A Study of Figures of Merit for High Frequency Behavior of MOSFETs in RF IC Applications

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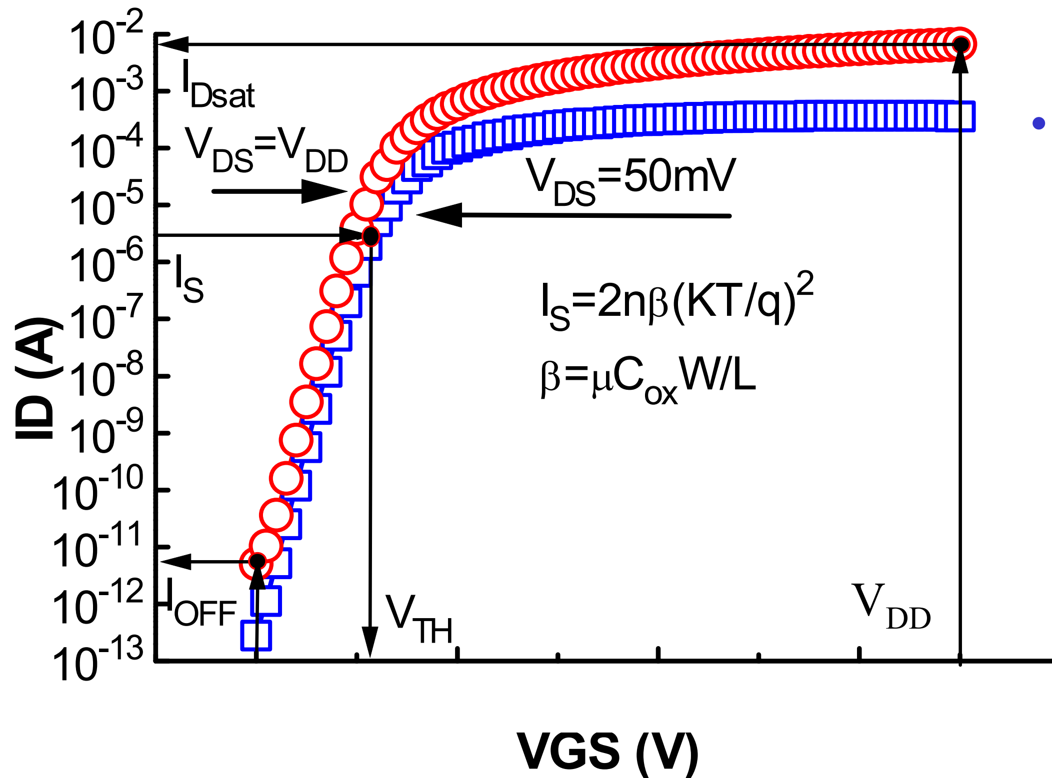
Device Figures-of-Merit and Applications

- CMOS becomes a lower cost solution for various RF applications.
  - Recent speed improvements and better noise behavior of CMOS transistors have made it feasible to implement RF circuits for wireless products.
  - Tremendous efforts are dedicated to RF CMOS, driven by System-on-Chip (SoC).
- Device figures-of-merits are needed to evaluate device behavior for RF applications.
  - As performance targets for analog/RF process development by technology developers.
  - As qualification specifications for model validation by Modelers.
  - As critical parameters for circuit design and optimization by designers.

Objectives

- Review Figures-of-Merits (FoM) in MOSFETs for analog/RF applications.
- Demonstrate model validation results with these FoMs.
- Initiate the efforts in using these FoM for technology development and model validations.

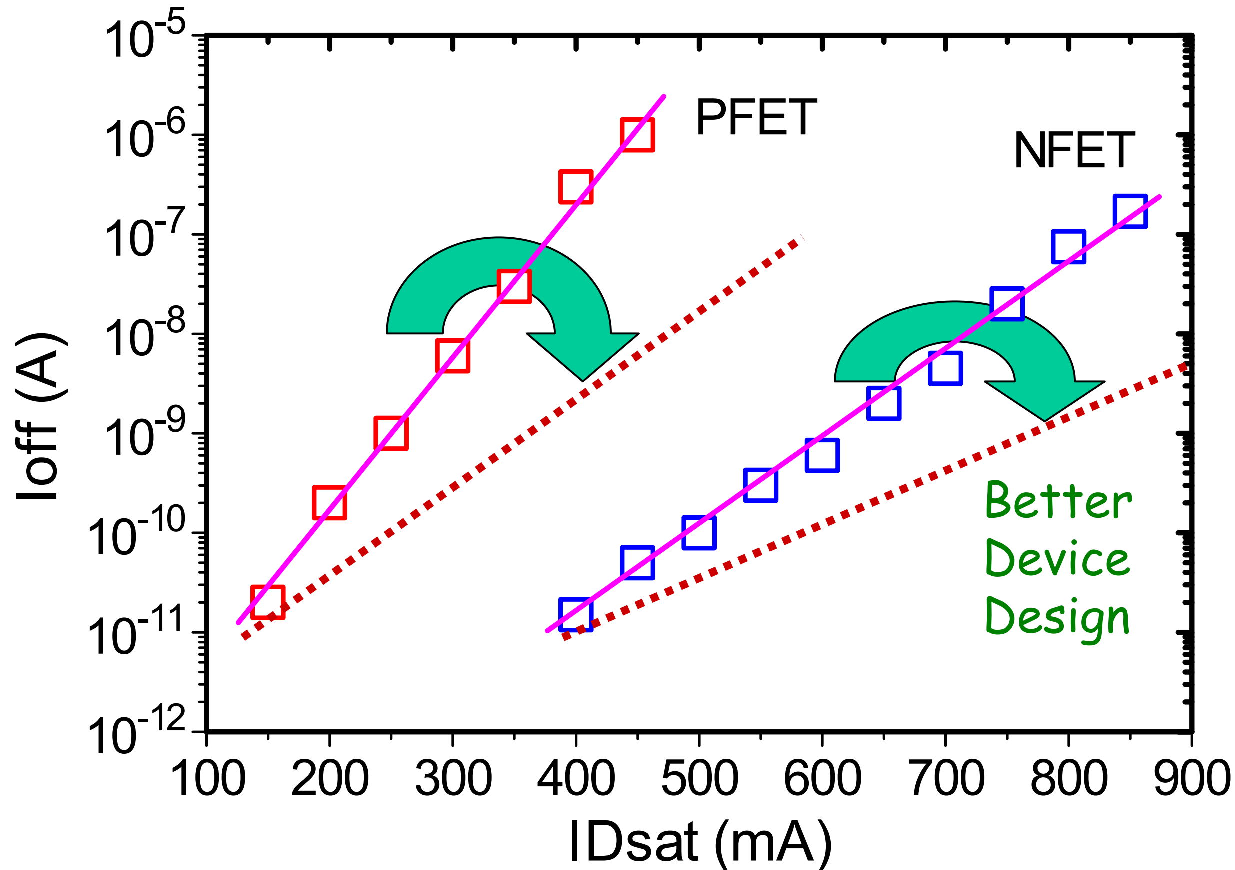
V_{TH}, I_{Dsat}, & I_{off}



- Direct FoMs:
  - V_{TH}: Threshold voltage
  - I_{Dsat}: Saturation current
  - I_{off}: Leakage current

- Derived FoMs:
  - I_{dsat} vs. I_{off} : Universal curves
  - $C_G V_{DD}/I_{dsat}$: Delay factor

I_{Dsat}/I_{off} Universal Curves



- A trade-off between I_{Dsat} and I_{off}.
- Better device design and material selection to reduce the slope of the universal curves.

