TOSHIBA
Leading Innovation

[4D-2]
Challenges of accuracy for the Design of Deep-Submicron RF-CMOS circuits

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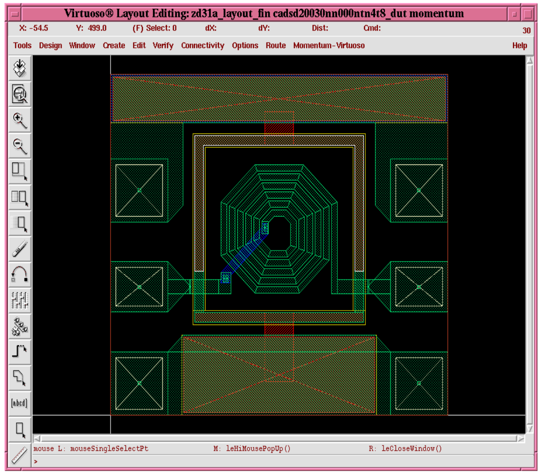
Contents

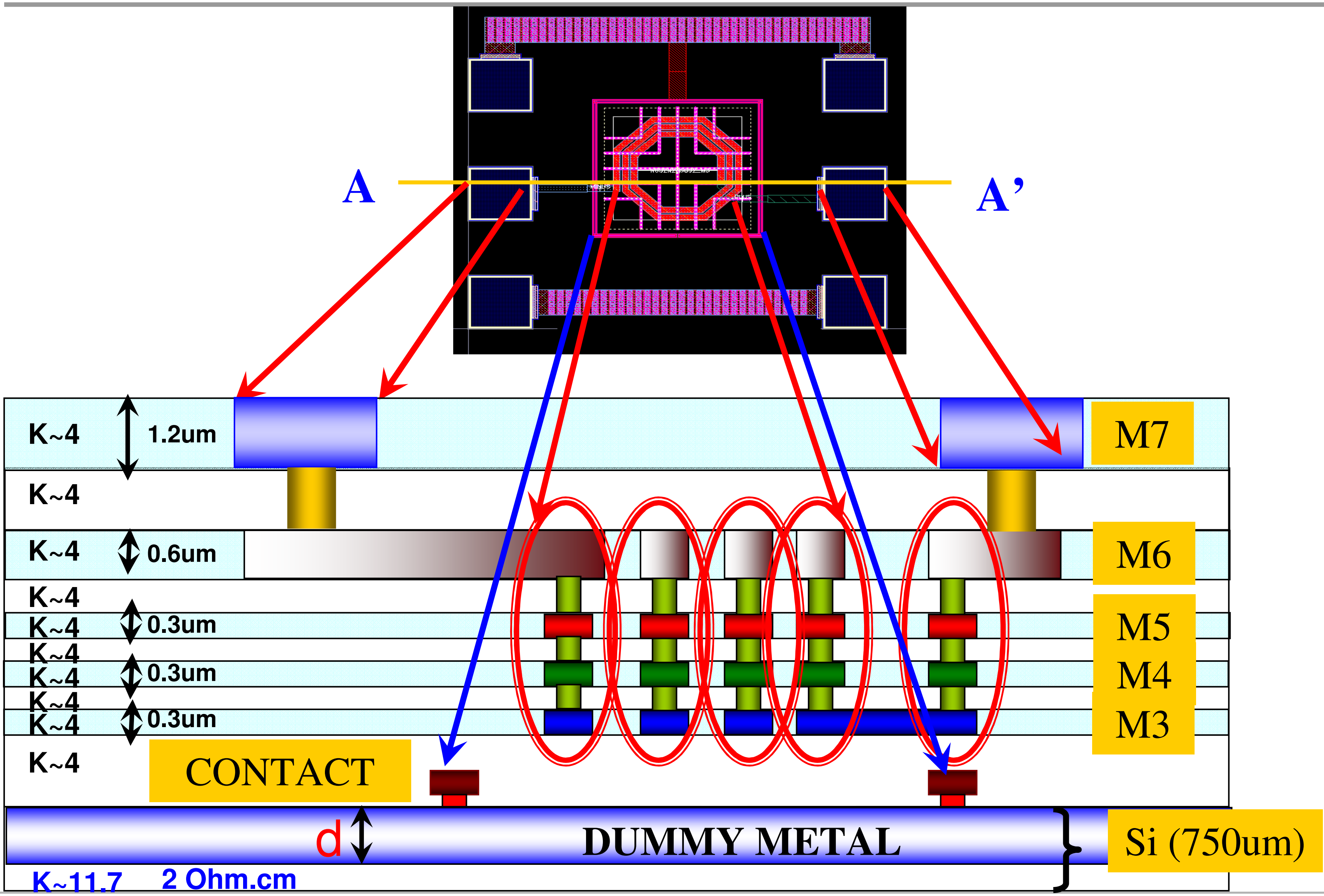
1. *Make the best of Electro-Magnetic (EM) simulation.*
   - Is EM simulator applicable for silicon technology ?
   - EM simulator enables accurate modeling of passive devices (Inductor and MIM capacitor) on silicon.



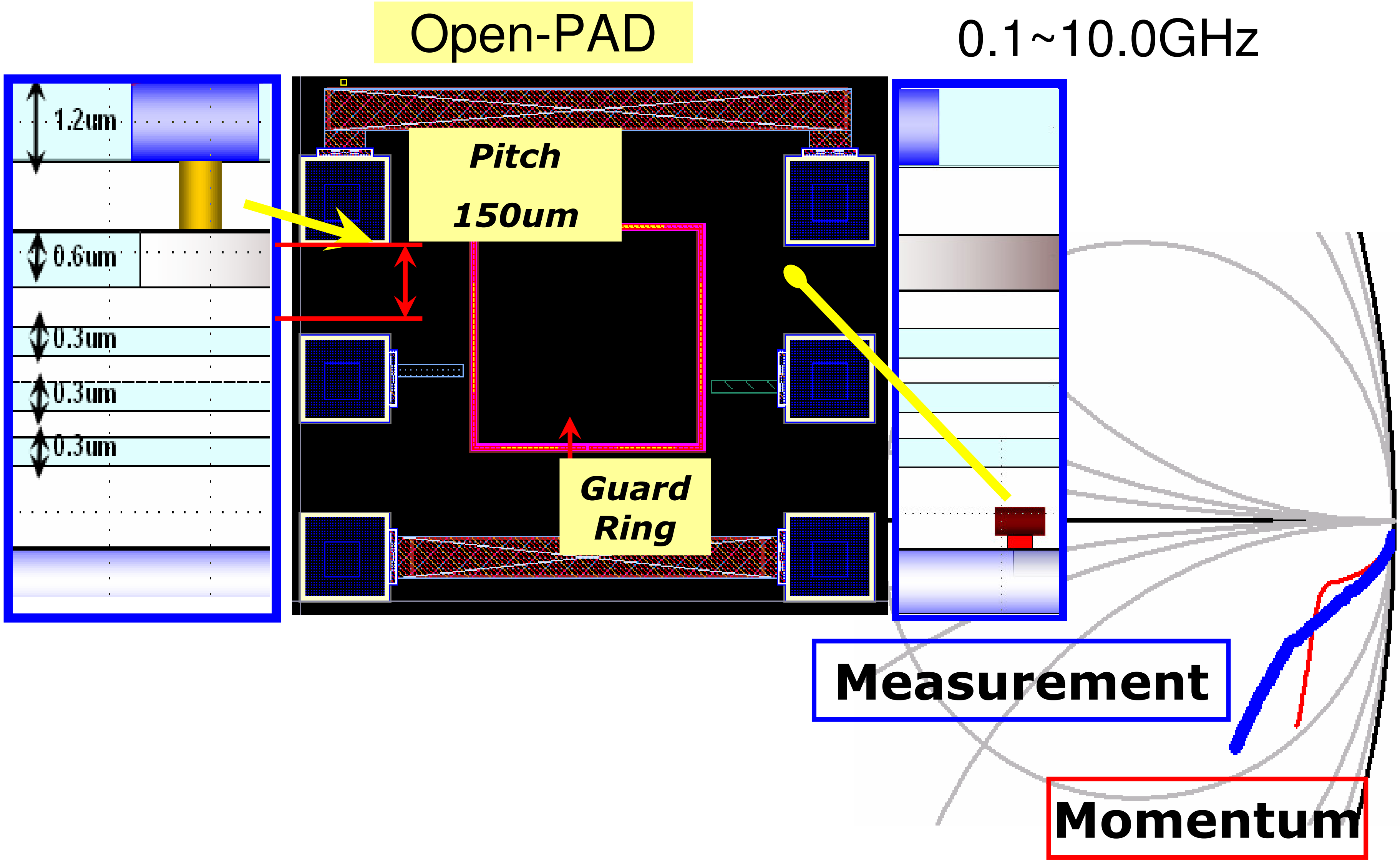
2. *Utilize "very-accurate" compact model.*
   - Looking at the EKV3.0 MOSFET Model.
     - Accuracy of conductance.
     - NQS effects.

3. *Use the Co-simulation Technique for final evaluation.*
   - Case1:CMOS Amplifier
   - Case2:CMOS VCO
   - Case3:BiCMOS LNA

Cross Section of 130nm CMOS

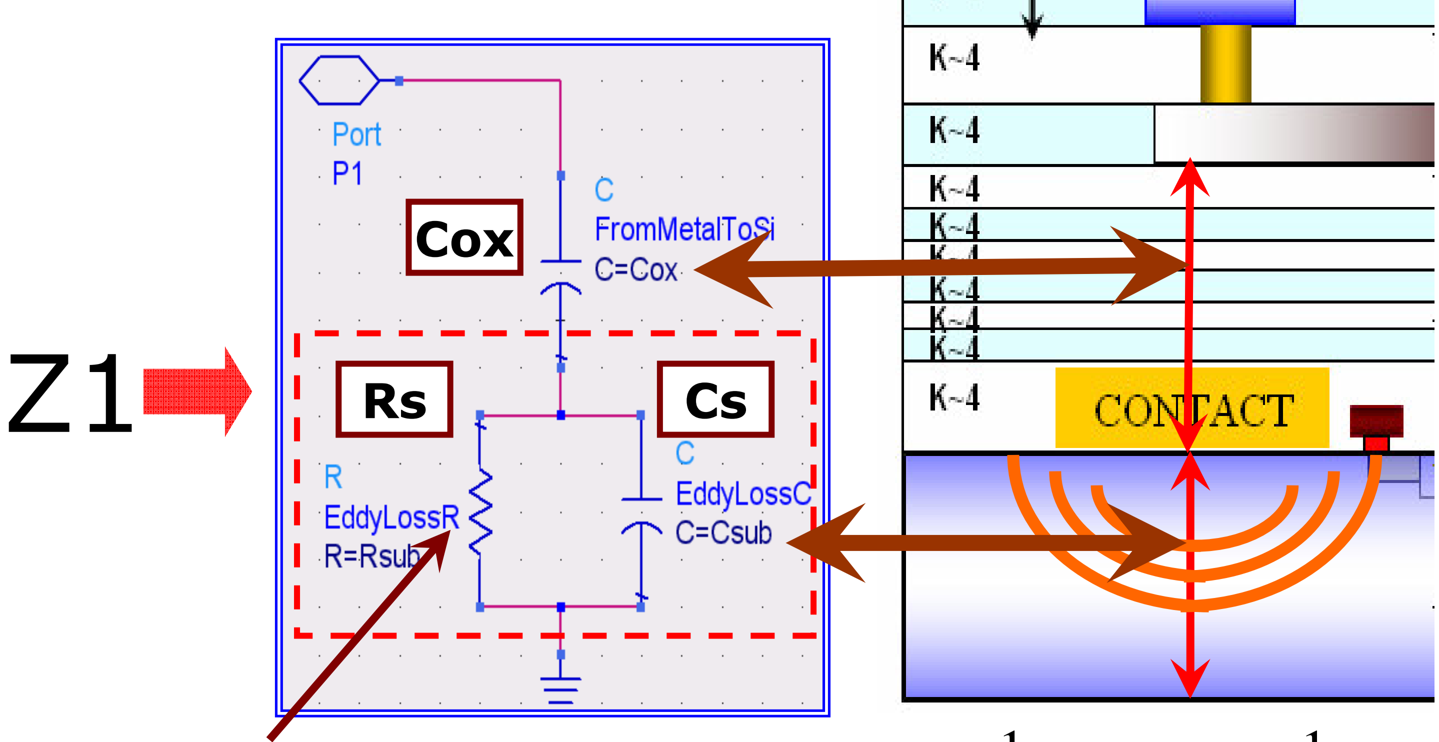


Preliminary Analysis



Equivalent circuit of PAD structure

Eqilvalent Circuit

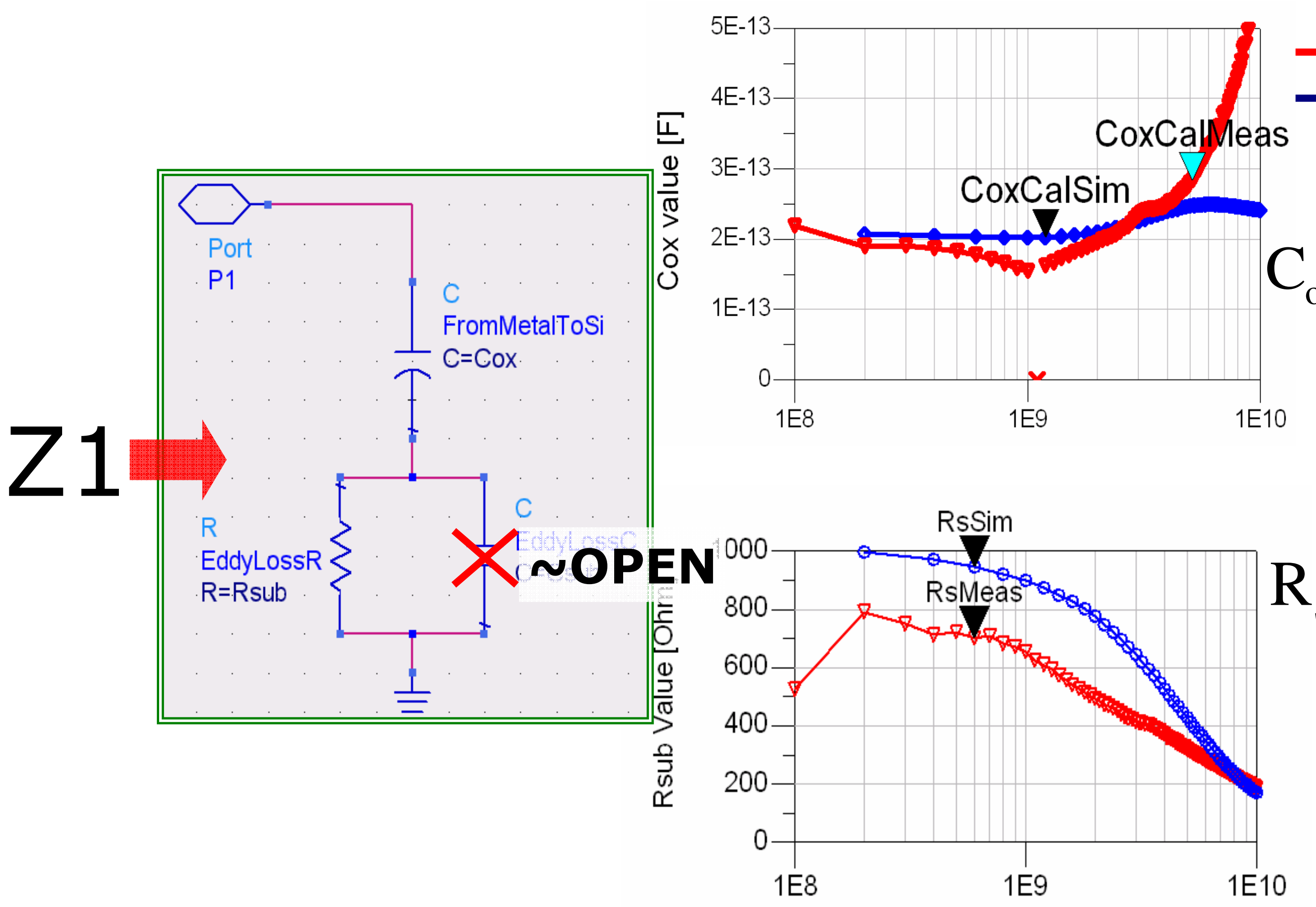


Zsub (Eddy-Current Loss of Silicon)

$$Z_{SUB} \equiv Z_1 - \frac{1}{j\omega C_{ox}} = \frac{1}{j\omega C_{SUB} + 1/R_{SUB}}$$

