



RF/Analog SiGe BiCMOS Device Modeling

# Investigation of Substrate Current Effects and Modeling of Substrate Resistance Network for RFCMOS

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# Outline

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- **Motivation – How to create good  $S_{22}$  and  $Y_{22}$  models?**
- **Substrate Current ( $I_{sub}$ ) Mechanism**
- **Substrate Current Effects in RFCMOS Modeling**
- **Substrate Resistance ( $R_{sub}$ ) Network**
- **$S_{22}$  Correlation Based on the Proposed Network with an Accurate  $I_{sub}$  Model**
- **Noise Figure Discussion**
- **De-embedding Investigation**
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# Motivation

- **How to create good  $S_{22}$  and  $Y_{22}$  models?**

- Consider it from the low frequency to the high frequency region.
- Neglecting the gate resistance ( $R_g$ ) and source-bulk junction capacitance ( $C_{jsb}$ ), the simplified  $Y_{22}$  is given by

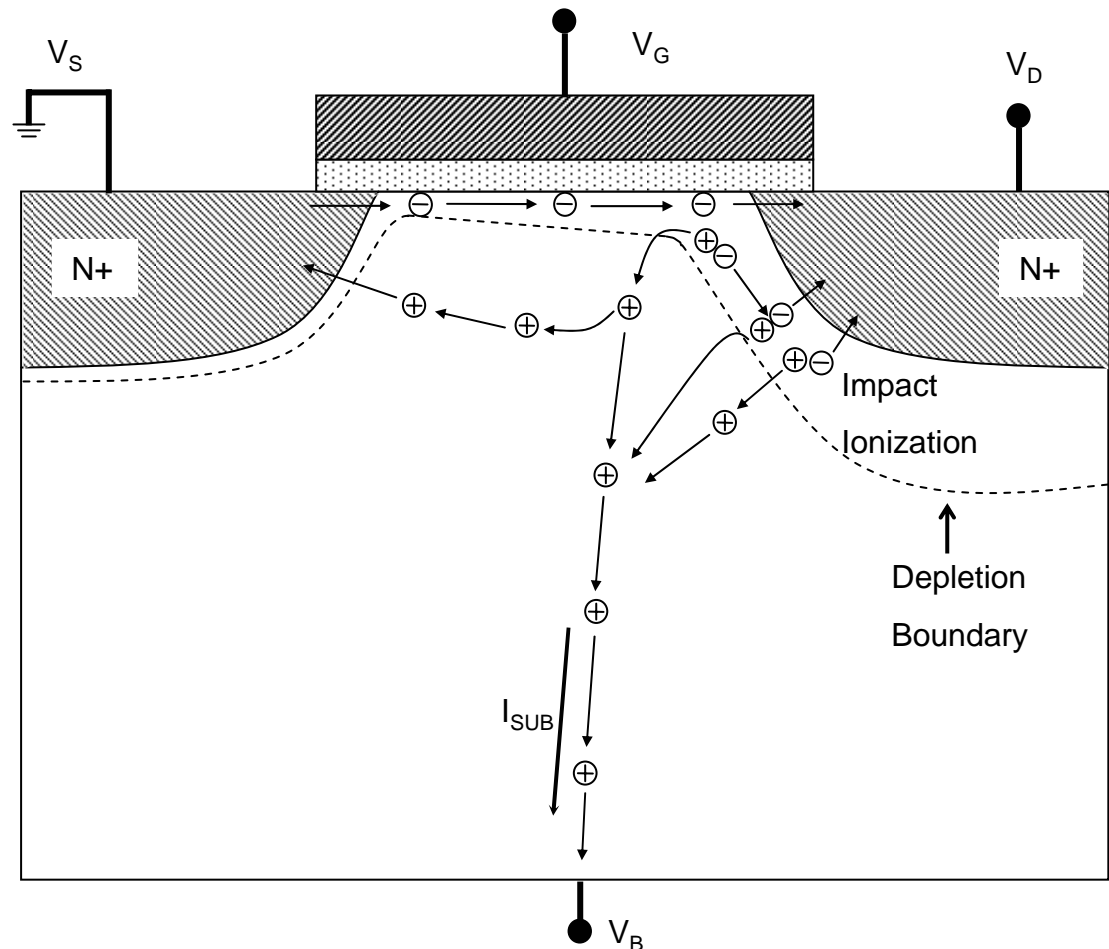
$$Y_{22} = G_{ds} + \frac{\omega^2 R_{sub} C_{jdb}}{1 + D^2} + j\omega \left( C_{gd} + \frac{C_{jdb}}{1 + D^2} \right)$$

