

ADVANCED COMPACT MOSFET (ACM) MODEL

Self-Consistent DC, AC, Noise and Mismatch MOSFET Models for Circuit Design.

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OUTLINE

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 - Experimental Results
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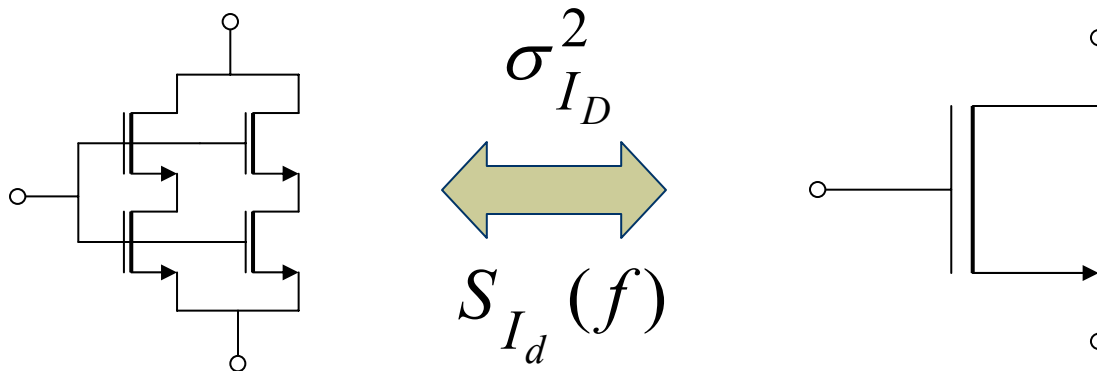
INTRODUCTION

- ◆ Predicting accuracy (mismatch & noise) is fundamental in analog and digital IC design.
- ◆ Traditional models are inconsistent, inaccurate, or too complex for predicting mismatch & noise.
- ◆ Mismatch (spatial fluctuation) and noise (temporal fluctuation) are similar phenomena, both depending on process, device dimensions, and bias.

INTRODUCTION

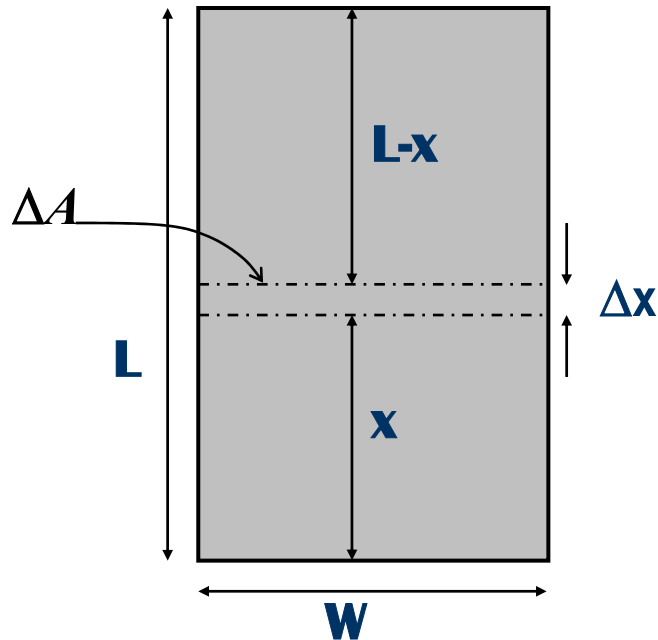
A note on model consistence:

Total mismatch (noise) resulting from contribution of individual elements of a series-parallel association **must be the same** as mismatch (noise) of equivalent component.

