On-Chip Spiral Inductors for Silicon-Based Radio-Frequency Integrated Circuits

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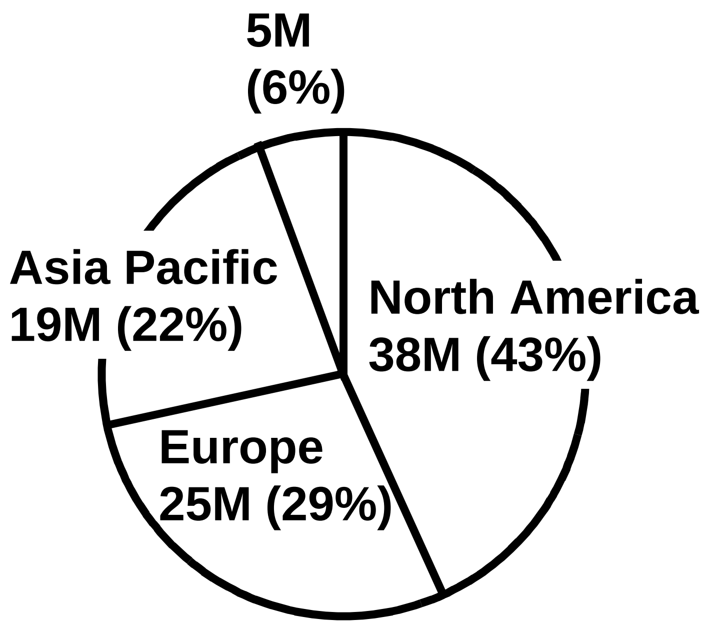
Outline

- Overview
- A physical model for on-chip inductors
- Effects of process and layout parameters
- Design methodology
- Inductors with patterned ground shields
- Substrate noise coupling
- Conclusions

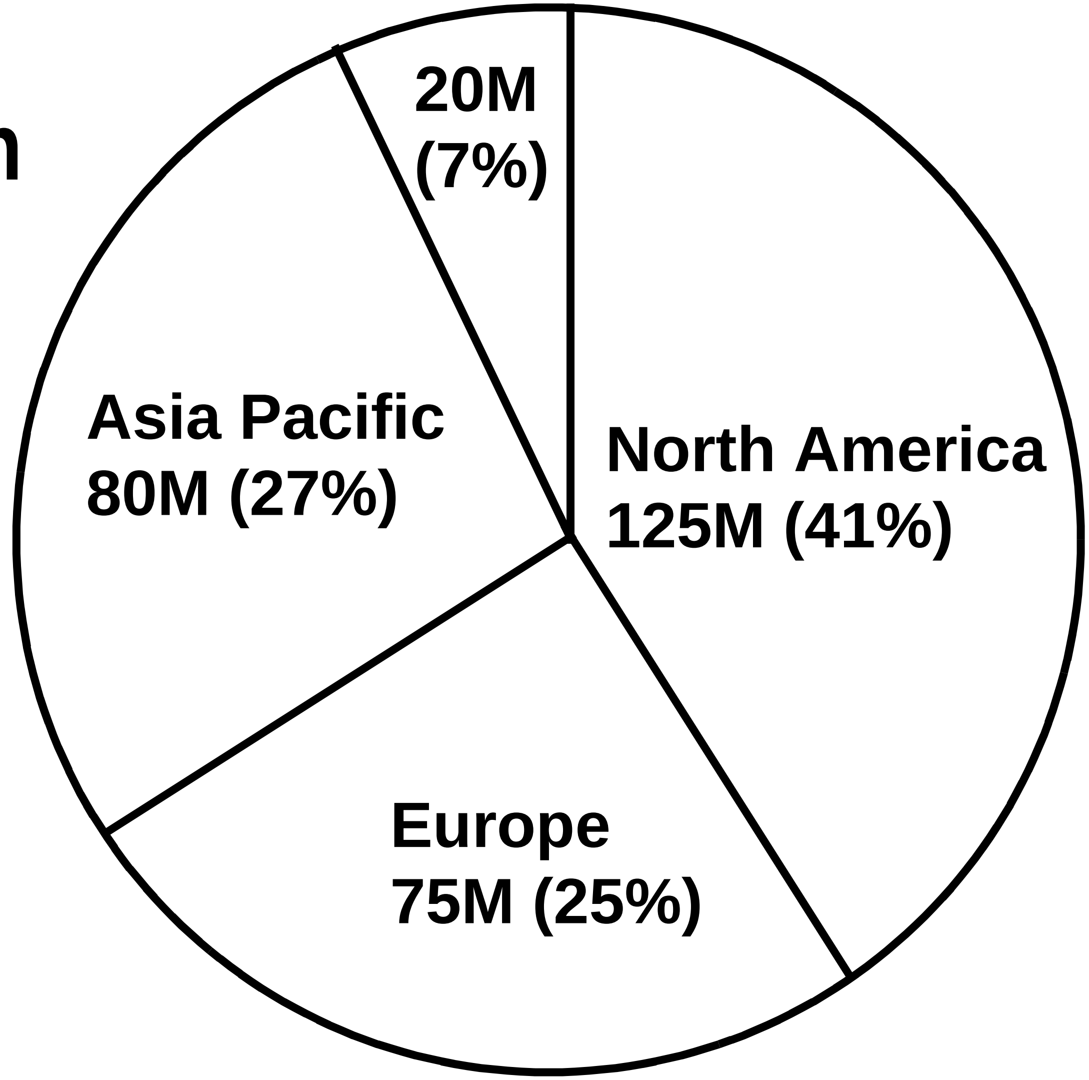
Worldwide Wireless Market

36% Annual Growth

(Source: CTIA, 1996.)

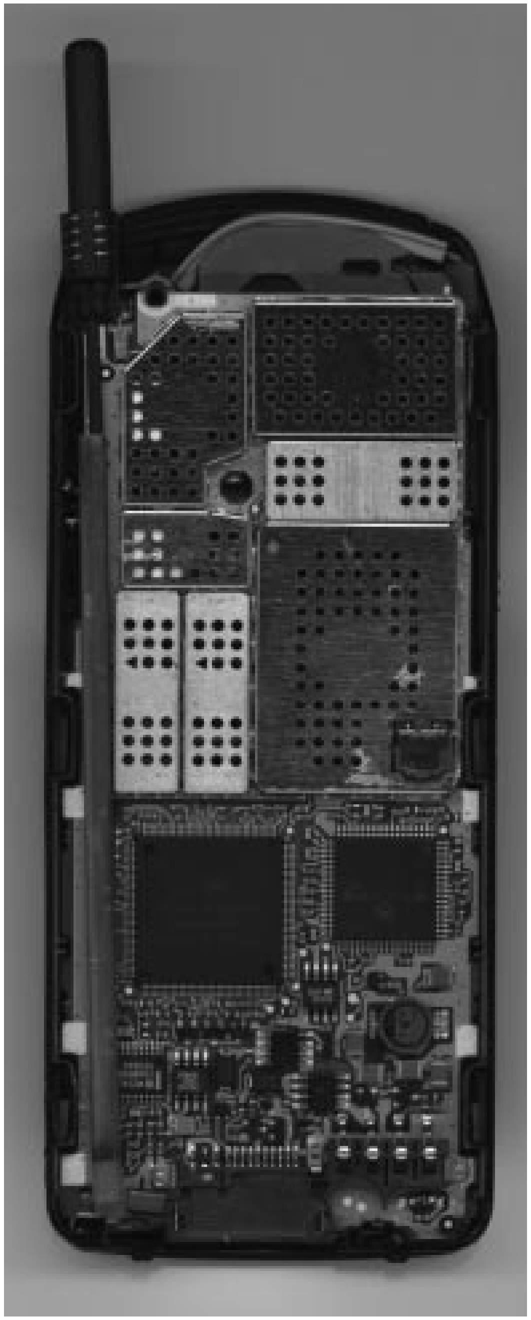


1996 Total: 87M



2000 Total: 300M

A Typical Cellular Phone



RF front-end component count:

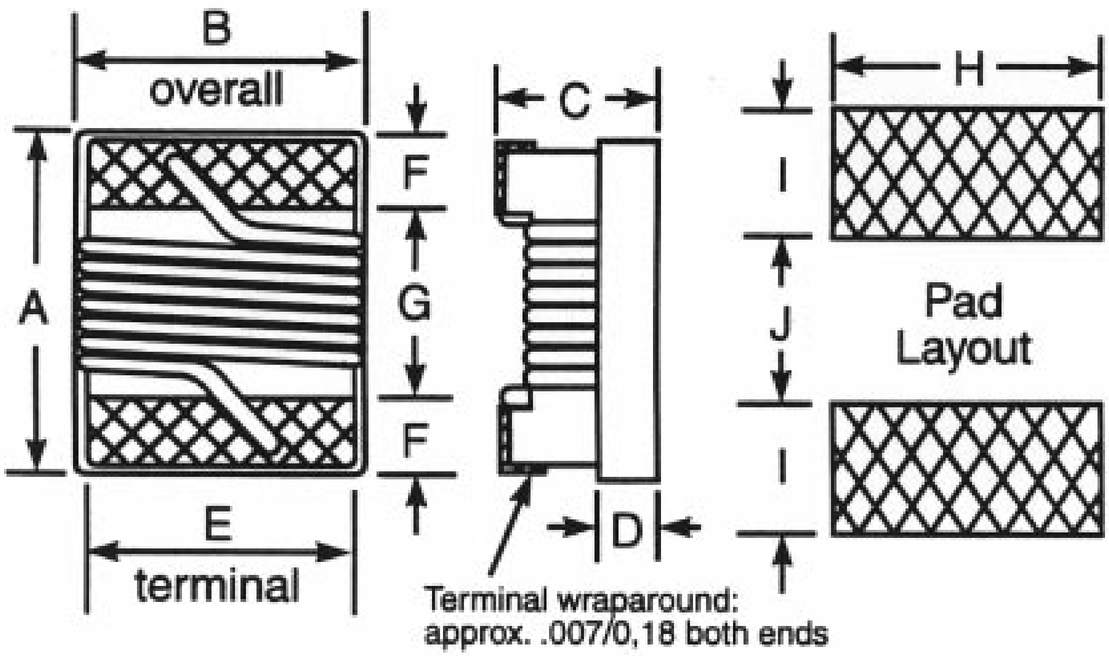
Inductor	11
Capacitor	>100
Resistor	>50
IC	5
Transistor	12
Crystal	1
Filter	2

(Source: Bosch, 1997.)

Advantages of Integration

- Cost: assembly and packaging
- Power: fewer parasitics
- Design Flexibility: signals stay on chip
- Size
- Reliability
- Tolerance

Discrete Inductors

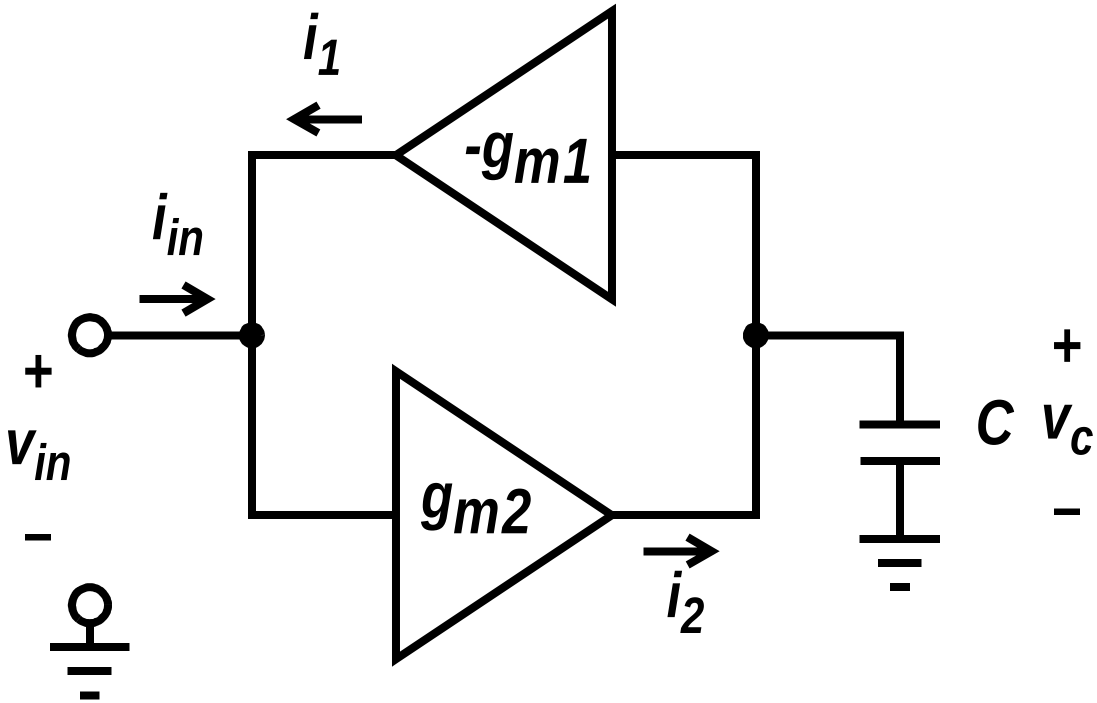


A Max.	B Max.	C Max.	D Ref.	E	F	G	H	I	J	
.071	.044	.040	.015	.030	.013	.034	.040	.025	.025	inch
1,80	1,12	1,02	0,38	0,76	0,33	0,86	1,02	0,64	0,64	mm

(Source: Coilcraft, 1997.)

- L: 2 to 20 nH (2 to 10%)
- Q: 50 to 200 (1 to 2 GHz)
- srf: 4 to 10 GHz

Active Inductors

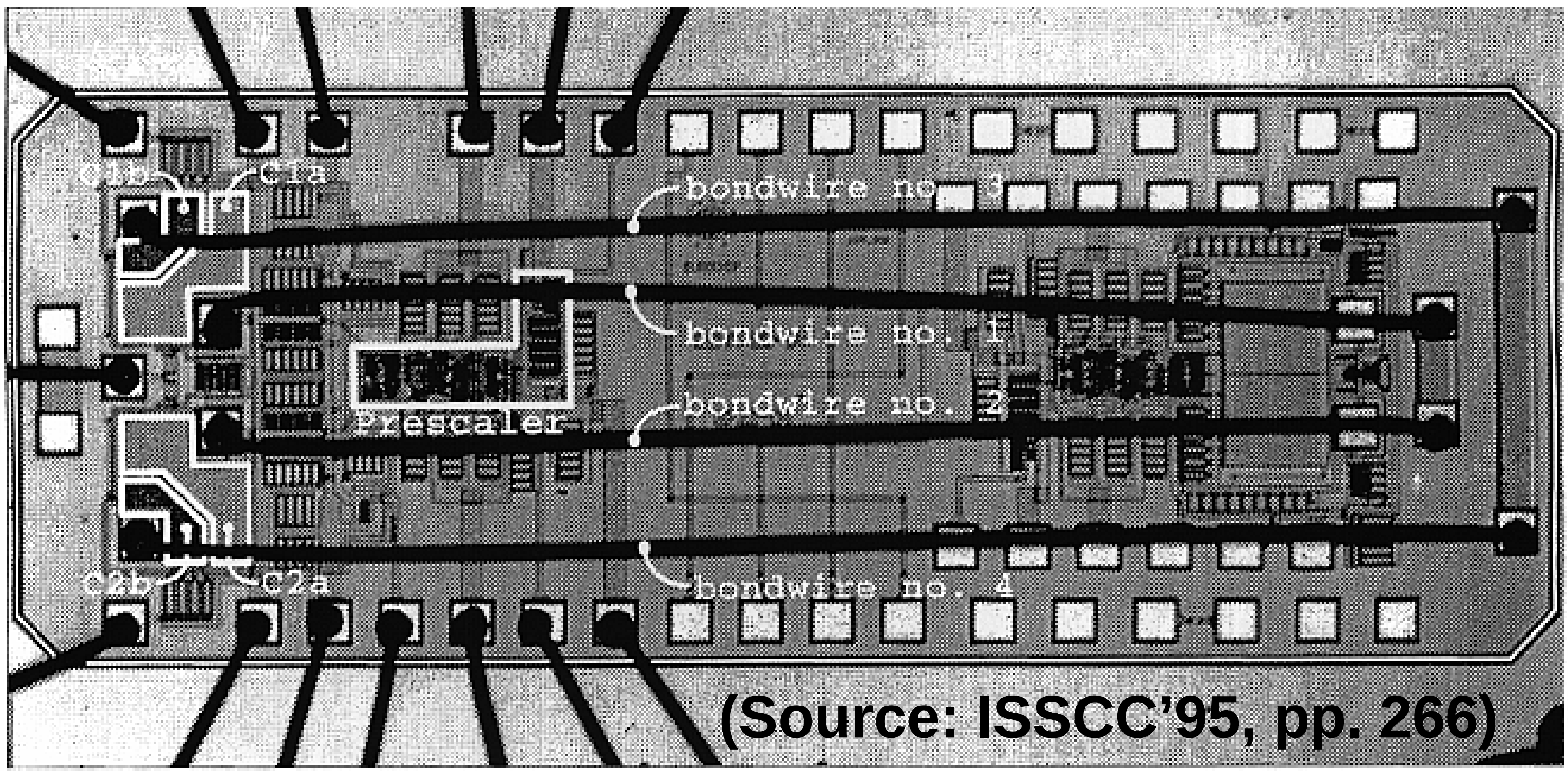


- Excess Noise
- Extra Power
- Limited Linearity

$$L = \frac{C}{g_{m1}g_{m2}}$$

Bond Wire Inductors

- Predictability
- Repeatability
- Unwanted Couplings
- Limited Inductance



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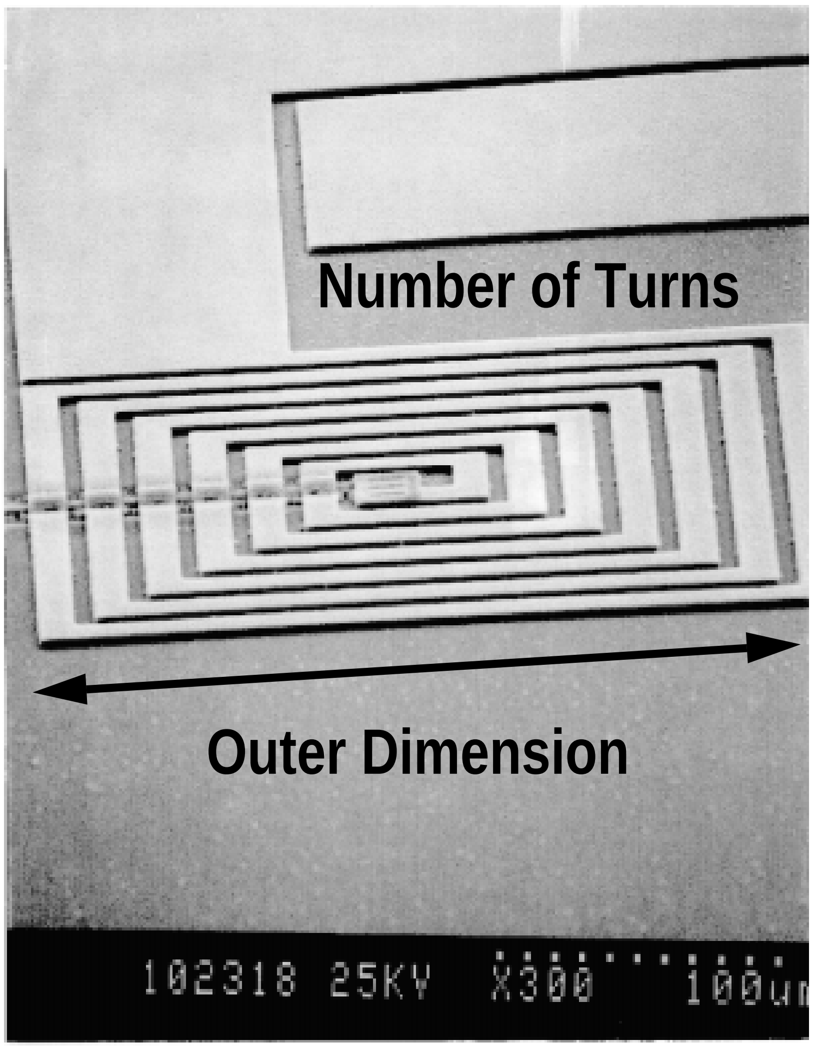
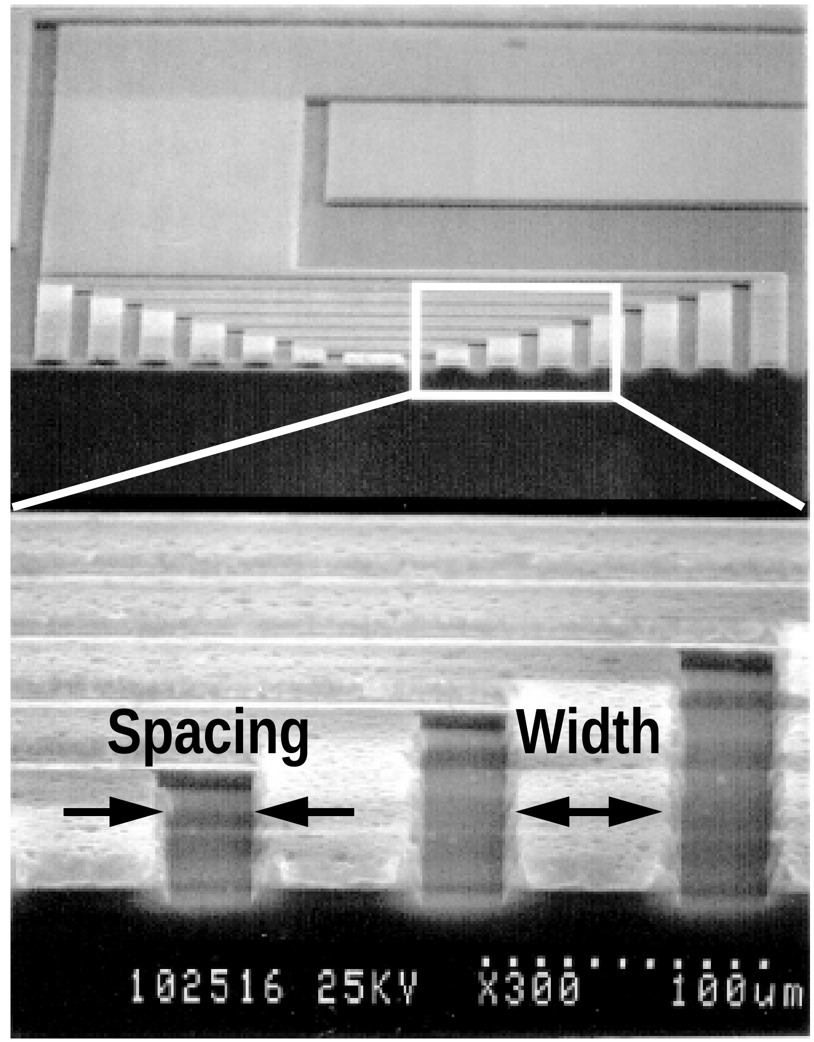
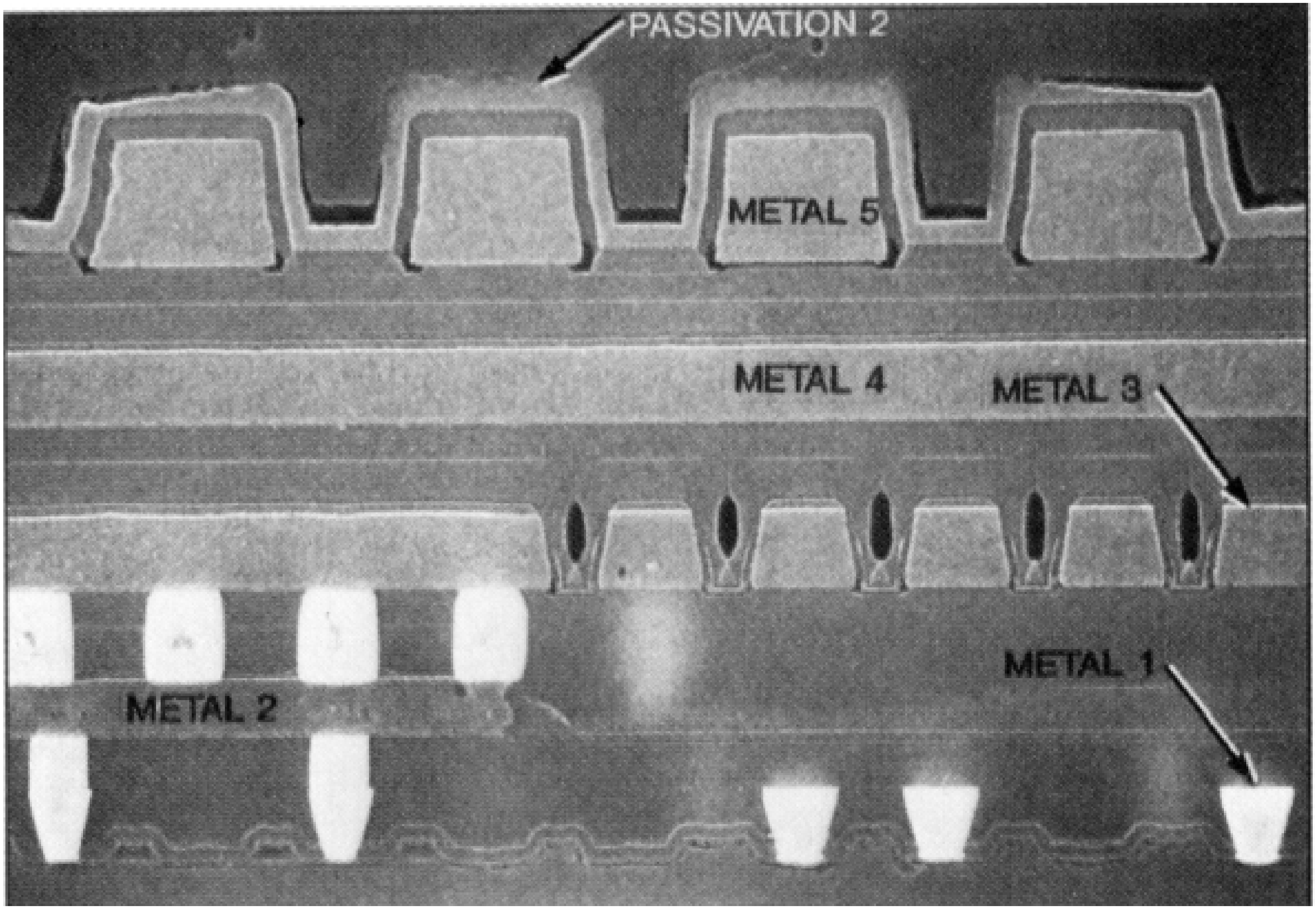
A Typical Planar Spiral Inductor