Where  $G_{ds}$  is the output conductance,  $C_{jdb}$  is the drain-bulk junction capacitance,  $C_{gd}$  is the gate to drain capacitance and  $D = \omega R_{sub} C_{jdb}$

- $S_{22}$  can be obtained from Y-parameter convention.
  - (1)  $G_{ds}$  controls low frequency region
  - (2) Capacitance (like  $C_{gd}$ ) controls high frequency region
  - (3) Substrate resistance ( $R_{sub}$ ) controls from the medium frequency to the high frequency region

# Substrate Current Mechanism: Impact Ionization

- At high  $V_{ds}$ , electrons in the channel gain considerable kinetic energy.
- When colliding with lattice, these electrons generate electron-hole pairs (EHPs).
- The generated holes are swept into the substrate and constitute the substrate current.



# Substrate Current Effects

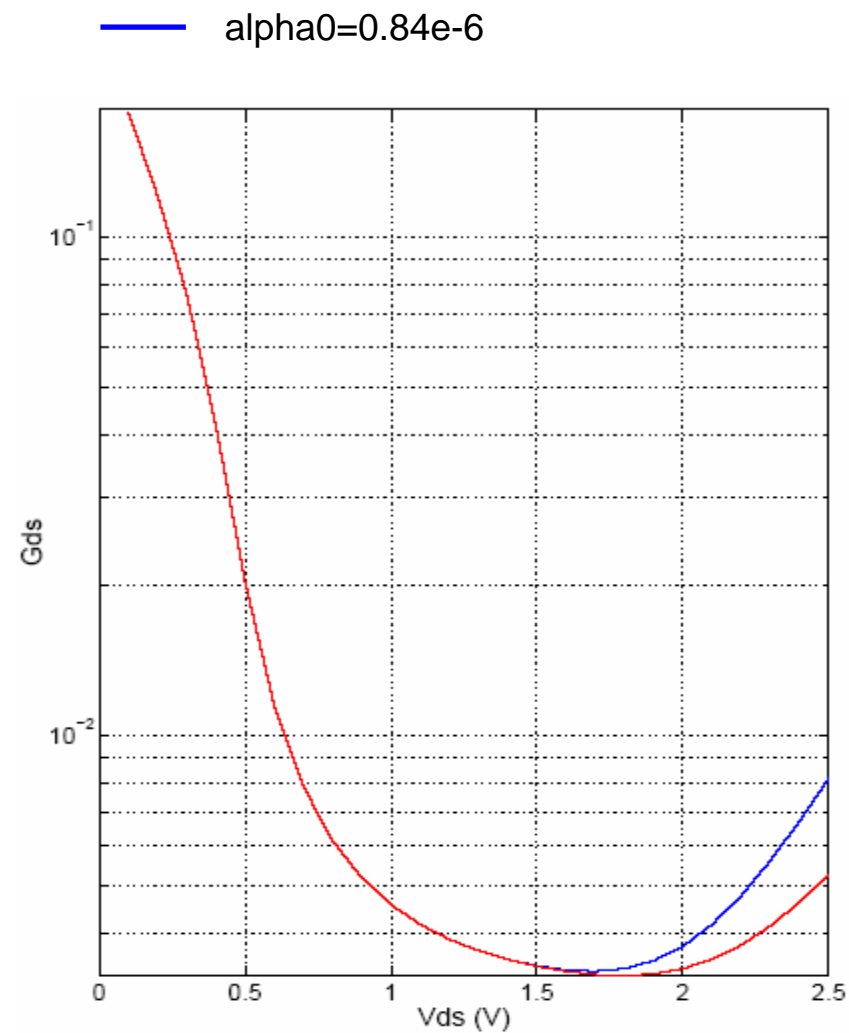
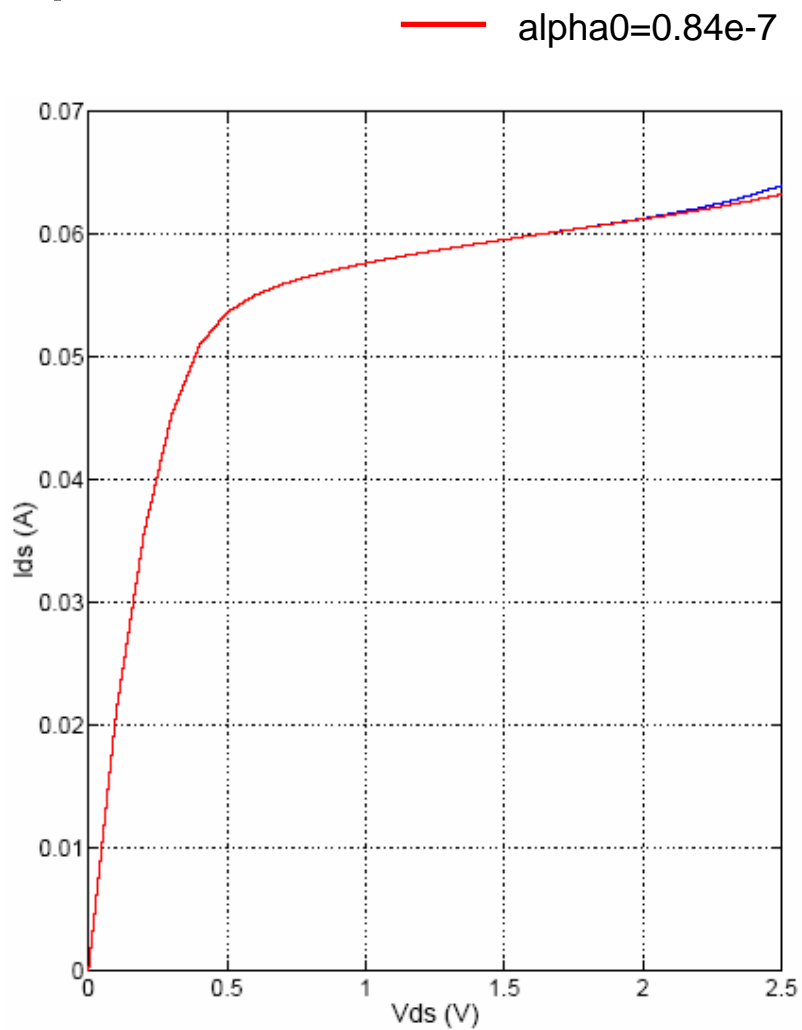
- The substrate current ( $I_{\text{sub}}$ ) is often regarded as unimportant in the DC model because the magnitude of  $I_{\text{sub}}$  is much smaller than the channel current ( $I_{\text{dch}}$ ).
- However, it significantly impacts  $G_{\text{ds}}$  behavior because

$$G_{\text{ds}} = \frac{d(I_{\text{ds}})}{dV_{\text{ds}}} = \frac{d(I_{\text{dch}})}{dV_{\text{ds}}} + \frac{d(I_{\text{sub}})}{dV_{\text{ds}}}$$

- Example: NFET device of 7.5x0.24umx32 fingers at  $V_{\text{gs}}=1.5\text{V}$  and  $V_{\text{ds}}=2.5\text{V}$ , and the different  $I_{\text{sub}}$  models by adjusting the BSIM3v3 alpha0 parameter (alpha0 increases by one order of magnitude)

