_{ox}=200nm, after erasing:*

I_S=6.7μA n=140 V_{TO}=-28.44V θ=0V^{-1} I_{off}=0.6μA

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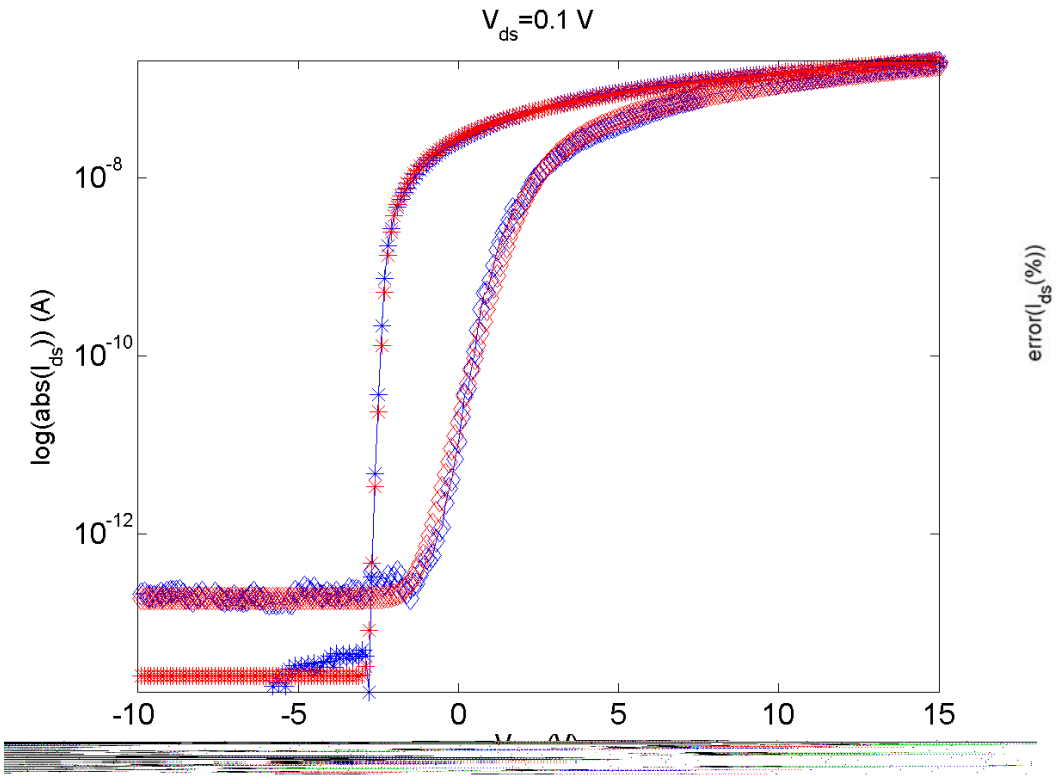
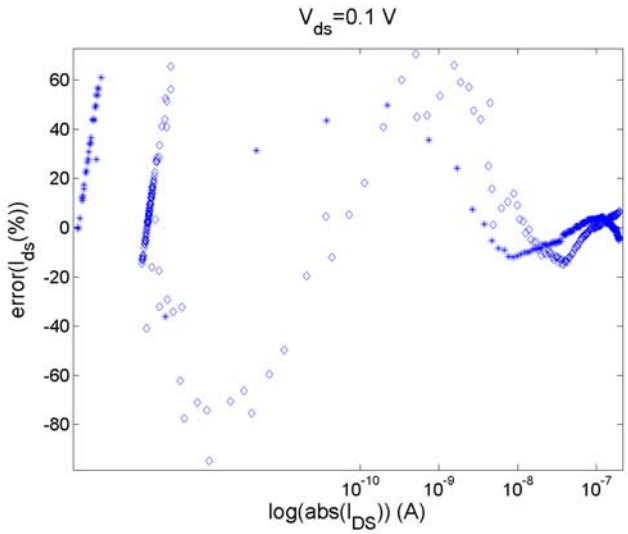
Fitting ZnO Memory FET to the EKV Model. Experimental Results





✕ *Device bottom gated ZnO nanowire, L=3μm, t_{ox}=100nm, V_{GS} swept -10V to 15V:*

I_S=0.5521nA n=1.84 V_{TO}=-2.3675V θ=0.0006V^{-1} I_{off}=0.0259pA

♦ *Device bottom gated ZnO nanowire, L=3μm, t_{ox}=100nm, V_{GS} swept 15V to -10V:*

I_S=6.7μA n=10.88 V_{TO}=1.6554V θ=0V^{-1} I_{off}=0.1926pA

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Conclusions

- We have shown how to extend in a compact manner the continuous EKV/ACM model to model mismatch including 2nd order effects relevant for mismatch.
- The model has been tested on 0.35um and 90nm CMOS technologies.
- We have indicated how one can simulate the model in a conventional circuit simulator.
- We have indicated how to include Pelgrom's Distance Term efficently in a CAD layout-aware mismatch simulator.
- We have shown the potential of the EKV/ACM continuous model to model some of new nano-FET devices.

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