Multilevel Interconnects



(Source: *Semiconductor International*, 1997.)

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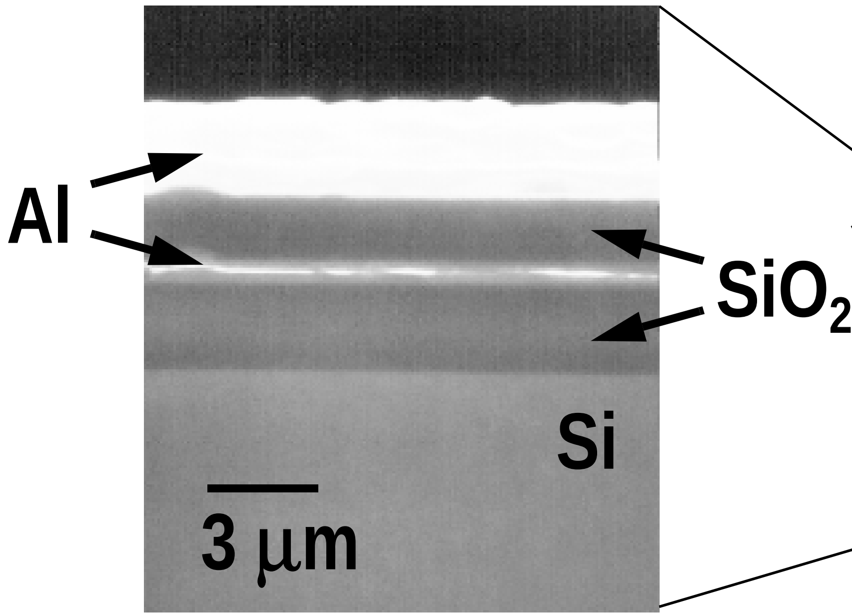
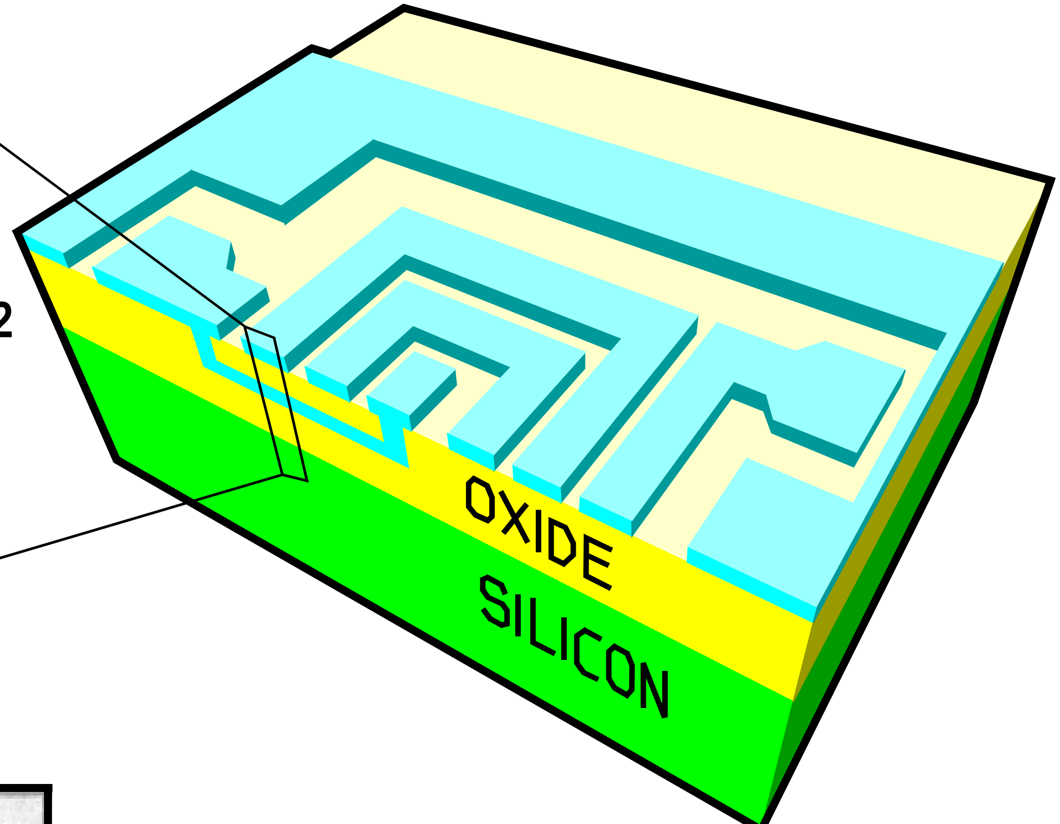
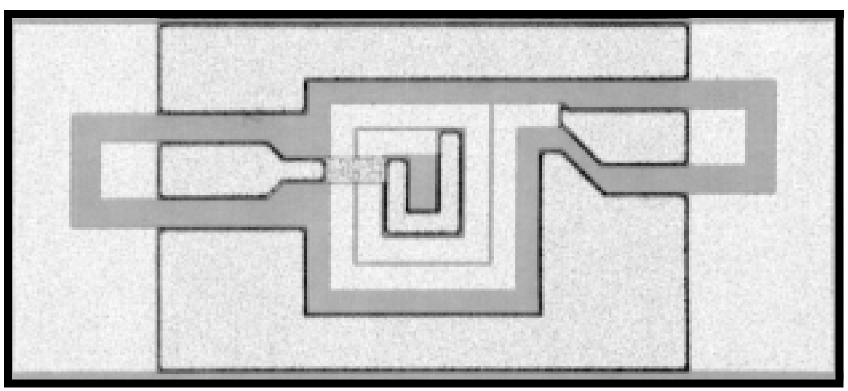
A Typical Inductor On Silicon





3D Perspective View



Top View

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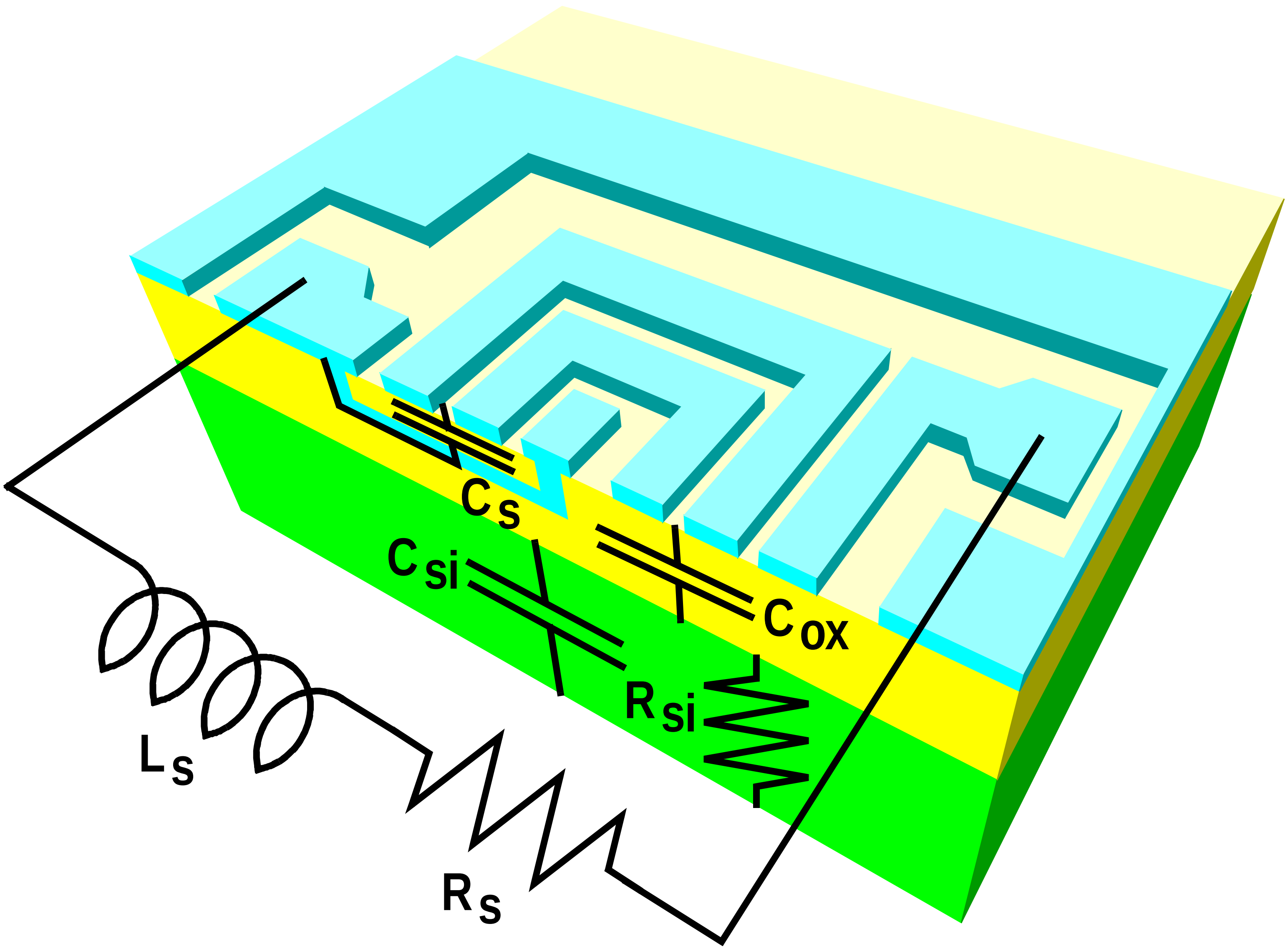
Model Description



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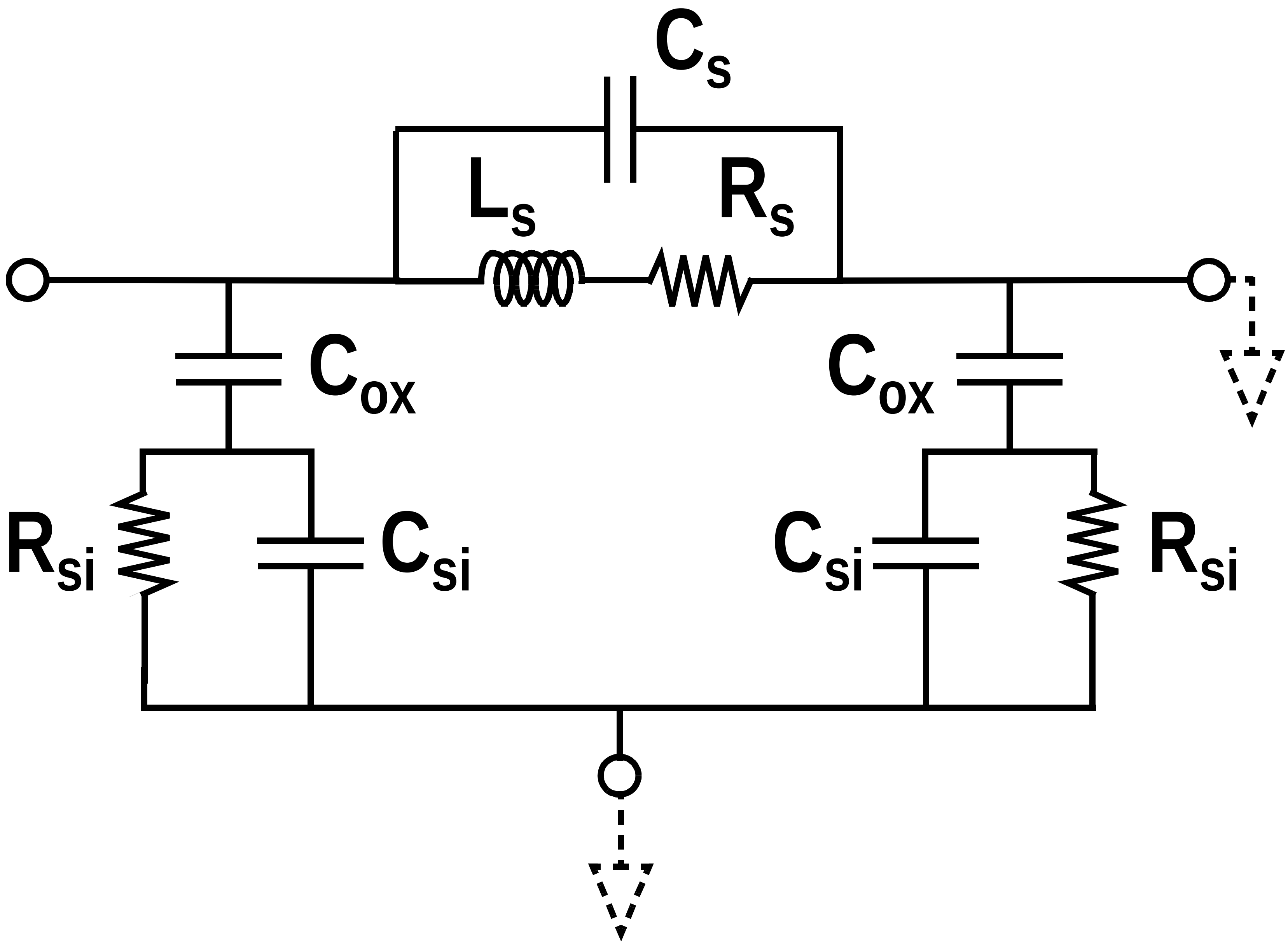
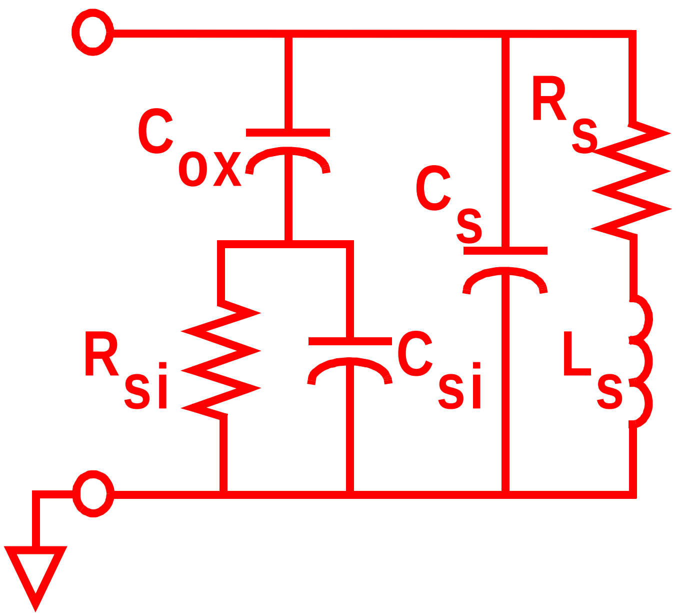
Model Description



Model Description

Physical Model of Inductor on Silicon		Effects
	L_s: Greenhouse Method	Mutual Couplings
	$R_s = \dfrac{\rho \cdot l}{w \cdot \delta \cdot (1 - e^{-t/\delta})}$	Eddy Current
	$C_s = n \cdot w^2 \cdot \dfrac{\varepsilon_{ox}}{t_{ox\ M1\text{-}M2}}$	Feed-Through Capacitance
	$C_{ox} = \dfrac{1}{2} \cdot l \cdot w \cdot \dfrac{\varepsilon_{ox}}{t_{ox}}$	Oxide Capacitance
	$C_{si} = \dfrac{1}{2} \cdot l \cdot w \cdot C_{Sub}$	Si Substrate Capacitance
	$R_{si} = \dfrac{2}{l \cdot w \cdot G_{Sub}}$	Si Substrate Ohmic Loss