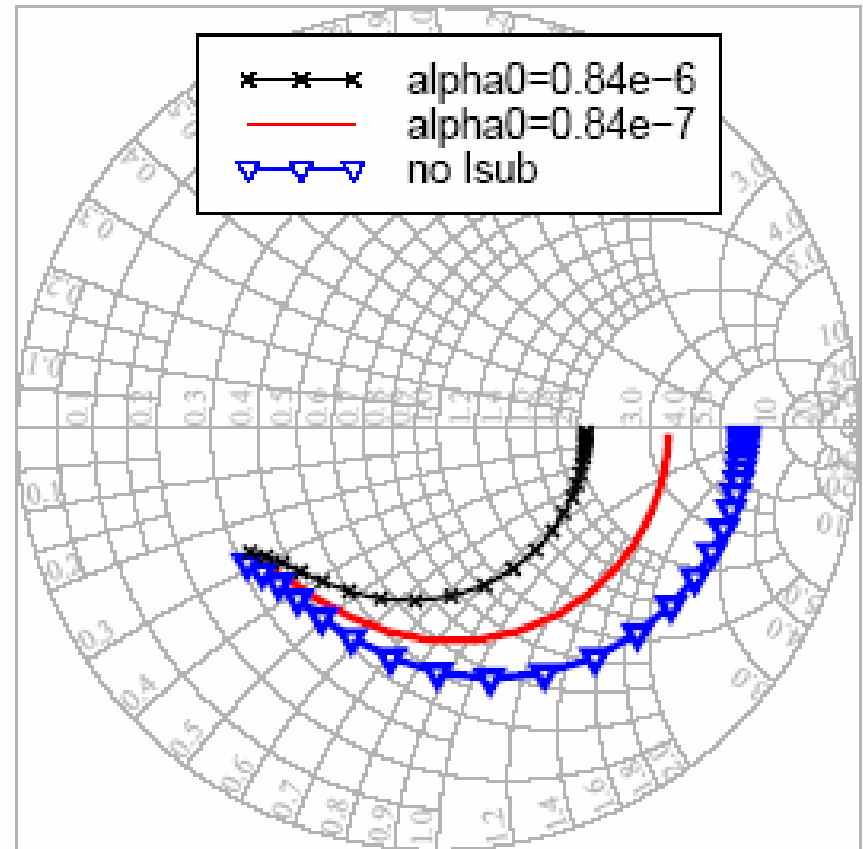
	alpha0= 0.84e-7	alpha0= 0.84e-6	Difference (%)
$I_{\text{ds}}$ (A)	6.32e-2	6.39e-2	+1.13%
$G_{\text{ds}}$	5.26e-3	8.19e-3	+55.65%

# Effects of Substrate Current on $I_{ds}$ and $G_{ds}$



# Substrate Current and $S_{22}$

- The low frequency region of the  $S_{22}$  characteristics of a FET is determined by the total output conductance ( $G_{ds}$ ), which is sensitive to the  $I_{sub}$  variation.
- A good  $I_{sub}$  model is the foundation of  $S_{22}$  model.





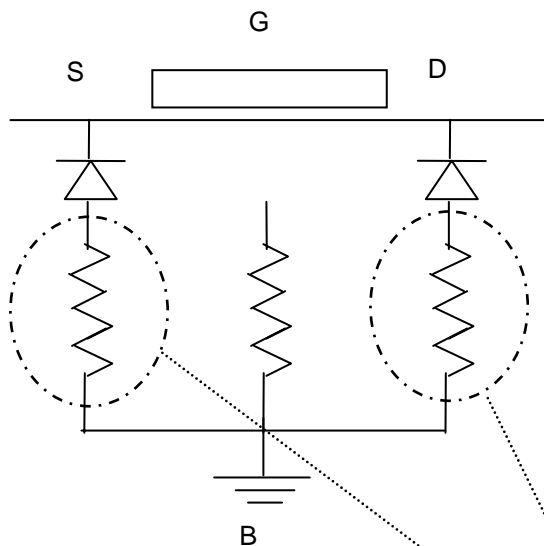
## Substrate Resistance ( $R_{sub}$ ) Network