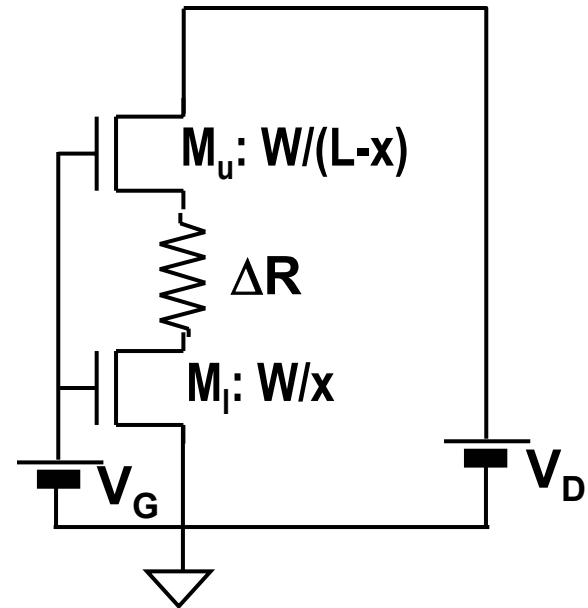


MOSFET CHANNEL MODEL

- ◆ Channel splitting



- ◆ Transistor equivalent circuit



MOSFET CHANNEL MODEL

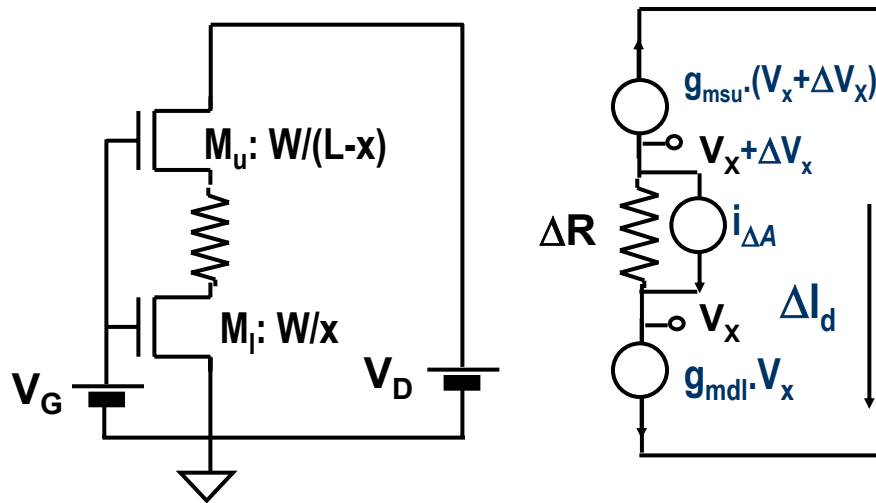
Drain current formulation using quasi-Fermi potential (valid from weak inversion to strong inversion)

$$I_D = -\mu \frac{W}{dx} Q_I' \cdot dV_X \quad (1)$$

results in an incremental resistance for the small channel element equal to

$$\Delta R = \frac{\Delta V_x}{I_D} = -\frac{\Delta x}{\mu W Q_I'} \quad (2)$$

MOSFET CHANNEL MODEL



small-signal equivalent circuit

$$\Delta R = -\frac{\Delta x}{\mu W Q'_I}$$

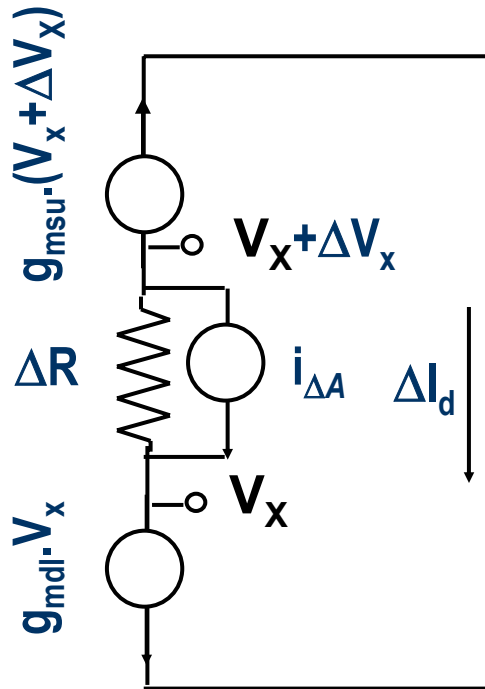
$$g_{msu} = -\mu \frac{W}{L-x} Q'_{IX}$$