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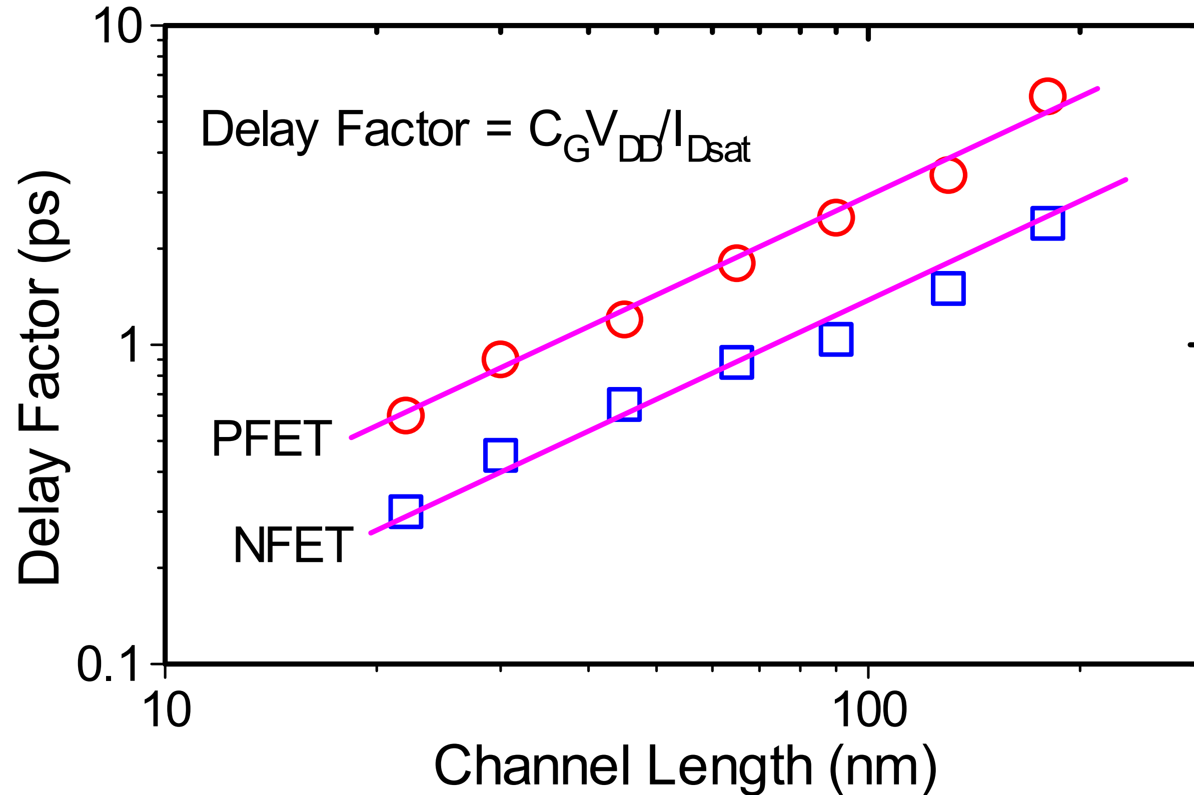
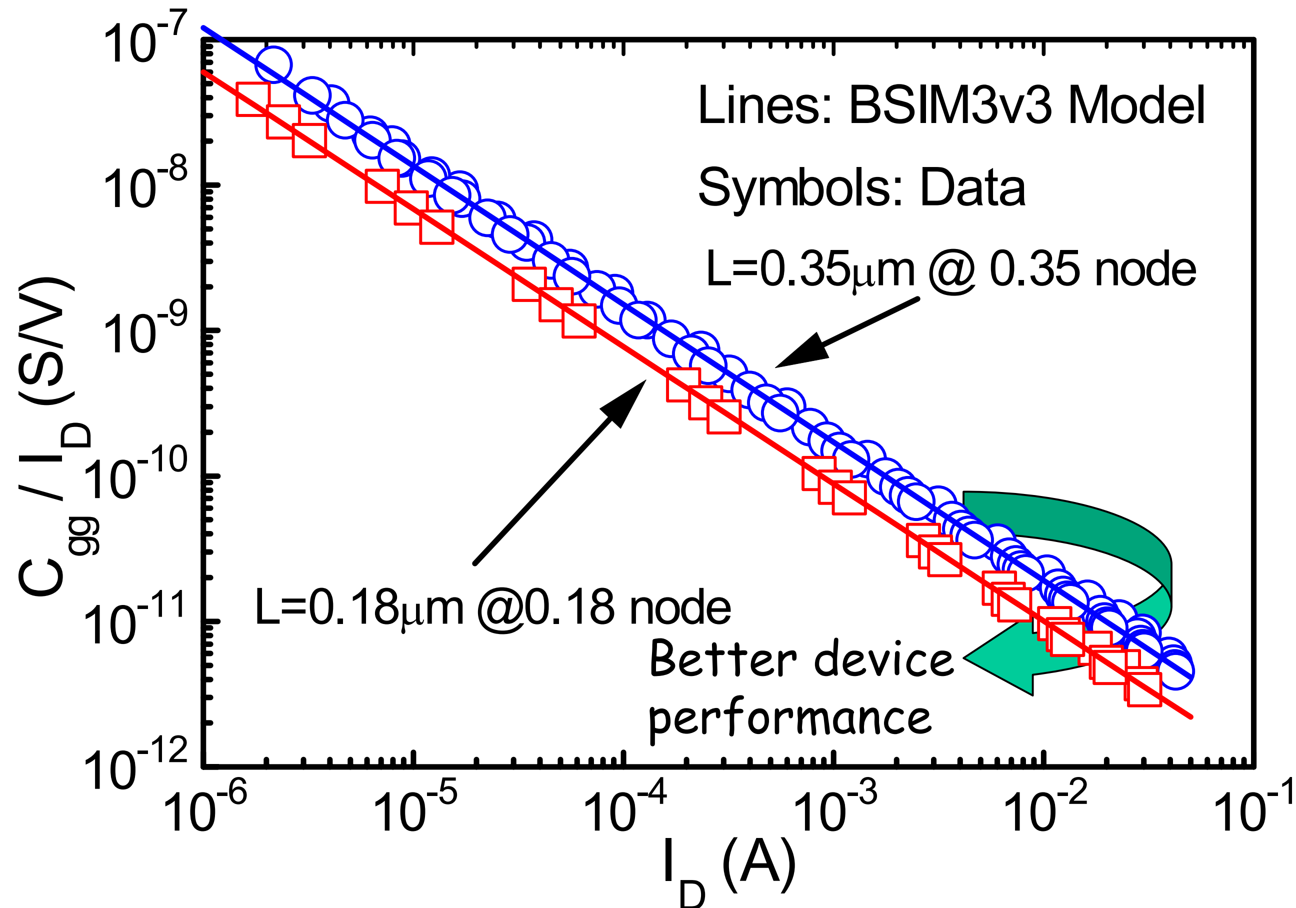
Gate Delay Factor: $C_G V_{DD}/I_{Dsat}$



- To reduce the delay, reduce capacitance loads and increase the driving current I_{Dsat}, at given supply voltage.
- However, as shown in the universal curves, leakage will increase to maintain higher I_{Dsat}.
- A trade-off between the speed and leakage optimization.

C_{gg}/I_D: Measured vs. Fitted



- Better device design for smaller C_{gg}/I_D.
- A parameter obtained easily from PCM/WAT measurement.

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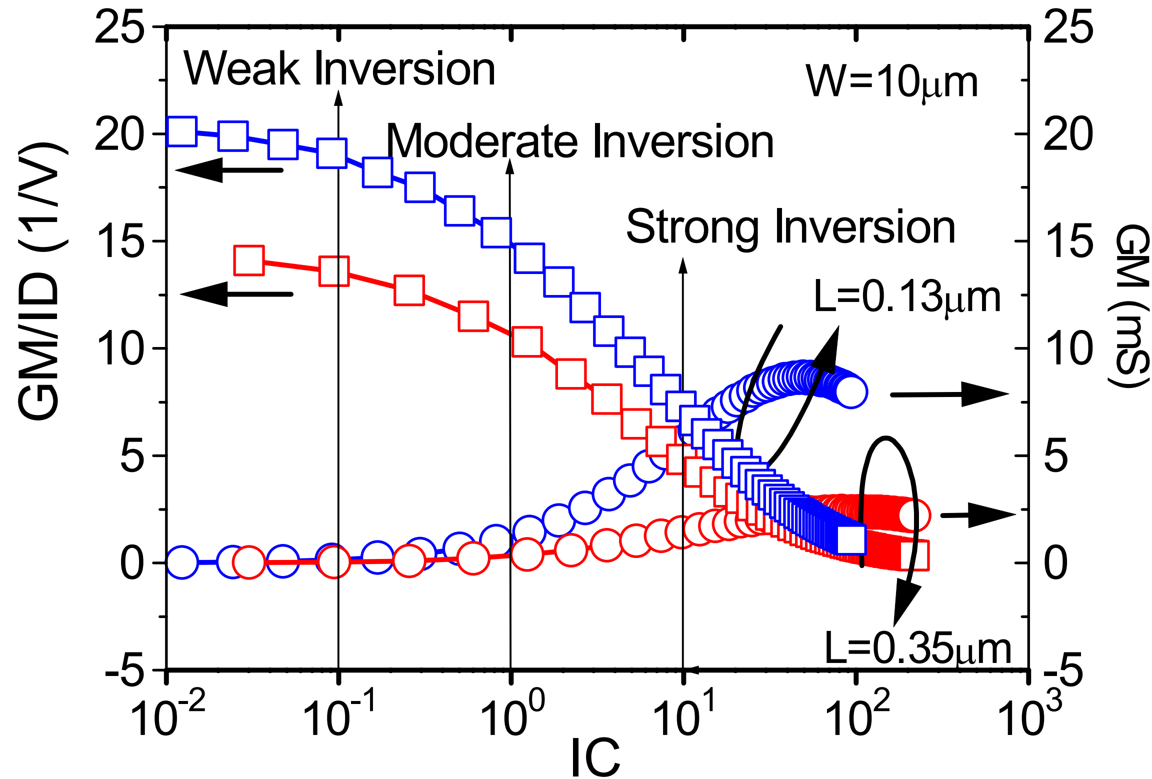
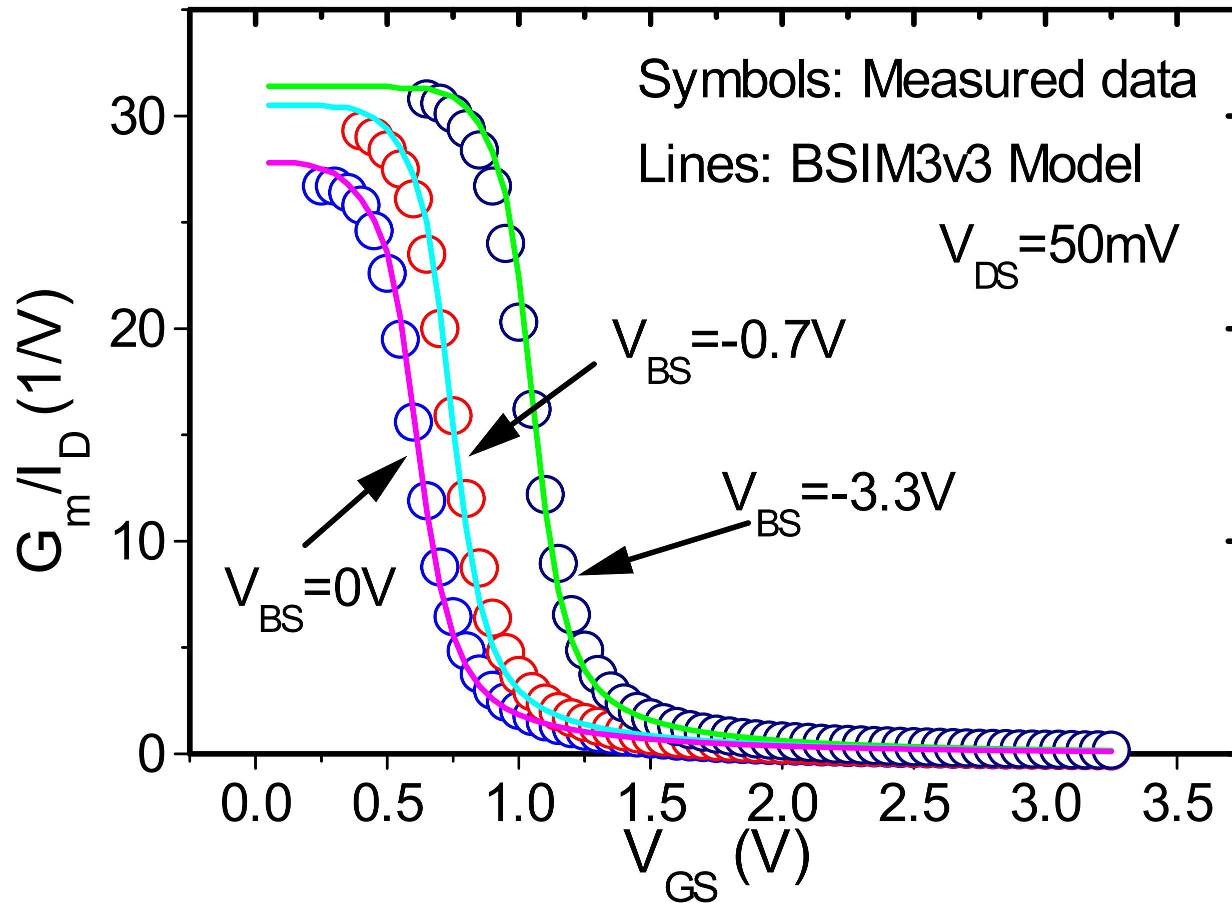
G_m & G_m/I_D