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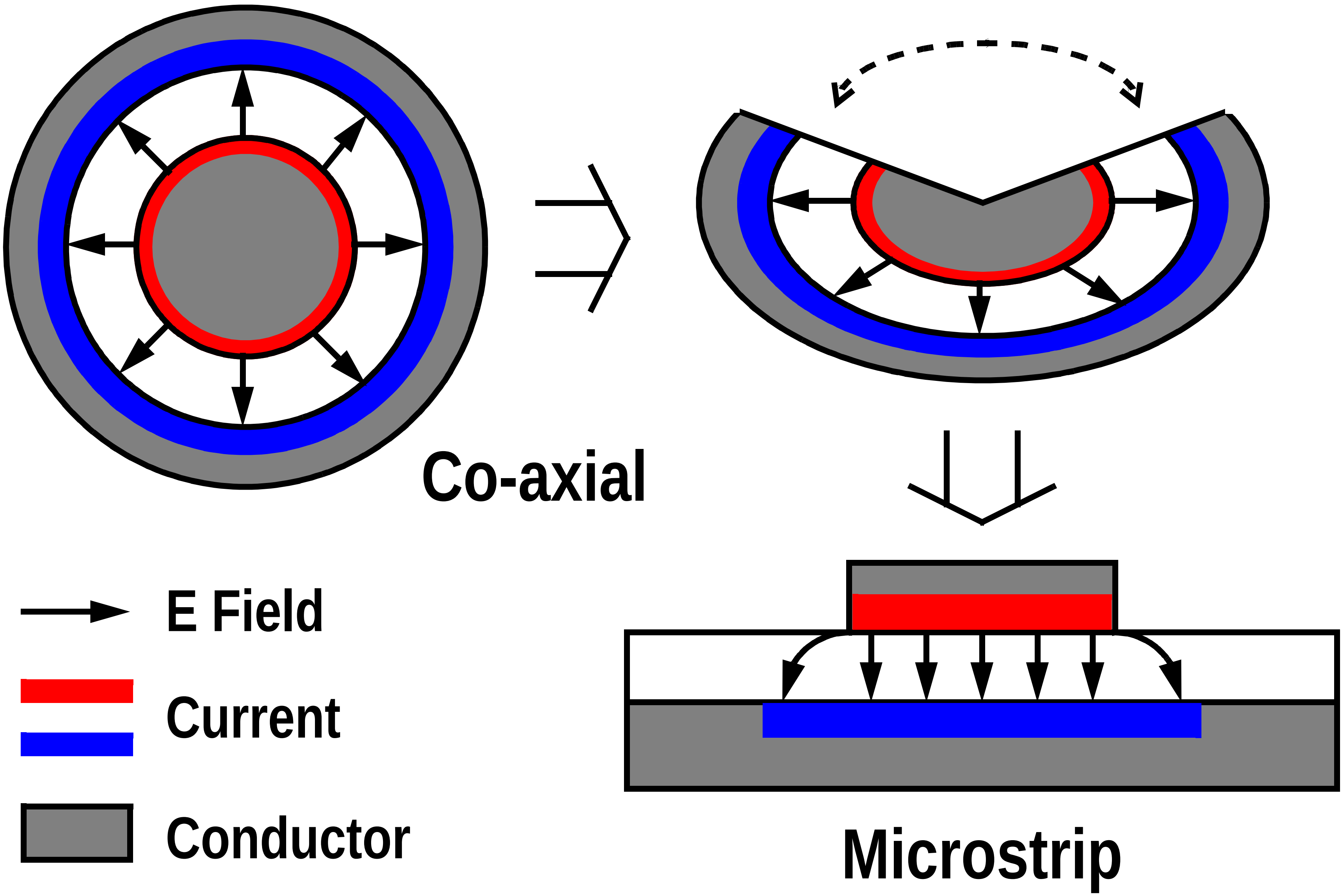
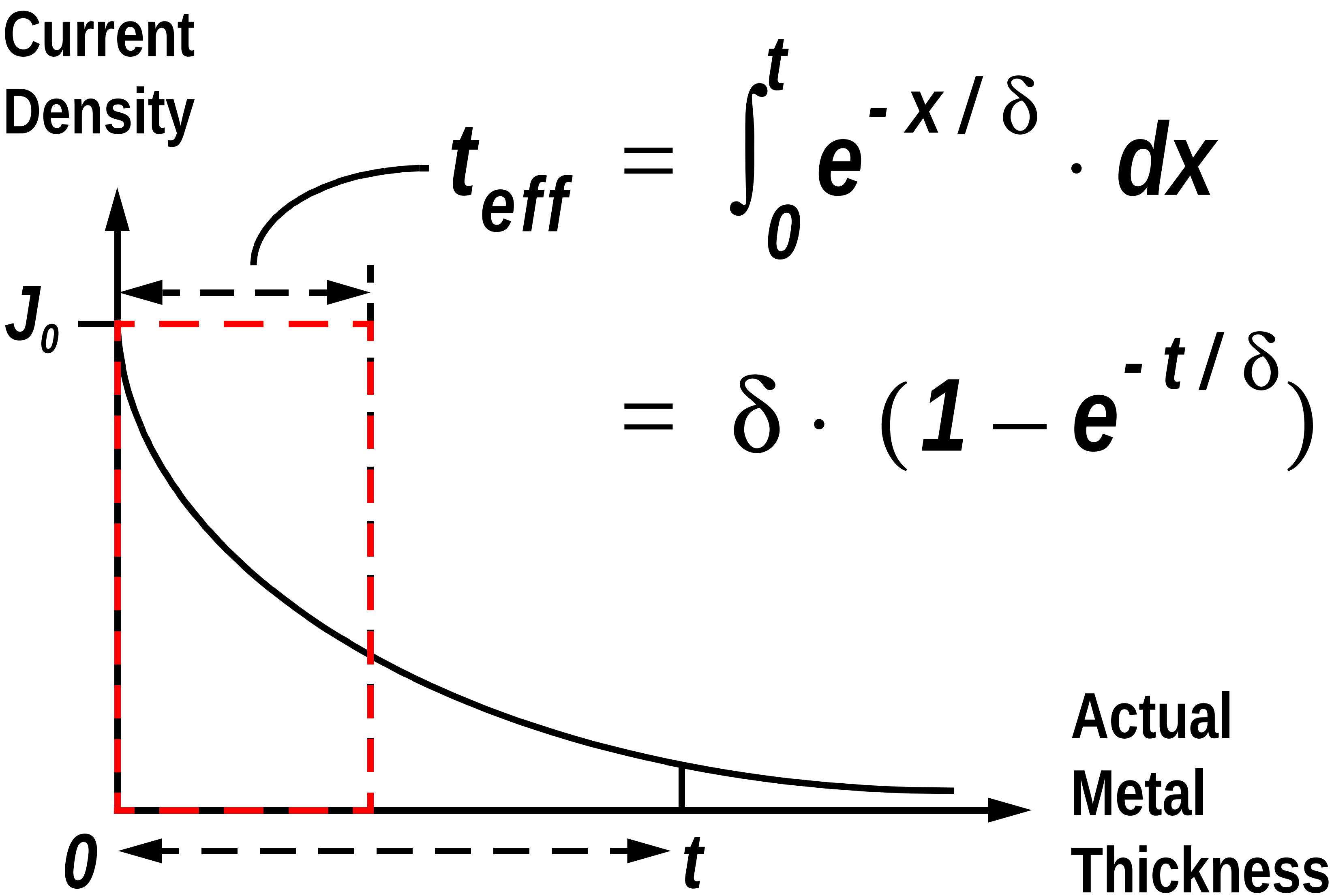
Skin Effect



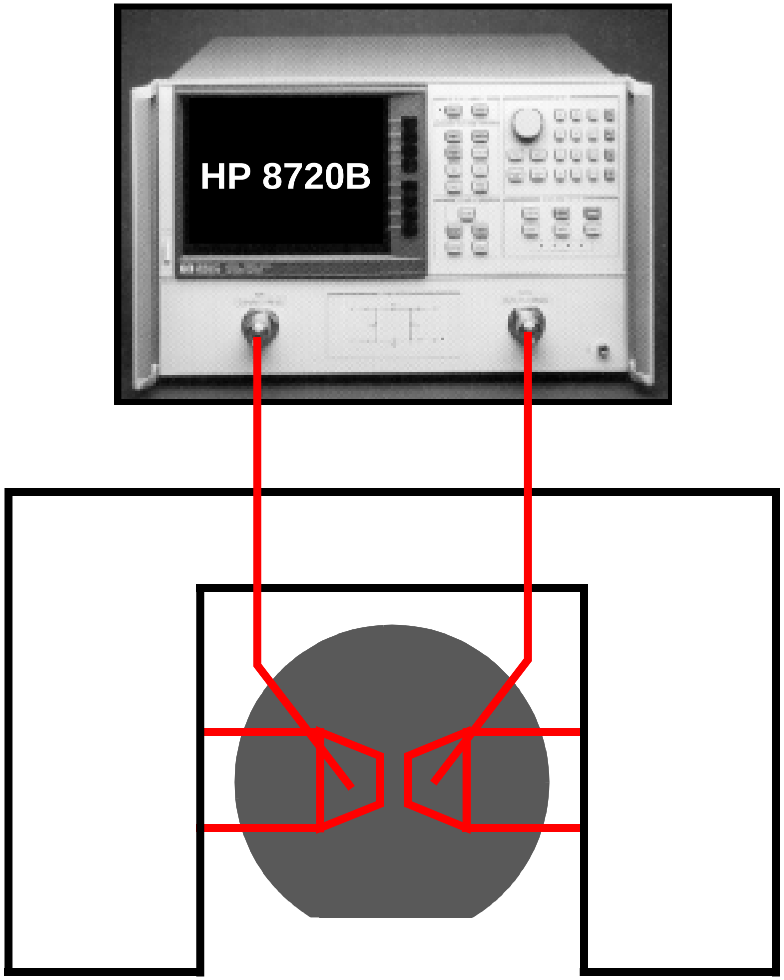
Effective Metal Thickness



$$t_{eff} = \int_0^t e^{-x/\delta} \cdot dx$$

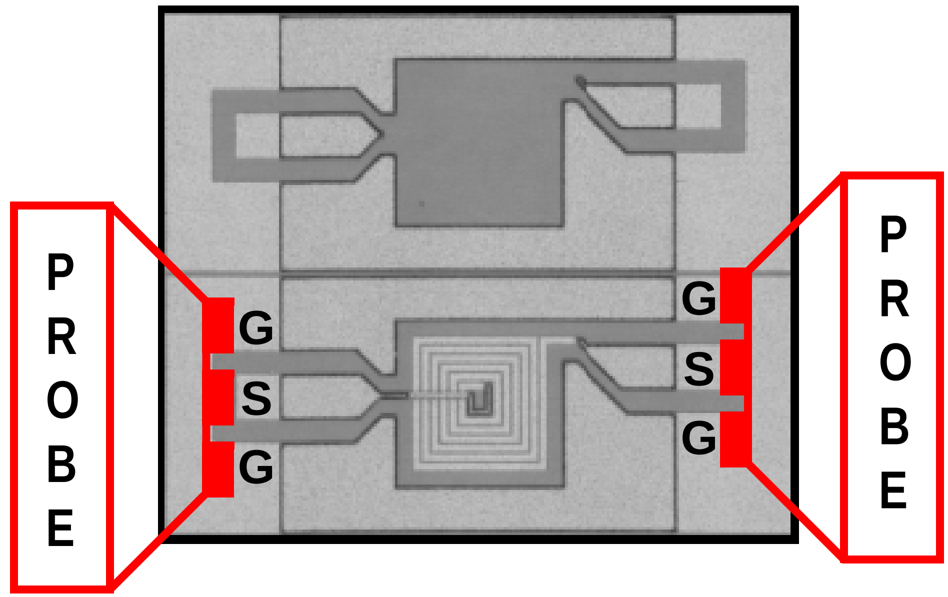
$$= \delta \cdot \left(1 - e^{-t/\delta}\right)$$

Measurement Setup



Probe Station

Open Structure



Device Under Test

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Parameter Extraction Procedure

De-embedded S Parameters →

S to Transmission Matrix Conversion

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \rightarrow \begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

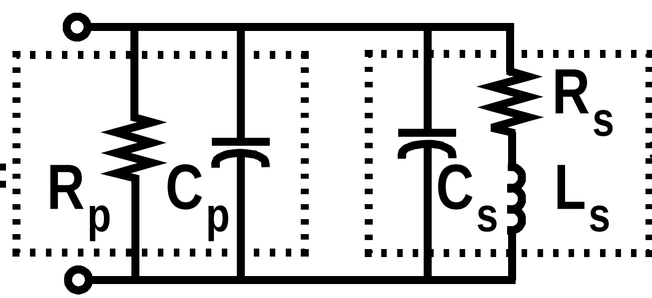
↓

Solve for Propagation Constant (Γ) and Characteristic Impedance (Z_0)

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cosh \Gamma l & Z_0 \sinh \Gamma l \\ Z_0^{-1} \sinh \Gamma l & \cosh \Gamma l \end{bmatrix}$$

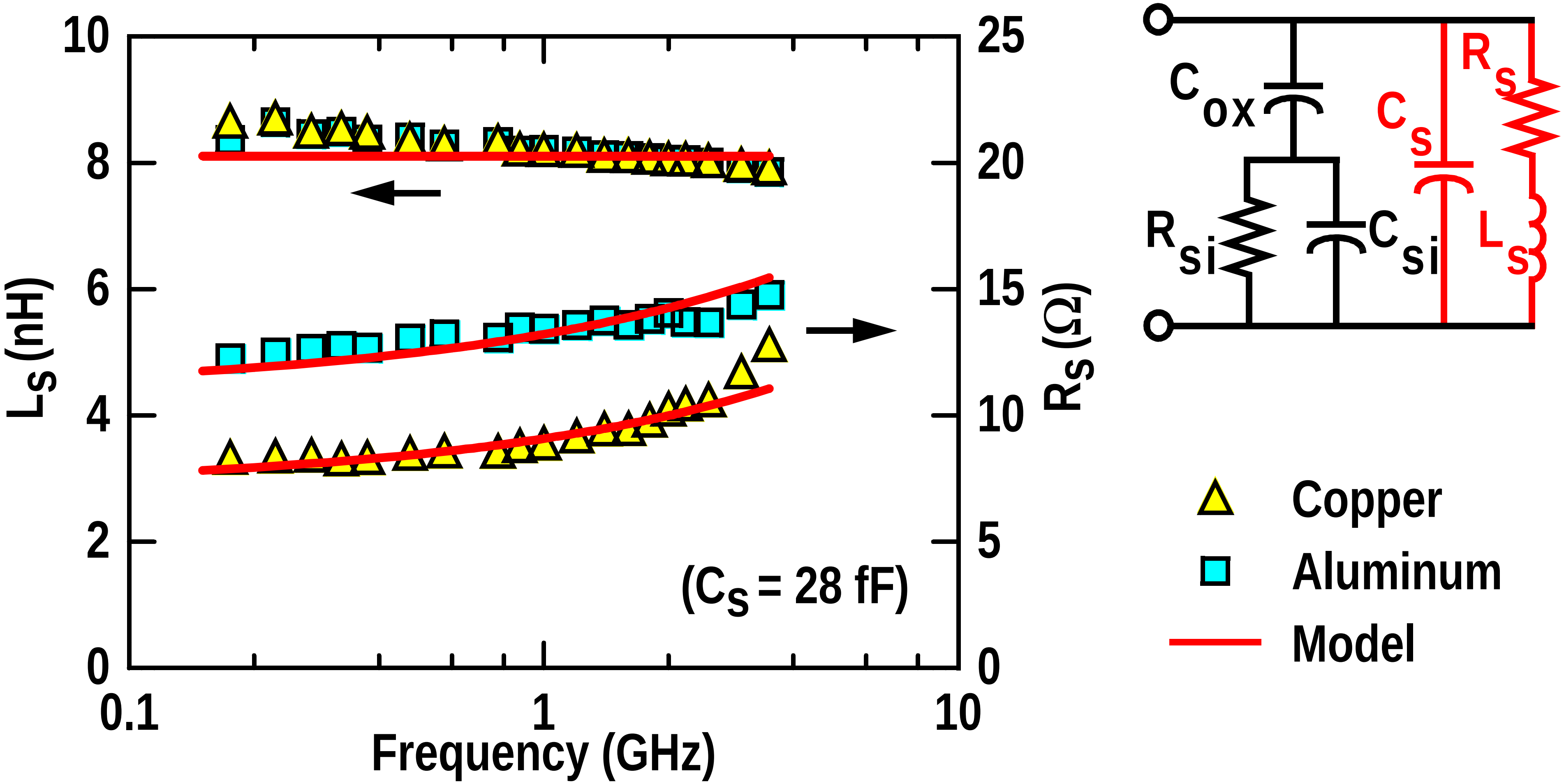
↓

$$\frac{2Z_0}{\Gamma \cdot l} =$$



$$= \Gamma \cdot l \cdot Z_0$$

Measured and Modeled Values of L_S and R_S



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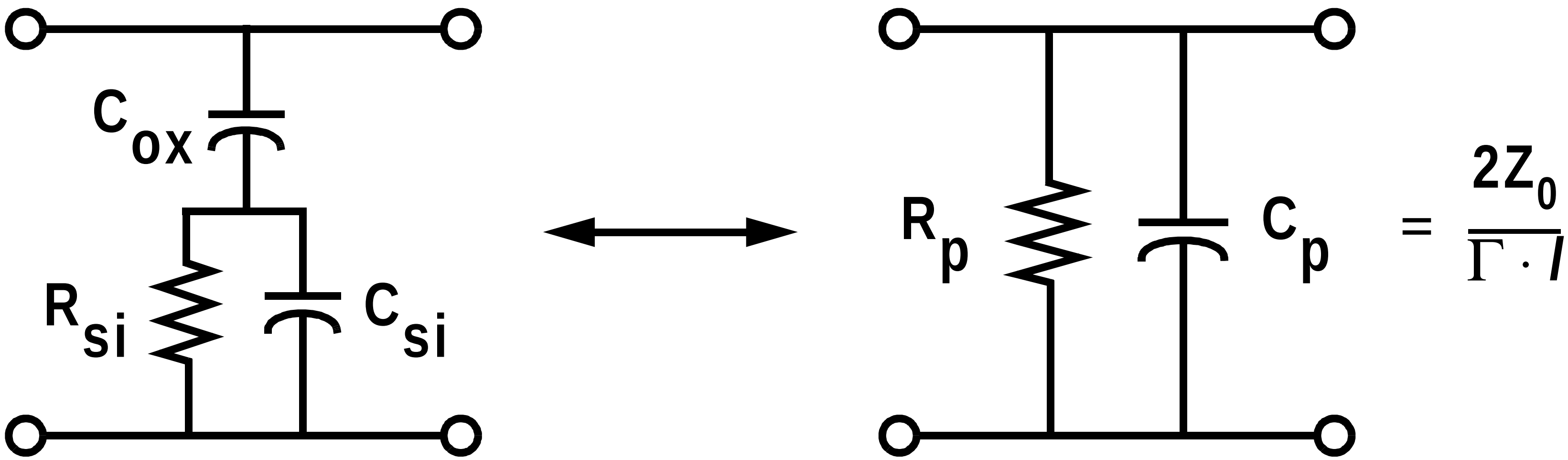
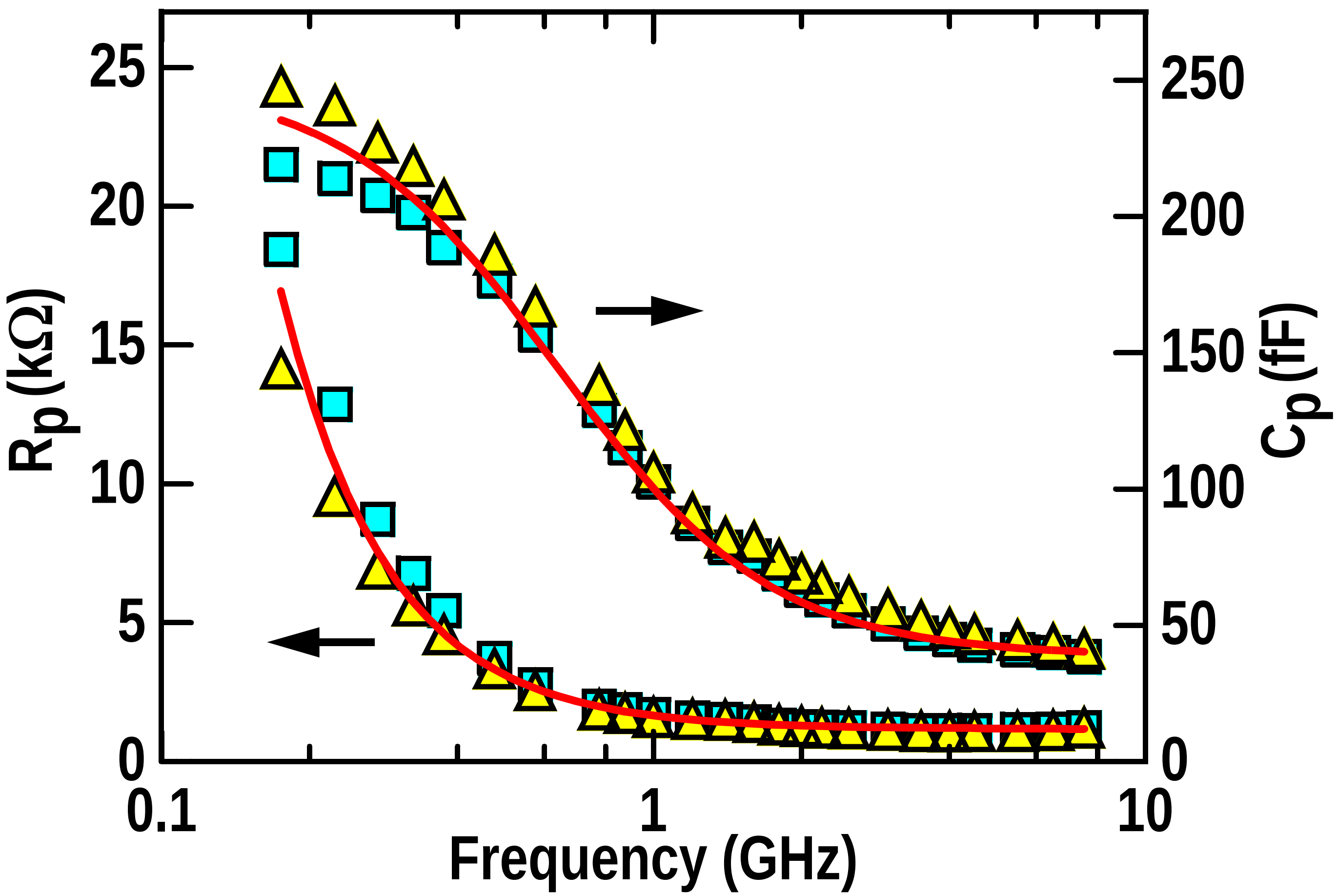
Substrate Modeling

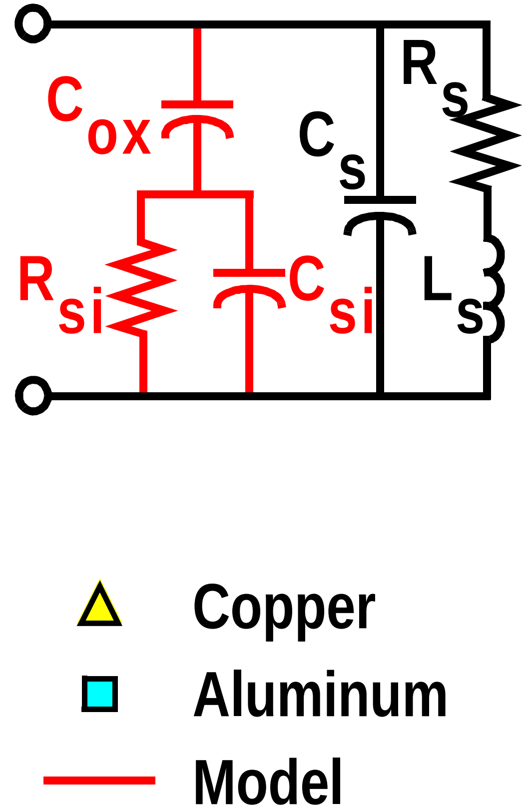


Physical Model

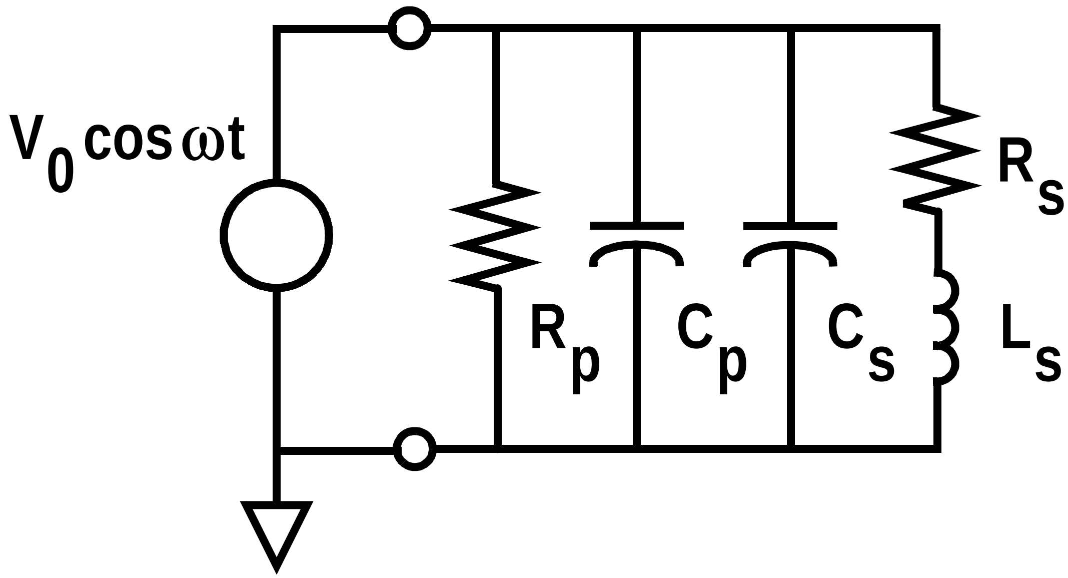
Extracted Capacitance and Resistance

Measured and Modeled Values of R_p and C_p





Definition of Inductor Quality Factor



$$Q = 2\pi \frac{|\text{Peak Magnetic Energy} - \text{Peak Electric Energy}|}{\text{Energy Loss in One Oscillation Cycle}}$$

$$\frac{\omega L_s}{R_s} \times \underbrace{\frac{R_p}{R_p + [(\omega L_s / R_s)^2 + 1] \cdot R_s}}_{\text{Substrate Loss Factor}} \times \underbrace{\left(1 - \frac{R_s^2 (C_p + C_s)}{L_s} - \omega^2 L_s (C_p + C_s)\right)}_{\text{Self-Resonance Factor}}$$