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- **Accuracy in Predicting  $S_{22}$  cannot be achieved without a reliable  $R_{sub}$  network in addition to the  $I_{sub}$  model.**
- **Most of the prior studies and BSIM4 RF model either have a problem with geometric scalability or difficulty with the model parameter extraction.**
- **An accurate, compact and scalable  $R_{sub}$  network for the  $S_{22}$  modeling mainly in the medium and high frequency region is proposed here.**

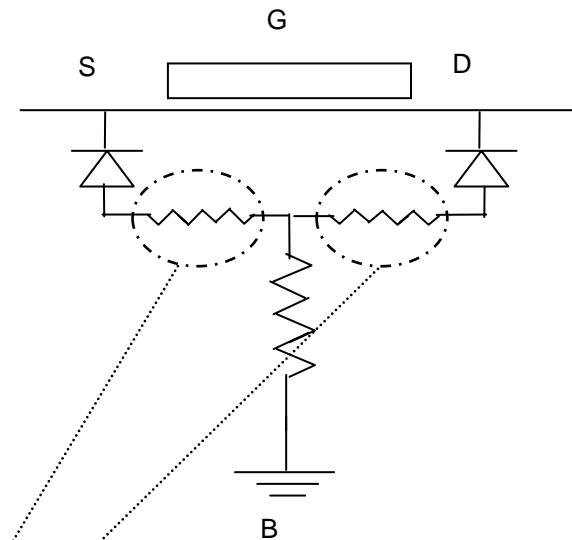
# Proposed Rsub Network vs. Another Network

(a)



The proposed "All ground" Rsub network

(b)

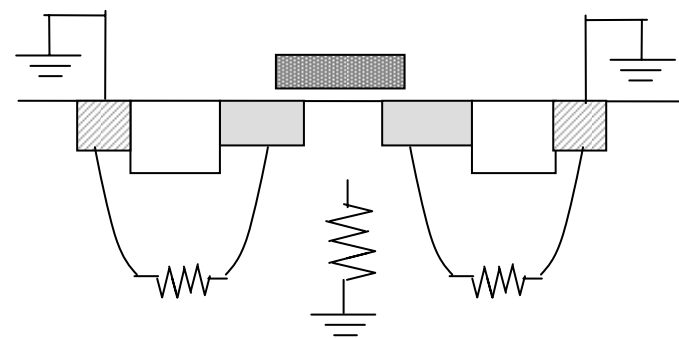
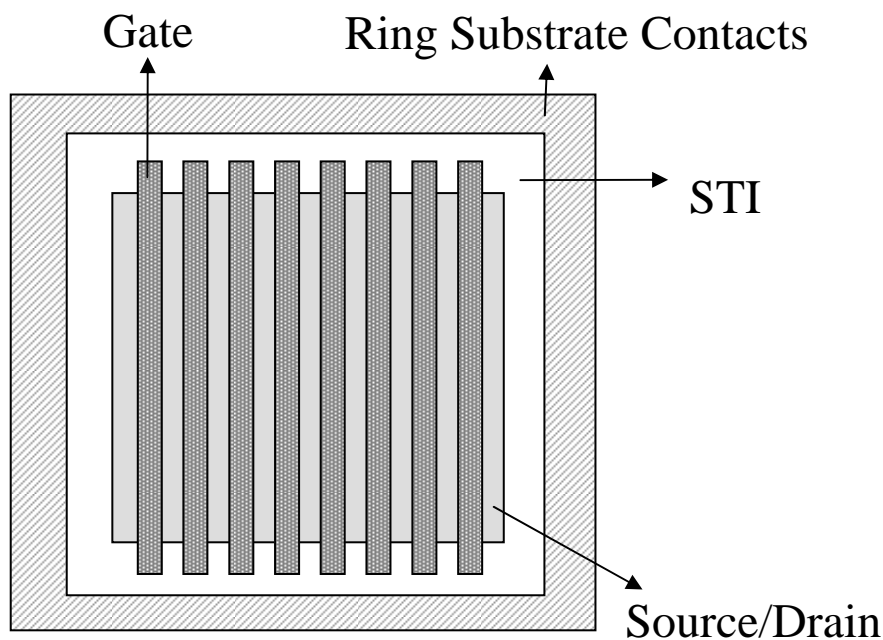


"T" shape Rsub network

Control the high frequency region of the  $S_{22}$

# RF Device Layout Configuration

- Basically, the proposed Rsub network is more consistent with physical layout configuration.