Frequency behavior of the PAD (1/2)

Low Frequency

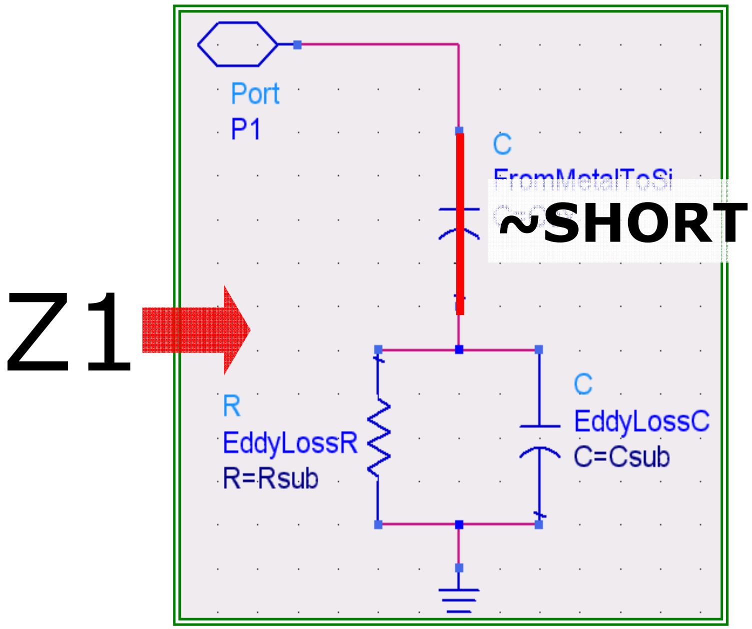


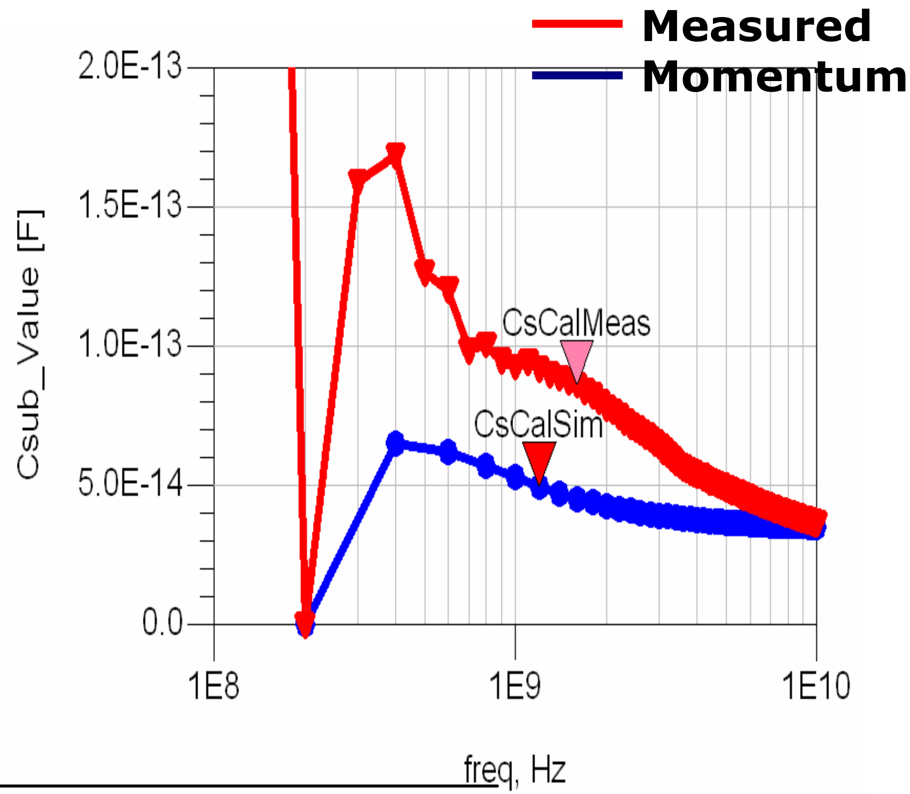
$$C_{ox} \approx \frac{-1}{\omega \cdot \mathrm{imag}[Z_1]}$$

$$R_{SUB} \approx \mathrm{real}[Z_{SUB}]$$

Frequency behavior of the PAD (2/2)

High Frequency

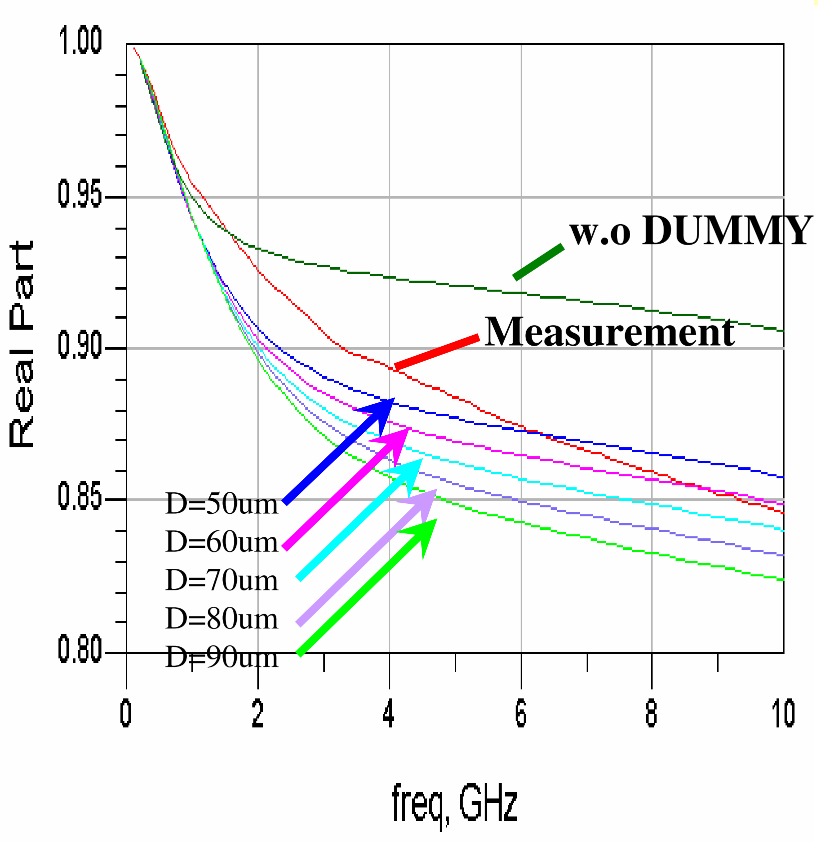


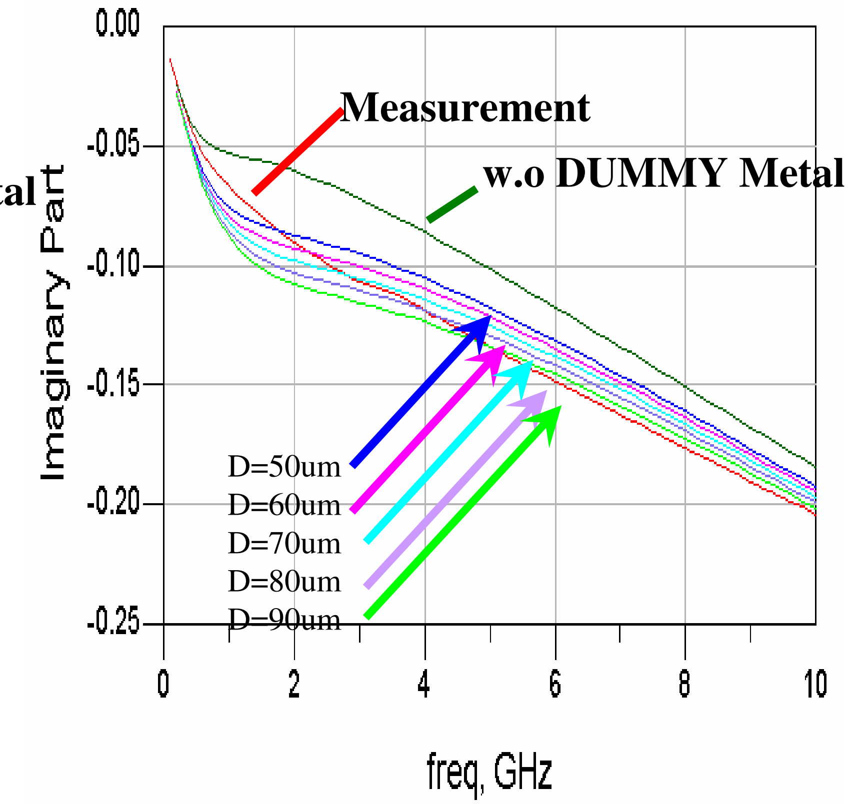


$$C_{SUB} = \frac{1}{\omega R_{SUB}} \sqrt{\left({R_{SUB}} \big/ {\mathrm{real}(Z_{SUB})} \right) - 1}$$

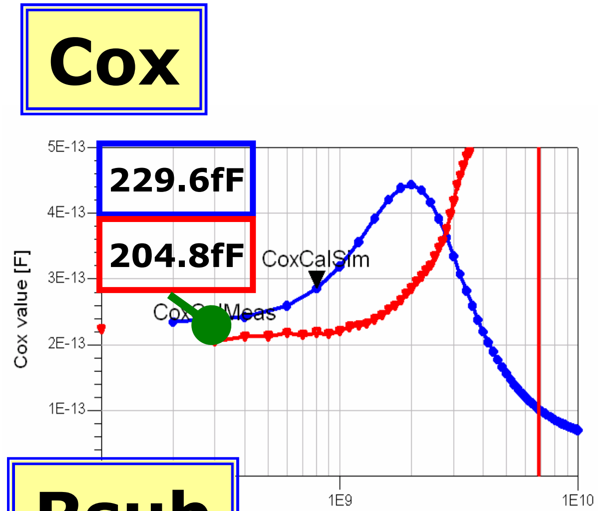
Introduction of "DUMMY METAL"

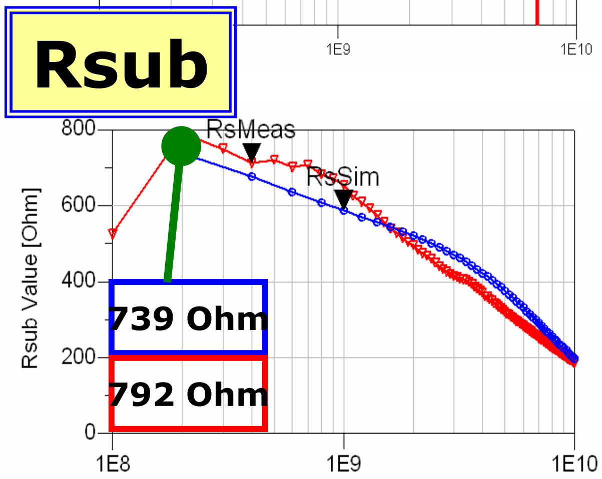
- Insert the metal layer (thickness "d") that covers silicon substrate.
- This metal layer has the same conductivity as the silicon substrate.
- Total thickness of silicon substrate should keep the original value.