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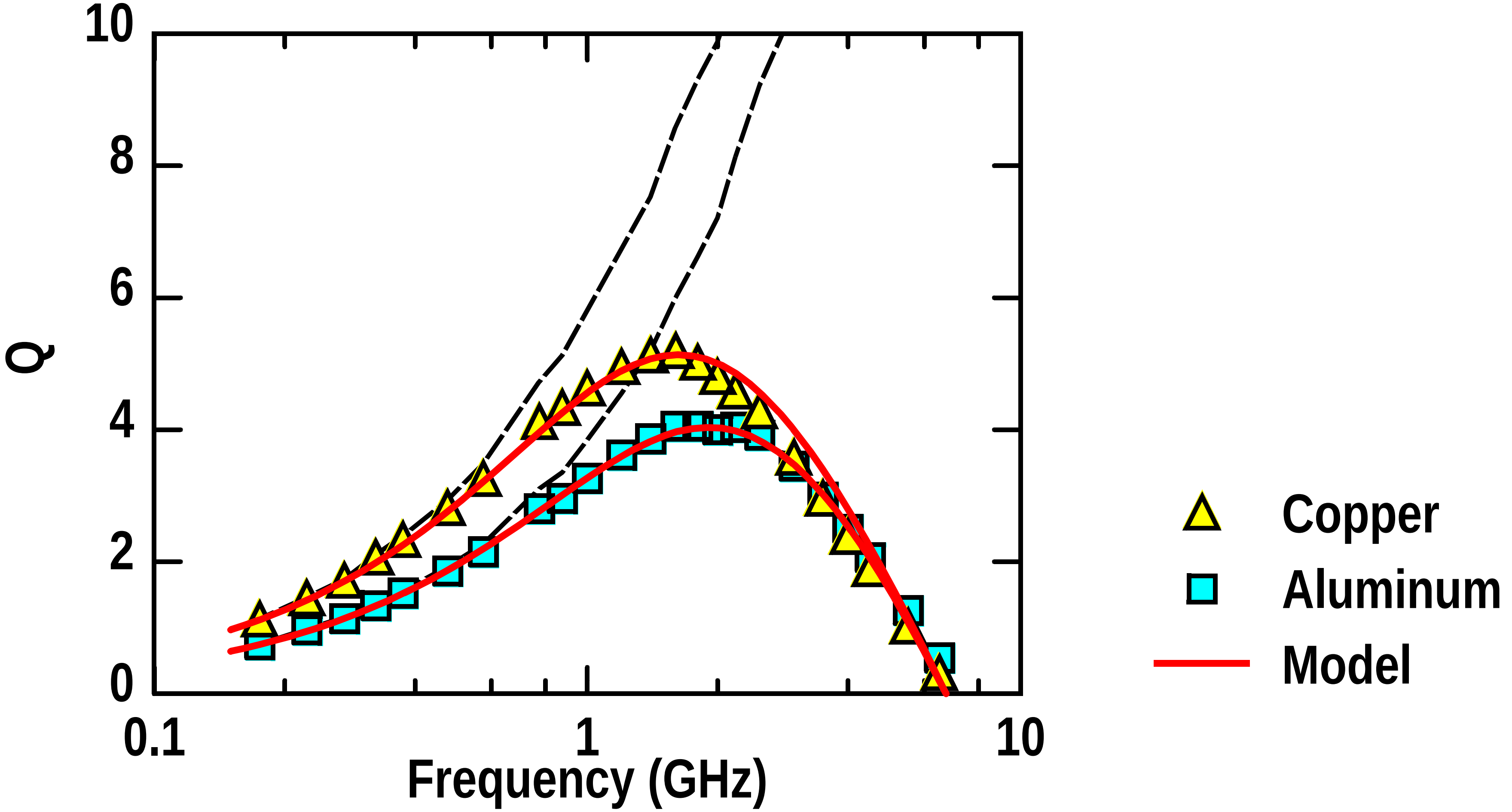
Measured and Modeled Value of Q



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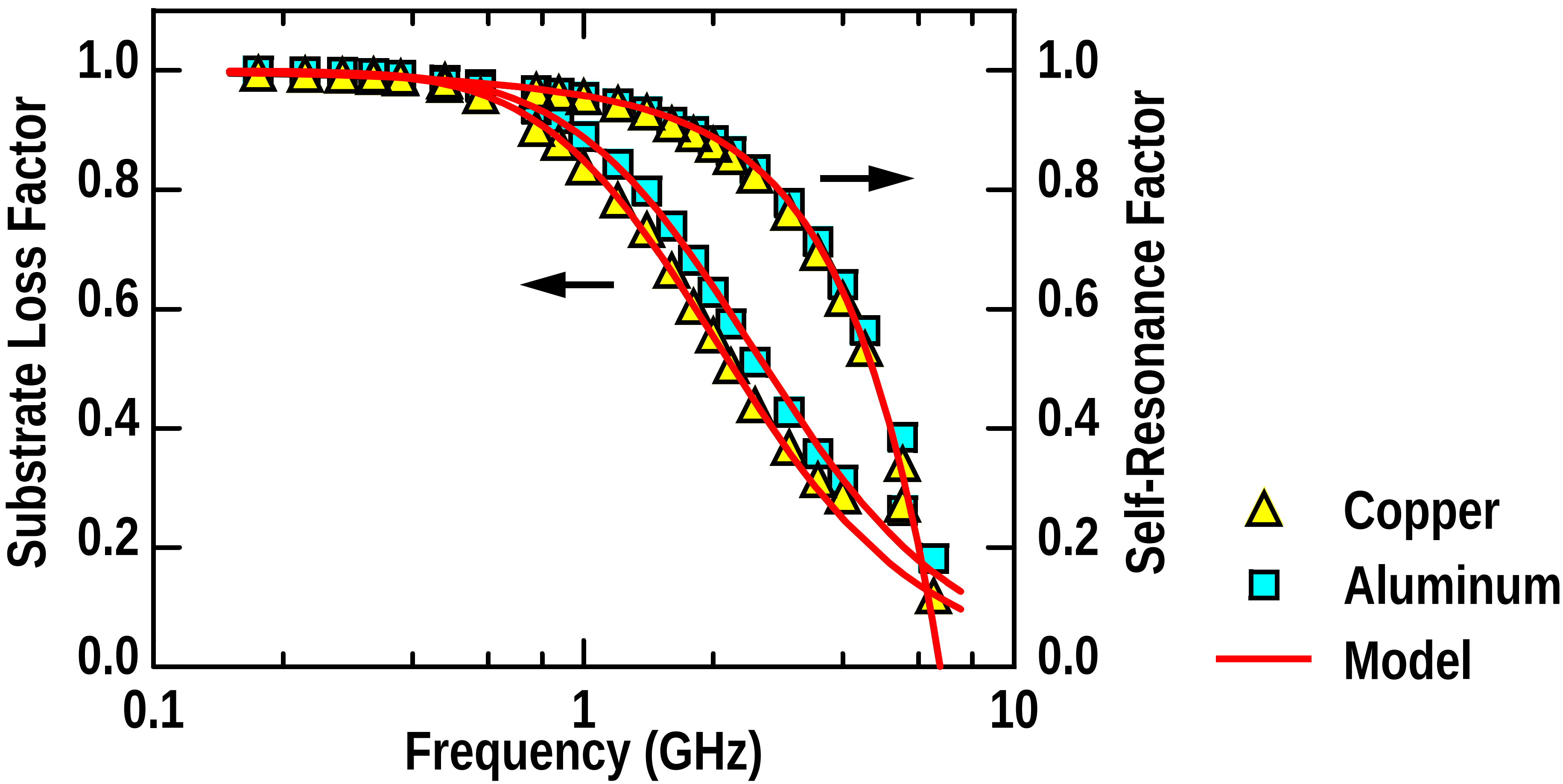
Measured and Modeled Values of Substrate Factors



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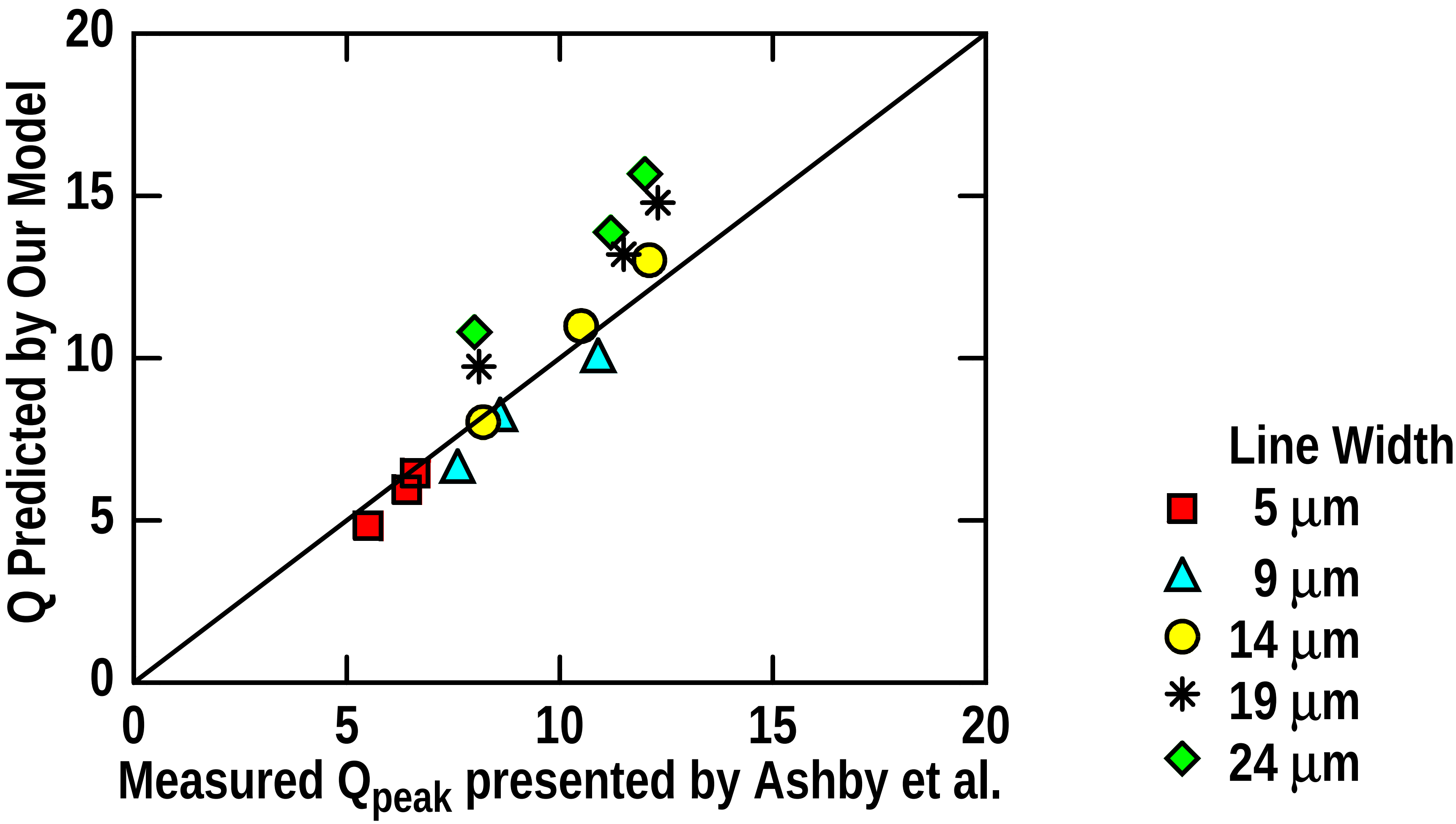
Comparison to Published Results



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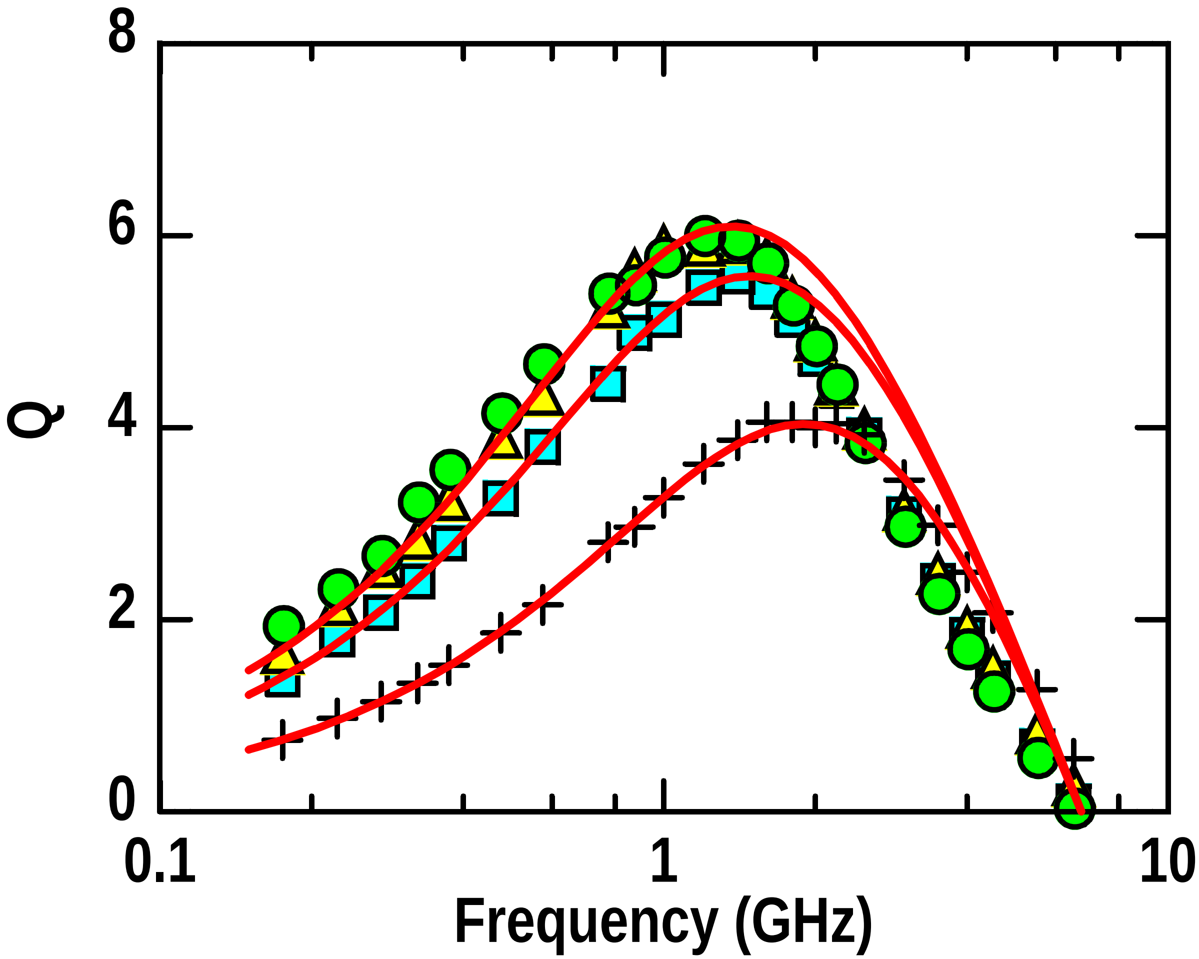
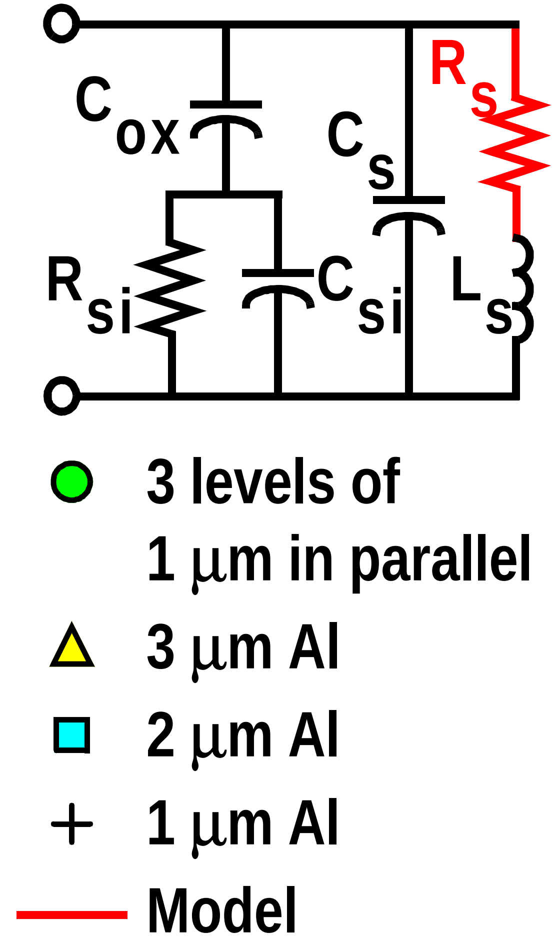
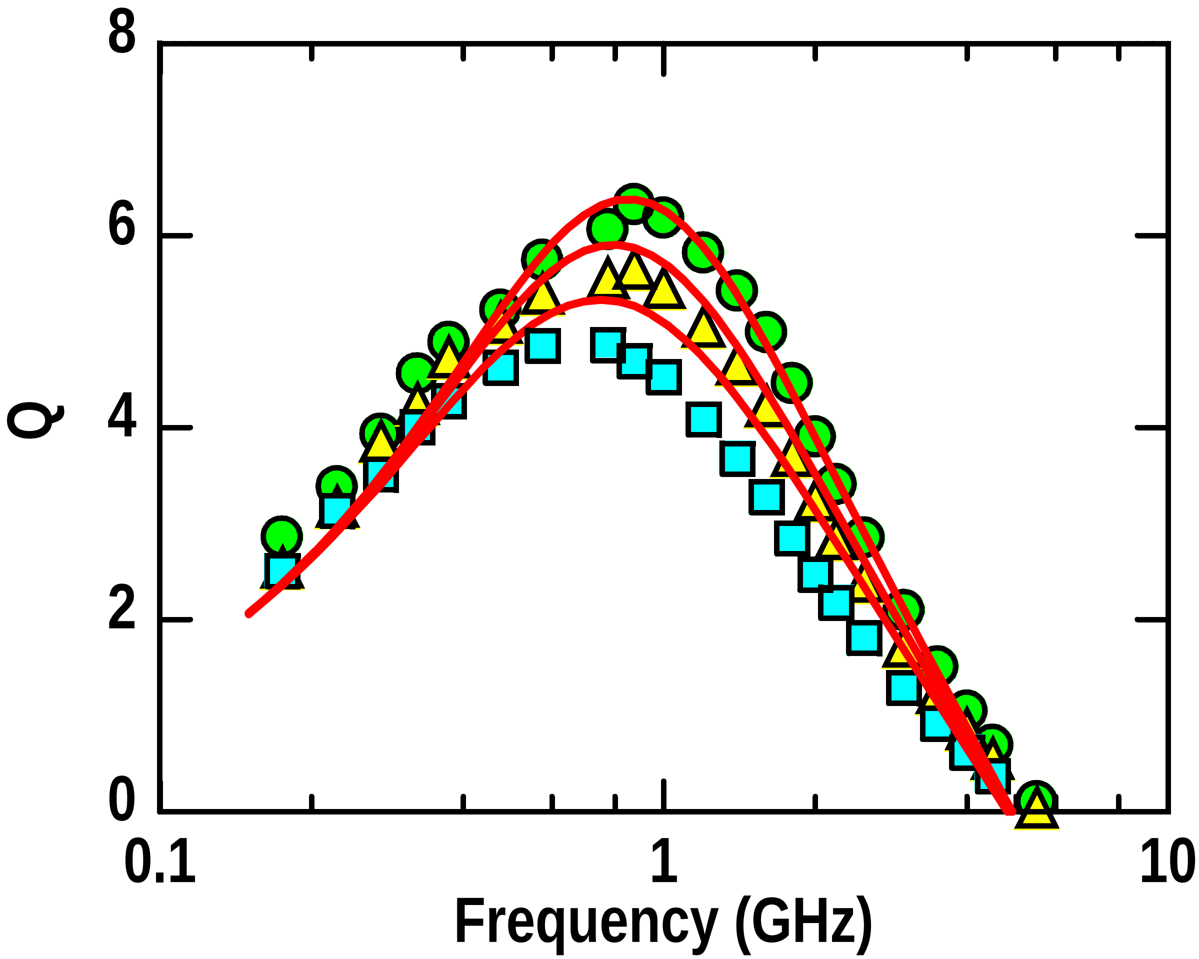
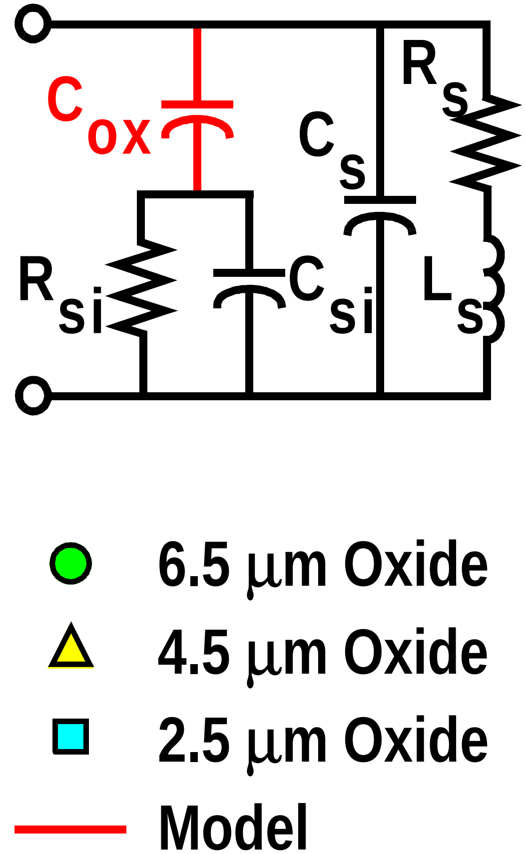
Effect of Metal Scheme on Q