- G_m, the most important parameters in analog design.
- G_m/I_D, a universal characteristic of MOSFETs to evaluate the transconductance efficiency, how efficiently the current is used to generate transconductance.
- Inversion Coefficient (IC), ratio of I_D/I_S, is proposed as a measure of MOS inversion level.

G_m/I_D: Measured vs. Fitted



- G_m/I_D has been proposed a FoM for model validation for analog applications.

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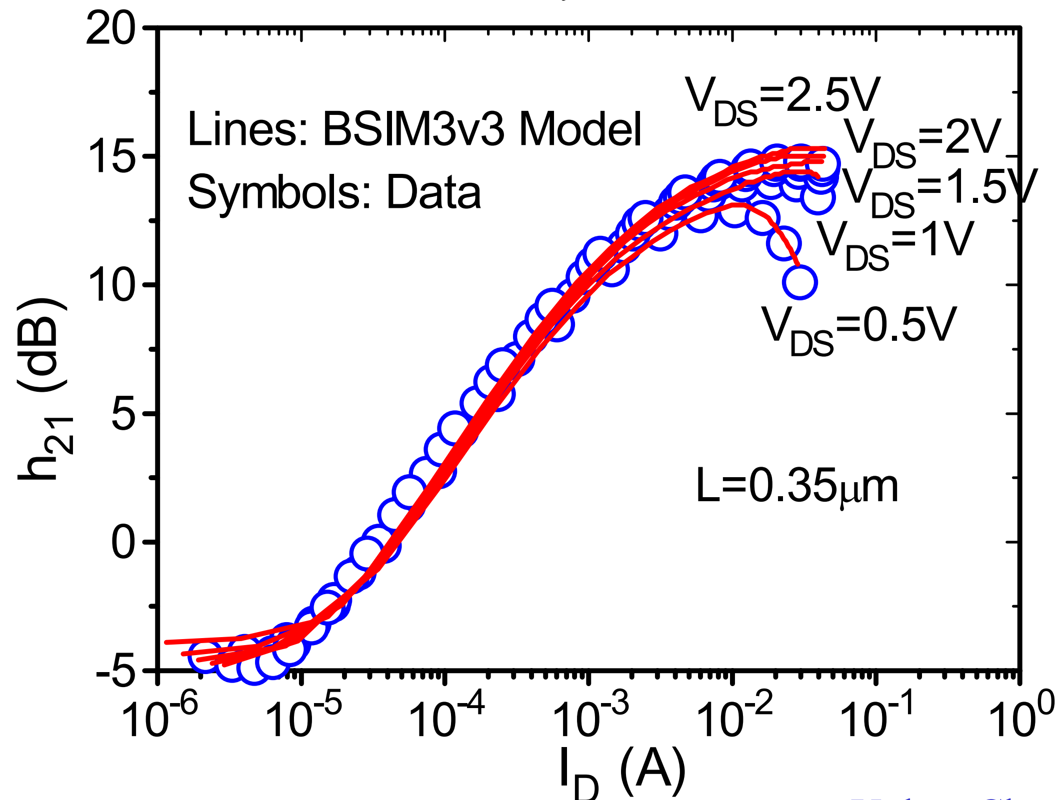
Current Gain: h_{21}

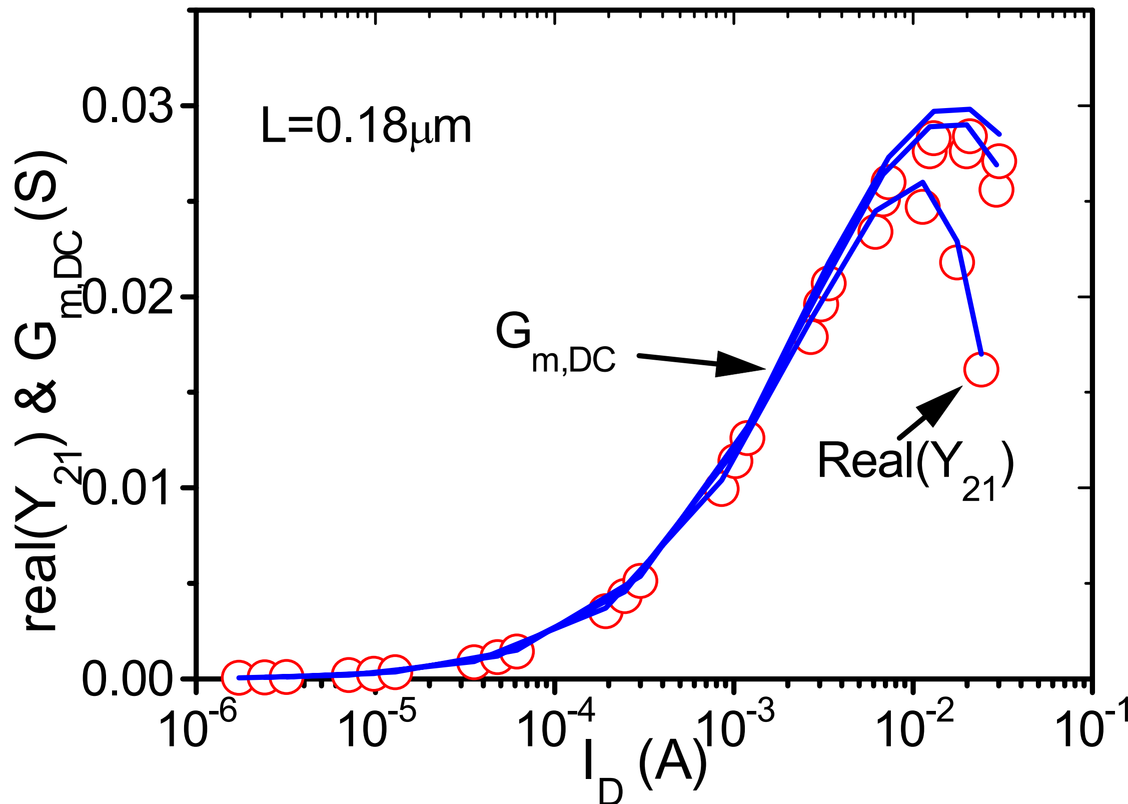
- The h parameters were used to describe the HF behavior of transistors.
- The short circuit current gain, h_{21}

$$h21 = \frac{i2}{i1} = \frac{y21}{y11}$$



$Re(Y_{21})$: A Parameter for DC Gain

- For MOSFET, $Re(Y_{21})$ is often used to represent current Gain.
- $Re(Y_{21})$ can have a good match to $G_{m,DC}$