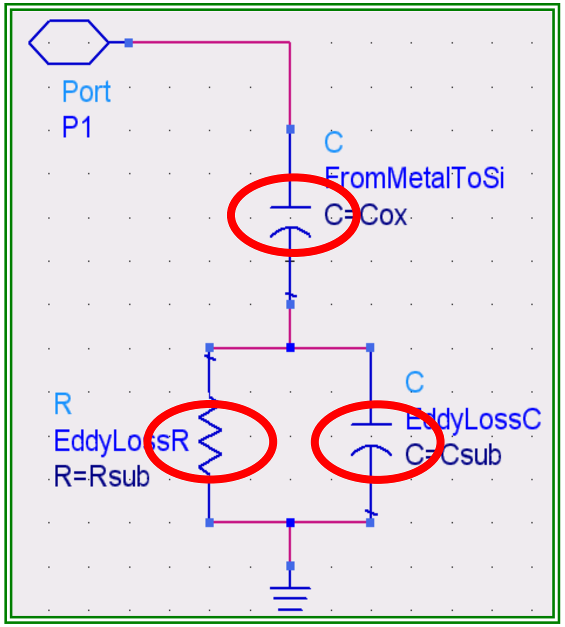


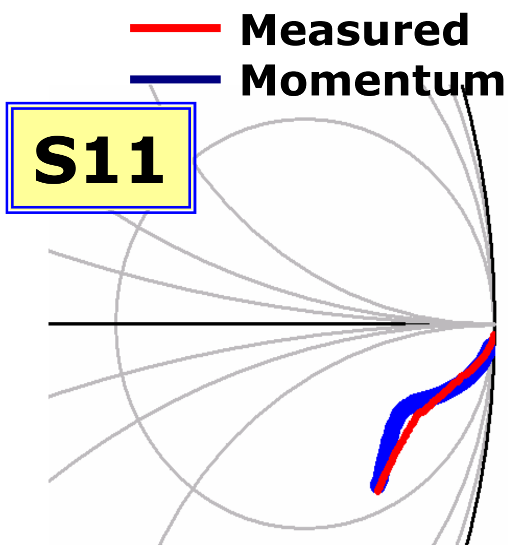


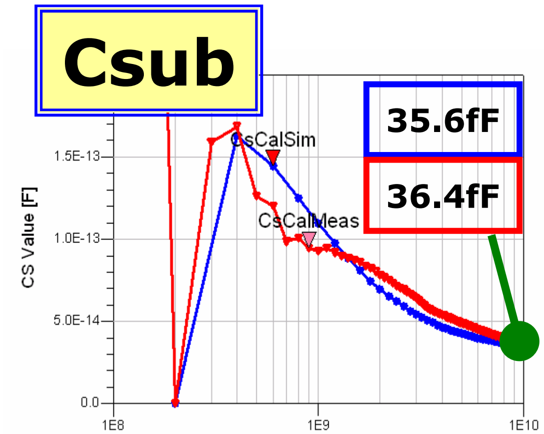
Comparison with measurement data at D=60um



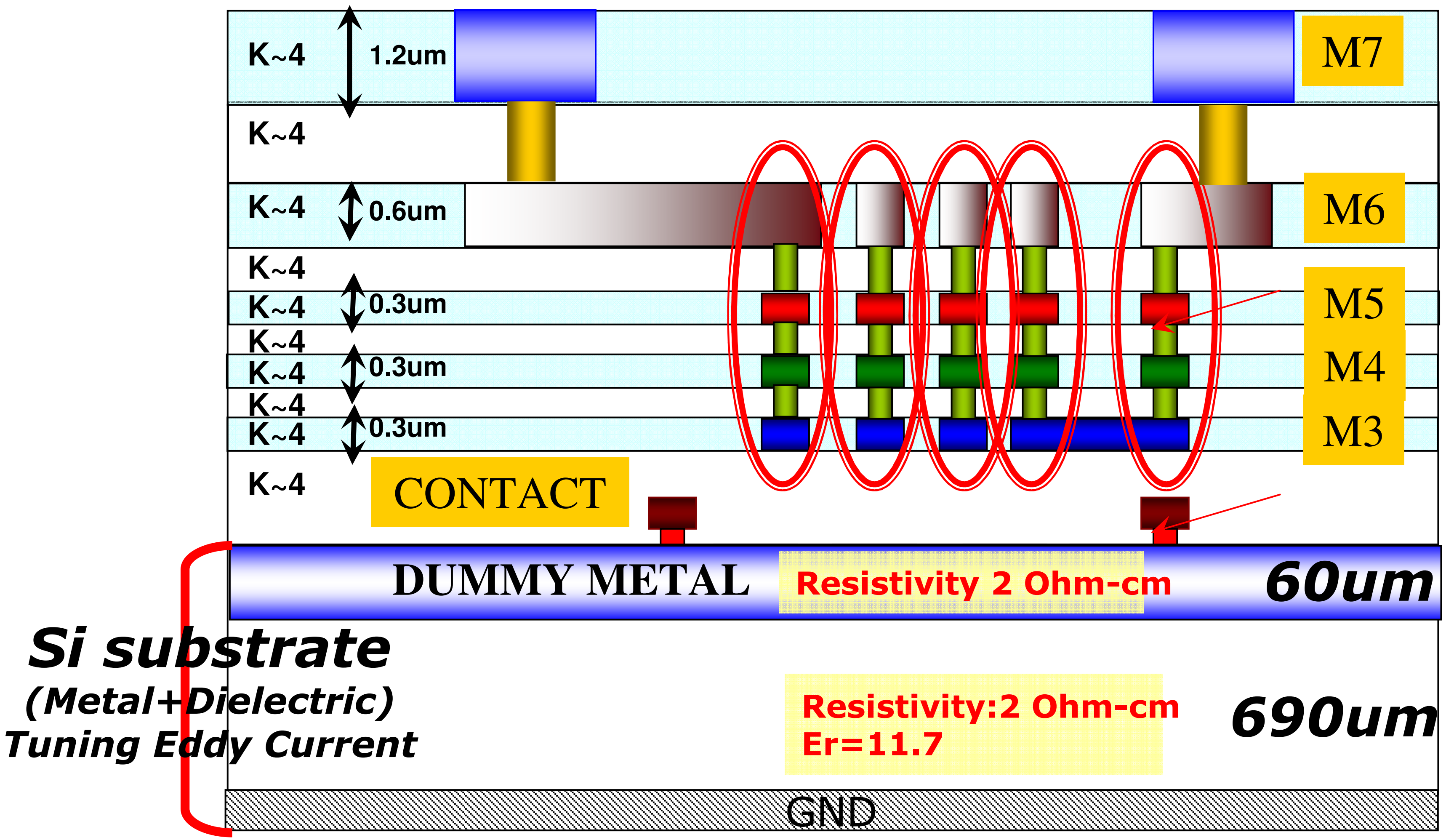








Cross Sectional setup for EM simulation



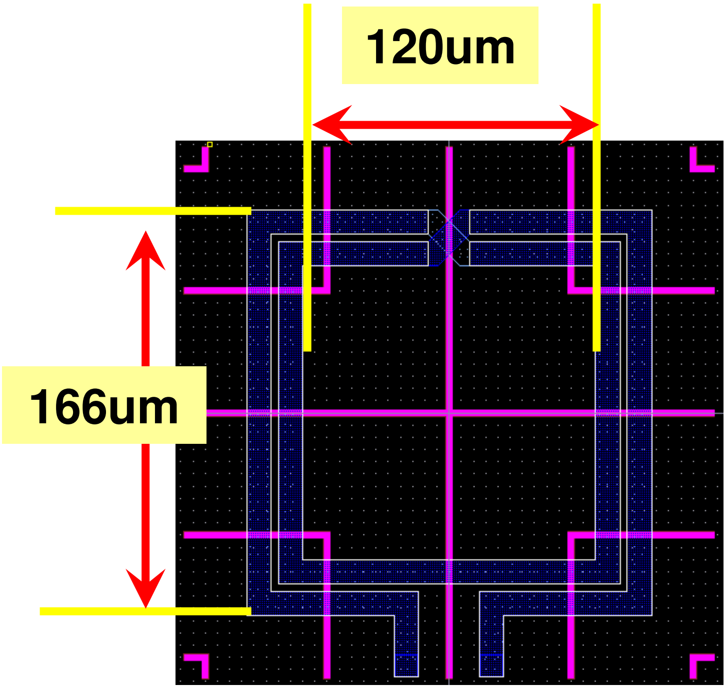
Verification with the measurement

Simulator Setup

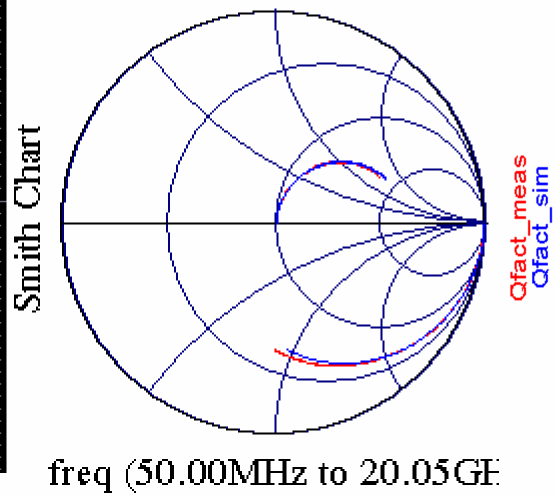
- Agilent's RFDE　Momentum (2005A or later)
- 50MHz-26.5GHz (max)
- RF　Mode
  - Mesh　Frequency　26.5GHz
  - 20 Cells/Wavelength
  - 3D=ON, Thickconductor=ON, EDGE Mesh=Off
  - **Dedicated setup for "DUMMY Layers"**
    - 3D=OFF
    - Thickconductor=OFF
    - EDGE Mesh=ON