$$g_{mdl} = -\mu \frac{W}{x} Q'_{IX}$$

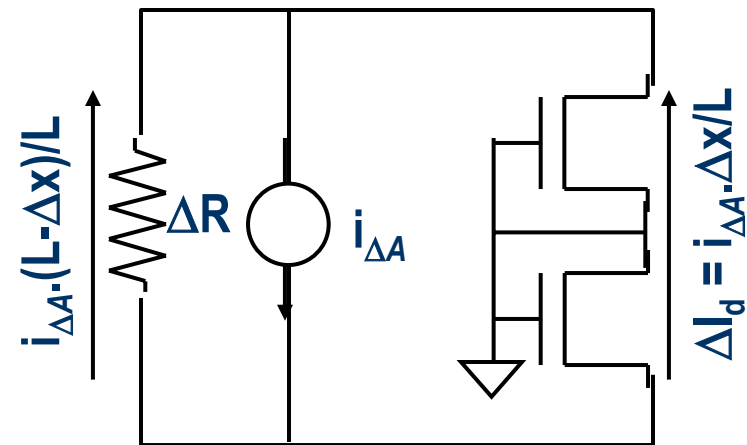
- ◆ mismatch and noise result from local current fluctuation ($i_{\Delta A}$) in the small channel element.

MOSFET CHANNEL MODEL

- ◆ Small-signal equivalent circuit



- ◆ Equivalent current divider



MOSFET CHANNEL MODEL

- ◆ Contribution of the local current fluctuation ($i_{\Delta A}$) to the drain current (ΔI_d) is

$$\Delta I_d = (\Delta x/L).i_{\Delta A} \quad (3)$$

- ◆ Total drain current variance is the sum of (uncorrelated) individual contributions

$$(\Delta I_D)^2 = \sum_L (\Delta I_d)^2 = \lim_{\Delta x \rightarrow 0} \sum [(\Delta x/L)i_{\Delta A}]^2 = \frac{1}{L^2} \int_0^L [\Delta x(i_{\Delta A})^2] dx \quad (4)$$

↑↑
contribution of the channel
element to total current

CONSISTENT MISMATCH MODEL

- ◆ A consistent mismatch model must contain the contributions of the randomly varying parts of the technological parameters.
- ◆ The fluctuation of the threshold voltage (V_T) is a very significant factor in total drain current mismatch.
- ◆ Consistence derives from considering the local fluctuation of V_T rather than considering it as a lumped model parameter.

FLUCTUATION OF CHARGE DENSITY

From
$$I_D = -\mu \frac{W}{dx} Q'_I \cdot dV_X \quad (1)$$

we derive
$$i_{\Delta A} = I_D \frac{\Delta Q'_I}{Q'_I} \quad (5)$$

- (5) gives the fluctuation of the local current in terms of the fluctuation of the local charge density.
- In most of the cases, the fluctuation of the local charge is the main contribution to mismatch.
- We can analyze the effects of fluctuation of mobility and dimensions on matching using (1) as the basis for the analysis.

FLUCTUATION OF CHARGE DENSITY

From the Unified Control Charge Model (UCCM)

$$\frac{\Delta Q'_I}{Q'_I} = \frac{-C'_{ox} \Delta V_T}{Q'_I - nC'_{ox} \phi_t} \quad (6)$$

- (6) gives the relative variation of the local charge in terms of the fluctuation of the threshold voltage.

Local fluctuation of V_T under ΔA can be estimated from Pelgrom's expression

$$\sigma_{VT}^2 = \frac{A_{VT}^2}{LW} \quad \Rightarrow \quad \overline{\Delta V_T^2} = \frac{A_{VT}^2}{\Delta x W} \quad (7)$$

(lumped model)

(distributed model)

NUMBER FLUCTUATION MODEL

The square of the total drain current fluctuation

$$(\Delta I_D)^2 = \sum_L (\Delta I_d)^2 = \lim_{\Delta x \rightarrow 0} \sum [(\Delta x/L) i_{\Delta A}]^2 = \frac{1}{L^2} \int_0^L [\Delta x (i_{\Delta A})^2] dx \quad (4)$$

$\uparrow\uparrow$
 contribution of the channel
 element to total current

(4) is calculated using (5), (6), (7) along with

$$I_D = \frac{\mu W}{nC'_{ox}} \left(\underbrace{-Q'_I}_{\uparrow\uparrow \text{ drift}} + nC'_{ox} \phi_t \right) \frac{dQ'_I}{dx} \quad (8)$$

$\uparrow\uparrow$
 diffusion

resulting in

$$\sigma_{I_D}^2 = \overline{\Delta I_D^2} = \frac{\mu C'_{ox} I_D A_{VT}^2}{nL^2} \int_{Q'_{IS}}^{Q'_{ID}} \frac{1}{nC'_{OX} \phi_t - Q'_I} dQ'_I \quad (9)$$