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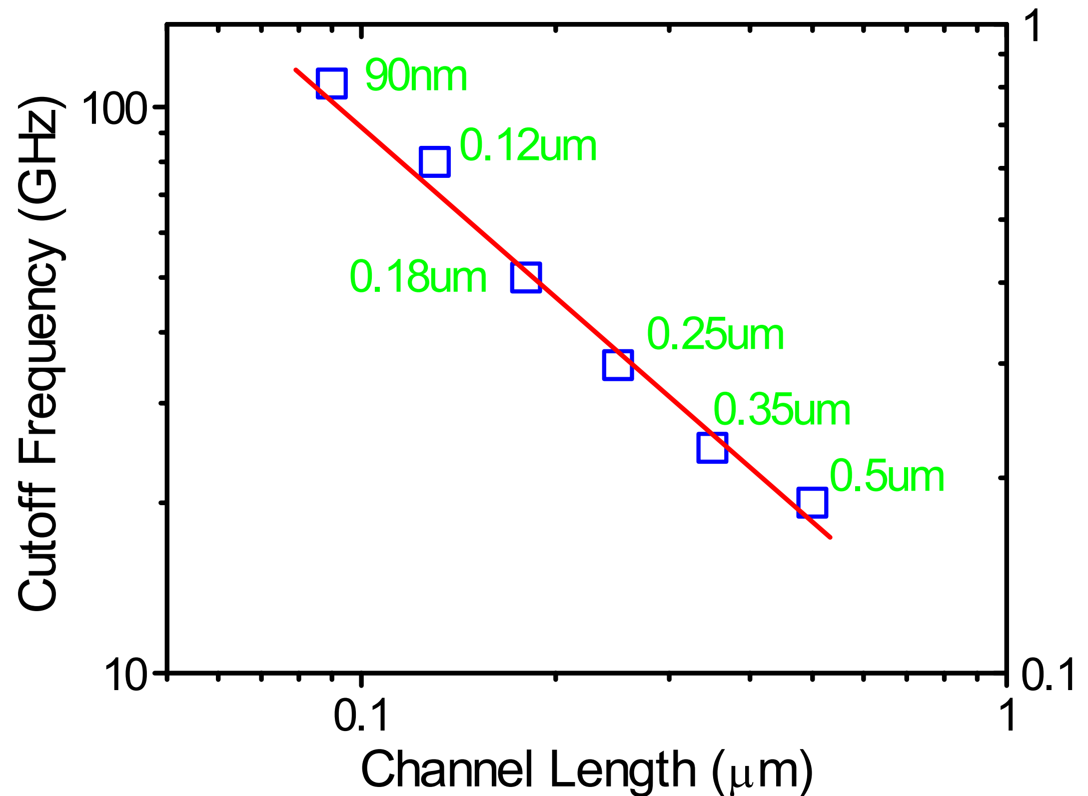
Cut-off Frequency f_T

$$f_T = \frac{G_m}{2\pi C_{gg}} \approx \frac{G_m}{2\pi WLC_{ox}}$$

$$G_{msat} \approx W v_{sat} C_{ox}$$

$$f_{T\,peak} \approx \frac{v_{sat}}{2\pi L}$$



- A widely used FoM for HF device technology development.
- Approximately, fTpeak is inversely proportional to L and independent of W without considering the impact of parasitics.

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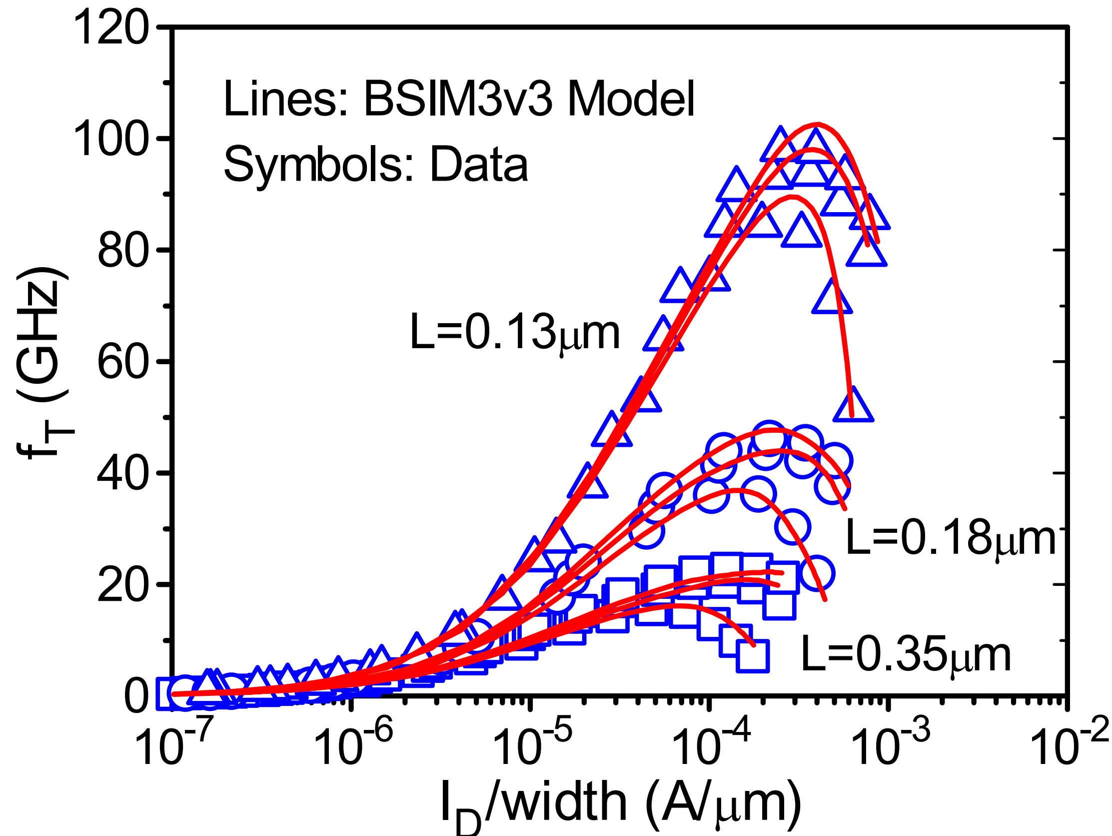
f_T: Measured vs. Fitted



- A standard device parameter for model validation.
- However, only f_T is not enough to describe HF behavior of MOSFETs, especially at technology nodes such as 0.13um and below.

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Power Gain and f_{max}

- The maximum power gain, $G_{T,max}$:

$$G_{T,\max} = \left|\frac{S_{21}}{S_{12}}\right|\left(K - \sqrt{K^2 - 1}\right) \qquad K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |S_{11}S_{22} - S_{12}S_{21}|^2}{2|S_{12}S_{21}|}$$

- K is the stability factor. The maximum stable power gain is defined as the $G_{T,max}$ when K=1:

$$G_{ST,\max} = \left|\frac{S_{21}}{S_{12}}\right|$$

- f_{max} is called the maximum frequency of oscillation, and is the frequency at which the maximum power gain equals to 1.

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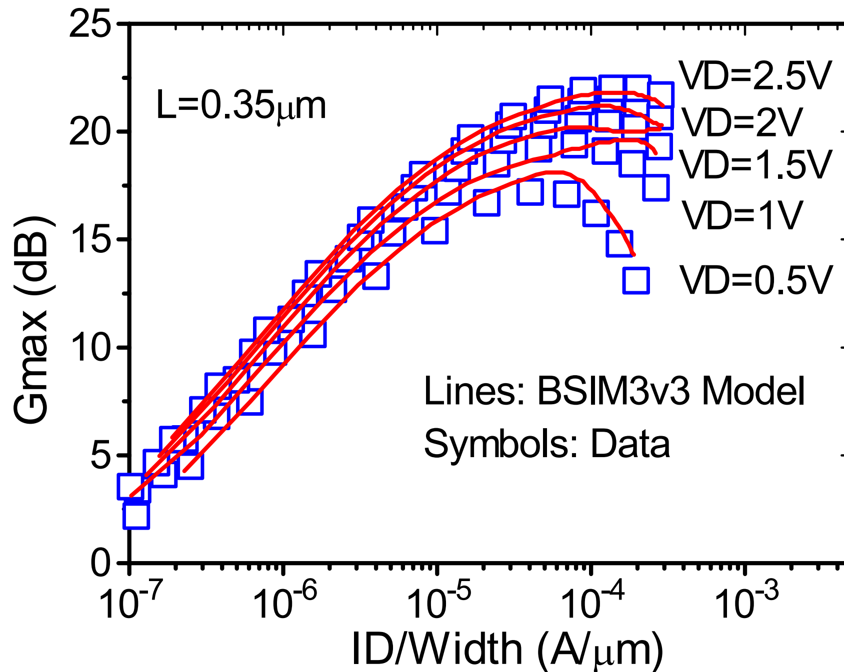
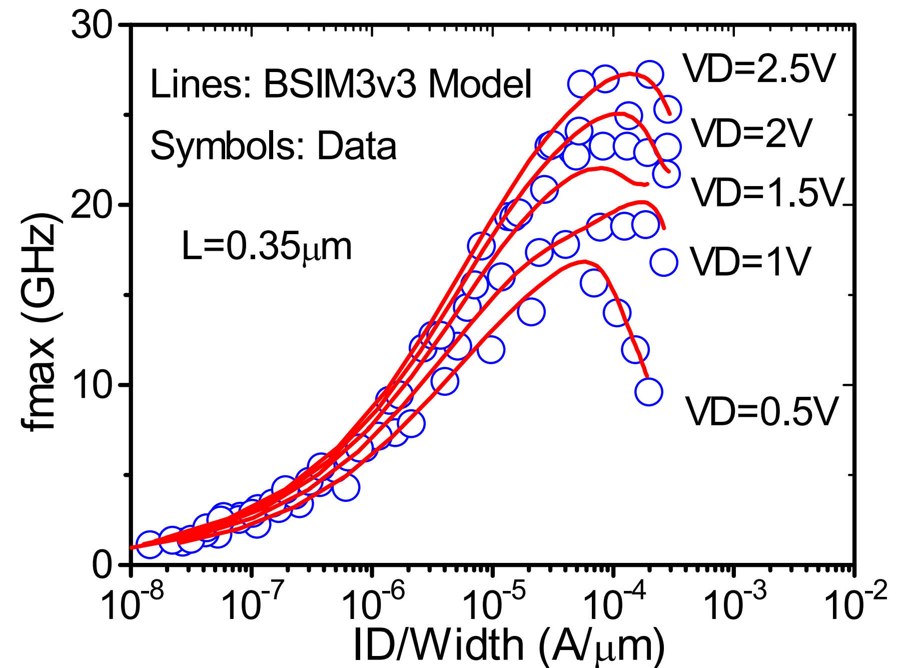
G_{max} and f_{max}: Measured vs. Fitted