Case1 Inductor

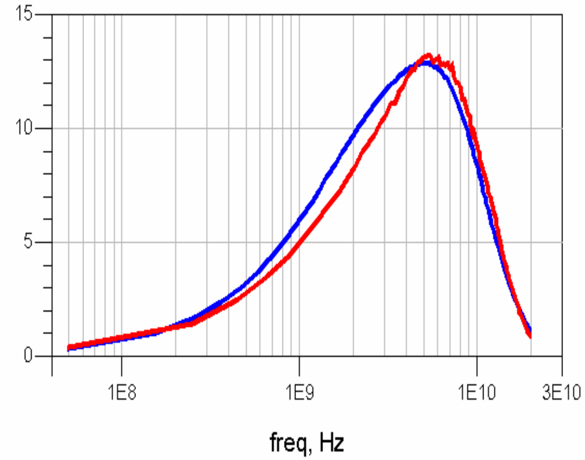
Measured
Momentum

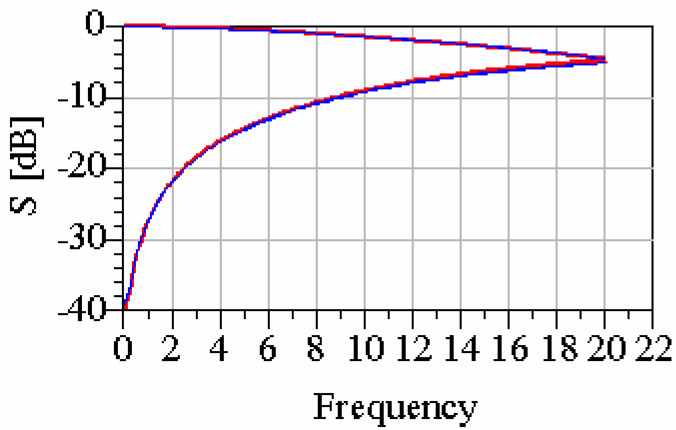


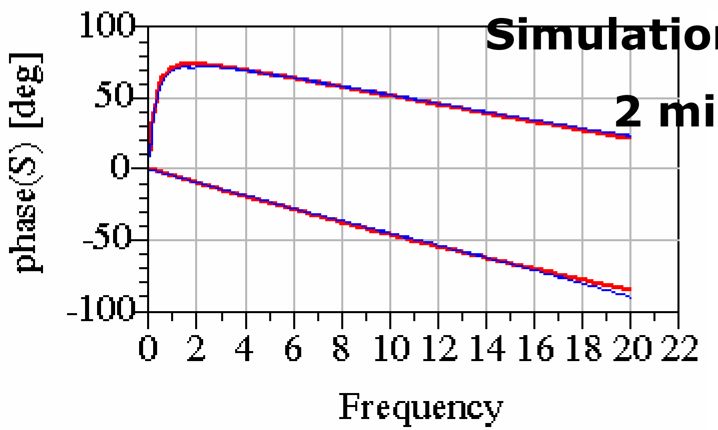
S-Parameters



Q-factor



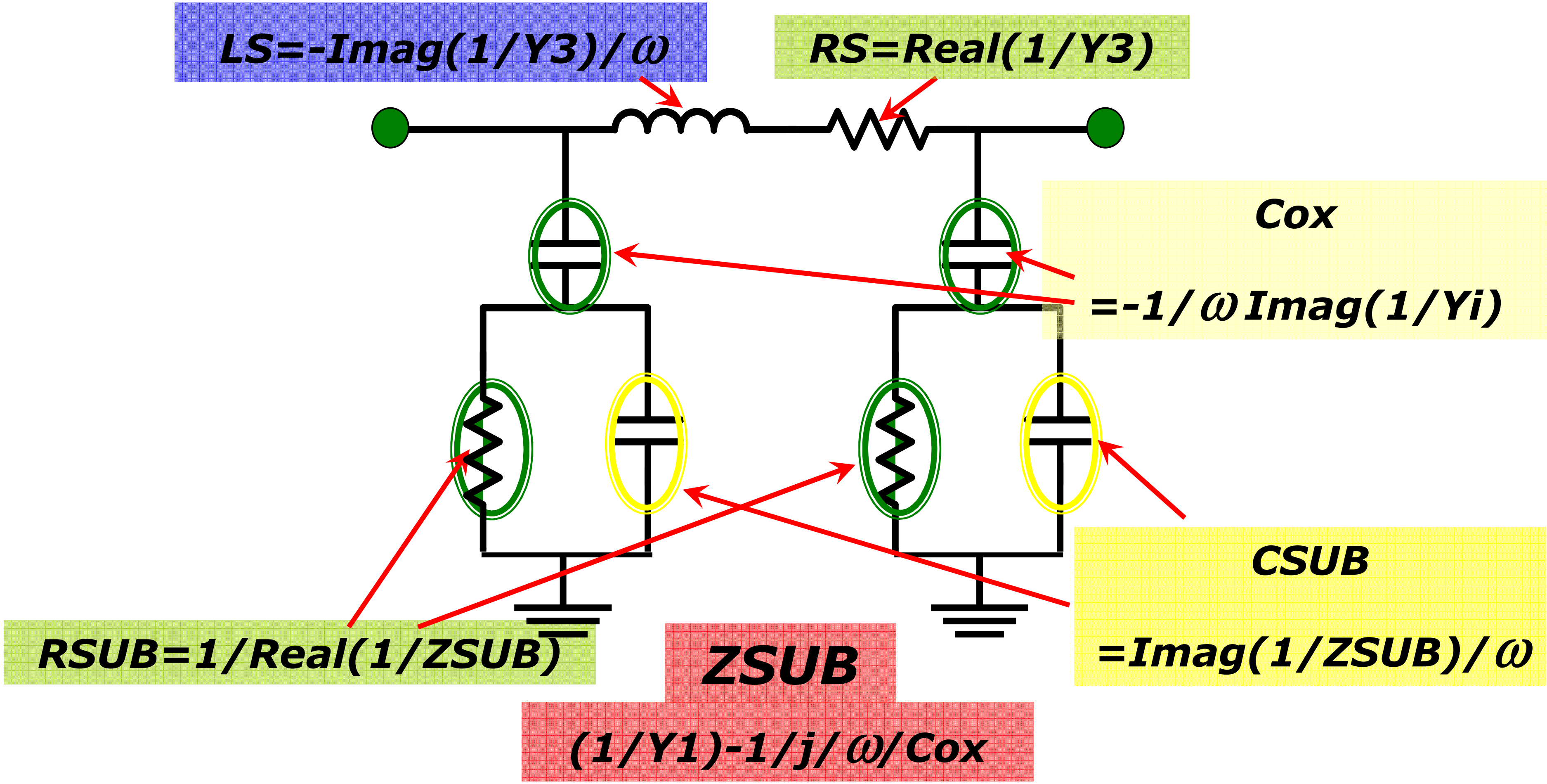




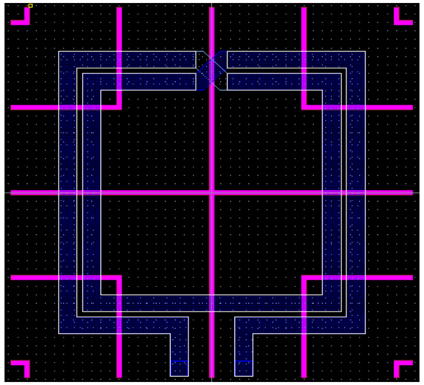
Simulation Time

2 min

Parameter extraction of Equivalent Circuit

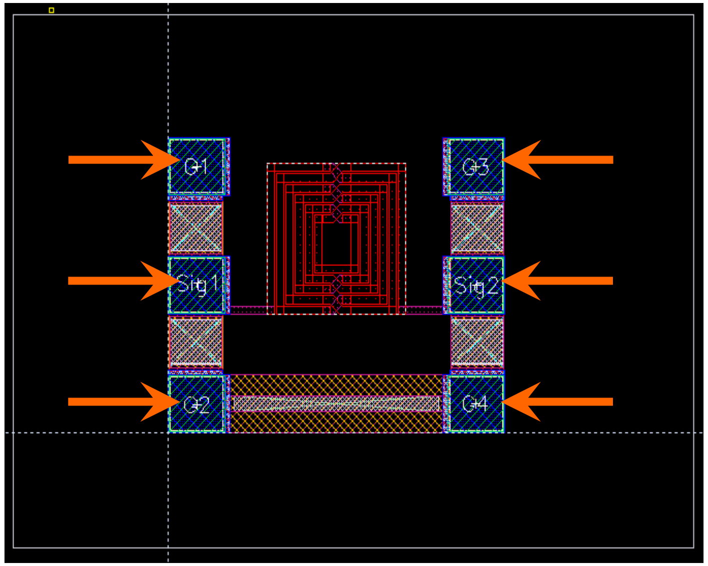


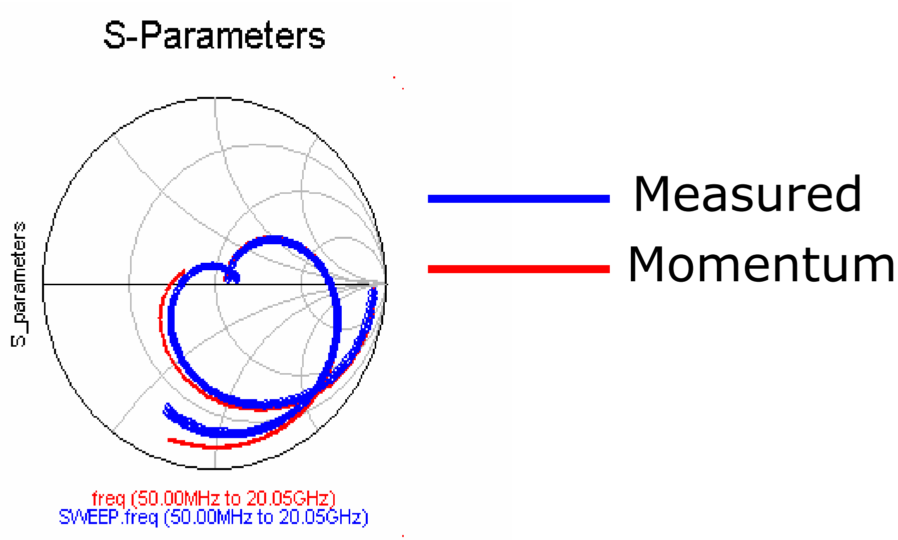
Comparison of model parameters



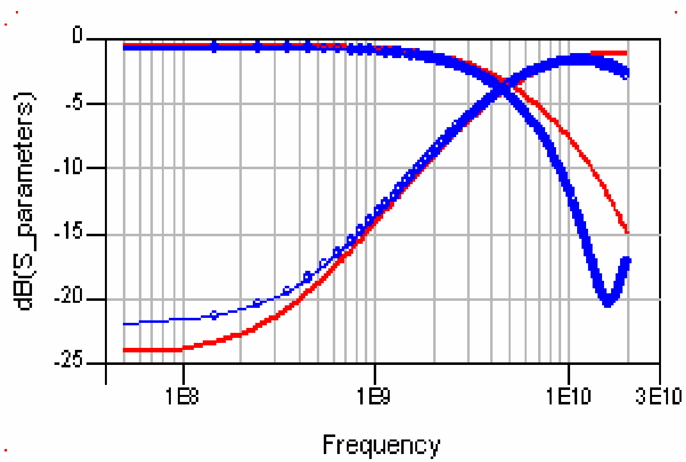
	Momentum	Measurement
Ls (50MHz)	1.06 nH	1.07 nH
Rs (50MHz)	1.23 Ohm	1.26 Ohm
Cox(154MHz)	297.6 fF	293.3 fF
Rsub(9.8GHz)	36.9 Ohm	28.3 Ohm

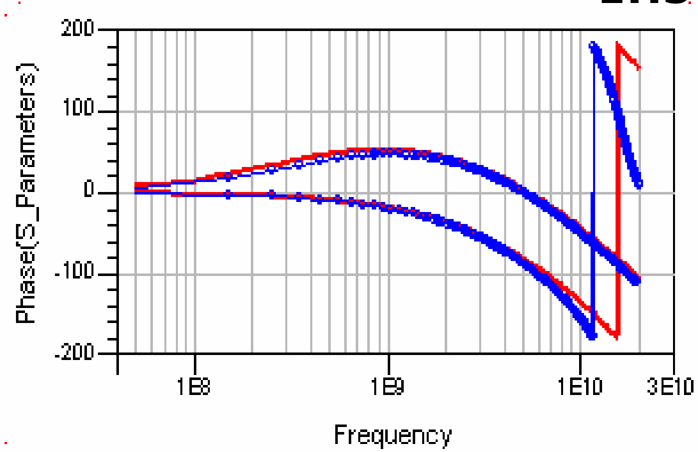
Case2 Inductor 90nm CMOS



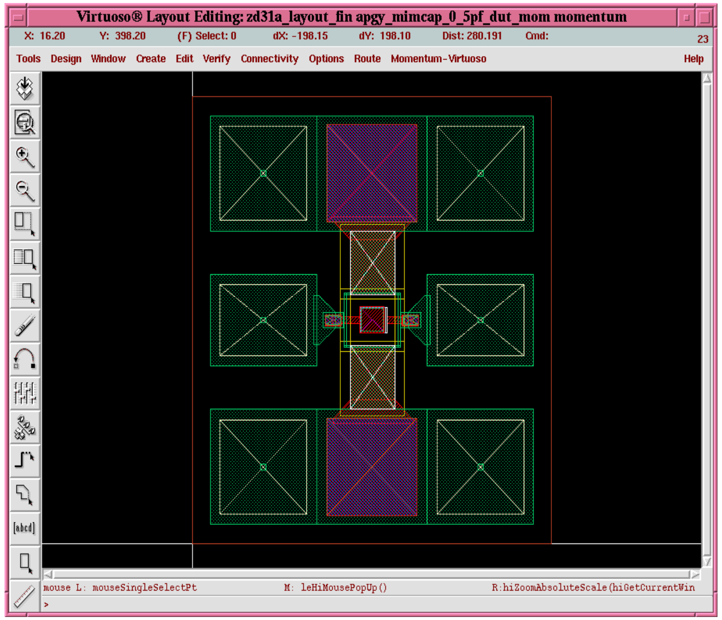


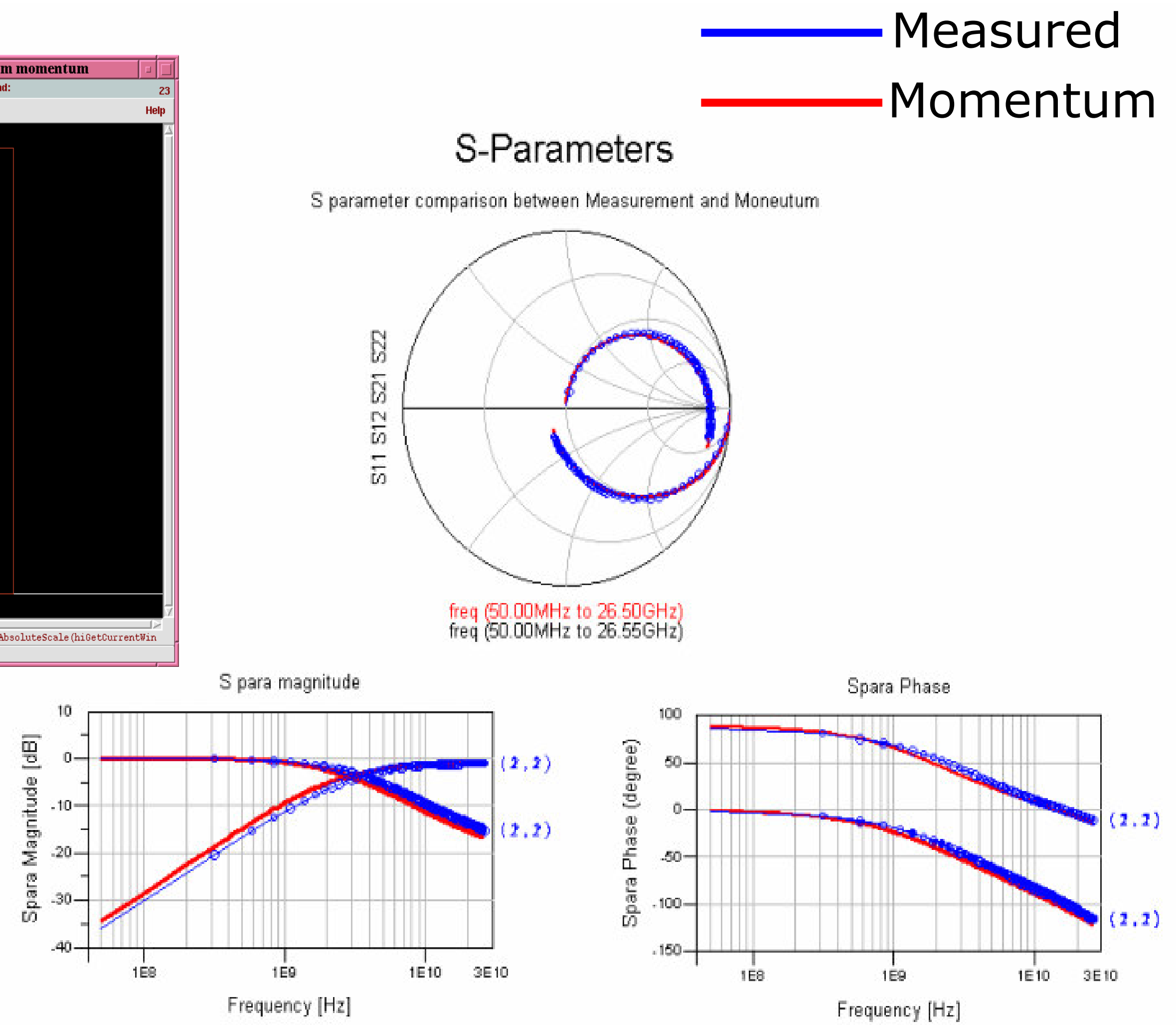
Simulation Time 1H51M





Case3 MIMCAP 500fF





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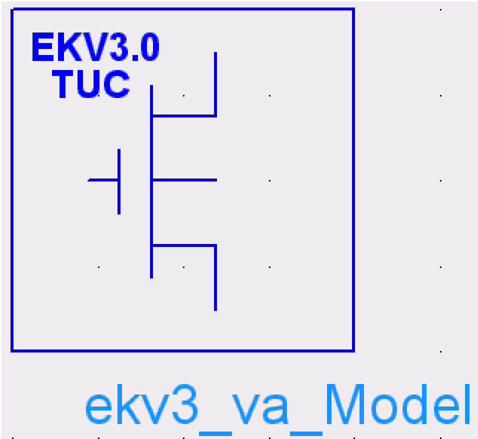

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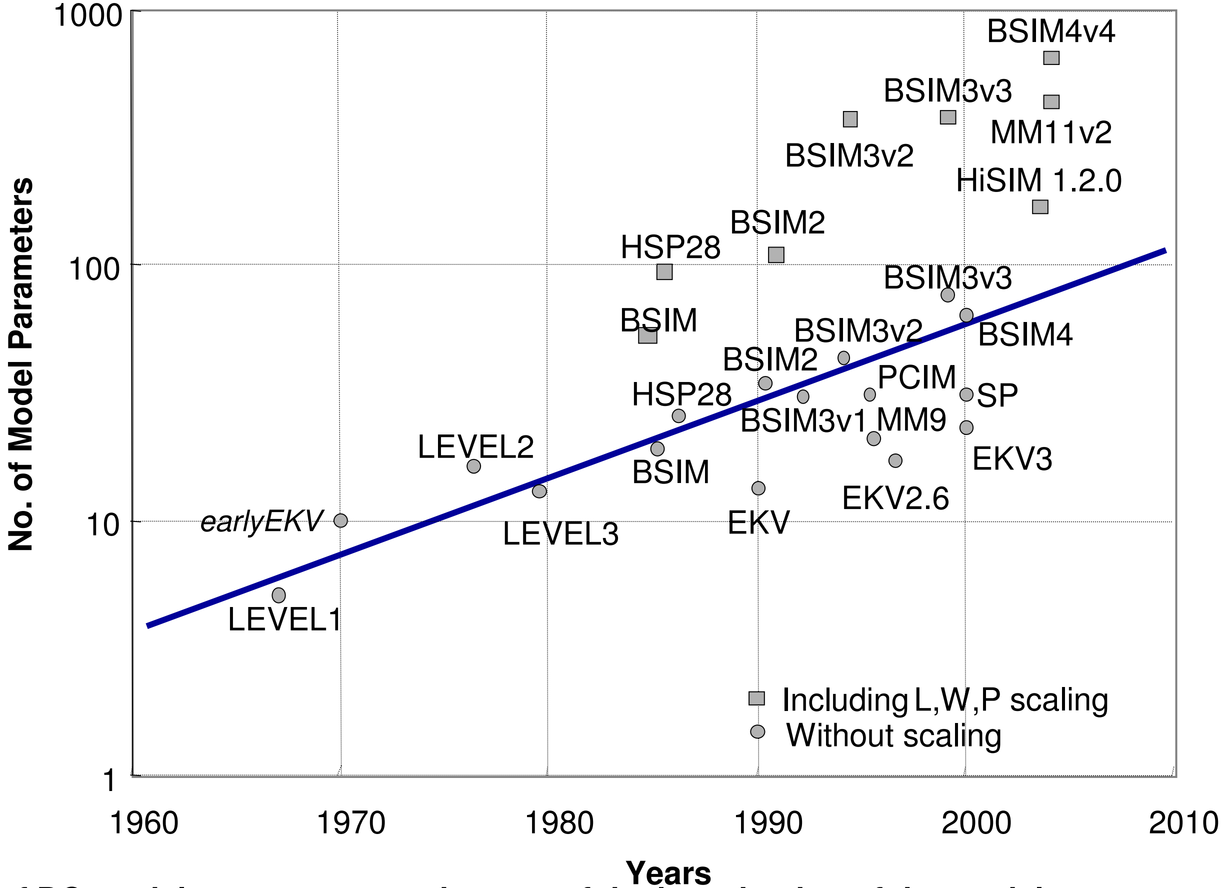
Development of MOS Compact Models