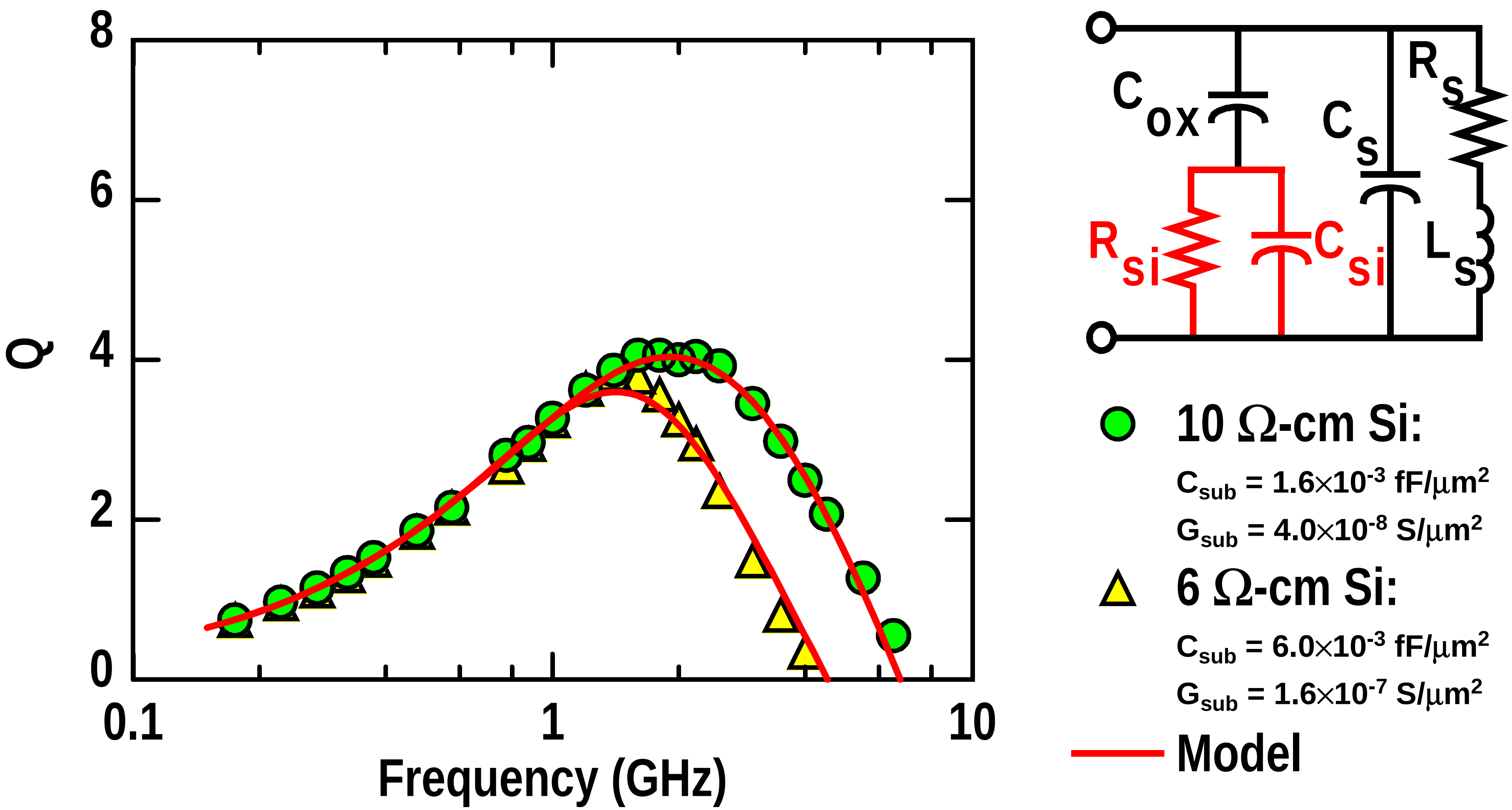


Effect of Oxide Thickness on Q





Effect of Substrate Resistivity on Q



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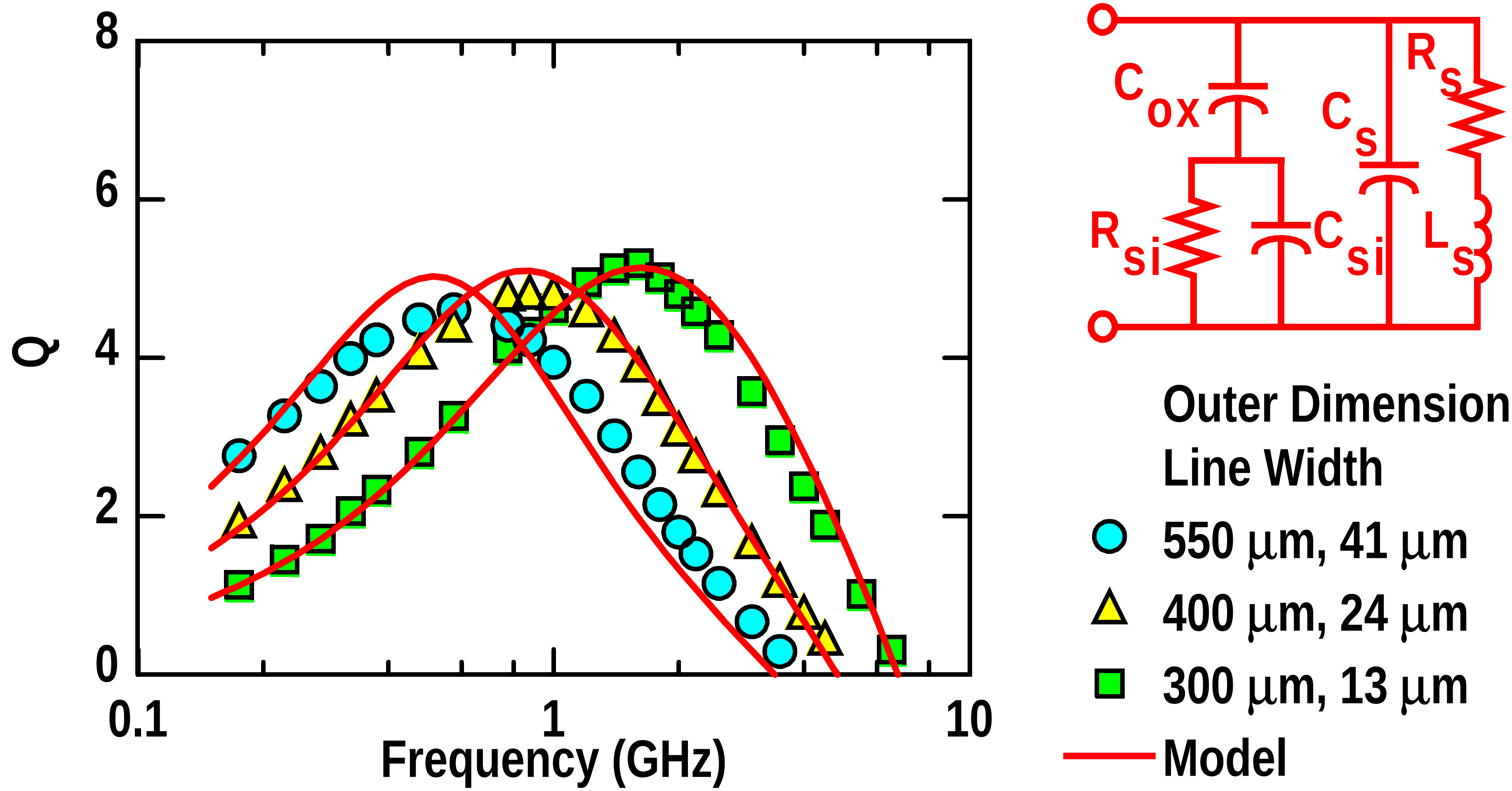
Effect of Layout Area on Q



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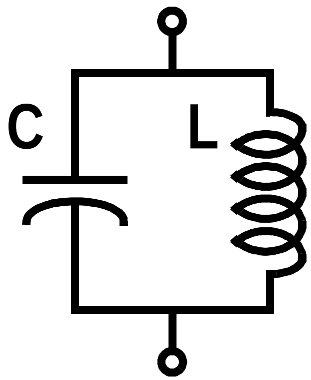
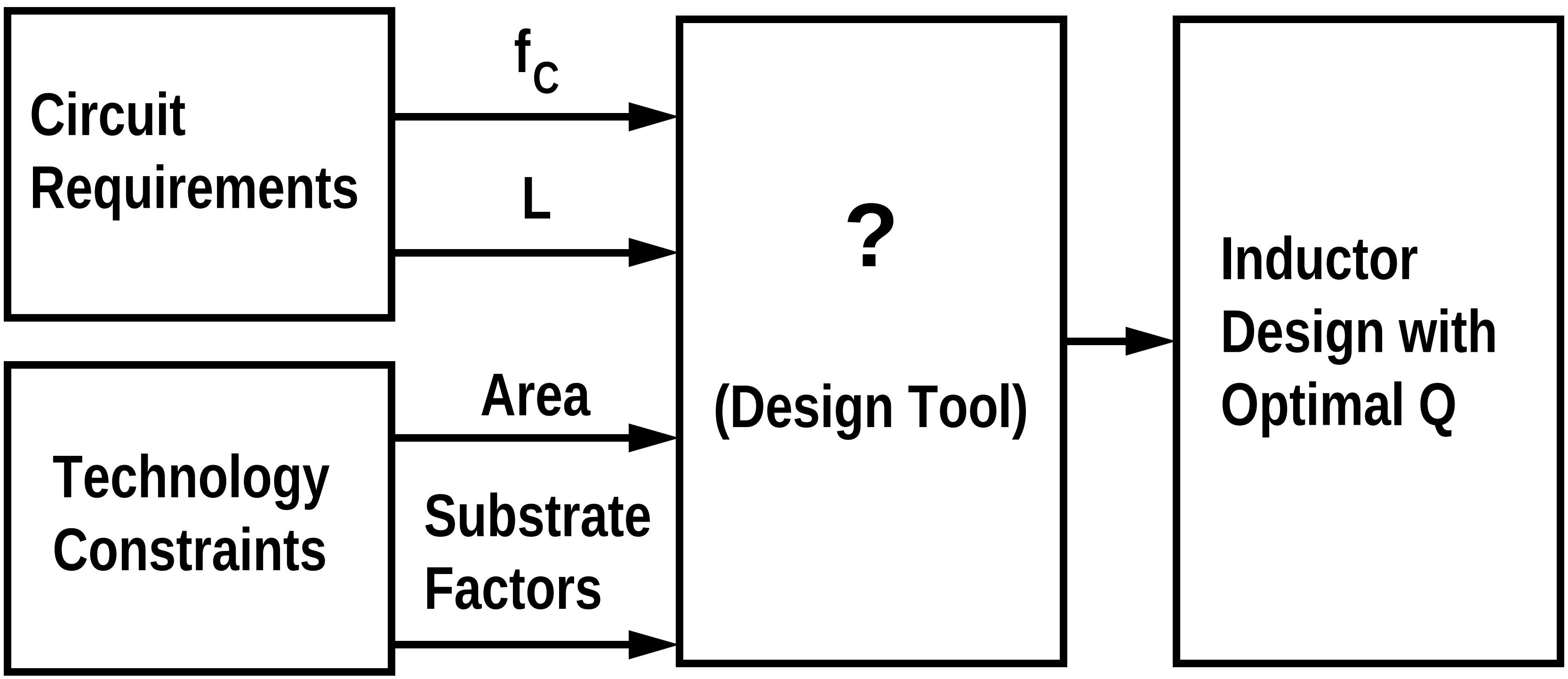
Application of Model

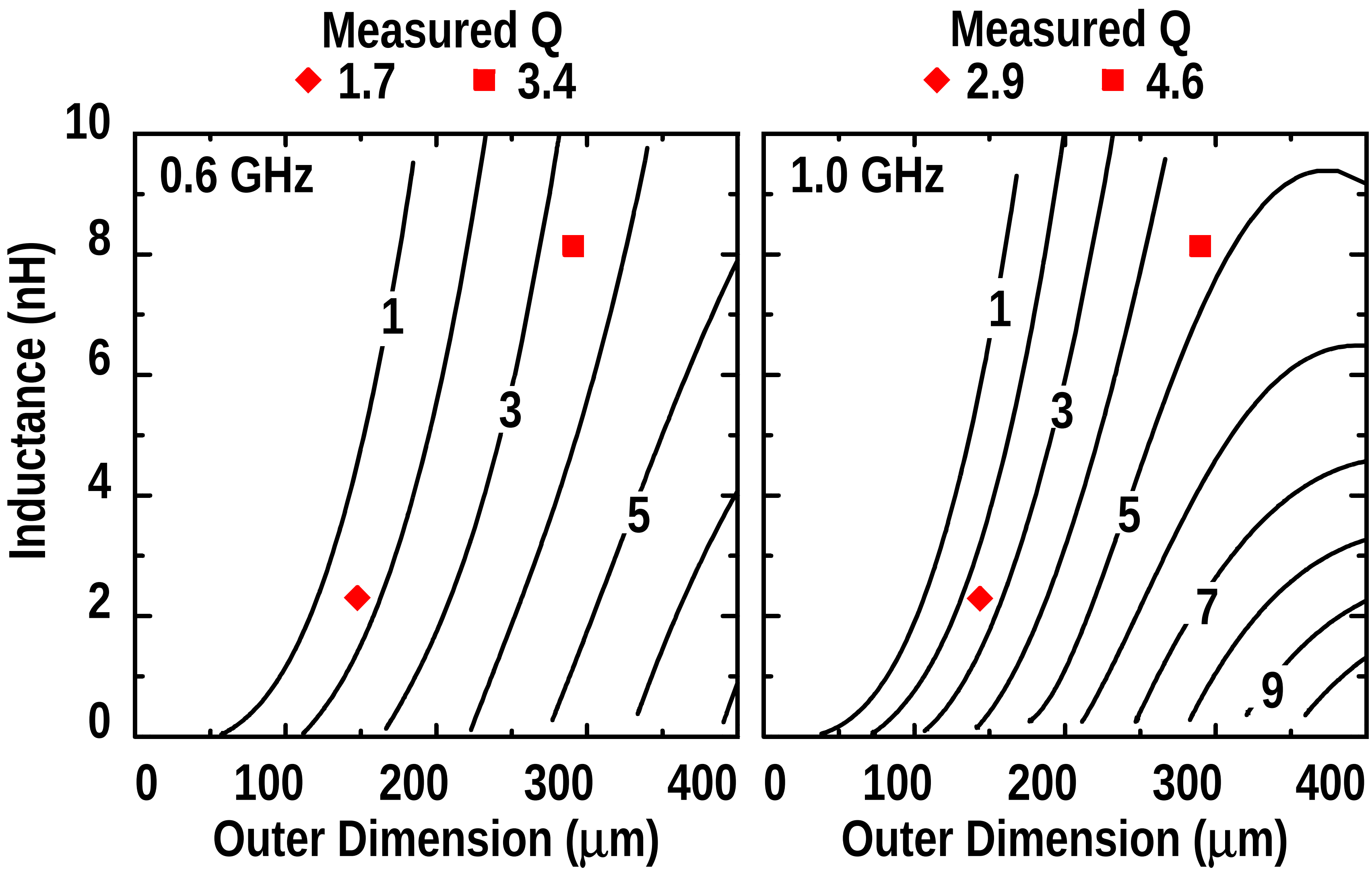


$$f_C = \frac{1}{2\pi\sqrt{L \cdot C}}$$

$$f_C = 1.6\text{ GHz},\ C = 1.2\text{ pF} \rightarrow L = 8\text{ nH}$$



Contour Plots of Q



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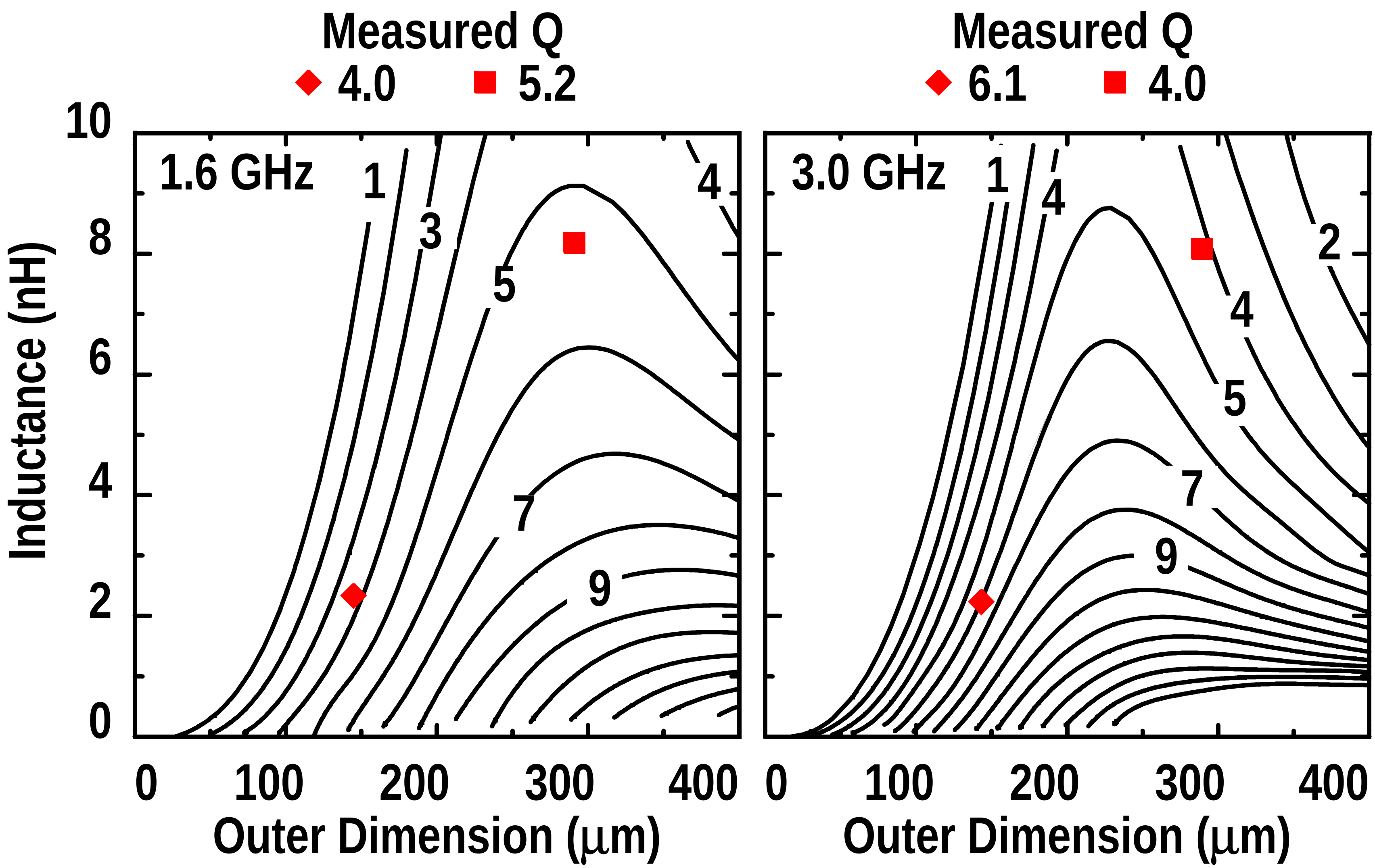
Contour Plots of Q



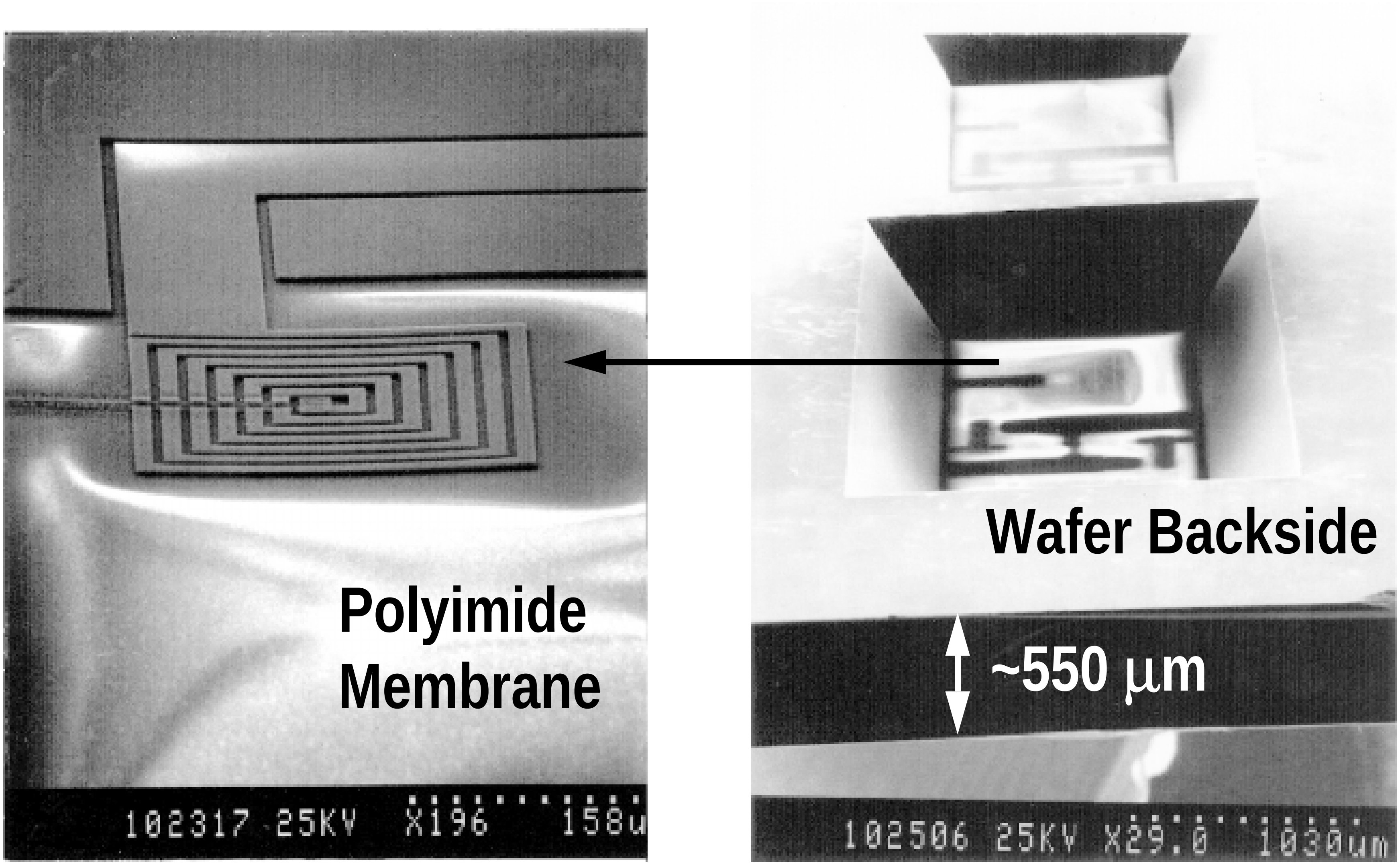
Outline

- Overview
- A physical model for on-chip inductors
- Effects of process and layout parameters
- Design methodology
- Inductors with patterned ground shields
- Substrate noise coupling
- Conclusions