- f_{max} contains the impacts from parasitics such as gate and substrate resistance and is a better FoM than f_T

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C-parameters

- C-parameters, such as Rin and Cin; Rout and Cout; Rfb and Cfb were proposed.
- Input resistance and capacitance, Rin and Cin:

$$Rin = real\left(\frac{1}{y11}\right) \qquad Cin = \frac{-1}{\omega \cdot imag\left(1/y11\right)}$$

- Output resistance and capacitance Rout and Cout:

$$Rout = real\left(\frac{1}{y22}\right) \qquad Cout = \frac{imag(y22)}{\omega}$$

- Feedback resistance and capacitance Rfb and Cfb:

$$Rfb = real\left(\frac{-1}{y12}\right) \qquad Cfb = \frac{1}{\omega \cdot imag\left(1/y12\right)}$$

- C-parameters derived from y parameters and more meaningful for circuit designers

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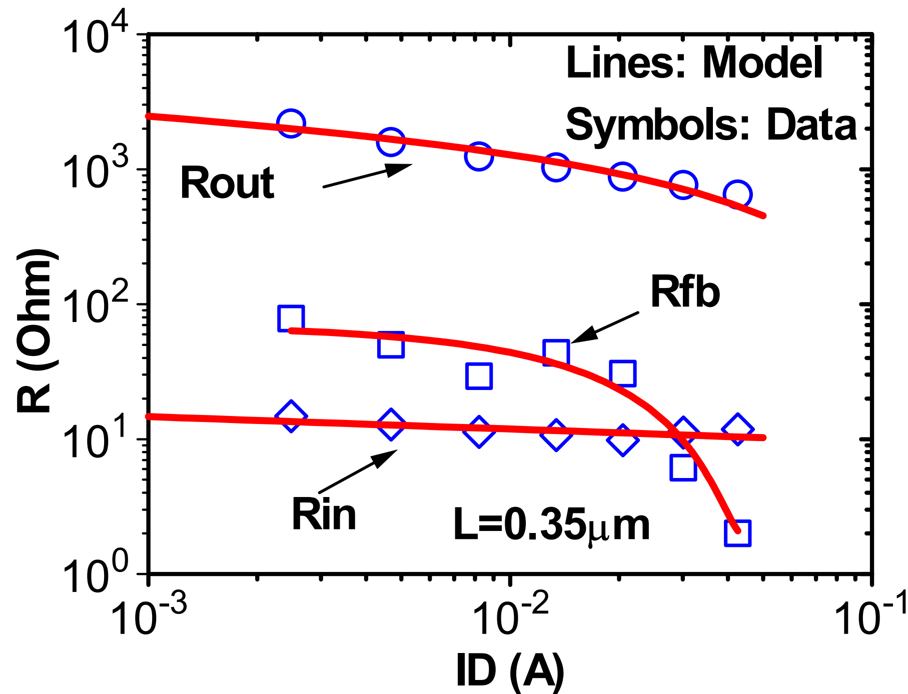
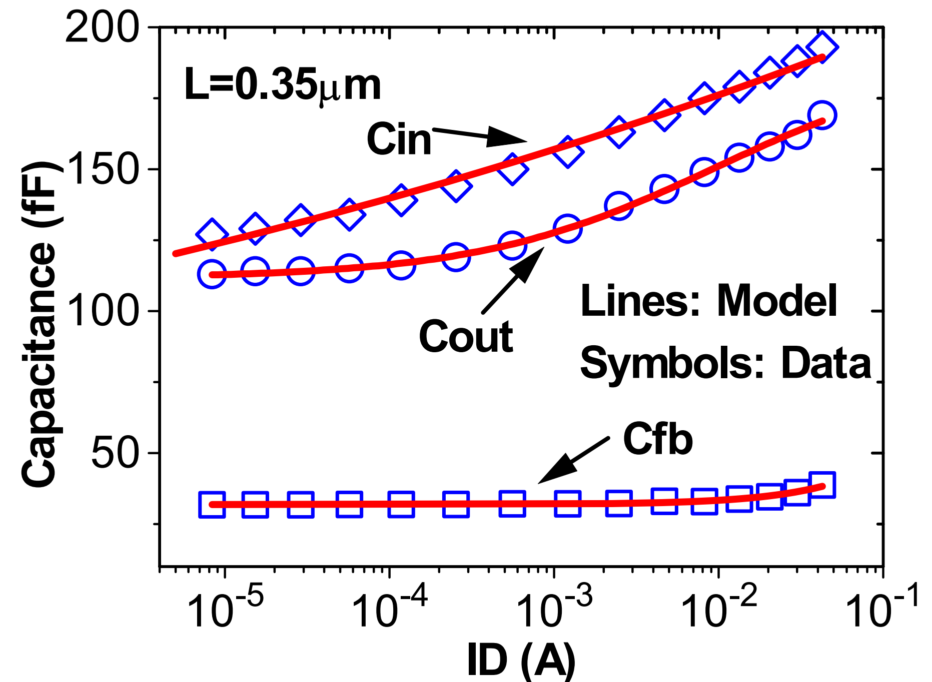
C-parameters: Modeled vs. Fitted





- C-parameters are more sensitive to the bias dependence of gate resistance and capacitance.
- Useful FoMs for model validation.

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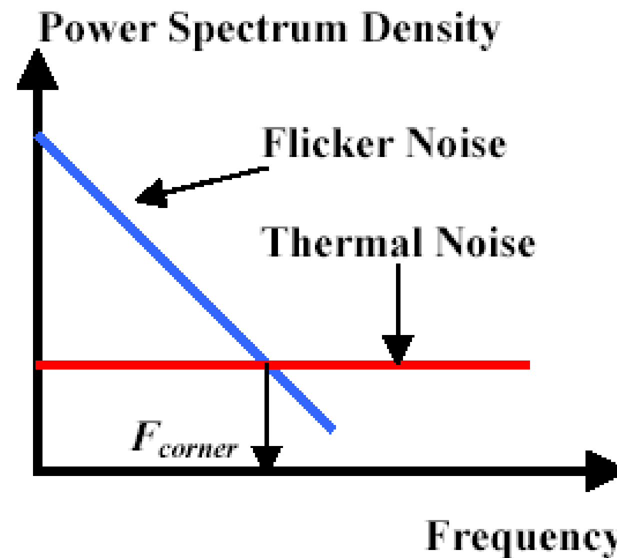
Flicker Noise & F_{corner}

- Flicker noise sets a lower limit on the level of signal detection and is one of the factors limiting the achievable dynamic range of MOS ICs.
- The impact of flicker noise cannot be neglected in RF circuits.



$$F_{corner} = \frac{K_F}{4 \cdot k \cdot T \cdot \gamma \cdot C_{ox} \cdot L^2 \cdot G_m / I_D}$$

- KF is often used to compare flicker noise behavior.
- F_{corner} is the frequency above which the noise amplitude is approximately equivalent to the thermal noises.
- F_{corner} is more straightforward to evaluate flicker noise.