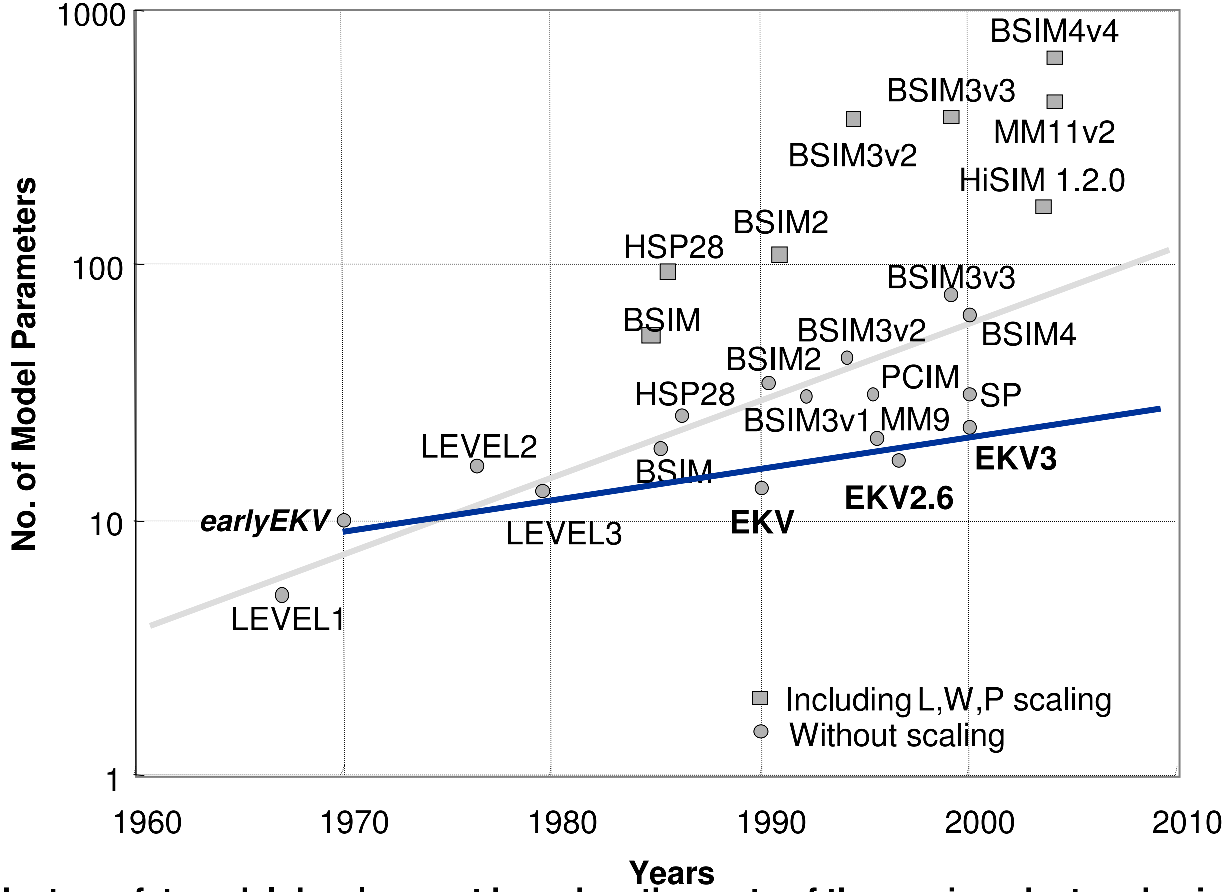
W.Grabinski "MOS-AK", IWCM2007



- **Number of DC model parameters vs. the year of the introduction of the model**
  Most recent versions of the EKV, HiSIM, MM11and SP models are included
- **Significant growth of the parameter number that includes geometry (W/L) scaling**

Trend of EKV Model Development

W.Grabinski "MOS-AK", IWCM2007



- Independent mosfet model development based on the roots of the semiconductor physics and the design driven EKV modeling methodology
- EKV3 preserves coherent charge-based framework for static/dynamic modeling

Model Parameters list of EKV3.0 (1/2)

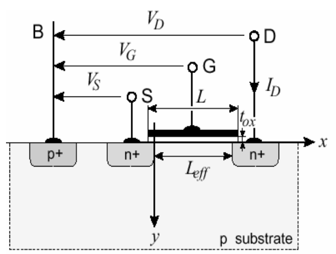
Modelled effect	Related parameters
Physical Modelling of Charges Including Accumulation Region Covering Polysilicon Depletion and Quantum mechanical effects	COX(TOX), PHIF, GAMMA(NSUB), VTO(VFB), GAMMAG(NGATE)
Bias-dependent Overlap Capacitances	LOV, GAMMAOV(NOV), VFBOV
Non-Uniform Vertical Doping	GAMMA2, VR, DVR
NQS (AC, noise)	--
Mobility (reduction due to vertical field effect) Covering: Surface Roughness, Phonon Scattering, Coulomb Scattering	KP(U0), E0, E1, ETA ZC, THC
Impact ionization current	IBA, IBB, IBN
Gate currents (IGS, IGD, IGB)	KG, XB, UB

A.Bazigos,"EKV3.0 model code & parameter extraction", EKV user meeting/workshop, Nov4-5, 2004.

Model Parameters list of EKV3.0 (2/2)

Modelled effect	Related parameters
Longitudinal Field Effect Velocity Saturation, Channel Length Modulation	UCRIT(VSAT), LAMBDA, DELTA
Reverse Short Channel Effect	LR, QLR, NLR
Inverse Narrow Width Effect	WR, QWR, NWR
Drain Induced Barrier Lowering	ETAD, SIGMAD
Source and Drain Charge Sharing	LETA, {LETA2}, WETA
Geometrical effects, Width scaling	Various parameters (DL, WQLR, …)
Noise (Flicker / Thermal)	AF, KF
Temperature Effects	various parameters (7)
TOTAL	~60

A.Bazigos,"EKV3.0 model code & parameter extraction", EKV user meeting/workshop, Nov4-5, 2004.



Concept of EKV3.0 model (1/3)

- ***Started from classic current transport equation***

$$I_D = \mu W\left(-Q_I' \cdot \frac{d\Psi_s}{dx} + U_T \cdot \frac{dQ_I'}{dx}\right) \qquad \textbf{1}$$

- ***Description of Ψs by using linearized Q'I***

$$\boxed{\frac{d\Psi_s}{dx} = \frac{1}{n_Q \cdot C_{ox}} \cdot \frac{d}{dx} Q_i'} \qquad \textbf{2}$$

- ***ID formula with linearized Q'I***

$$I_D = \mu W\left(-\frac{Q_i'}{n_Q \cdot C_{ox}'} \cdot \frac{d}{dx} Q_I' + U_T \cdot \frac{dQ_I'}{dx}\right) \qquad \textbf{3}$$

Concept of EKV3.0 model (2/3)

- ***Inversion charge densities at source and drain***

$$Q'_s \equiv Q'_I\Big|_{x=0} \qquad Q'_D \equiv Q'_I\Big|_{x=L} \qquad (4)$$

- ***Integration of (3)***

$$I_D = \mu \cdot \frac{W}{L} \cdot \left[\int_{Q'_{is}}^{Q'_{iD}} \frac{-Q'_i}{n_Q \cdot C'_{ox}} \cdot dQ'_I + \int_{Q'_{is}}^{Q'_{iD}} U_T \cdot dQ'_I \right] \qquad (5)$$

$$= \mu \cdot \frac{W}{L} \cdot \left[\frac{Q'^2_{iS}}{2 \cdot n_Q \cdot C'_{ox}} + U_T \cdot Q'_{iS} - \left\{ \frac{Q'^2_{iD}}{2 \cdot n_Q \cdot C'_{ox}} + U_T \cdot Q'_{iD} \right\} \right] \qquad (6)$$

$$\equiv I_F - I_R$$

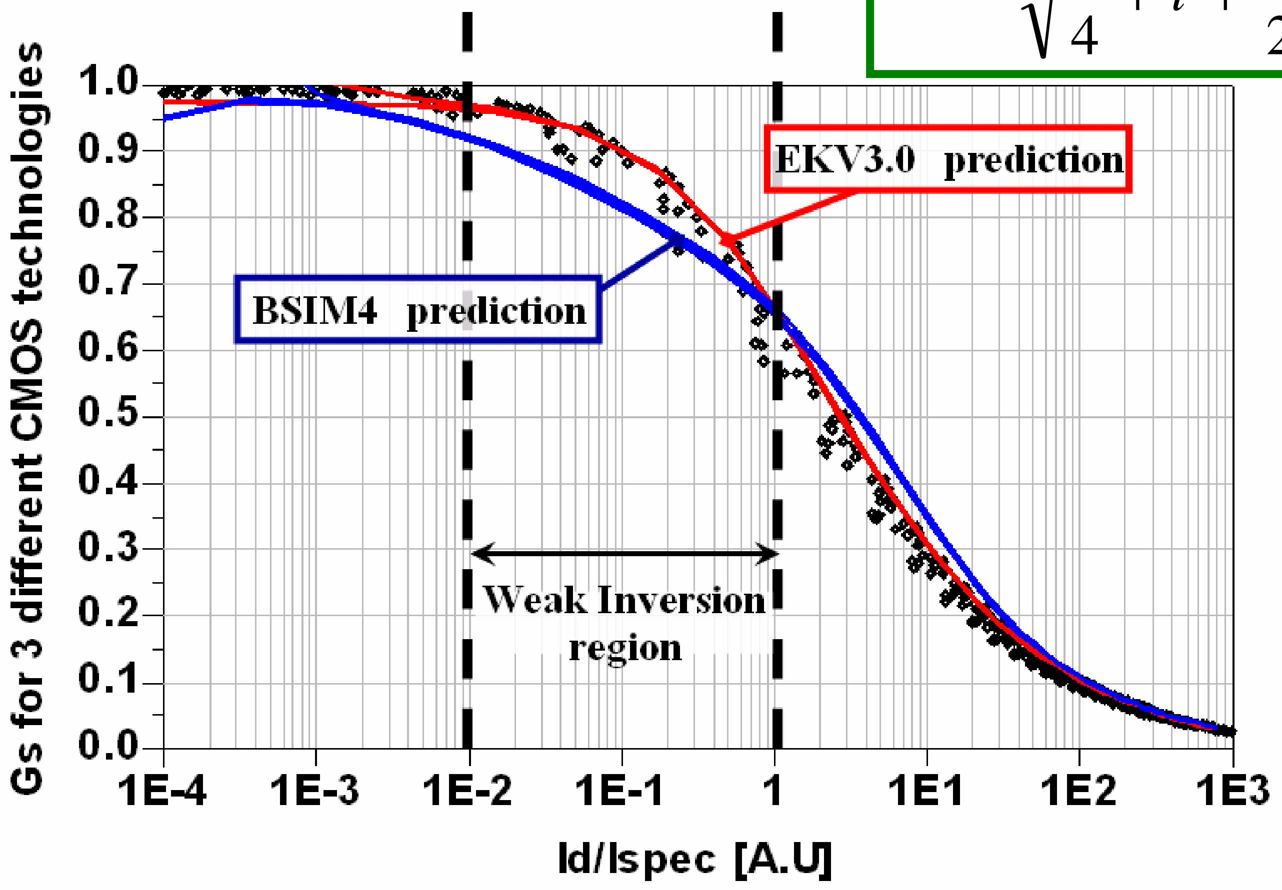
Drift **Diffusion**

$$I_{F(R)} = \mu \cdot \frac{W}{L} \cdot \left[\frac{Q'^2_{iS(D)}}{2 \cdot n_Q \cdot C'_{ox}} + U_T \cdot Q'_{iS(D)} \right] \qquad (7)$$

Nature of MOSFETs

$$-g_{ch} = -\frac{di}{dv_{ch}} = q_i = \sqrt{\frac{1}{4}+i} - \frac{1}{2} = i \cdot G_i$$

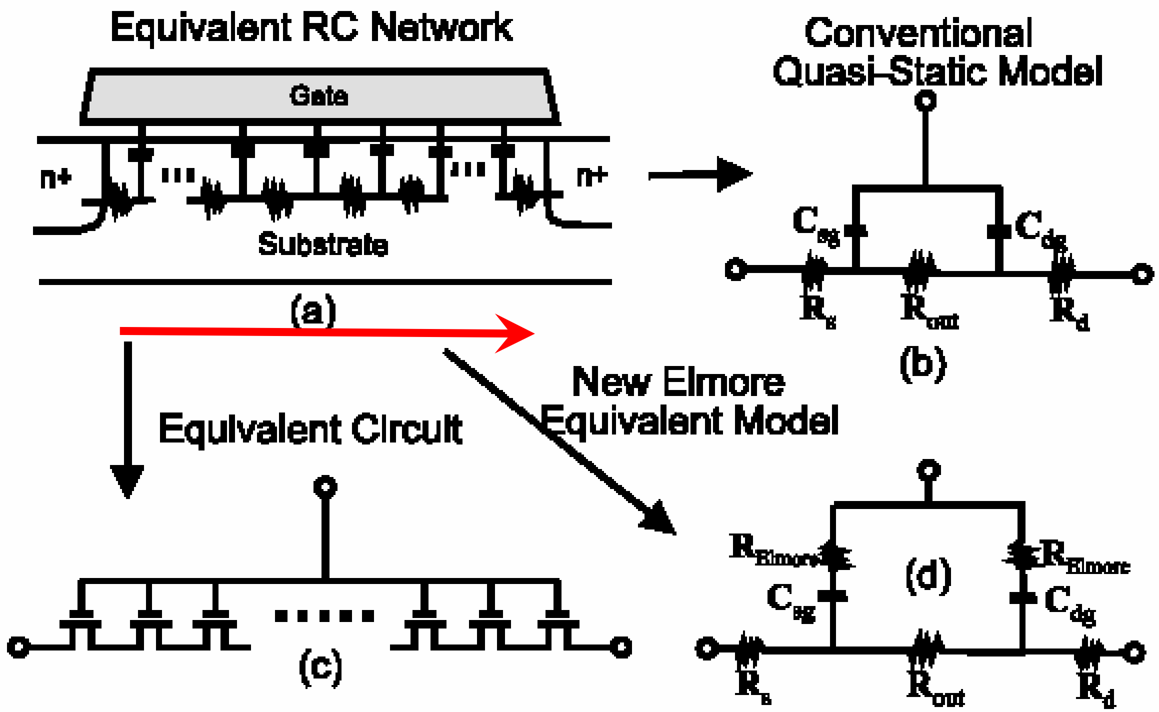
$$G_i = \frac{1}{\sqrt{\frac{1}{4}+i} + \frac{1}{2}}$$



110nm, 140nm, 0.6um CMOS Technologies included.