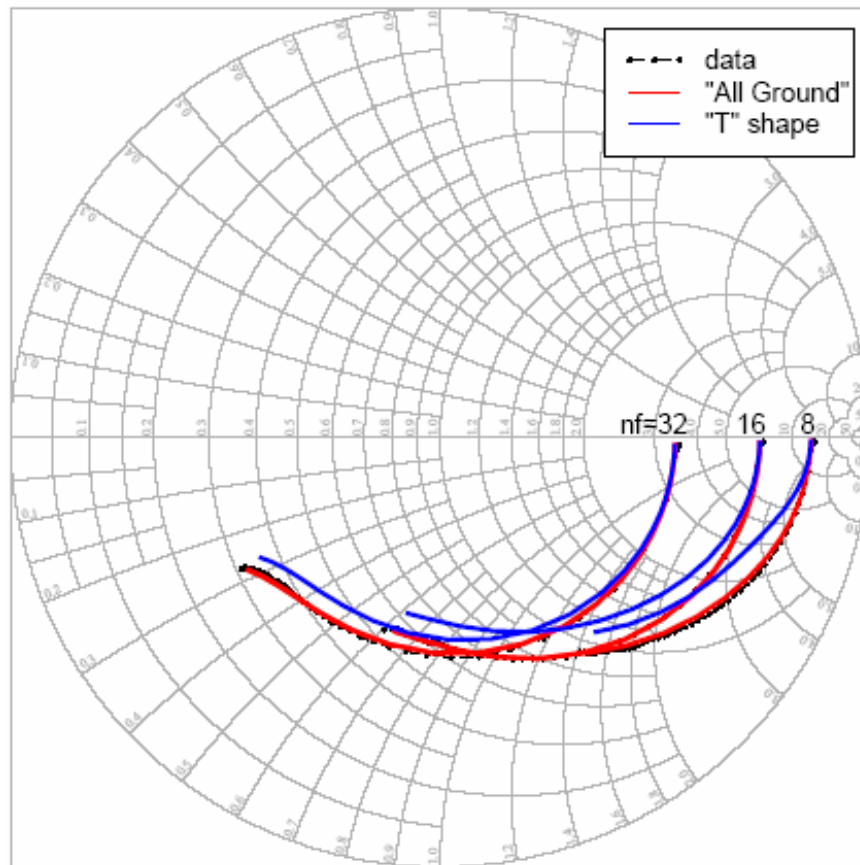


Top View Layout

A MOSFET Cross-section

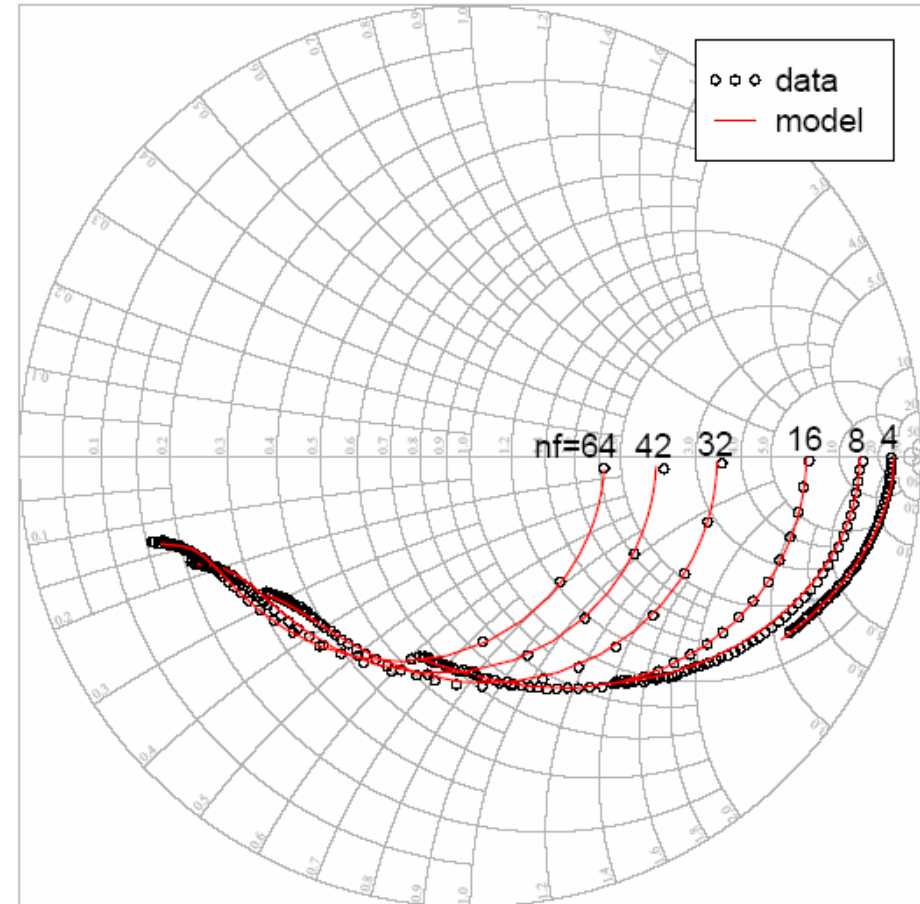
# S22 Comparison of Tow Networks

- The device widths of 240um (32 fingers), 120um (16 fingers) and 60um (8 fingers) at the fixed  $L=0.24\mu\text{m}$  ( $V_{gs}=1.5\text{V}$  and  $V_{ds}=2.5\text{V}$ ) are shown here.
- The simulation results show “All ground”  $R_{sub}$  network provides the best performance on  $S_{22}$  fitting.
- The simulation results also support the proposed  $R_{sub}$  network to be consistent with layout configuration.