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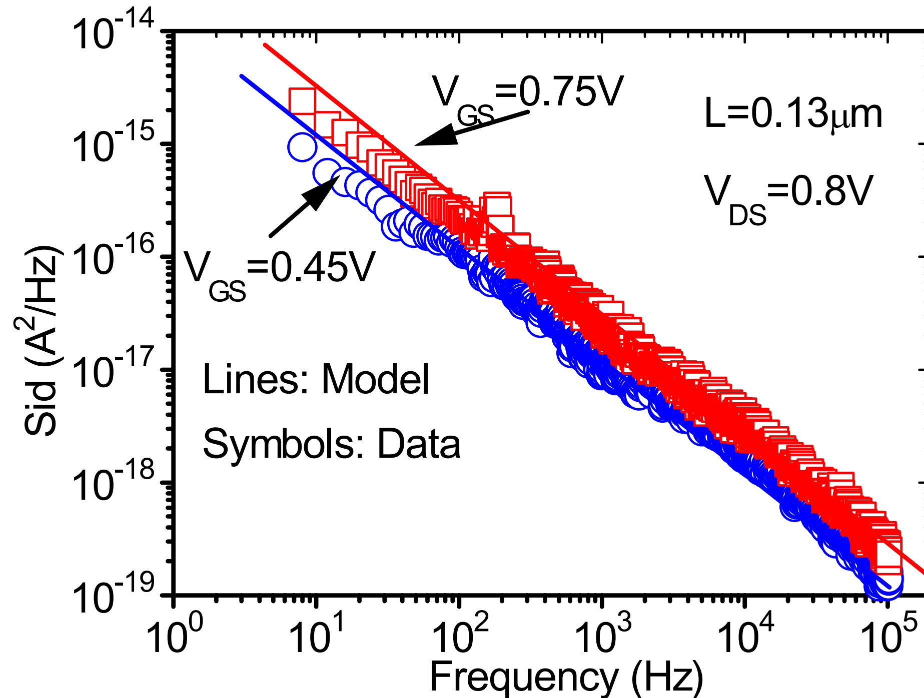
Flicker Noise: Measured vs. Fitted



- Flicker noise can be modeled at a range of given biases and geometries.
- It is difficult to measure F_{corner} directly due to the equipment limitation.
- Very important if the model could predict accurately F_{corner}.

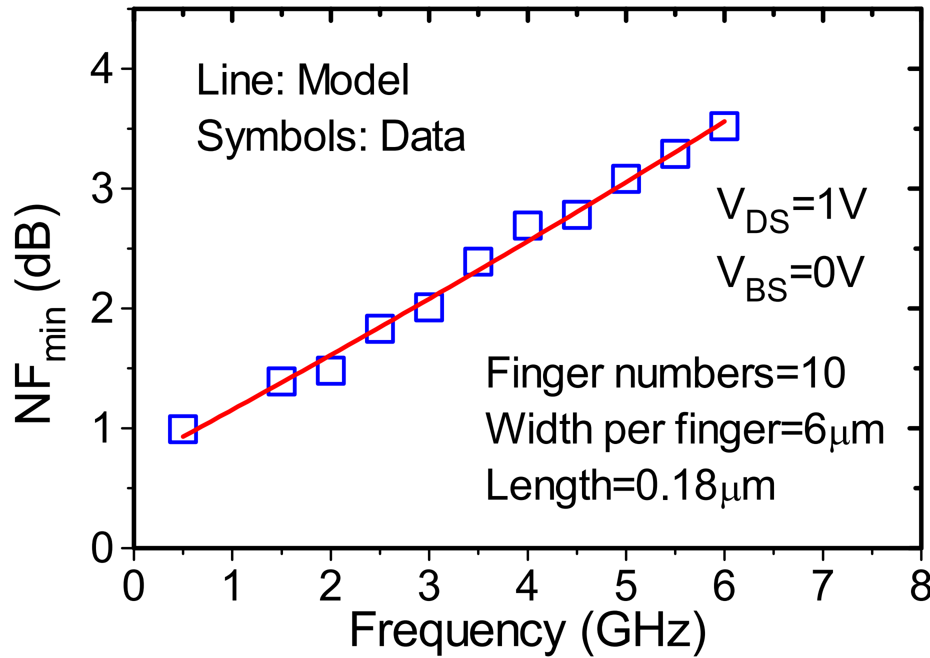
HF Noise Parameters

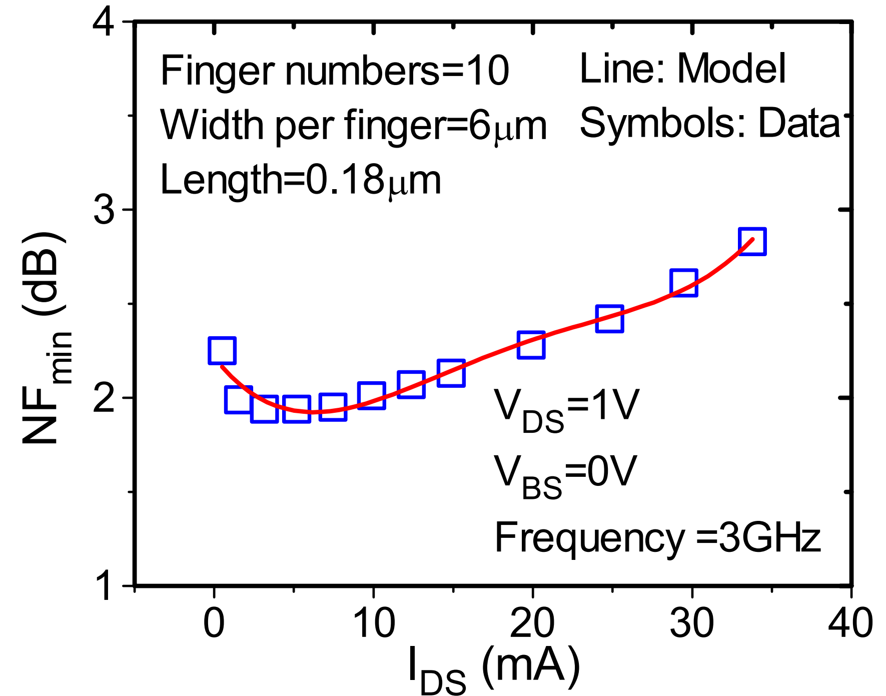
- The noise factor (N_F) is a function of minimum noise figure (N_{Fmin}), noise resistance (r_n), reflection coefficients Γ_s and Γ_{opt},

$$NF = NF\min + \frac{4 \cdot rn \cdot |\Gamma s - \Gamma opt|^2}{(1 - |\Gamma s|^2) \cdot |1 + \Gamma opt|^2}$$

- Each N_{Fmin} is associated with one value of Γ_{opt}.
- Microwave HF noise measurement provides the information on N_{Fmin} r_n, and Γ_{opt}.
- The noise performance of any linear two-port system can be compared at the known N_{Fmin} r_n, and Γ_{opt}.

Frequency and Bias Dependence of N_{Fmin}





- N_{Fmin} is a function of the biases (operating current) and frequency.
- N_{Fmin} of MOSFETs is determined primarily by transconductance (Gm) and intrinsic/parasitic capacitances.

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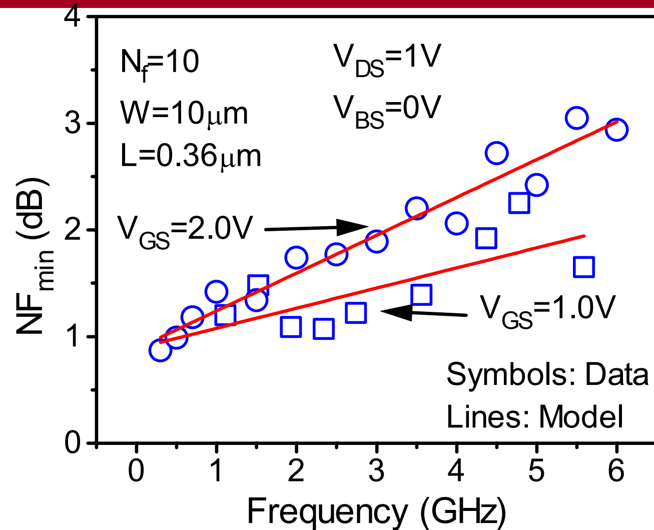
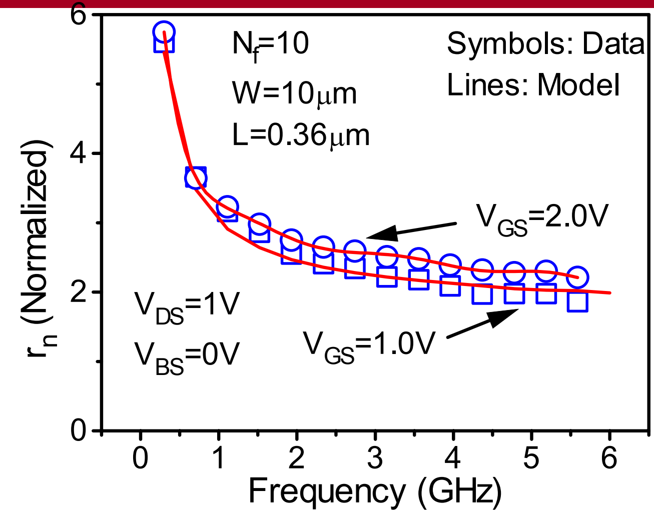
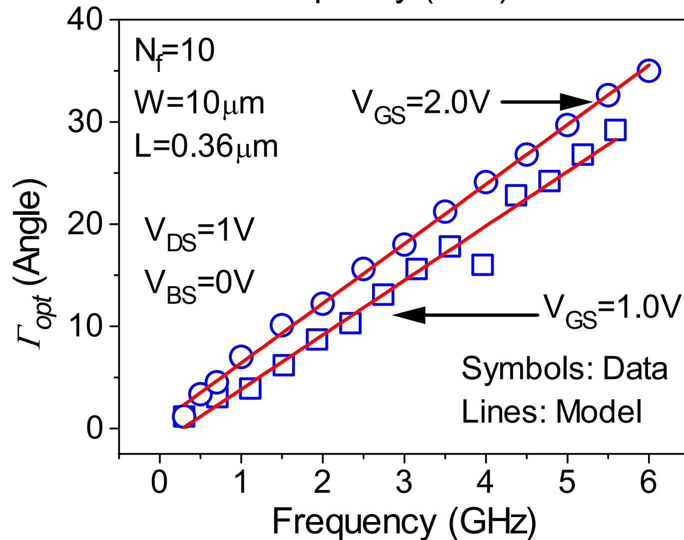
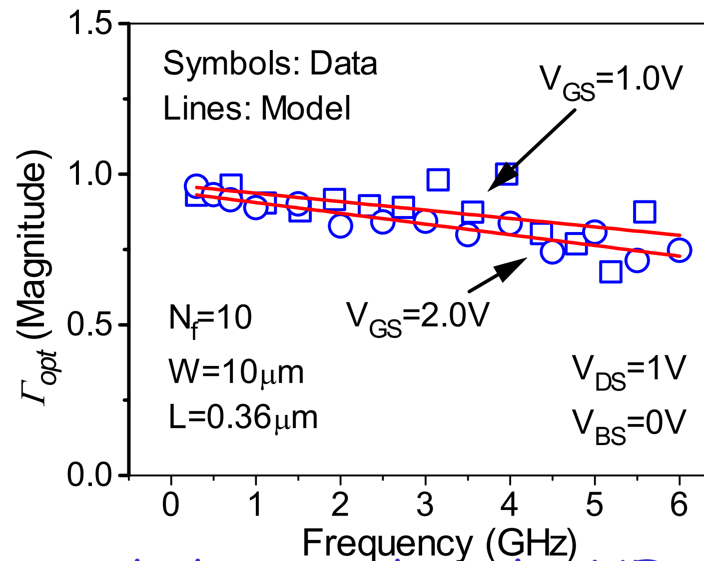
HF Noise Parameters: Measured vs. Fitted