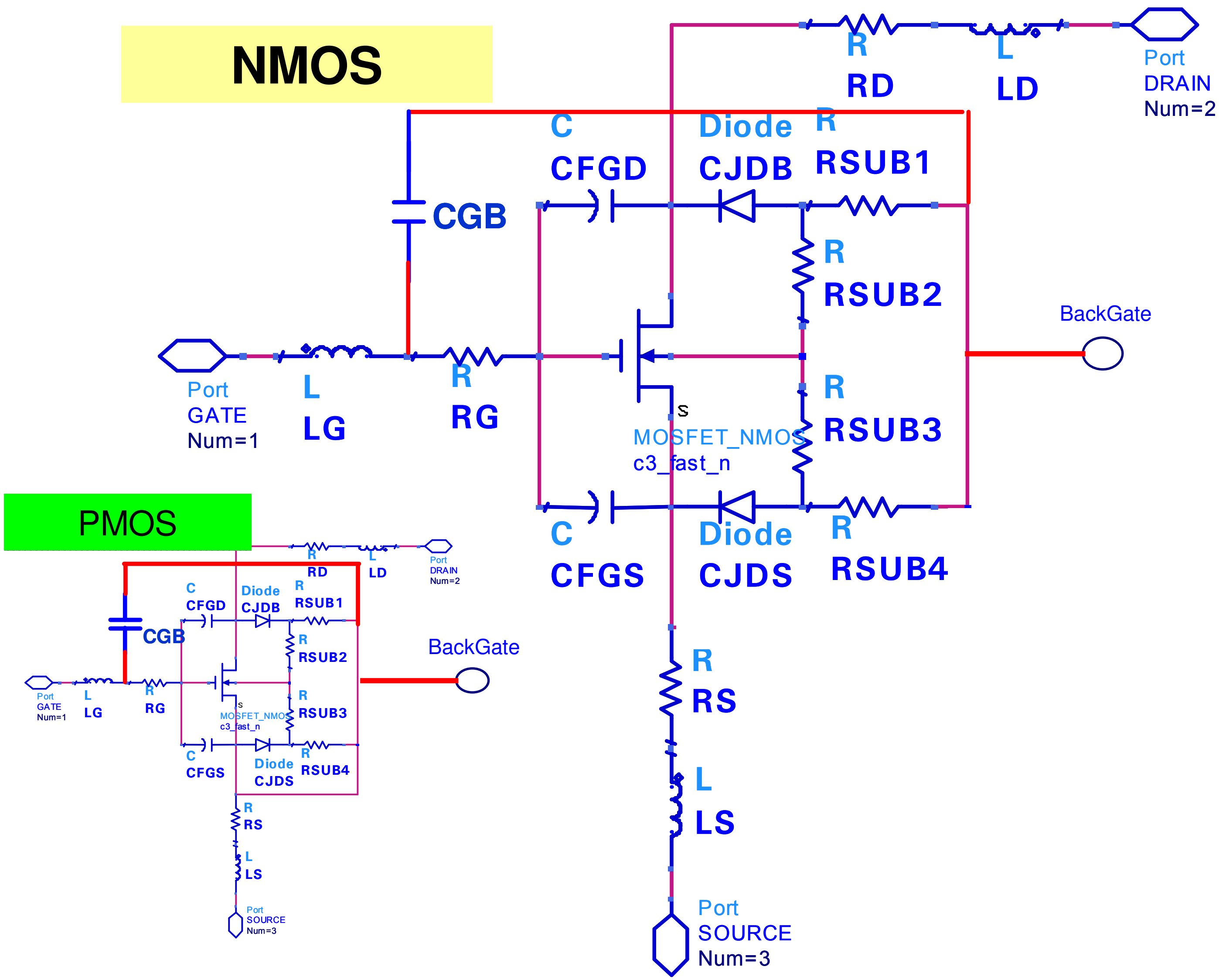
NQS Model

- Creating the segmentation of long-channel MOSFETs.
- General concepts can be found
  - **http://www-device.eecs.berkeley.edu/~bsim3/bsim4_get.html**
  - **http://www.mos-ak.org/montreux/papers/03_Smit_MOS-AK06.pdf**



- Take finite time for charge to travel throughout the channel.
  - **Distribution effect**
  - **"Memory effect"**

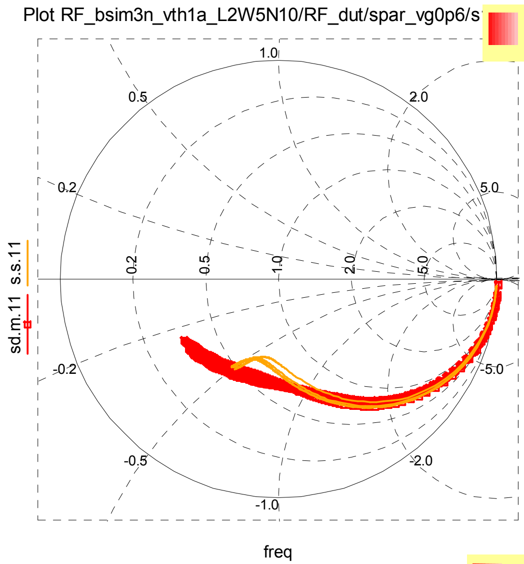
EKV3.0 model for RF-extension

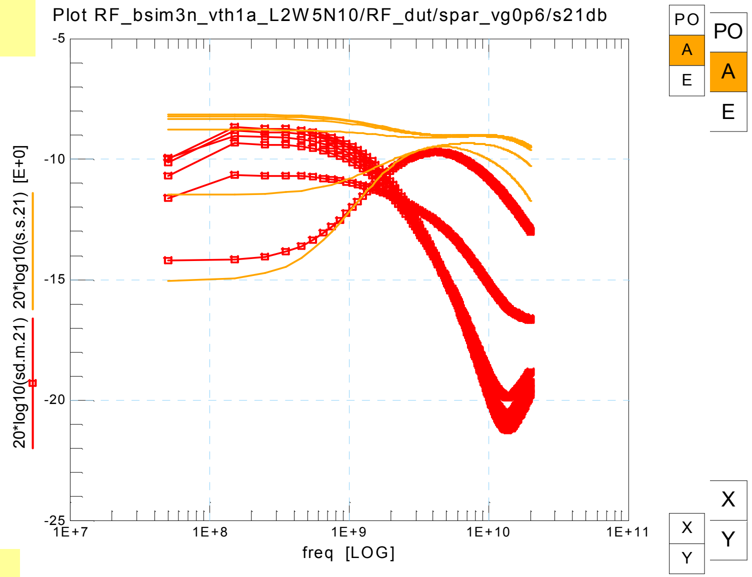


S-parameter Fitting Results

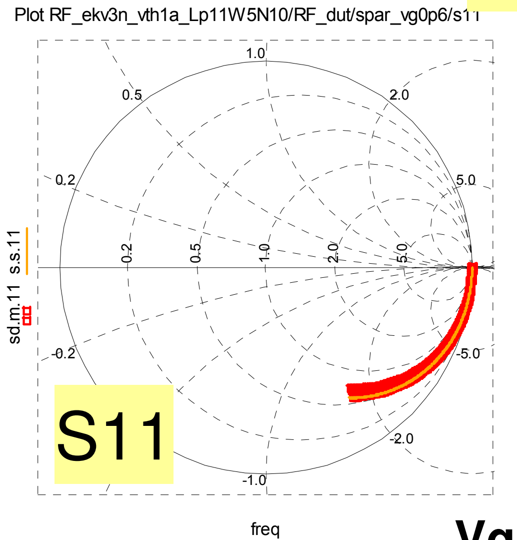
EKV3.0 (blue)
Measured (red)

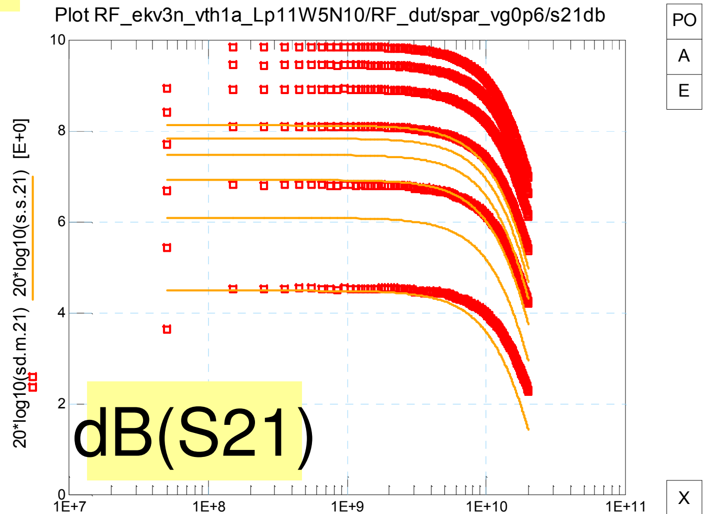
Lg=2.0um





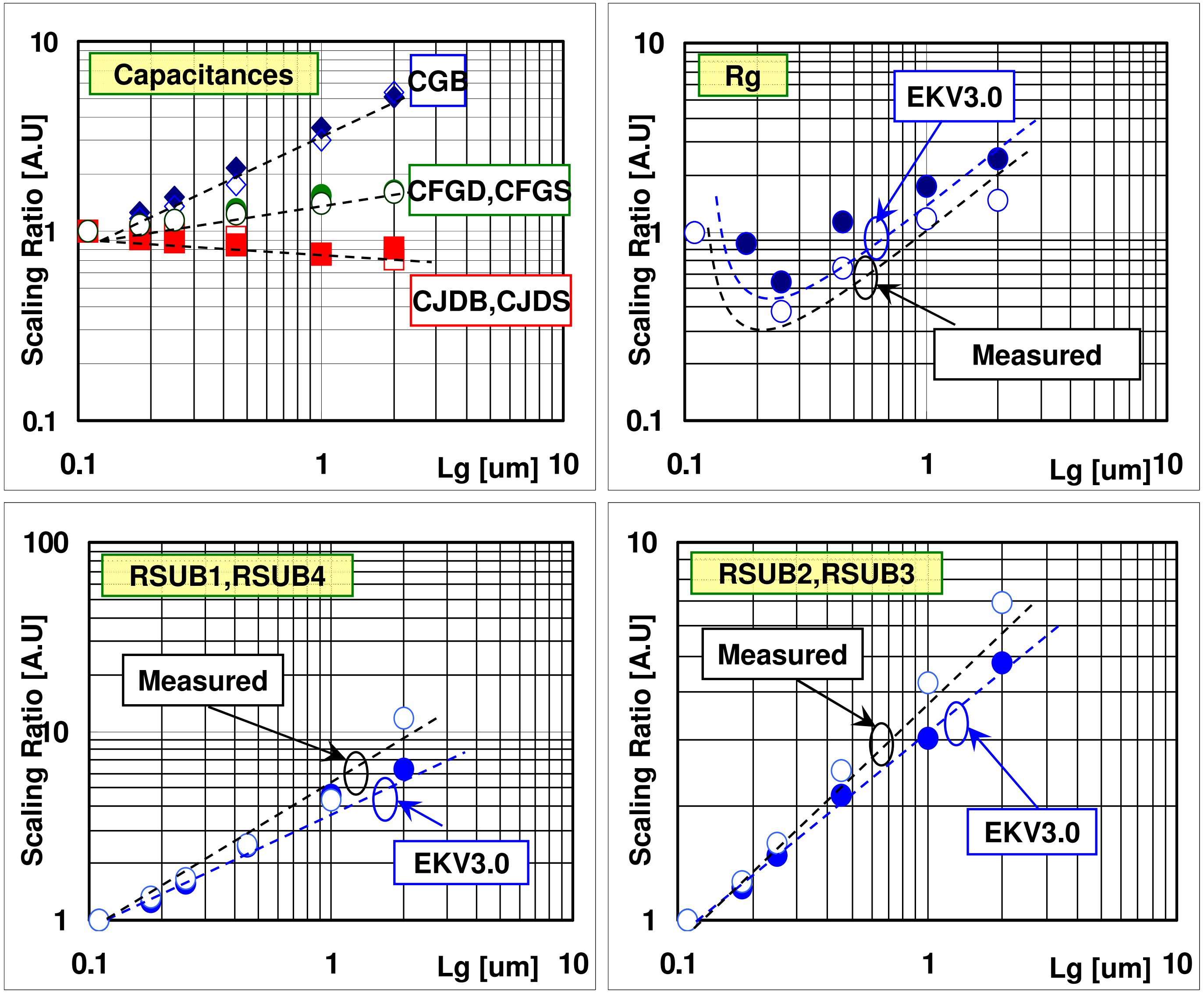
Lg=0.11um





Vg = 0.4 Volts, Vds=0.2,0.3,0.5,0.8,1.1 and 1.4Volts.

RF Scalability



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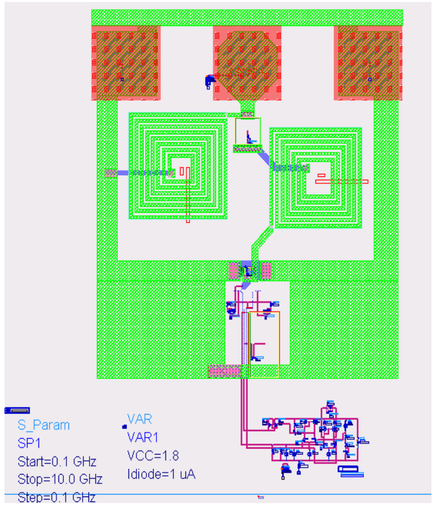