NUMBER FLUCTUATION MODEL

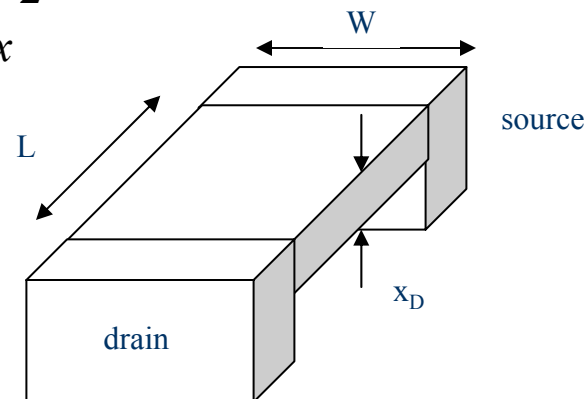
The integration of (9) from source to drain results in

$$\frac{\sigma_{I_D}^2}{I_D^2} = \frac{q^2 N_{oi} \mu}{L^2 n C'_{ox} I_D} \ln \left(\frac{n C'_{ox} \phi_t - Q'_{IS}}{n C'_{ox} \phi_t - Q'_{ID}} \right) \quad (10)$$

In (10), Poisson statistics has been assumed for depletion charge fluctuations, i. e.

$$A_{VT}^2 = \frac{q^2}{C'_{ox}} (N_{oi} x_D) = \frac{q^2}{C'_{ox}} N_{oi} \quad (11)$$

N_{oi} : effective number of impurities per unit area of gate



DEPENDENCE ON INVERSION LEVEL

In terms of inversion level†

$$\frac{\sigma_{I_D}^2}{I_D^2} = \frac{N_{oi}}{WLN^{*2}} \frac{1}{i_f - i_r} \ln\left(\frac{1 + i_f}{1 + i_r}\right) \quad (12)$$

where

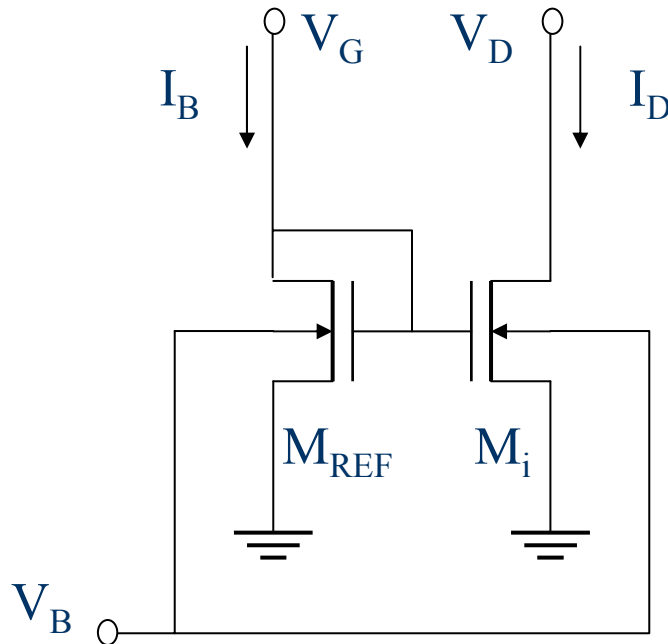
$$N^* = \frac{-Q'_{IP}}{q} = \frac{nC'_{ox}\phi_t}{q} \quad (13)$$