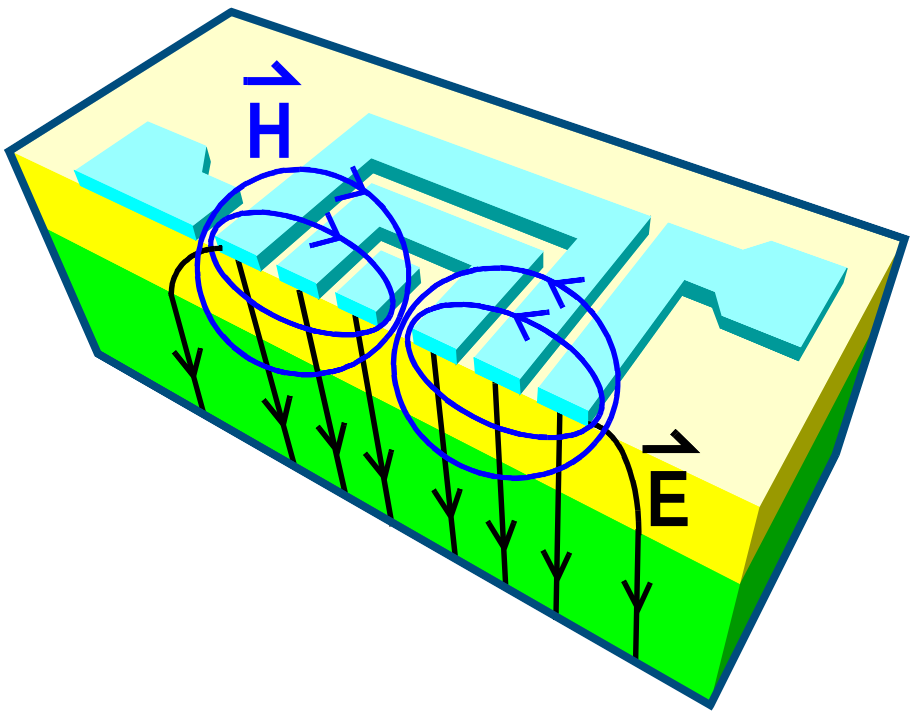
Overview

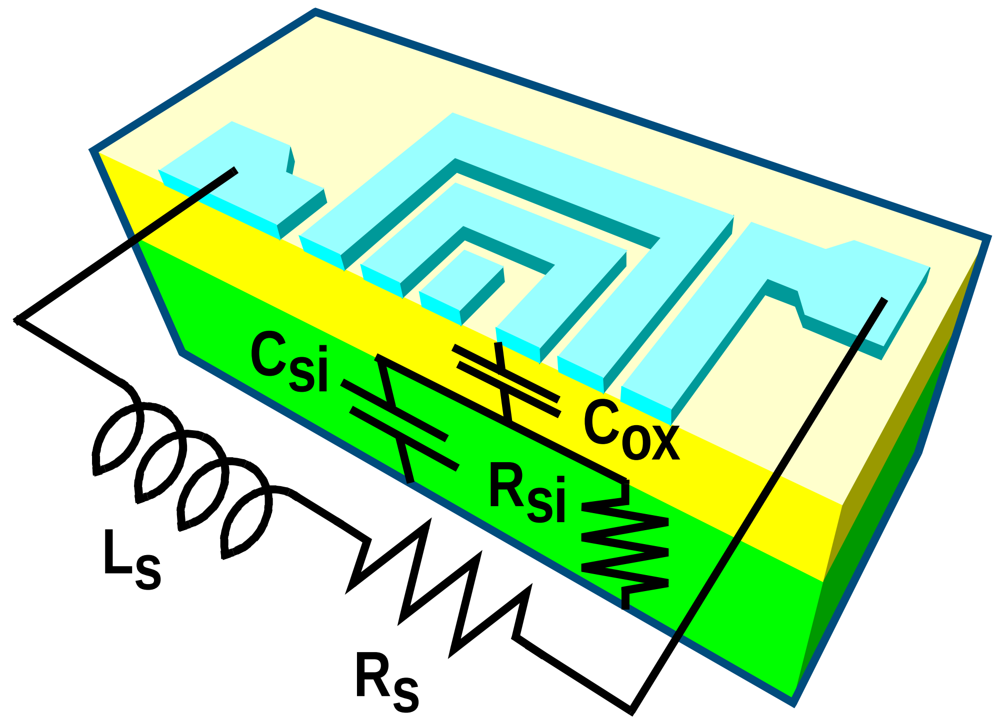
- Challenges
  - Q degraded by substrate loss
  - Substrate coupling
  - Modeling and characterization
  - Process constraints
- Approaches
  - Etch away Si substrate
  - Patterned Ground Shield

Suspended Inductors

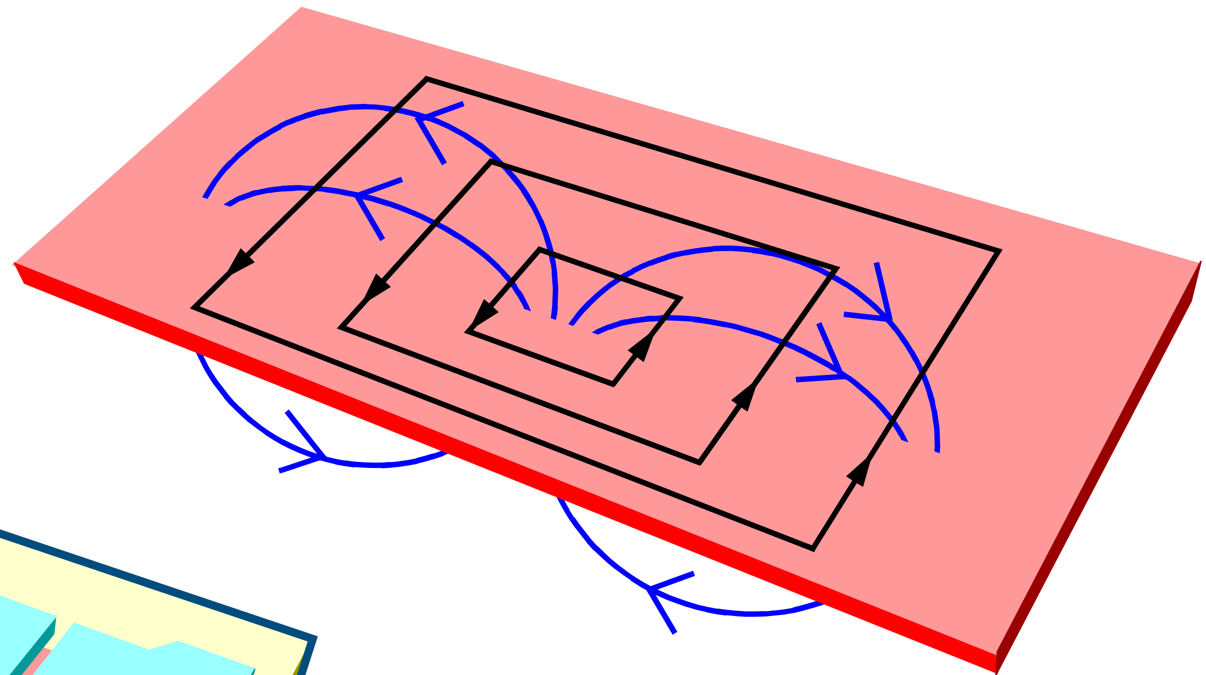


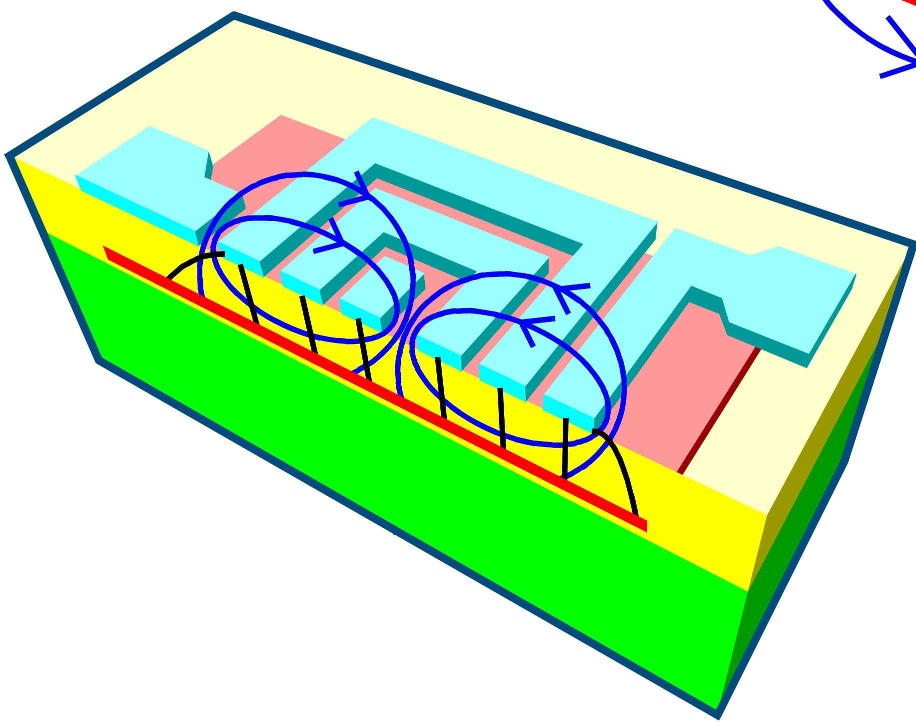
Electromagnetic Fields of Conventional On-Chip Inductors





Problems with Solid Ground Shield





Induced Loop Current and Magnetic Field

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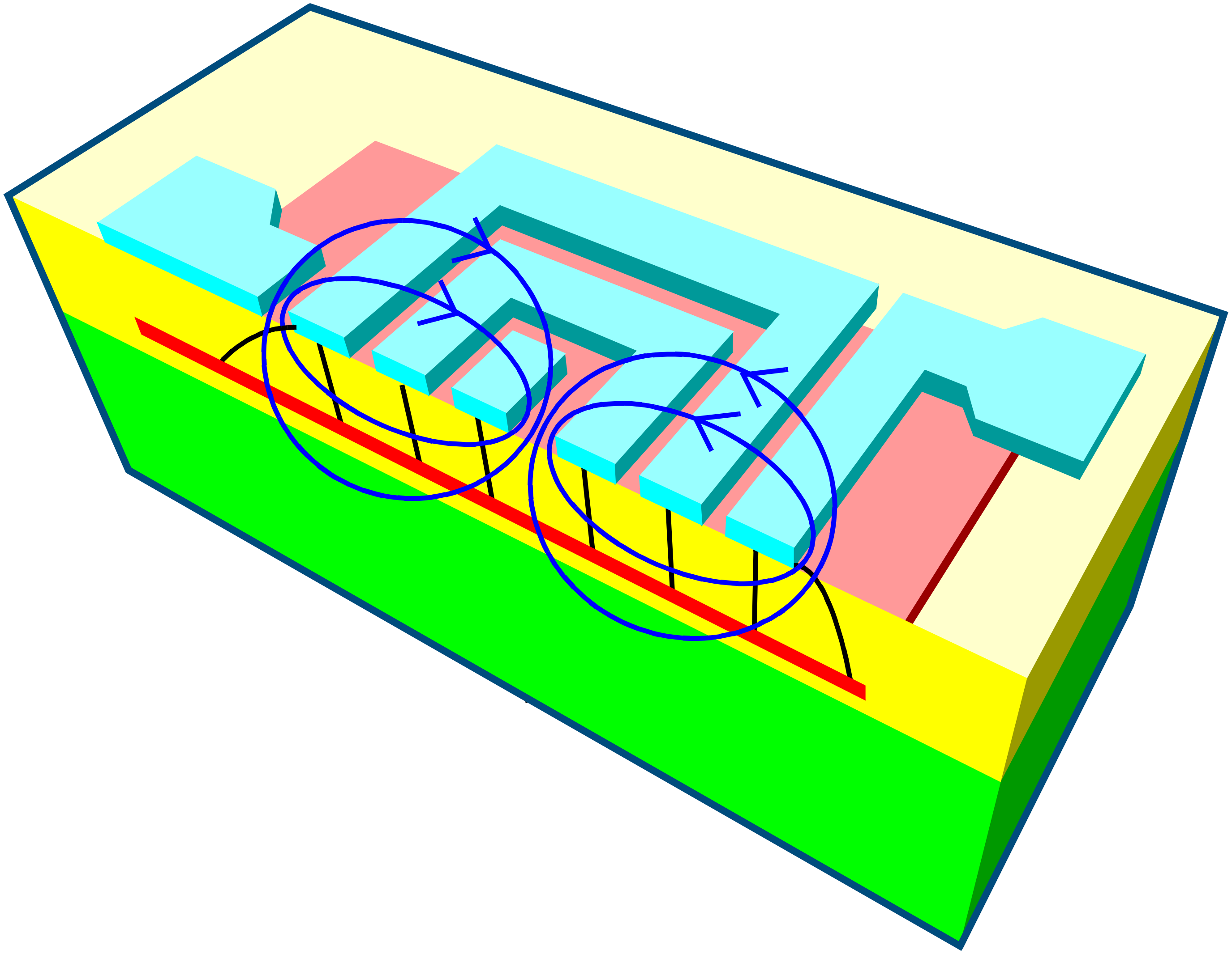
EM Fields of On-Chip Inductors with Patterned Ground Shield



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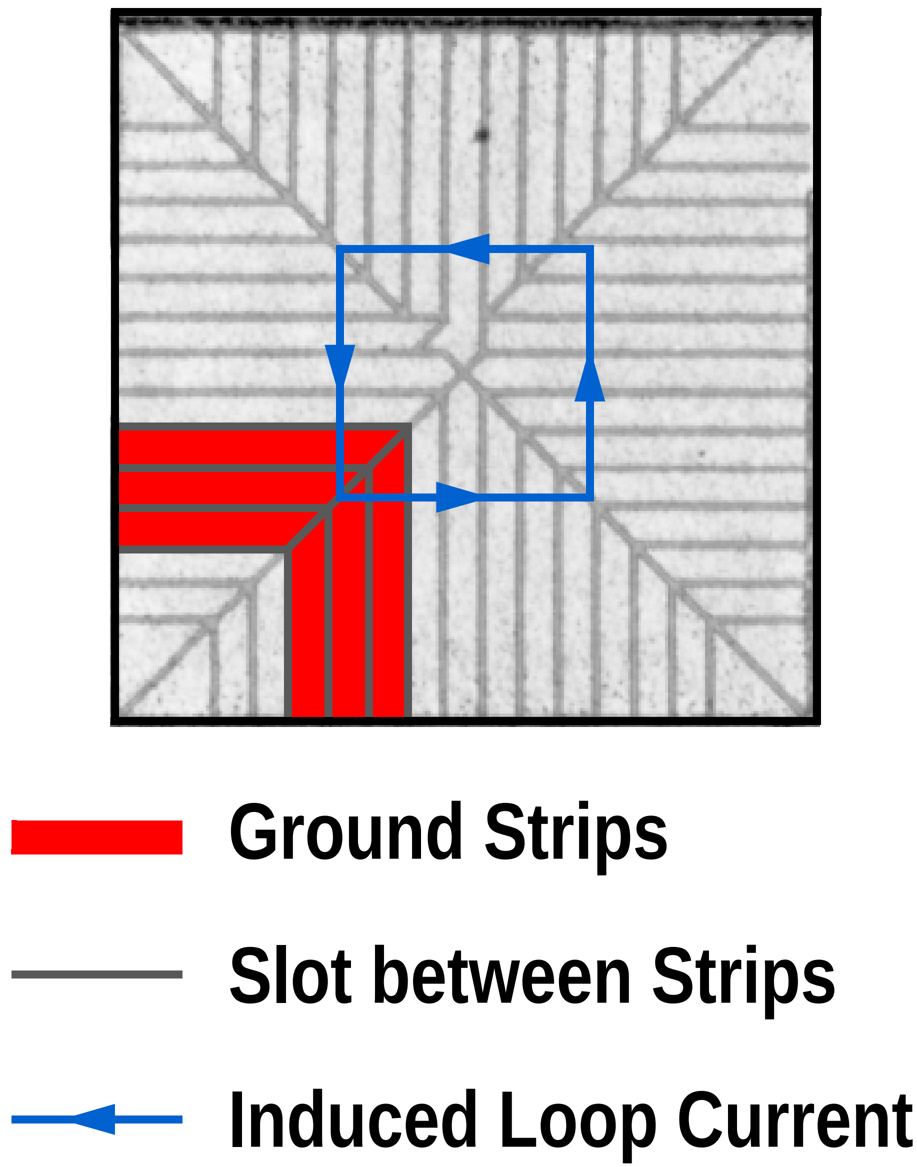
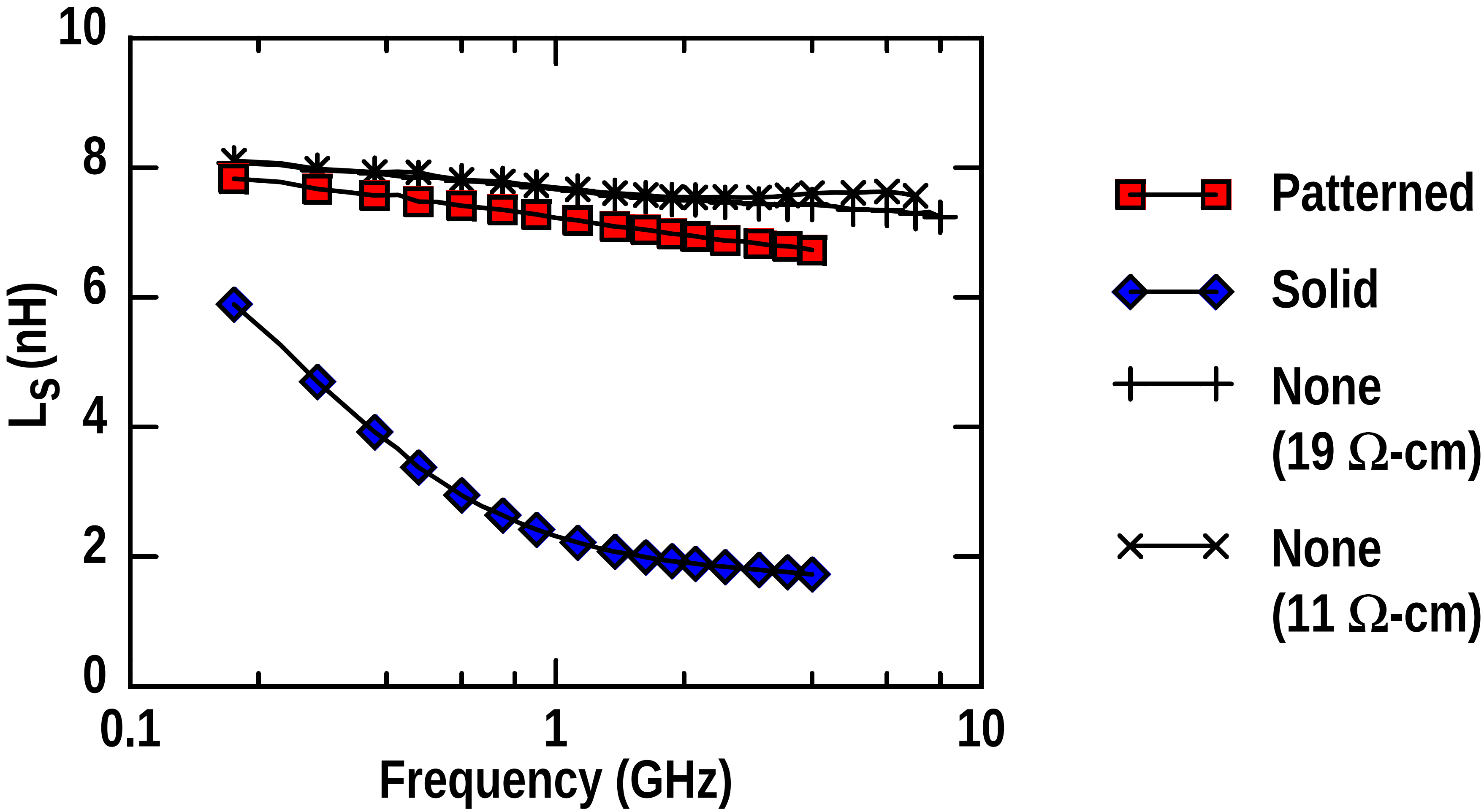
Patterned Ground Shield Design

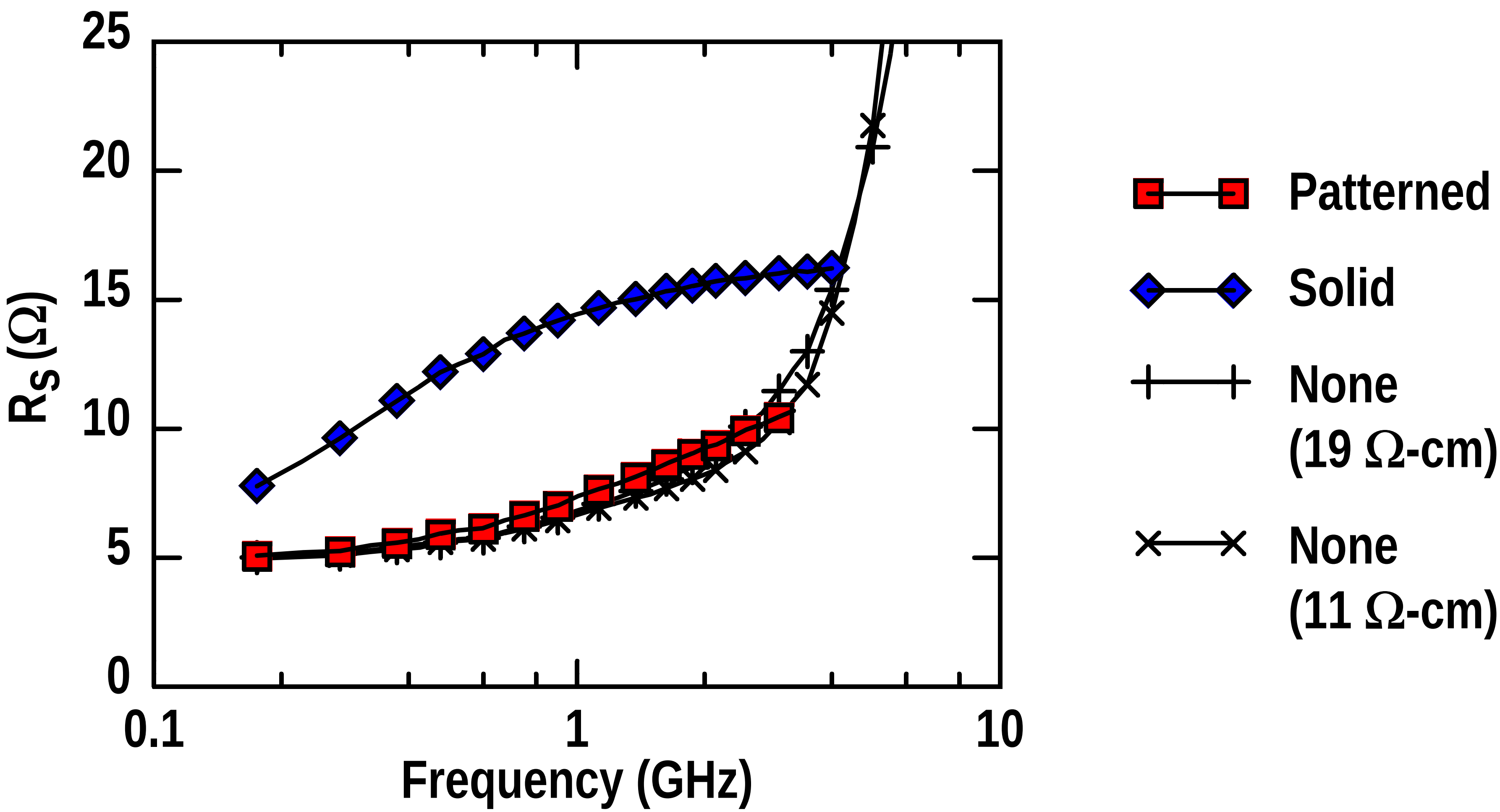
- Pattern
  - Orthogonal to spiral (induced loop current)
- Resistance
  - Low for termination of the electric field
  - Avoid attenuation of the magnetic field