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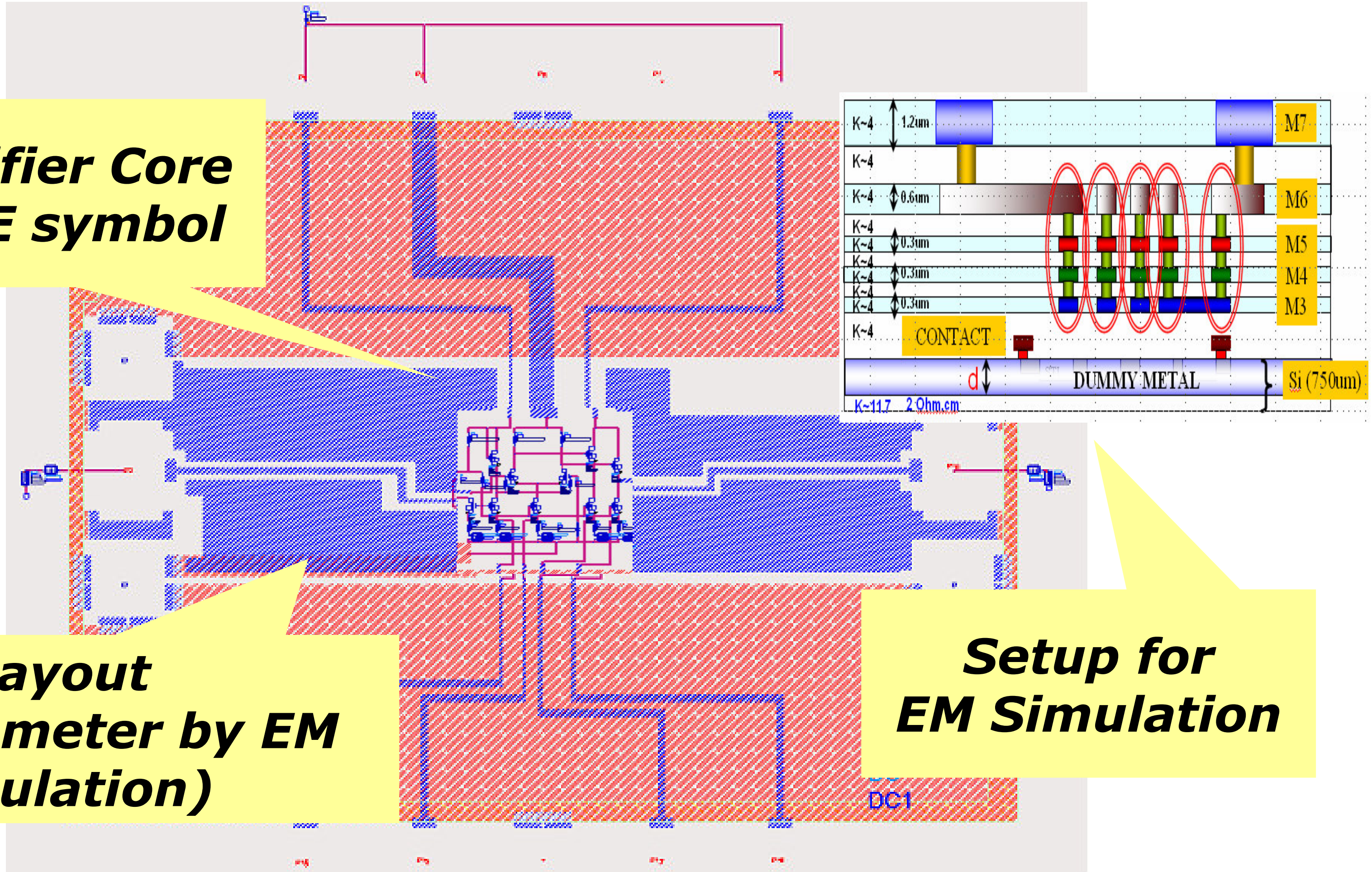
Case1: CMOS Amplifier



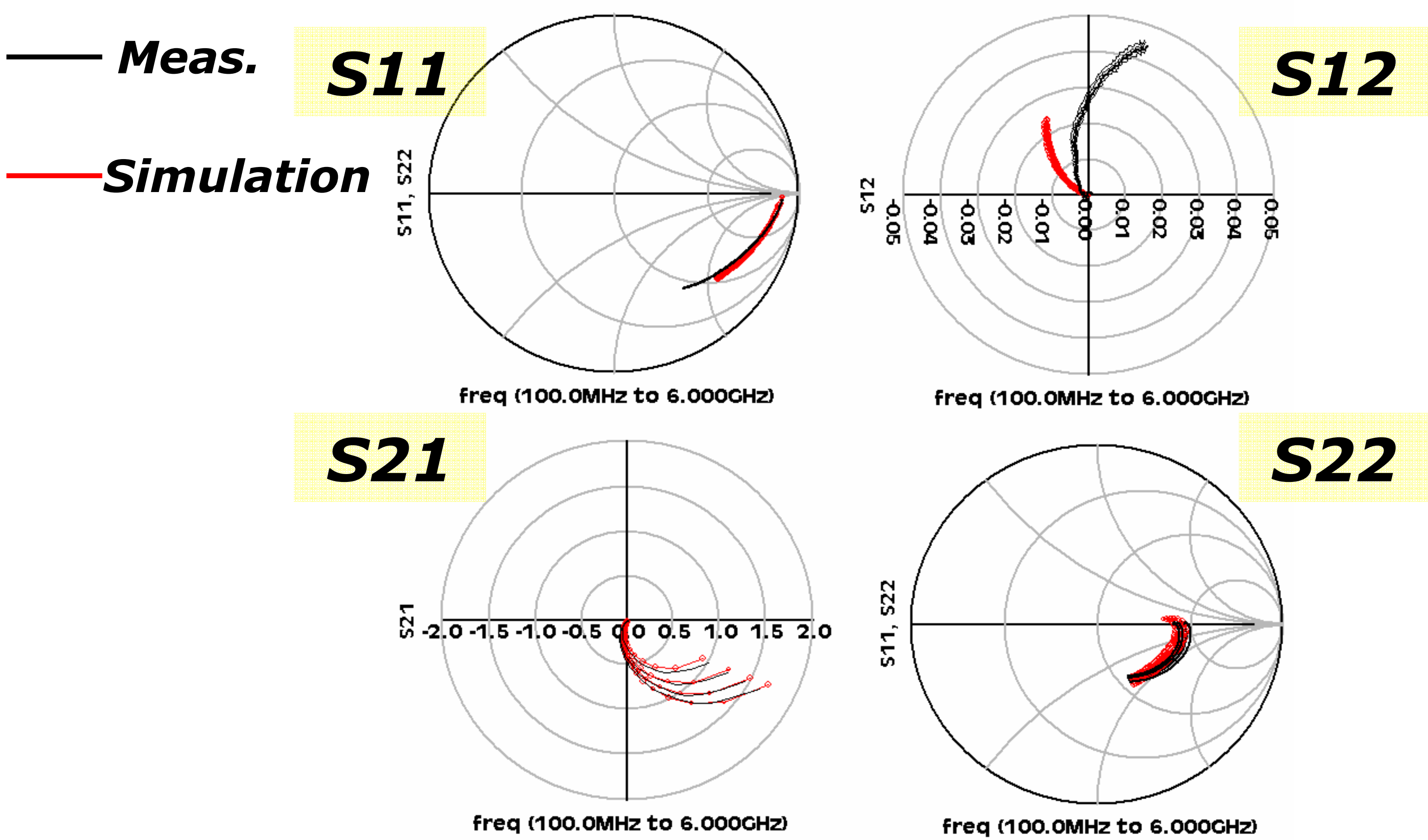
Amplifier Core SPICE symbol

Layout (S-parameter by EM simulation)

Setup for EM Simulation

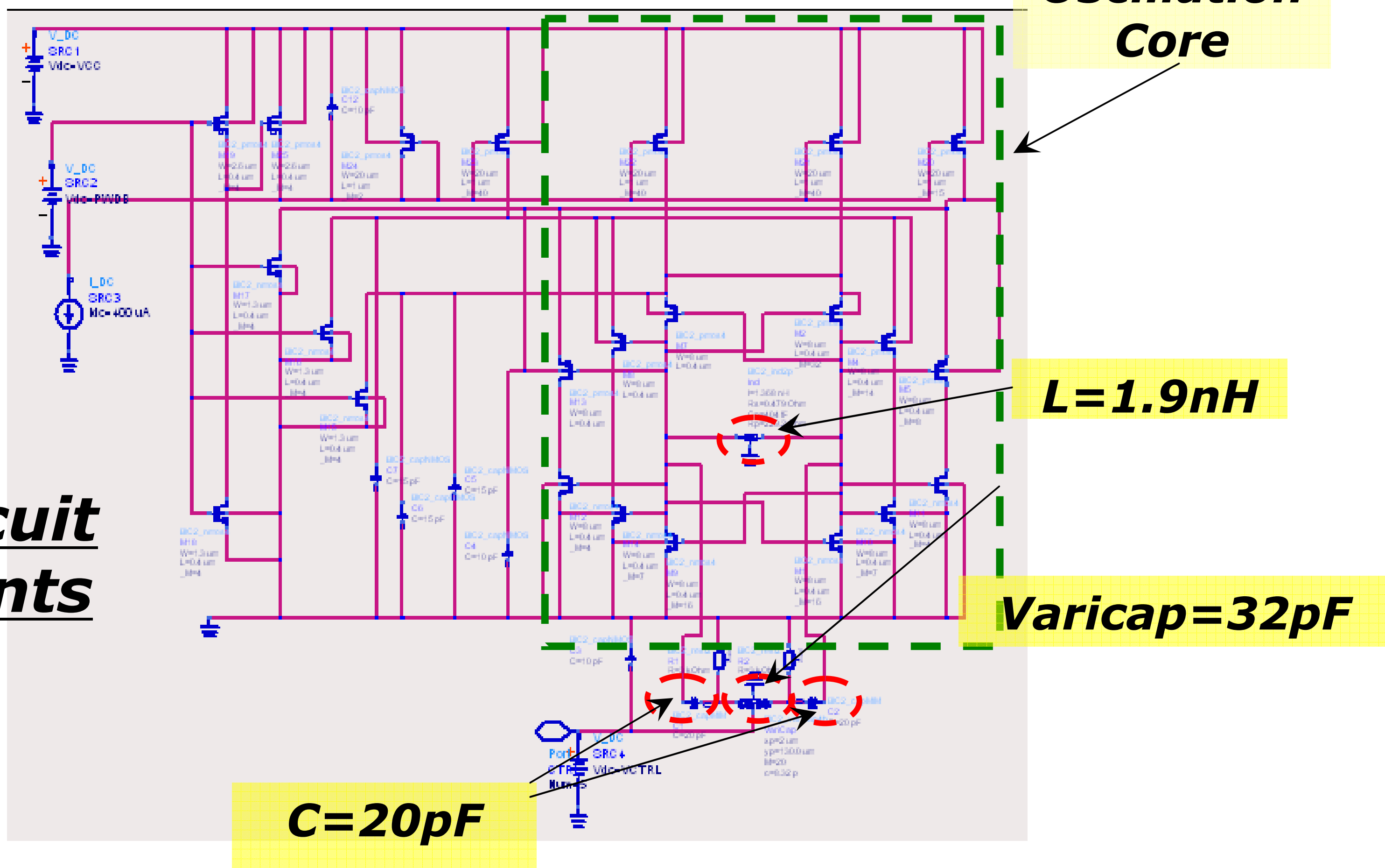
Verification (100MHz~6GHz)

- **Reasonable match has been observed.**
- **Further need to improve S12 accuracy**