# $S_{22}$ Correlation Based on the Proposed Network

- The devices of 64, 42, 32, 16, 8 and 4 fingers and 7.5 $\mu\text{m}$  width per finger at the fixed  $L=0.24\mu\text{m}$  ( $V_{gs}=1.5\text{V}$  and  $V_{ds}=2.5\text{V}$ ) are shown here.
- Accurate scalability with device geometry for  $S_{22}$  up to 25GHz is achieved using the “All ground”  $R_{sub}$  network and a desirable  $I_{sub}$  model



# Noise Figure Discussion

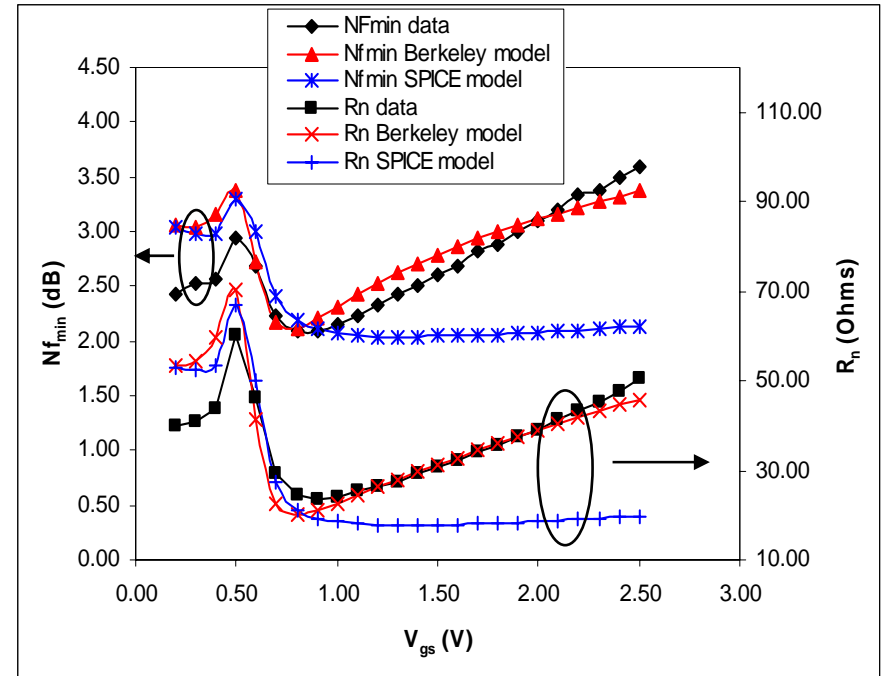
- **The SPICE model for channel thermal noise:**