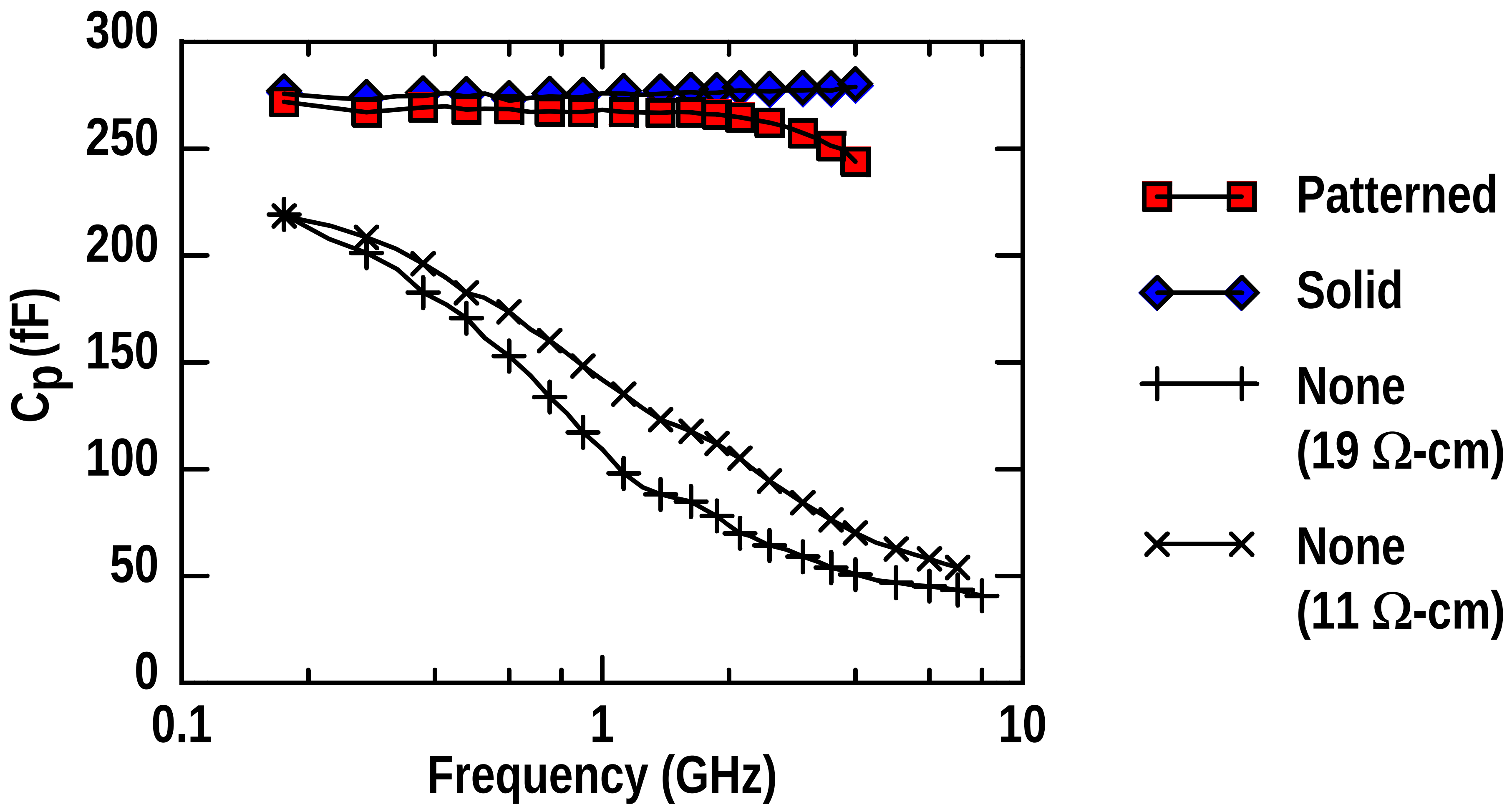
Effect of Aluminum Ground Shields on L



Effect of Aluminum Ground Shields on R



Effect of Aluminum Ground Shields on C



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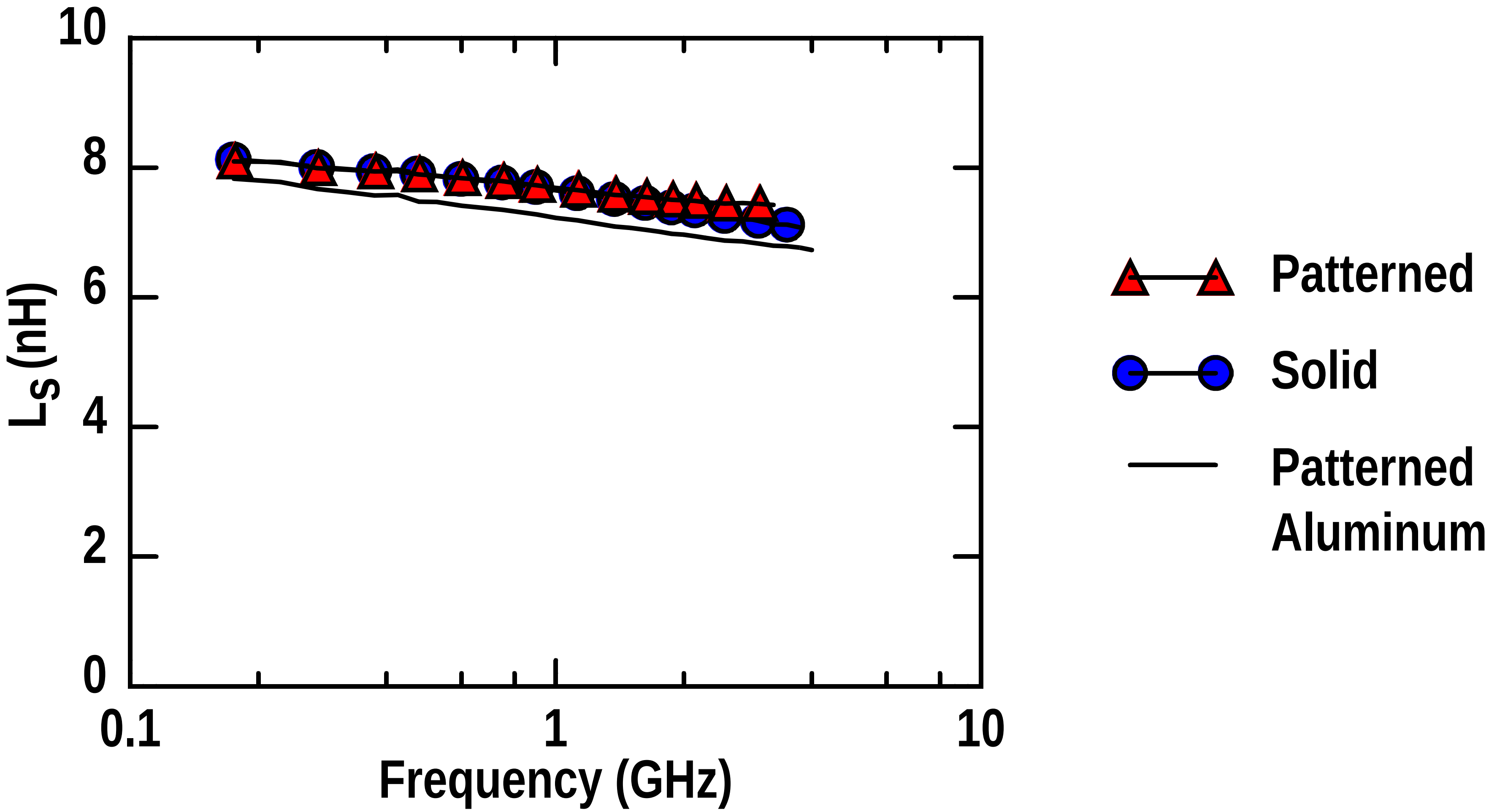
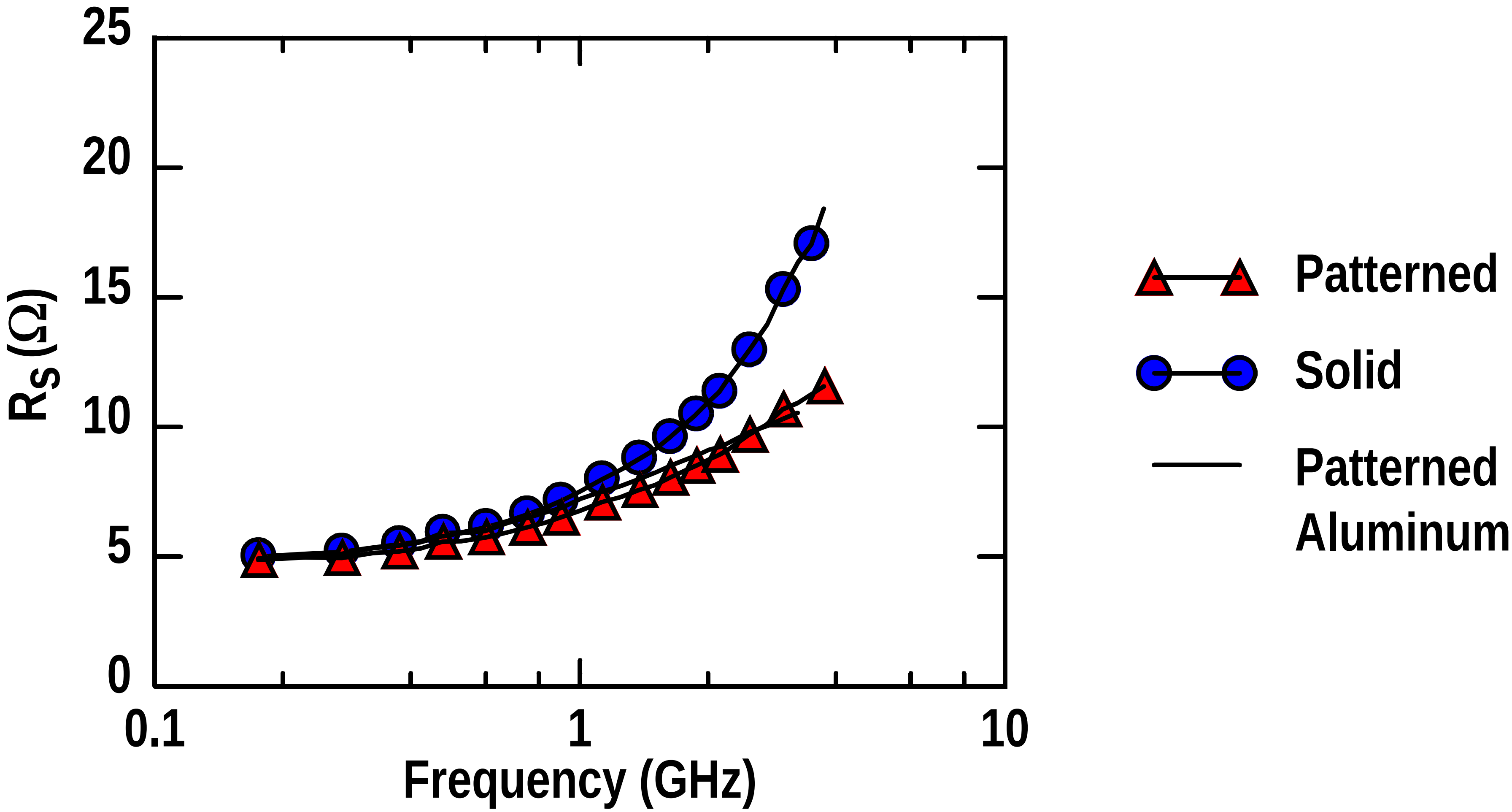
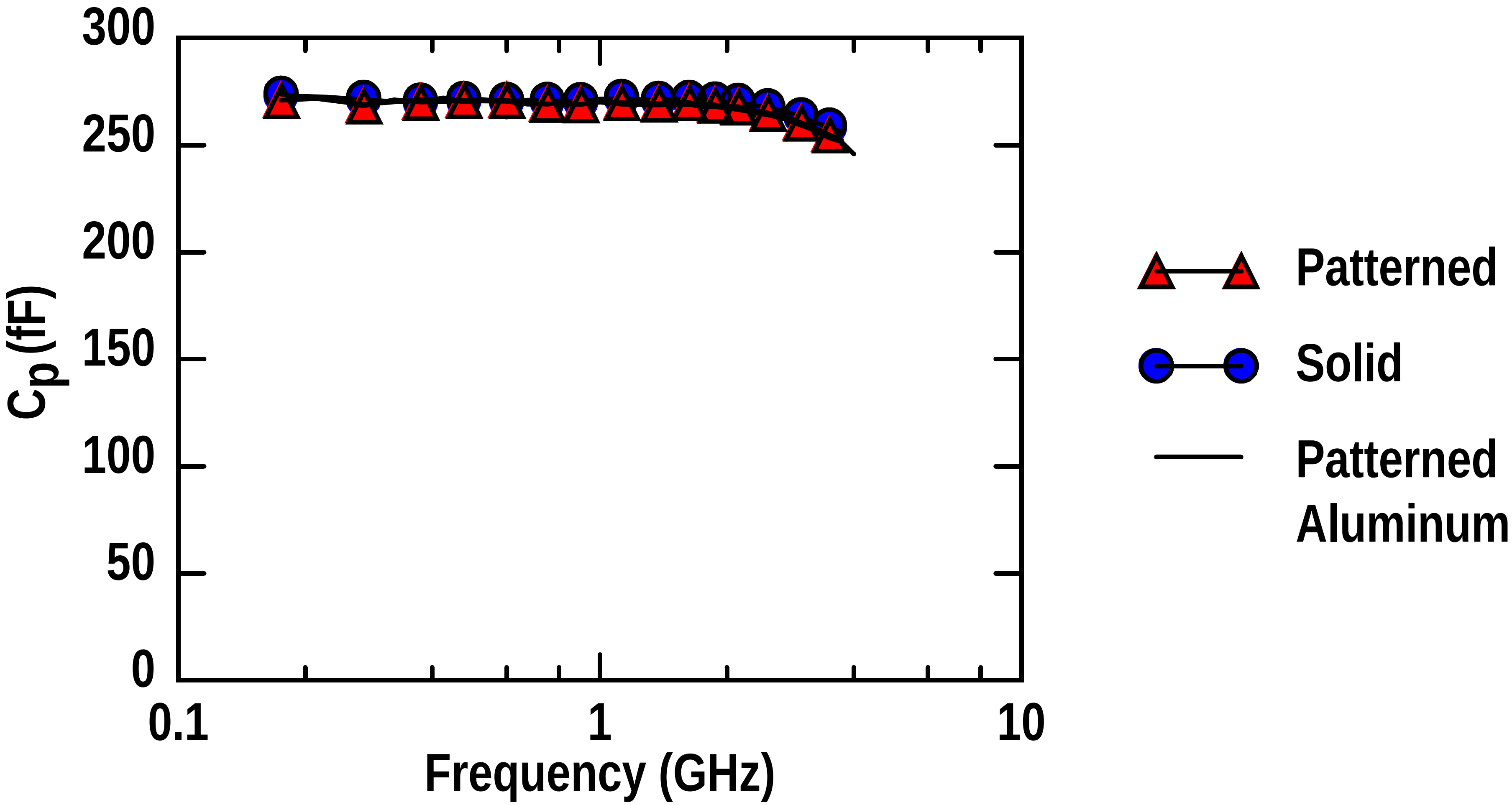
Effect of Polysilicon Ground Shields on L



Effect of Polysilicon Ground Shields on R



Effect of Polysilicon Ground Shields on C



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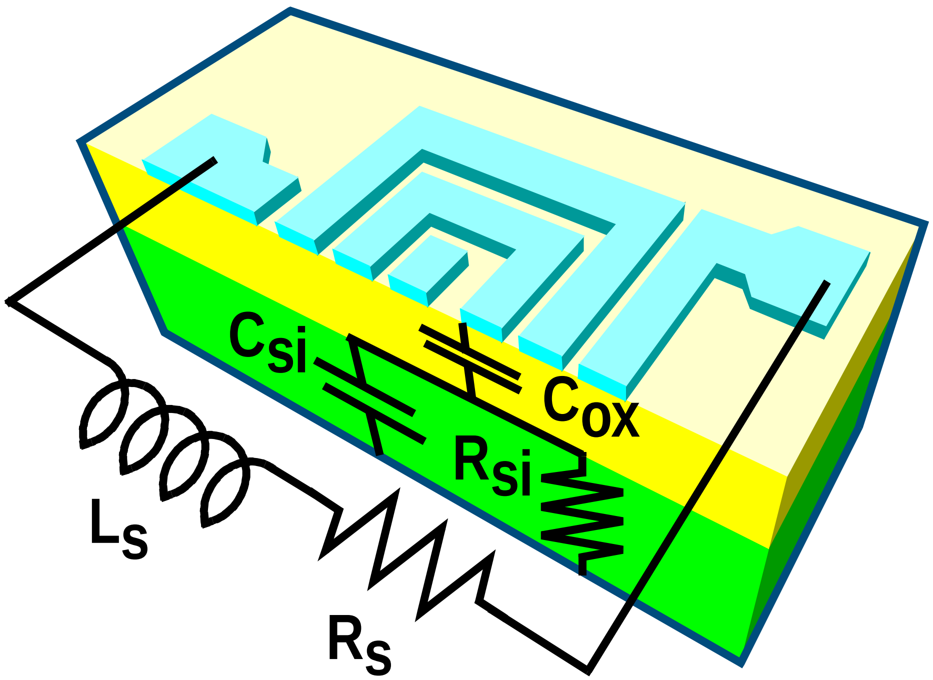
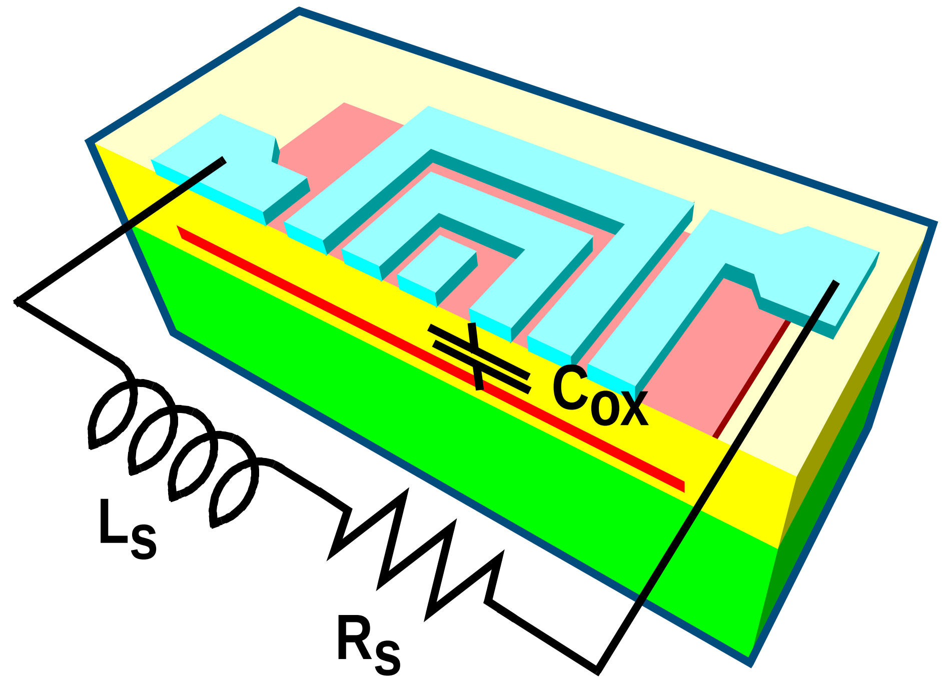
Circuit Models of On-Chip Inductors