Case2: 2GHz CMOS VCO

■ CMOS Power VCO



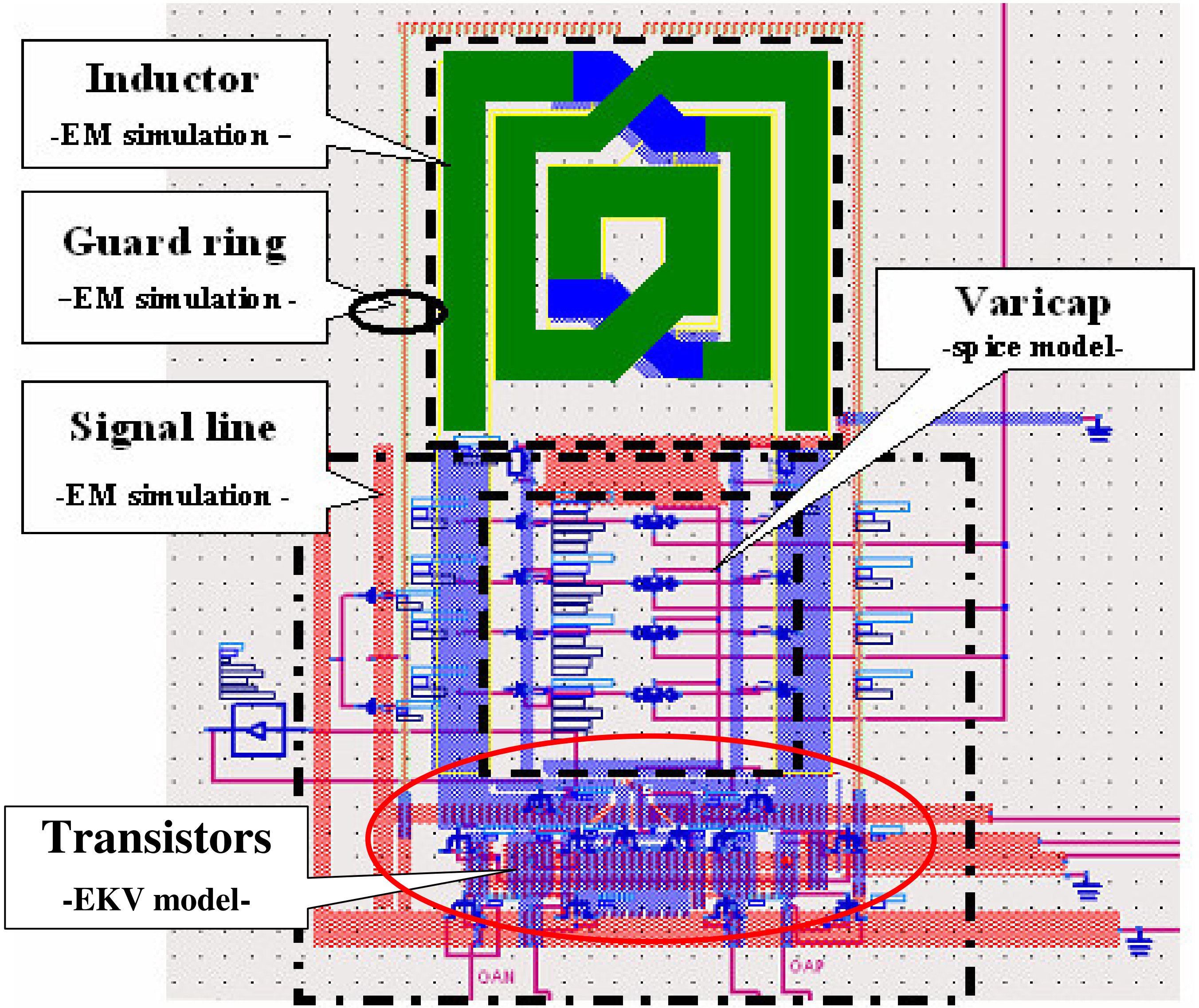
TANK Circuit Components

L=1.9nH

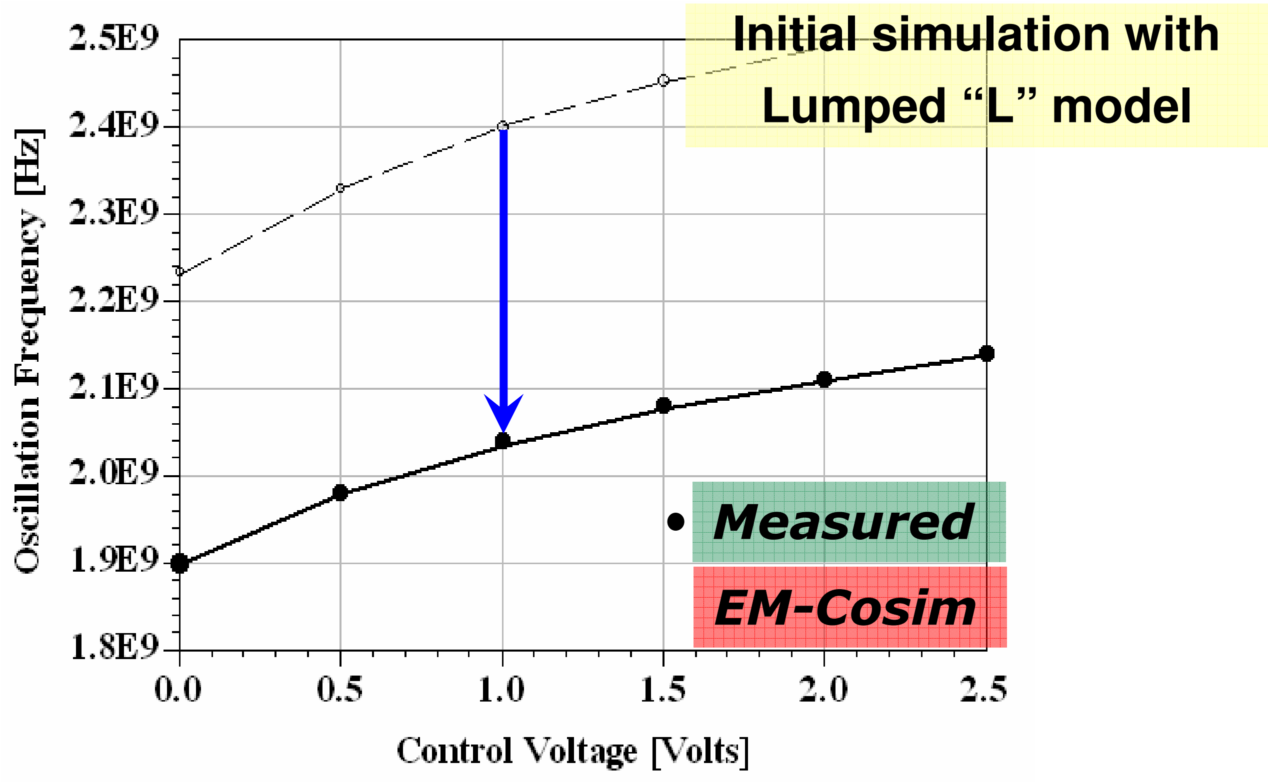
C=20pF

Varicap=32 pF

EM-Cosimulation setup

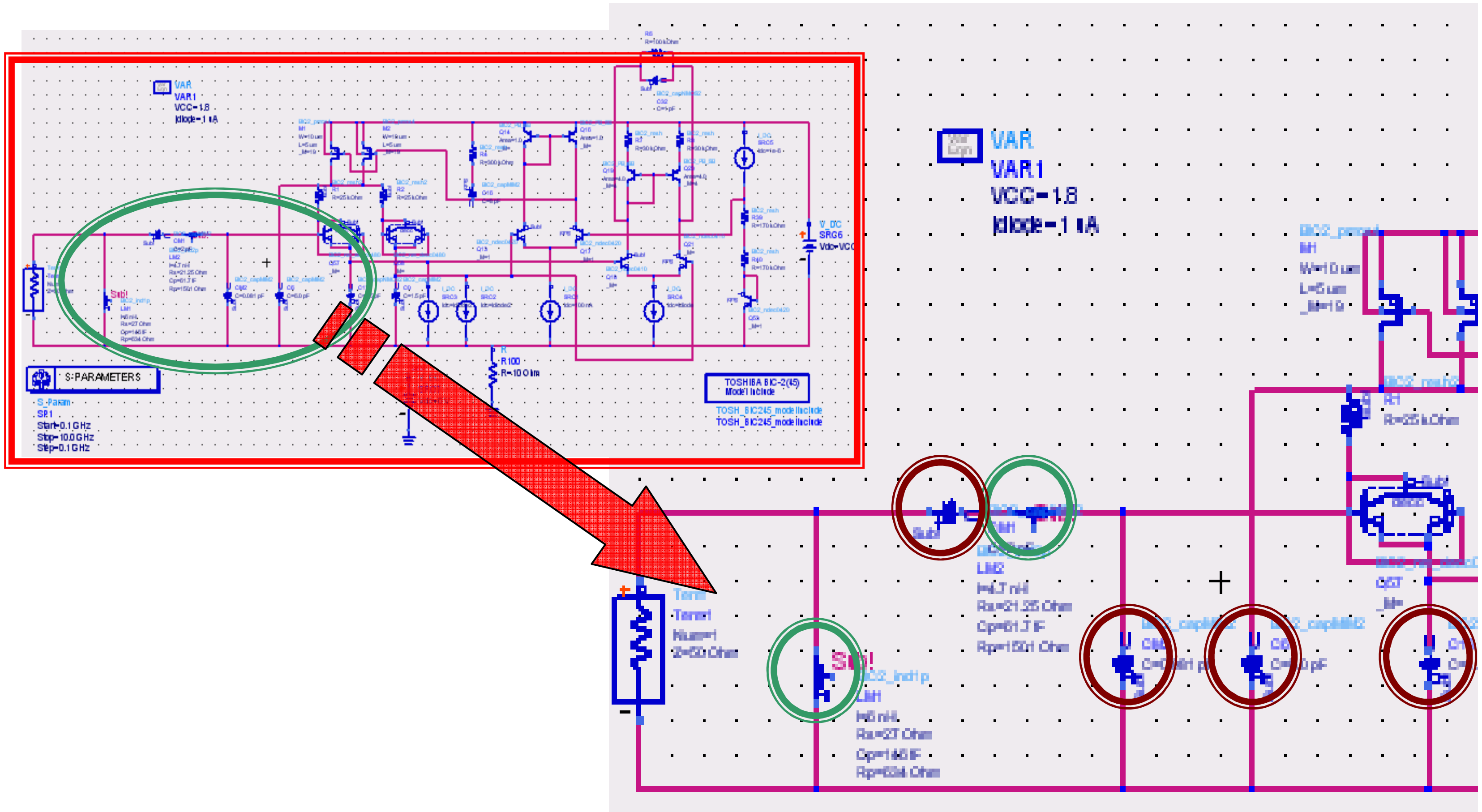


Simulation Result (TANK L by EM simulation)



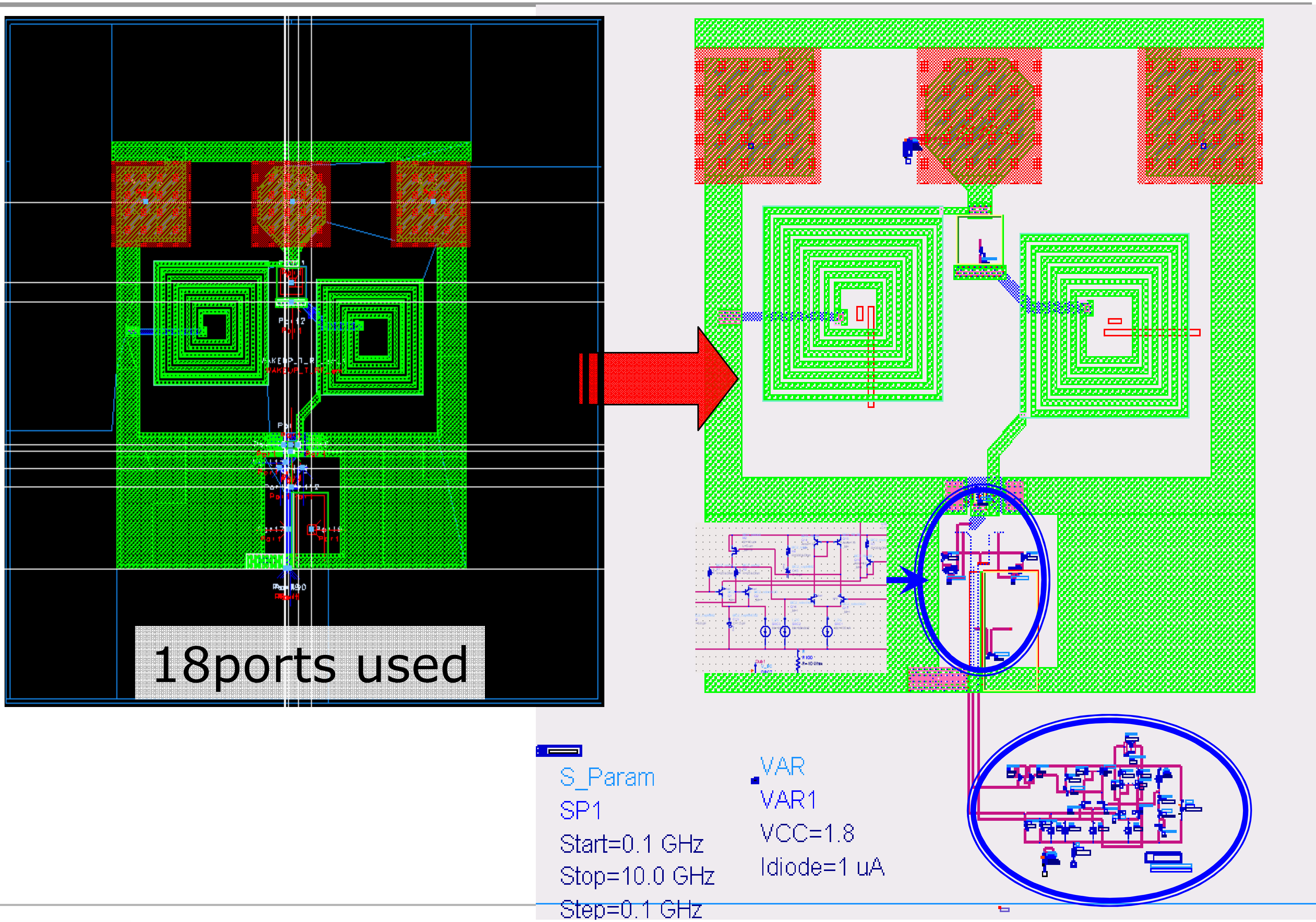
- **Oscillation frequency differs by 0.35 GHz**
- **EM-Cosim helps predict circuit behavior with an ultimate accuracy**

Case3:SiGe-LNA (5GHz)

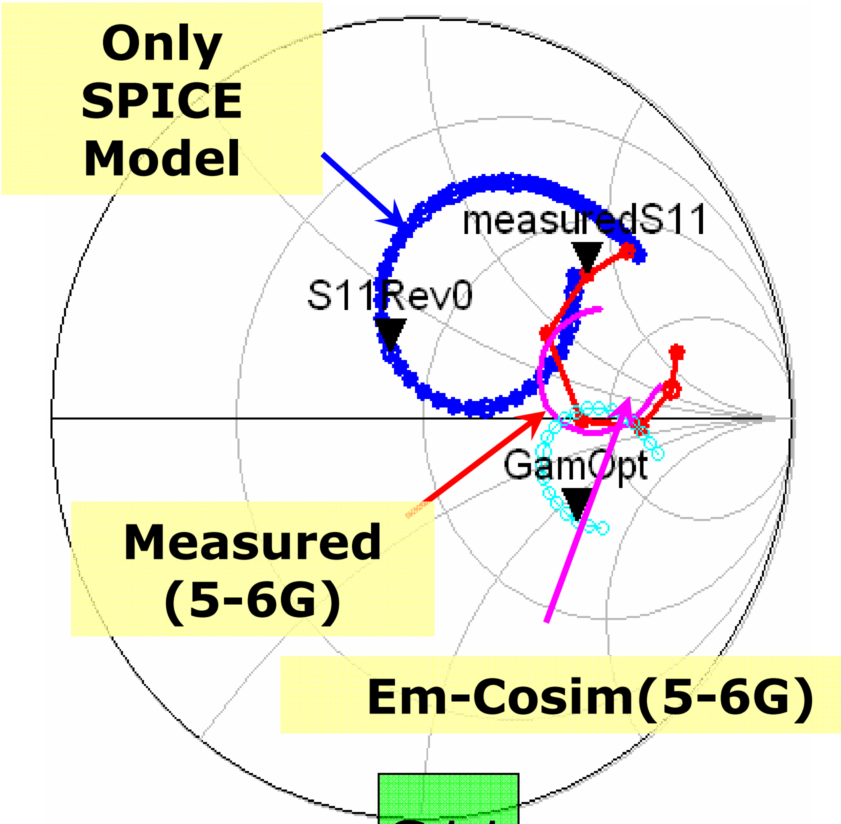


Run EM-cosim by incorporating layout of
PAD and Input matching network

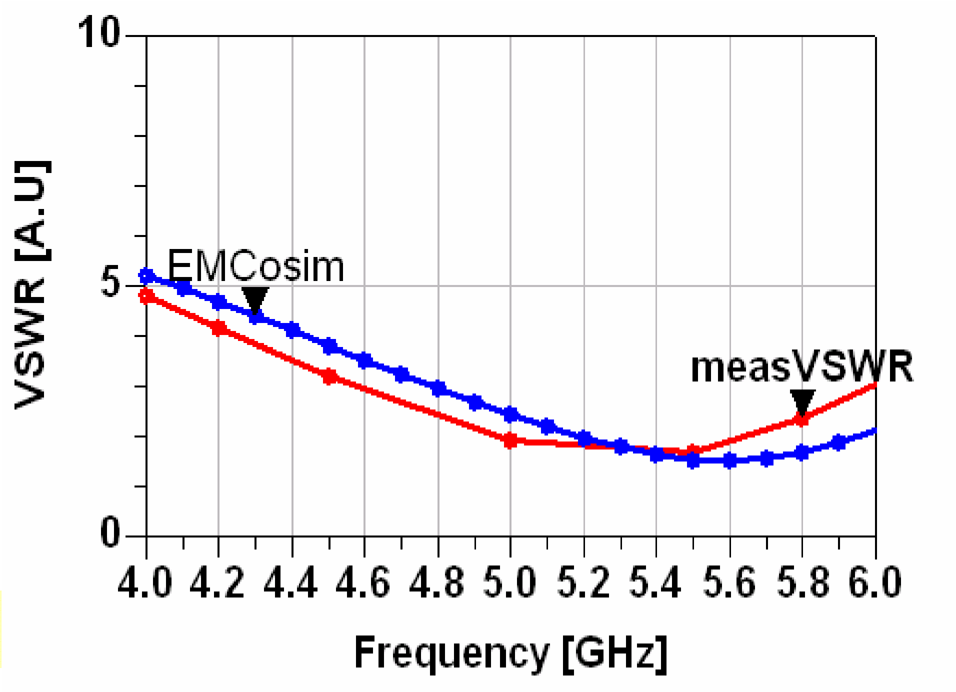
EM-Cosim Setup



Verification with the measurement data



S11



VSWR

Conclusion

- ***Simulation Technique for RF-CMOS circuit design.***
  - Next generation of Compact Model
    - Provides better accurate conductance and high-frequency behavior.
  - Make the best of Electromagnetic Tools
    - Doing more practice helps to overcome inaccuracy.
    - Worth trying “DUMMY METAL”.
      - If successful in PAD, successful in EM-Cosim, too.

Collaboration of Poisson and Maxwell equation is a way for successful simulation !