- Careful parameter extraction is needed to predict the HF noise parameters.

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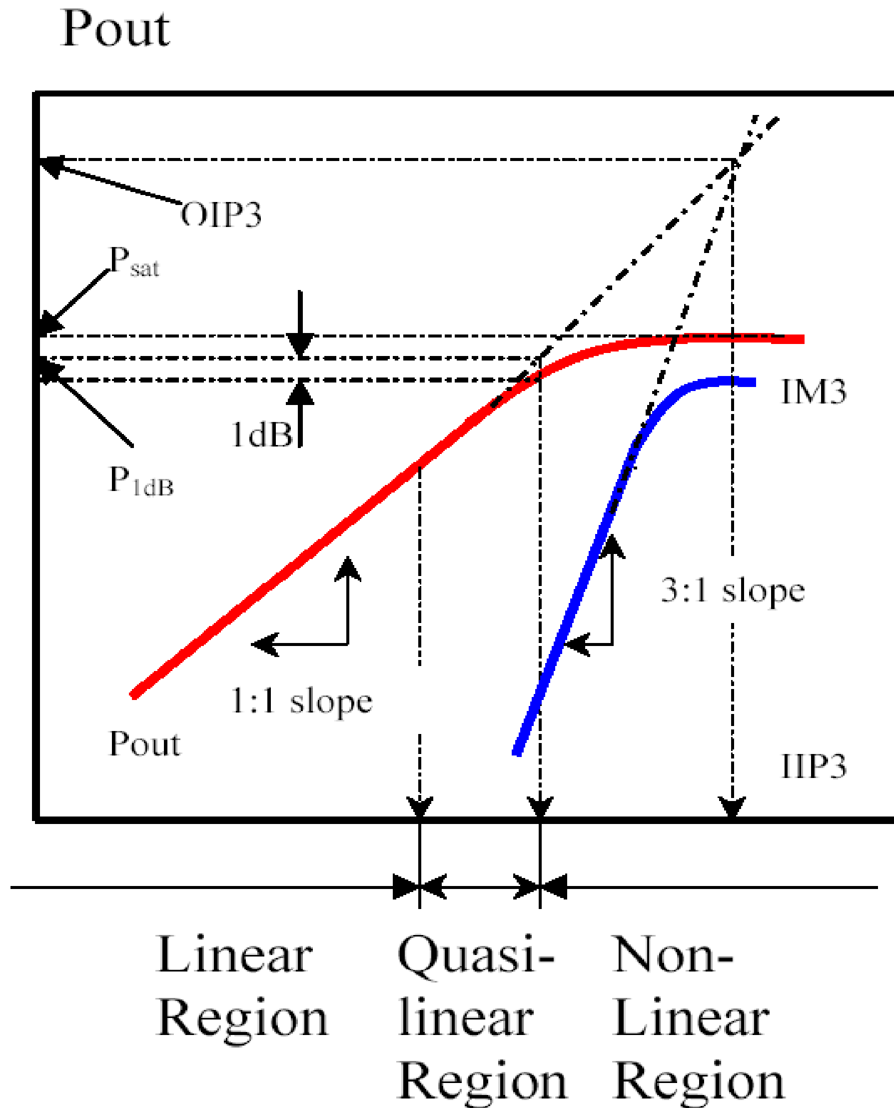
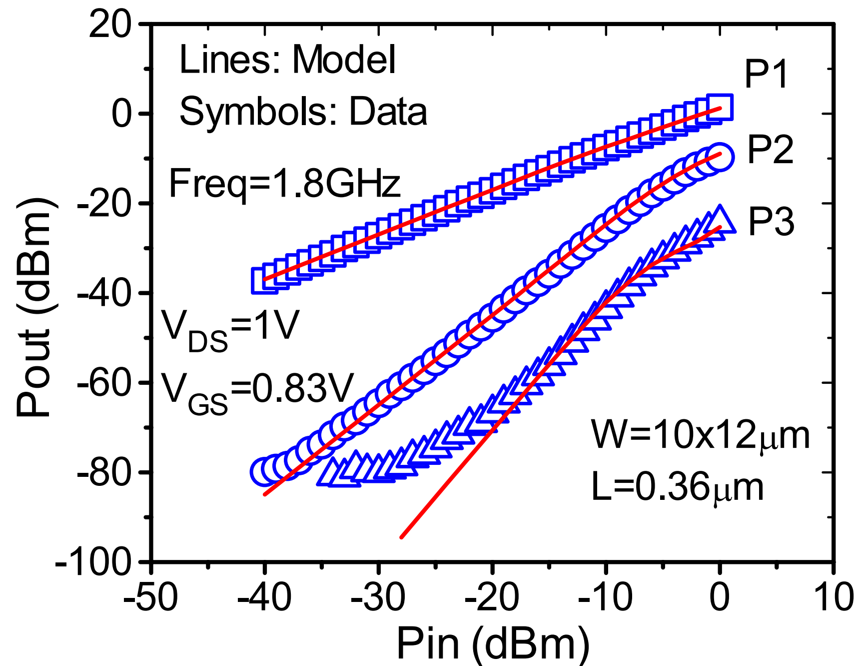
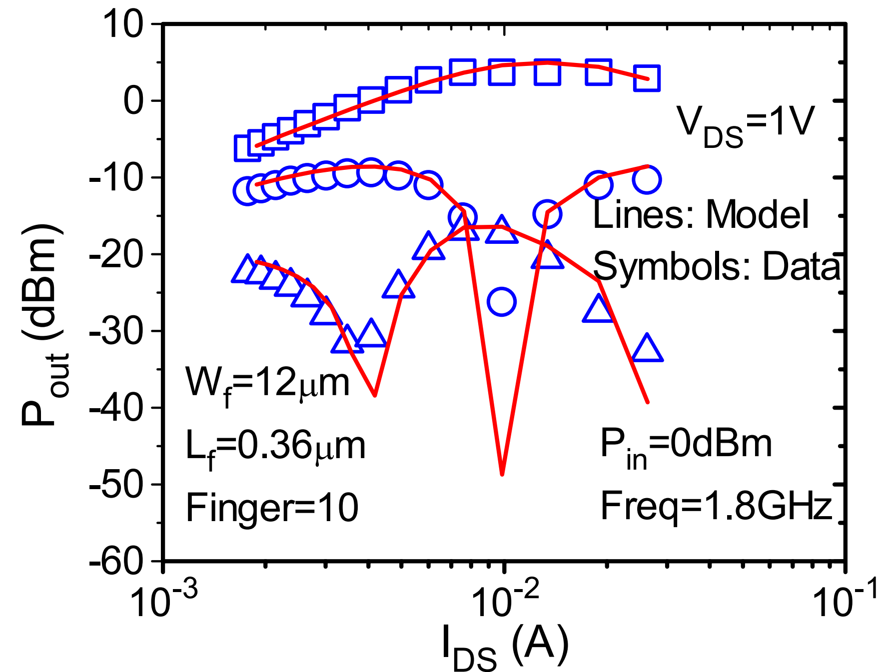
Large Signal Behavior



- P_{1dB}: the input power at which the linear gain of the amplifier has compressed by 1 dB.
  - An often-used measure of PA linear power handling capability.
- IIP3: Input third order intercept point
  - A metric when comparing RF blocks with different specifications as it is independent of the input power levels.

Large Signal Behavior: Measured vs. Fitted





- Below certain (the "LFL") frequency, the distortion behavior of MOSFETs is primarily determined by transconductance and capacitances.
- With careful parameter extraction at DC and HF small signal, a model can well predict the large signal distortion behavior.