† for long channel MOSFET, from ACM model

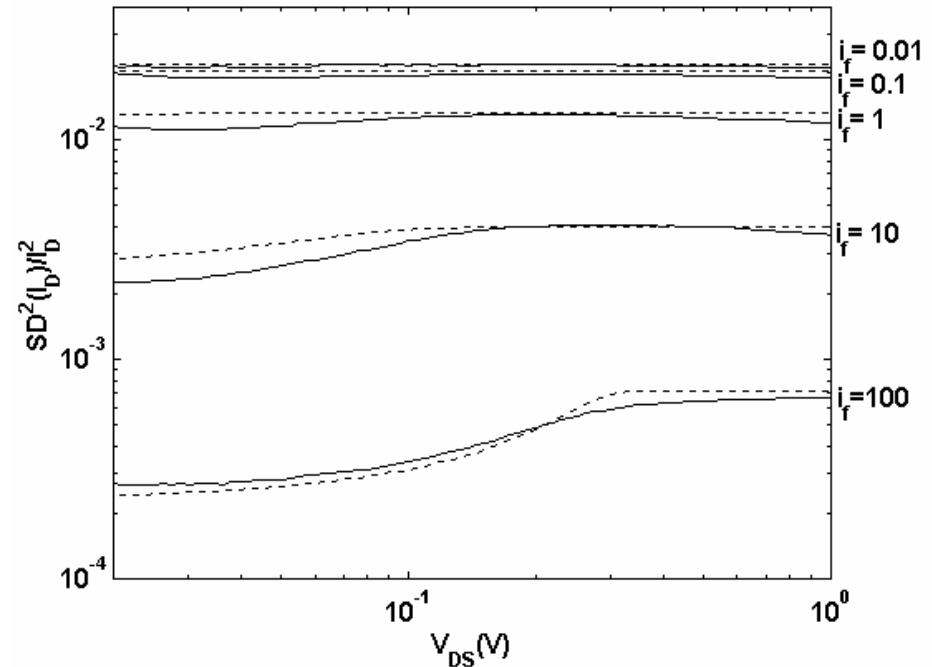
$$I_D = I_F - I_R = I_S(i_f - i_r) \quad \text{and} \quad I_S = \frac{1}{2} \mu C'_{ox} n \phi_t^2 (W/L)$$

EXPERIMENTAL RESULTS

Test circuit



Saturation level dependence



Measured: —; Model: ---

Test chip contains 24 NMOS $30\mu\text{m} \times 1.2\mu\text{m}$ transistors in the ES2 $1.2\mu\text{m}$ CMOS DLM process

NOISE x MISMATCH

- ◆ Mismatch of identically designed MOSFETs results from spatial fluctuation of process parameters that affect the number of carriers.
- ◆ MOSFET noise is generated by fluctuation in the velocity and/or number of carriers.
- ◆ Mismatch (spatial fluctuation) and noise (temporal fluctuation) are similar phenomena, both depending on process, device dimensions, and bias.
- ◆ Mismatch can be seen as a “dc noise”.

FLICKER NOISE ($1/f$)

- ◆ Power spectral density (PSD): $S(f) = K/f^\beta$ $\beta \cong 1$
- ◆ Mainly generated by fluctuations in number of carriers and mobility due to random trapping-detrapping of carriers near the surface of the semiconductor.
- ◆ Exact mechanism and statistics of resulting noise current, and correlation with technological parameters are not yet clear.

FLICKER NOISE MODEL

- ◆ Noise PSD of channel element ΔA ($S_{\Delta A}(x, f)$) results from the noise current produced by the channel element $i_{\Delta A}$.

- ◆ Total noise current can be expressed as

$$S_{Id}(f) = \frac{1}{L^2} \int_0^L S_{\Delta A}(x, f) dx \quad (17)$$

- ◆ Relationship between fluctuation in number of carriers and noise current

$$i_{\Delta A} = I_D \cdot \frac{\delta N}{N} \quad (18)$$

FLICKER NOISE MODEL

- ◆ Using Reimbold hypothesis (the ratio of the variation of the number of carriers to the number of traps is given by the capacitive divider $C'_I / (C'_I + C'_B + C'_{OX})$) the PSD of the fluctuation in the current is

$$\frac{S_{I_d}}{I_D^2} = \frac{q^2 N_{ot} \mu}{L^2 n C'_{OX} I_D} \cdot \ln \left[\frac{n C'_{OX} \phi_t - Q'_{IS}}{n C'_{OX} \phi_t - Q'_{ID}} \right] \cdot \frac{1}{f} \quad (19)$$

$$N_{ot} [\text{cm}^{-2}] = k_B T N_t(E) / \gamma$$

Not: effective number of traps (parameter to be adjusted)