$$S_{id}(f) = \gamma \cdot 4KT(g_m + g_{mbs} + g_{ds})$$

- **The Berkeley model for channel thermal noise:**

$$S_{id}(f) = \frac{4K_B T \mu_{eff}}{L_{eff}^2 + \mu_{eff} |Q_{inv}| \cdot R_{ds}} |Q_{inv}|$$

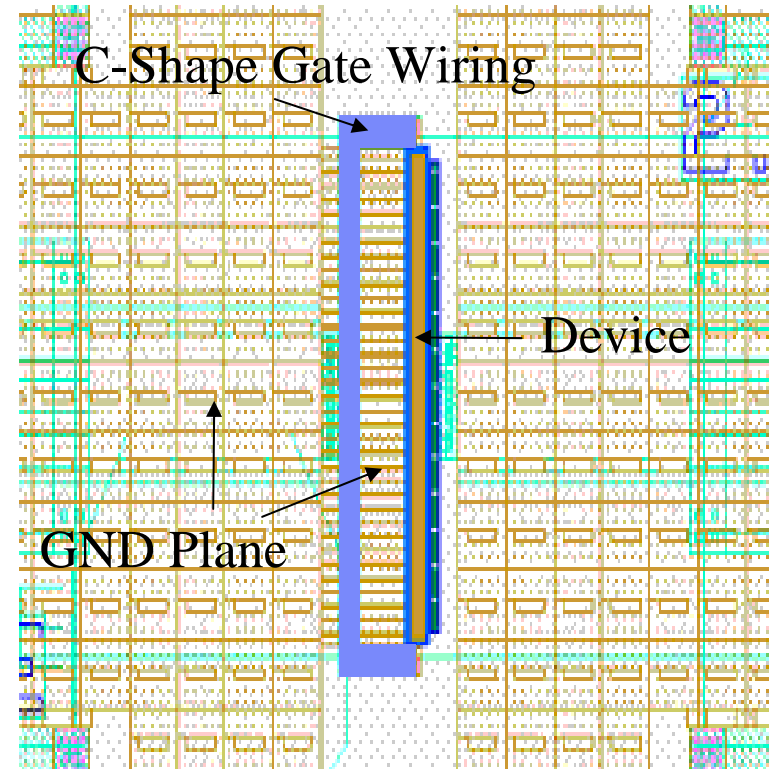
- **The plot shows the Berkeley model is better because it uses inversion charge for noise calculation, which has good bias dependence.**



SPICE and Berkeley model correlation with the data for NFmin and Rn vs. Vgs at 15GHz  
 $V_{ds}=1.5V$ ,  $W=240\mu m$  (32 fingers),  $L=0.24\mu m$

# De-embedding Investigation

- **Low-level C-shape gate wiring to the device without the ground plane introduces coupling to the substrate; which violates the assumption of Open-Short de-embedding scheme.**
- **Even the most sophisticated parasitic de-embedding scheme will not be successful if the coupling to substrate is not capture in the de-embedding structures.**
- **A solution is to have the ground plane all over the layout except the active device area and use high-level C-shape gate wiring to the device.**



Device and wiring layout with good shielding  
Under local gate wiring to prevent coupling to  
the substrate



## Conclusion

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- **The effects of  $I_{sub}$  on the output characteristics of NFET multi-finger device have been demonstrated in the low frequency region.**
- **Also, we examined the  $S_{22}$  modeling accuracy and geometric scalability using the proposed  $R_{sub}$  network containing three components.**
- **An excellent agreement between the  $S_{22}$  measured and simulated data was shown.**
- **The RF noise modeling and its de-embedding have been discussed.**