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FoM for PA

- Efficiency: Ratio of the output RF power and the supply power.

$$\eta = \frac{P_{out}}{P_{dc}}$$

- Power added efficiency (PAE) is often used as a FoM when comparing the performance of PAs with different input power levels

$$PAE = \frac{P_{out} - P_{\text{int}}}{P_{dc}}$$

Many RF amplifiers are designed to operate in the weakly nonlinear region, where PAE peaks.

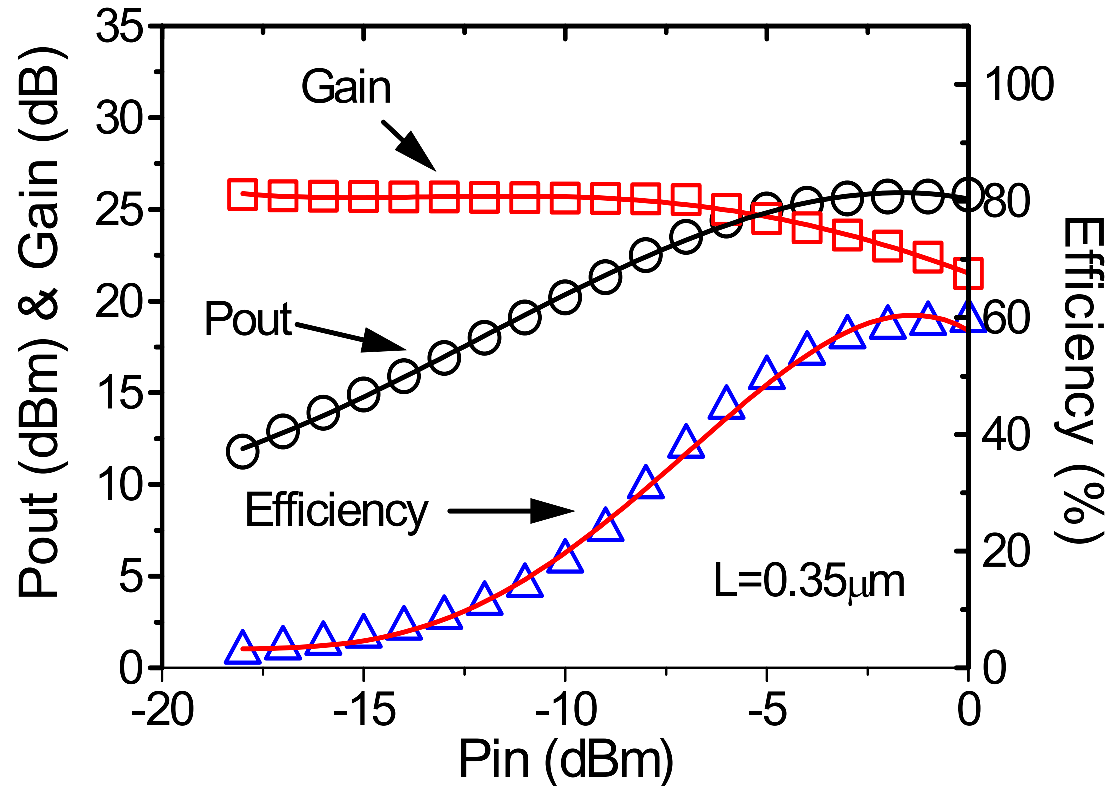
FoM for PA (CONT.)

- Linearity
  - MOSFET will be biased at as high as possible input signal amplitude to accommodate the smaller transconductance.
  - Increasing the input signal amplitude can dramatically degrade the PA linearity because the third-order nonlinearity of the device current is directly proportional to the cube of the input voltage amplitude.
  - The linearity of MOSFET is very critical to PA design.
- Baliga factor

$$Eb = \left(\frac{4 \cdot V_{bk}^2}{\varepsilon \cdot \mu \cdot R_{on}} \right)^{1/3}$$

  - An important FoM for high power MOSFET design
  - MOSFETs' breakdown behavior should be evaluated also when other device parameters are checked.

FoM for Model Validation



- For PA application, three parameters (gain, efficiency, and Pout) vs. Pin should be examined.
- From modeling point of view, the accuracy of capacitance model over frequency and biases is extremely critical to predict the large signal behavior.

FoM for RF Switch Applications

- On-state Insertion Loss (IL)

$$IL(dB) = 10 \cdot \log(P_{in}/P_{out}) = -20 \cdot \log|s21|$$

- Off-state Isolation

$$Isolation\,(dB) = 10 \cdot \log(P_{out}/P_{source})$$

- Linearity

Linearity can be measured as the difference between the powers of the fundamental P1,dBm and the third-order intermodulation P3,dBm.

$$P_{linearity}\,(dBm) = P_{1,dbm} - P_{3,dbm} = 10 \cdot \log(P_1/P_3)$$

P1 and P3 are the powers of the fundamental tone and the third order intermodulation tone.

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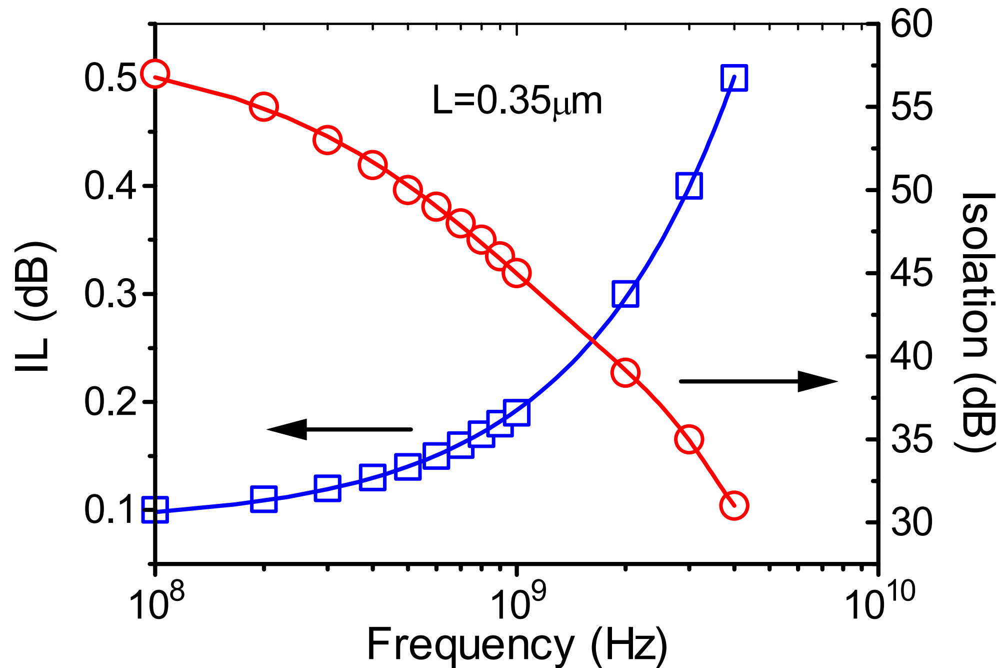
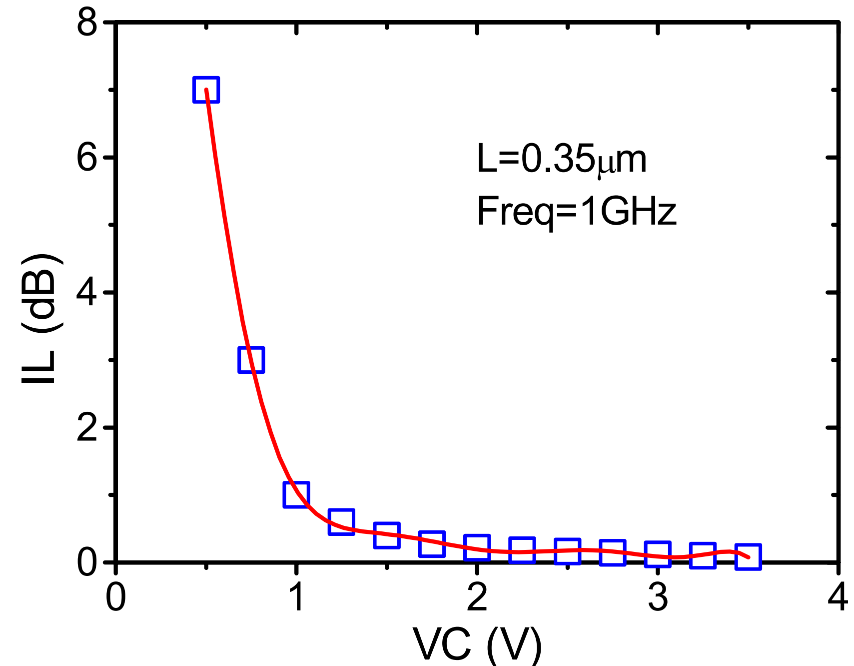
FoM for Model Validation





- A good RF model should predict the IL and isolation behavior over a wide frequency range.
- The bias dependence of IL over a wide range should be modeled.
- Careful parameter extraction might be needed to describe the IL behavior in the transition regime around V_{TH}.

Summary

- It is time to re-examine some important device parameters as a set of FoM in evaluating technology performance and qualifying device models for analog/RF applications.
- It would be desirable in the future that the process developers use most of these FoMs to guide the process technology development and that the modelers use them to qualify the device models targeted for analog/RF applications.
- This paper is to initiate the efforts using these FoM.
- Certain standard model QA routines should be developed based on these FoMs.

Thank You for Your Attention

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