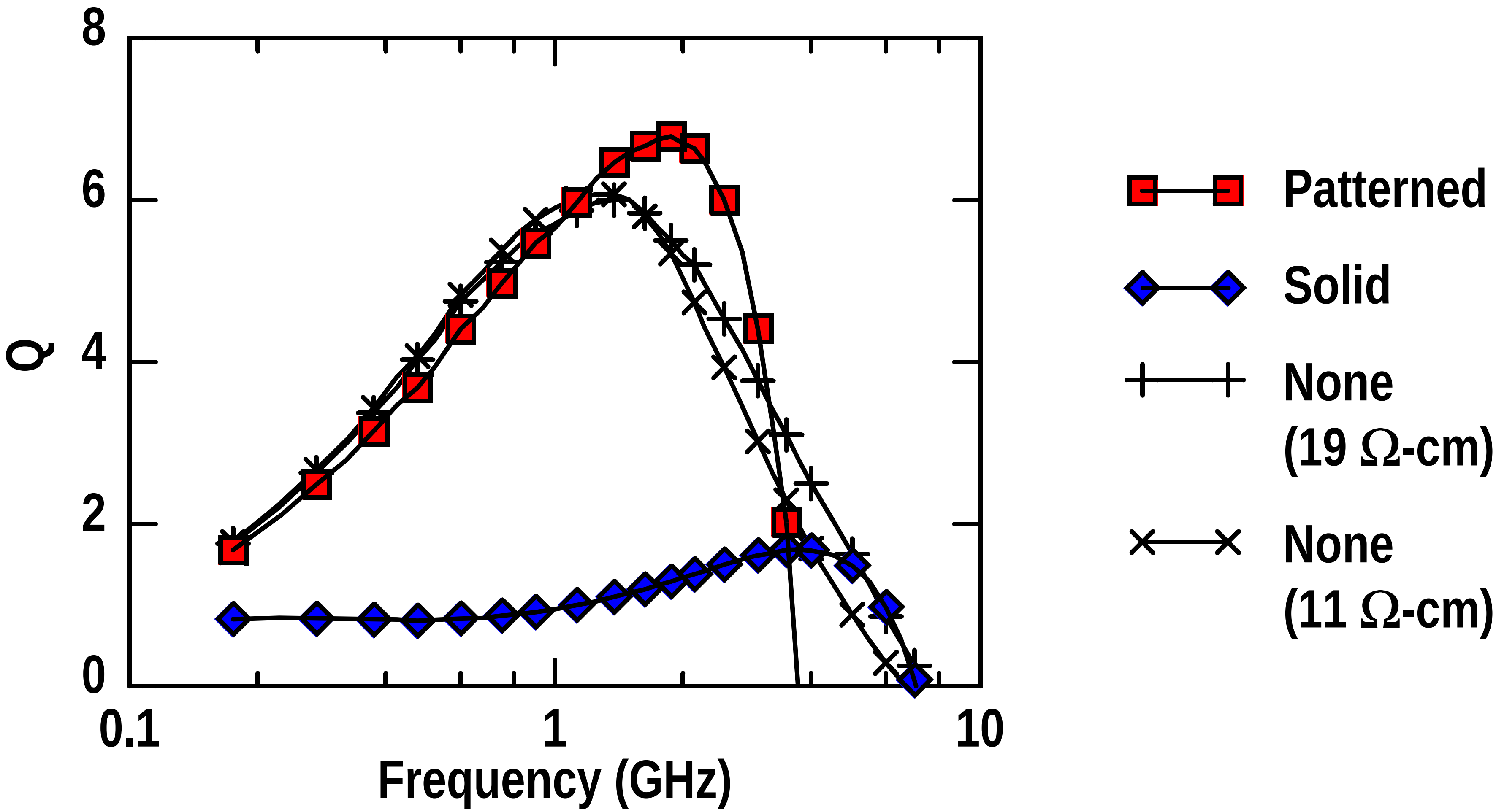


Conventional Design

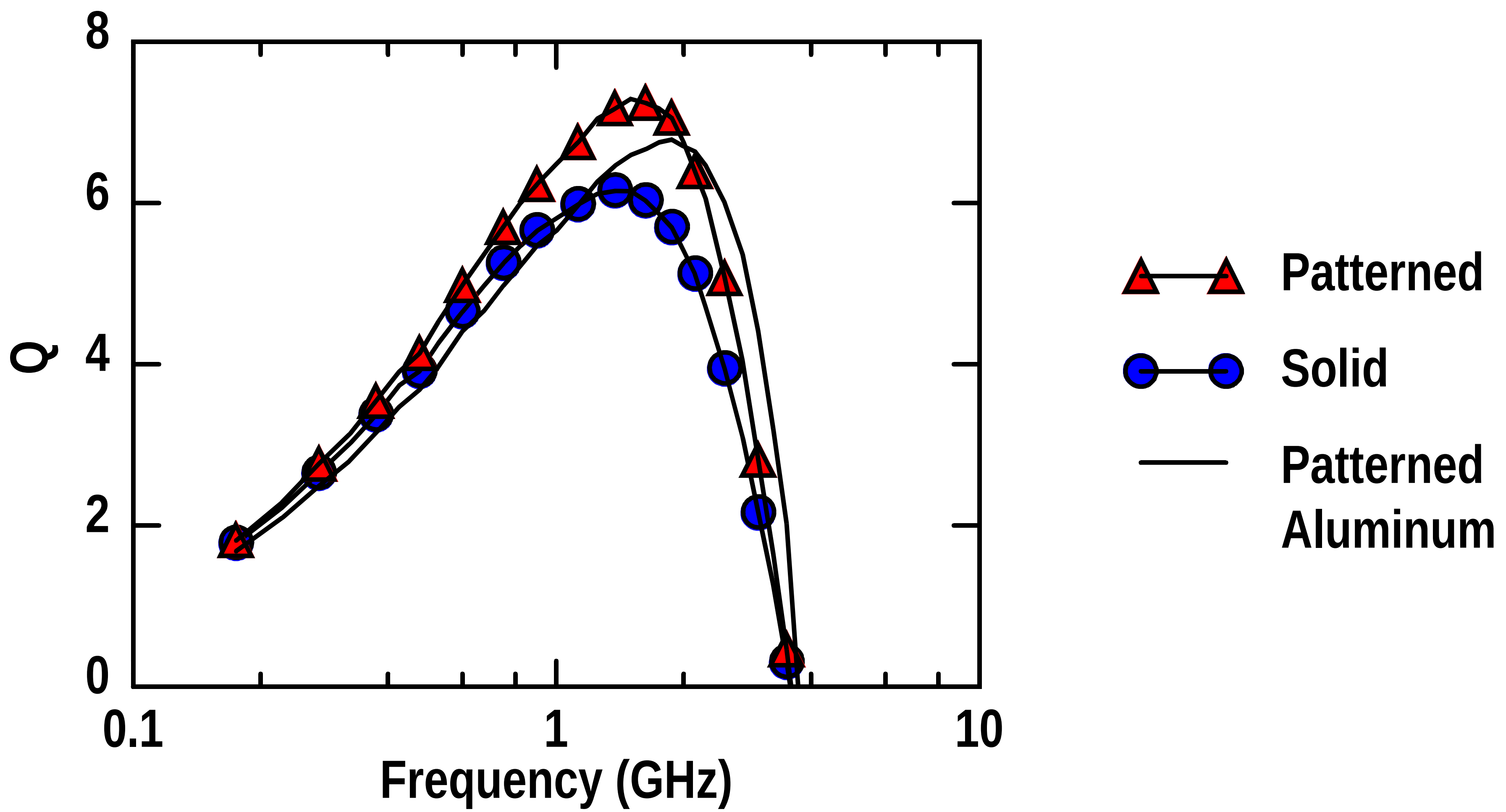


With
Patterned Ground Shield

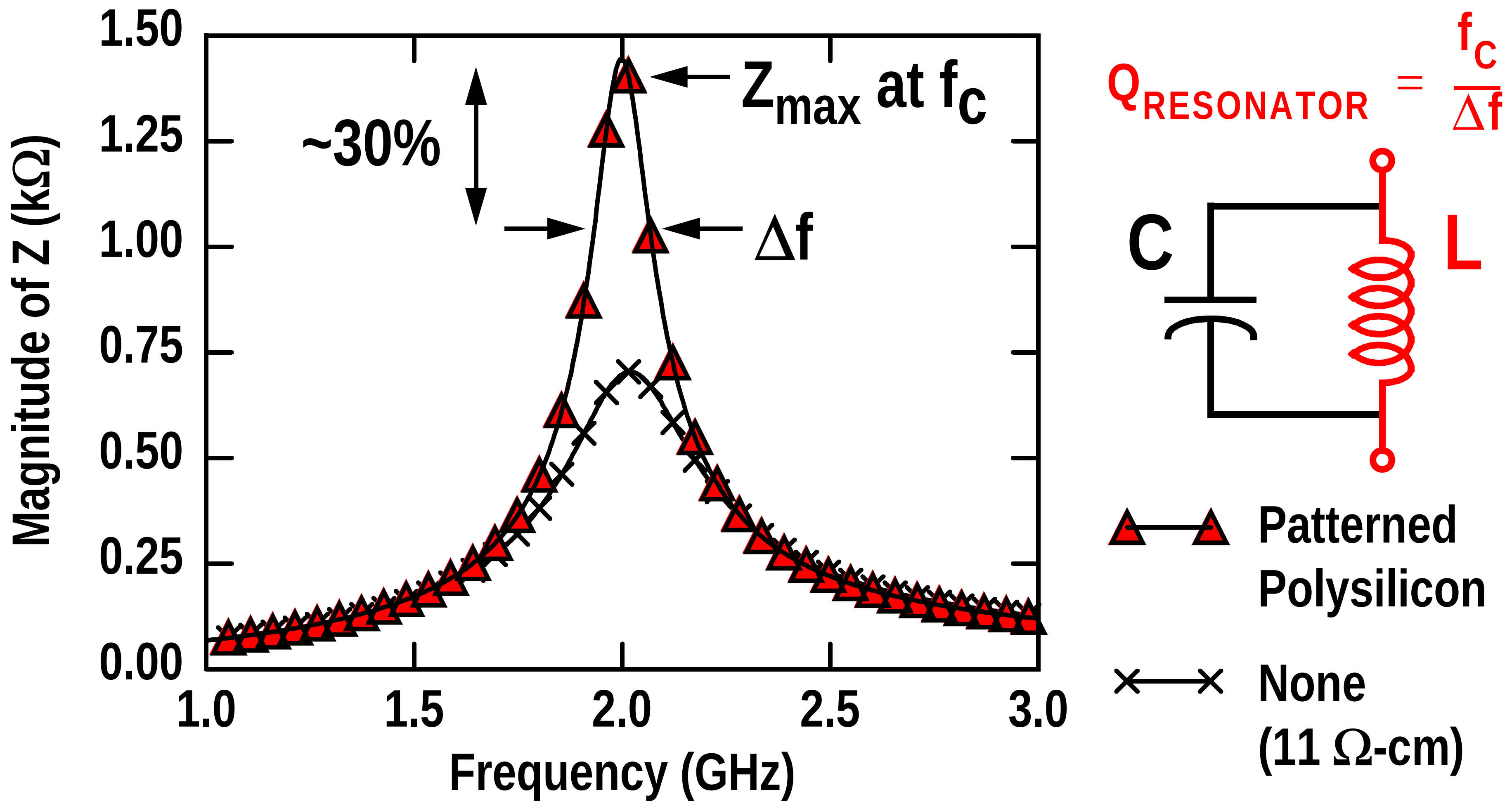
Effect of Aluminum Ground Shields on Q



Effect of Polysilicon Ground Shields on Q



Parallel LC Resonator at 2 GHz



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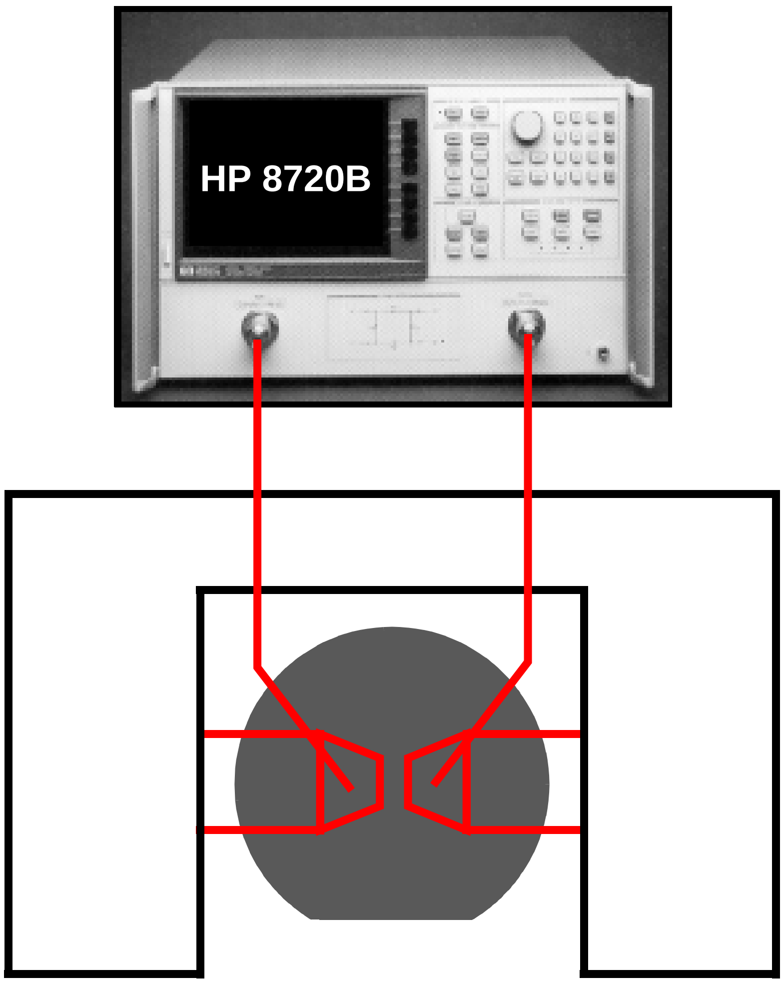
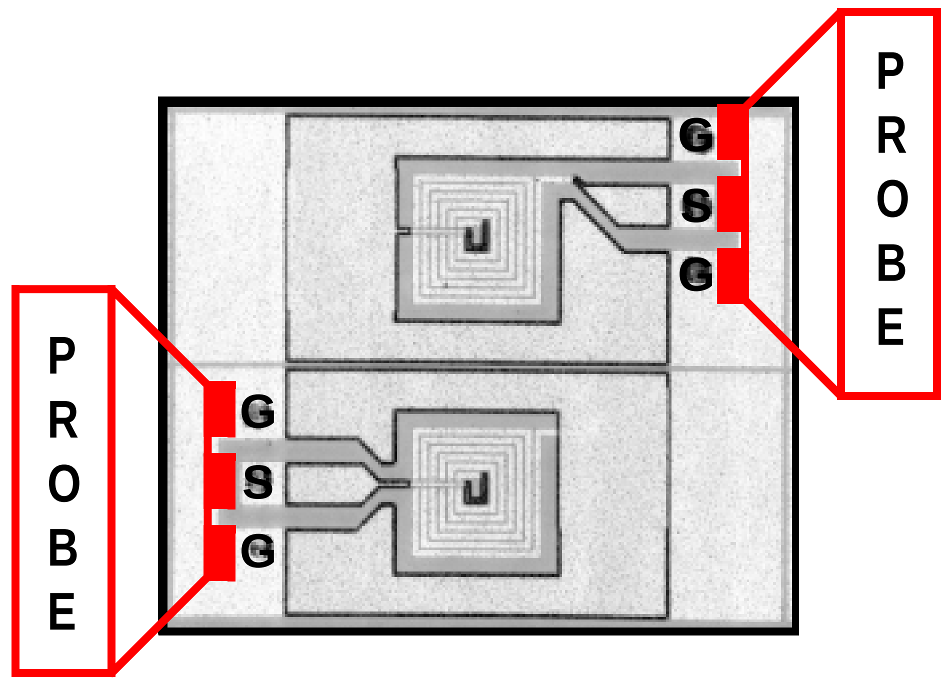
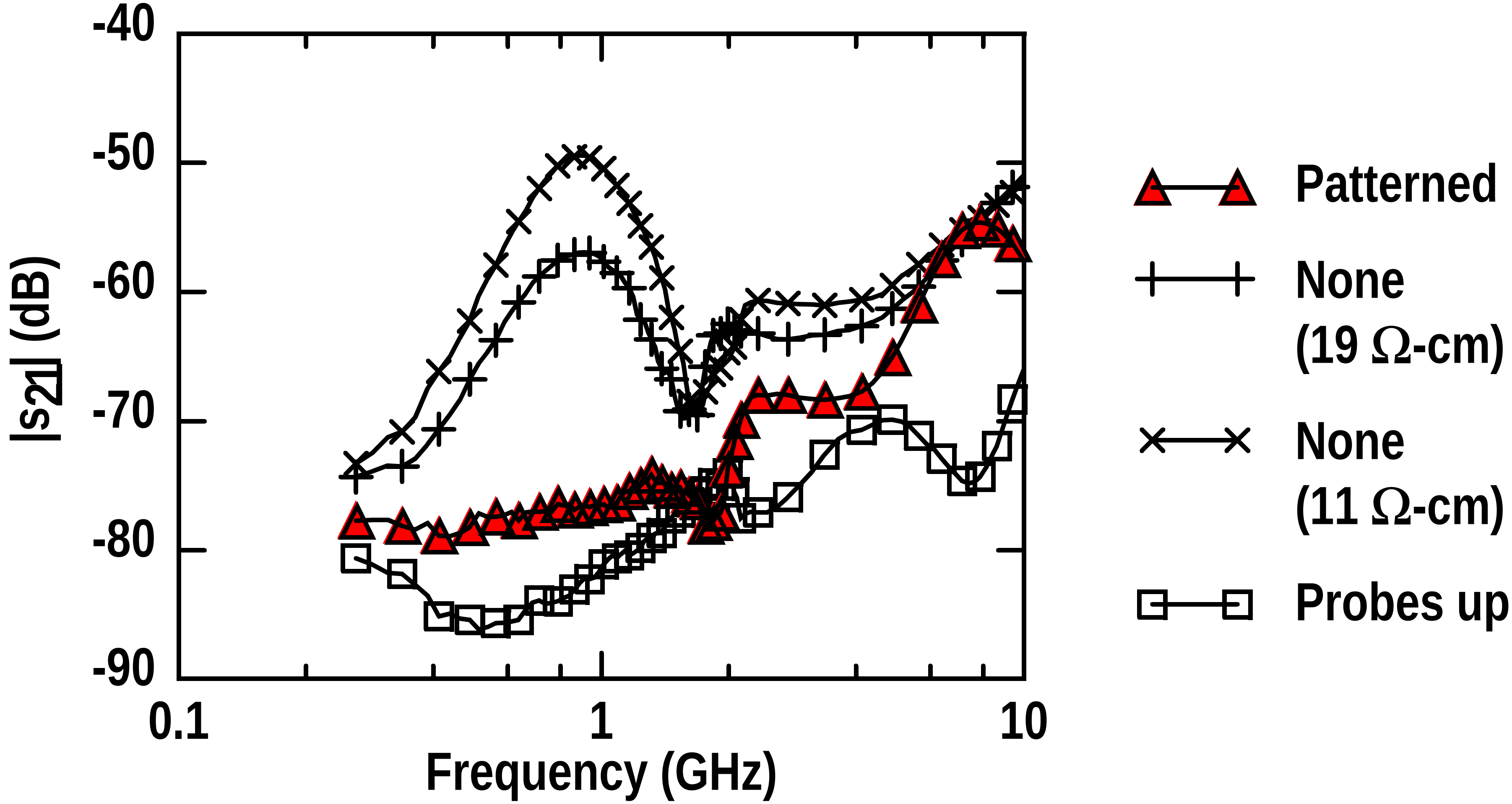
Noise Coupling Measurement



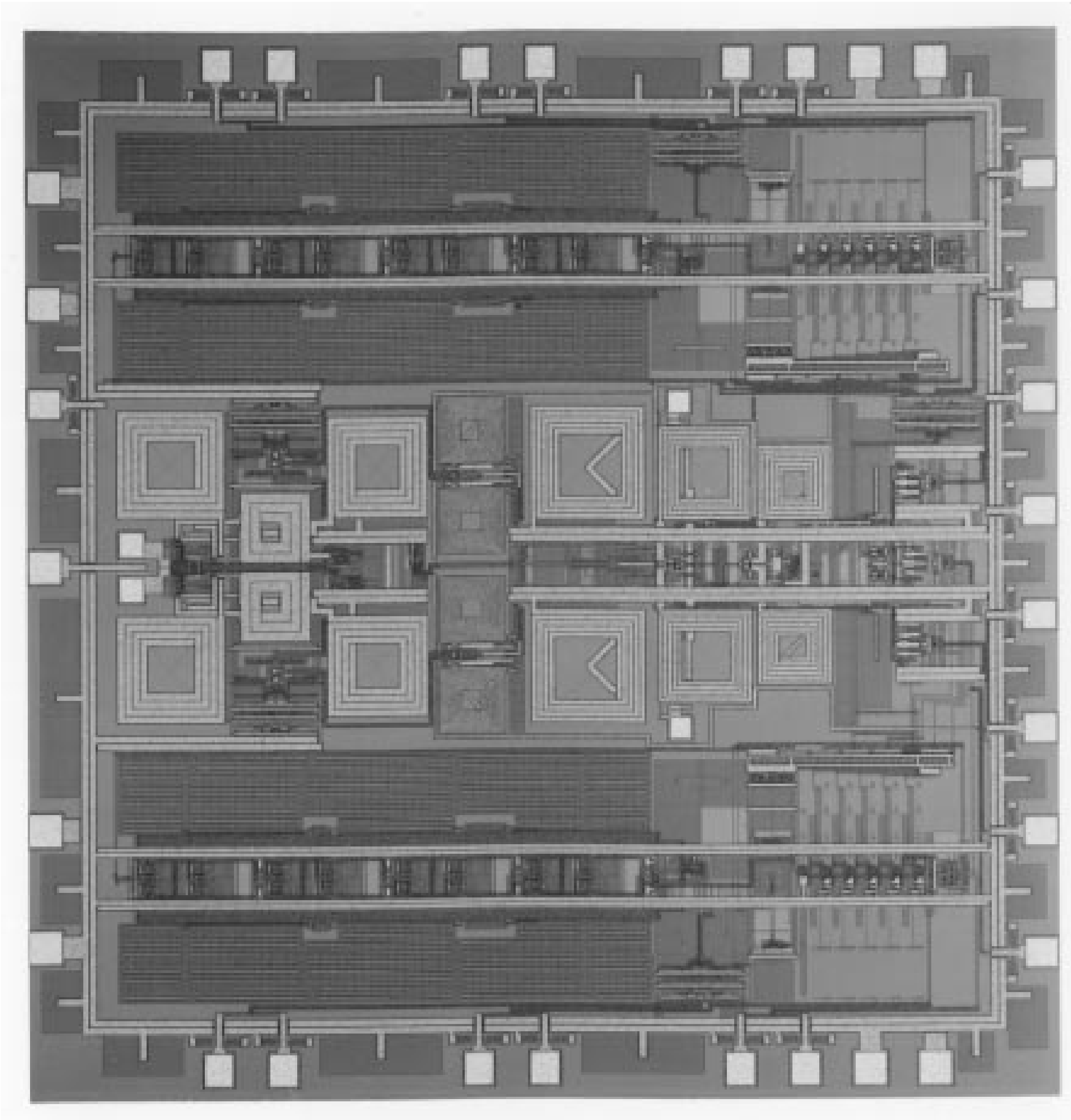
Probe Station



Effect of Polysilicon GS on Isolation



A Single-Chip CMOS GPS Receiver



Conclusions

- A compact model for spiral inductors on silicon has been presented.
- Physical phenomena important to limitation and prediction of Q were investigated.
- Effects of various structural parameters on Q have been demonstrated.
- The scalable model can be used as a design tool for optimizing Q.

Conclusions on Patterned Ground Shield

- Improves Q by eliminating substrate loss (up to 33% at 1-2 GHz)
- Improves isolation by preventing substrate coupling (up to 25 dB at 1 GHz)
- Simplifies modeling
- Eliminates substrate dependency
- Requires no additional process steps

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