$N_t(E)$: density of oxide traps/unit volume/unit energy

γ : McWhorter tunneling parameter

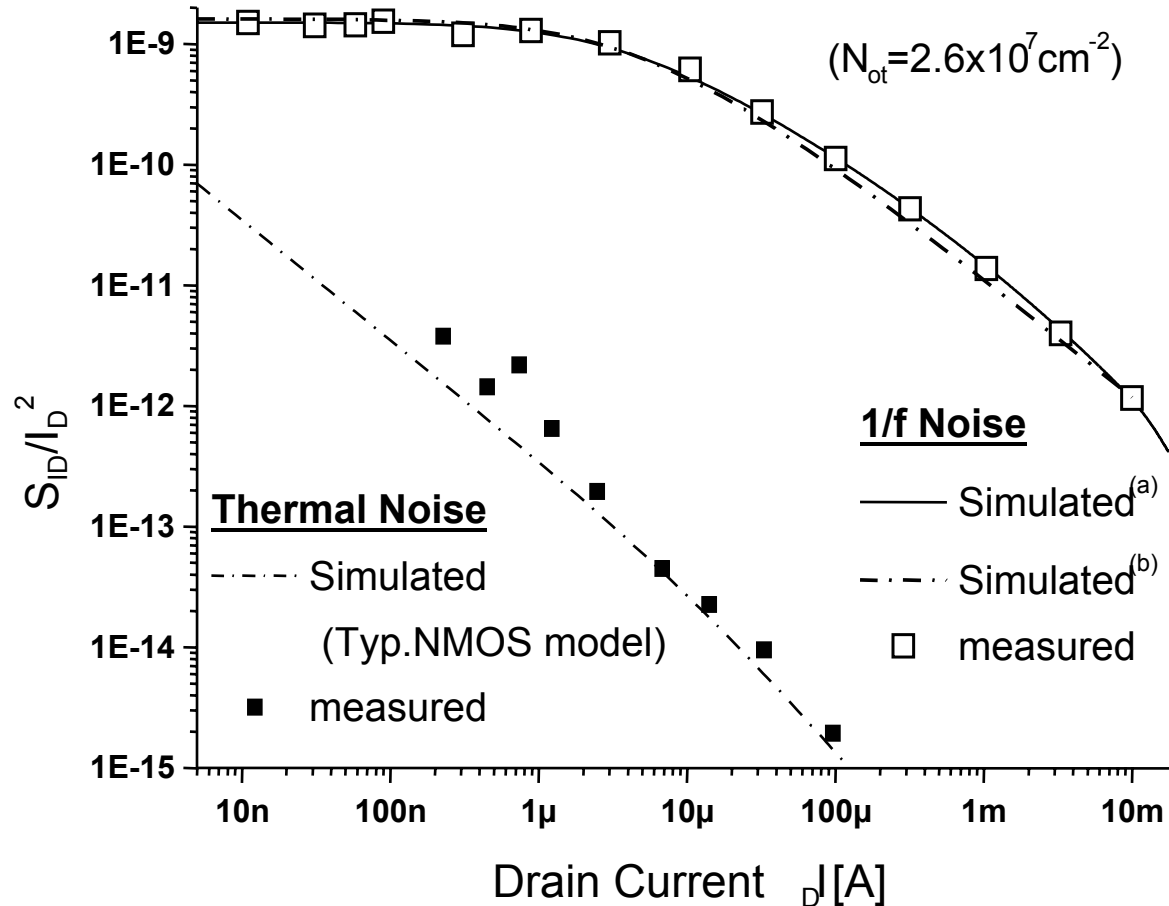
INVERSION LEVEL EFFECTS

- ◆ In terms of inversion level, (19) becomes

$$\frac{S_{I_d}}{I_D^2} = \frac{N_{ot}}{WLN^{*2}} \cdot \frac{1}{f} \cdot \frac{1}{(i_f - i_r)} \ln \left[\frac{1 + i_f}{1 + i_r} \right]. \quad (20)$$

$$N^* = nC'_{OX} \phi_t / q$$

EXPERIMENTAL RESULTS



Normalized flicker and thermal PSD at $f=1\text{kHz}$ for saturated NMOS (200/5)

CONCLUSIONS

- ◆ Mismatch and flicker/thermal noise models continuous in all operating regions.
- ◆ Physics-based approach (fluctuation in the number of carriers) common to derivation of mismatch & flicker noise .
- ◆ Use of ACM model resulted in a compact easy-to-use formula that covers any operating region.
- ◆ Experimental results confirmed the accuracy of our models under various bias conditions.
- ◆ Useful tools for designers to predict transistor mismatch and noise in an accurate and easy way.
- ◆ Simple parameters/models for interfacing foundries to users.