MEMS Variable Inductor for Multi-band RF CMOS Circuits

Hirotaka Sugawara, Yoshiaki Yoshihara, Hiroyuki Ito, Kenichi Okada, and Kazuya Masu

Precision and Intelligence Laboratory, Tokyo Institute of Technology, Japan

1. Background

On-chip inductors

The demand has been increasing for RF Si CMOS circuits.

Purpose

To realize a variable inductor on Si CMOS chip

The wireless communication system has several frequency bands which are required to cover several frequency bands.

Multi-band solutions are required to cover several frequency bands.

Variable RF Inductor

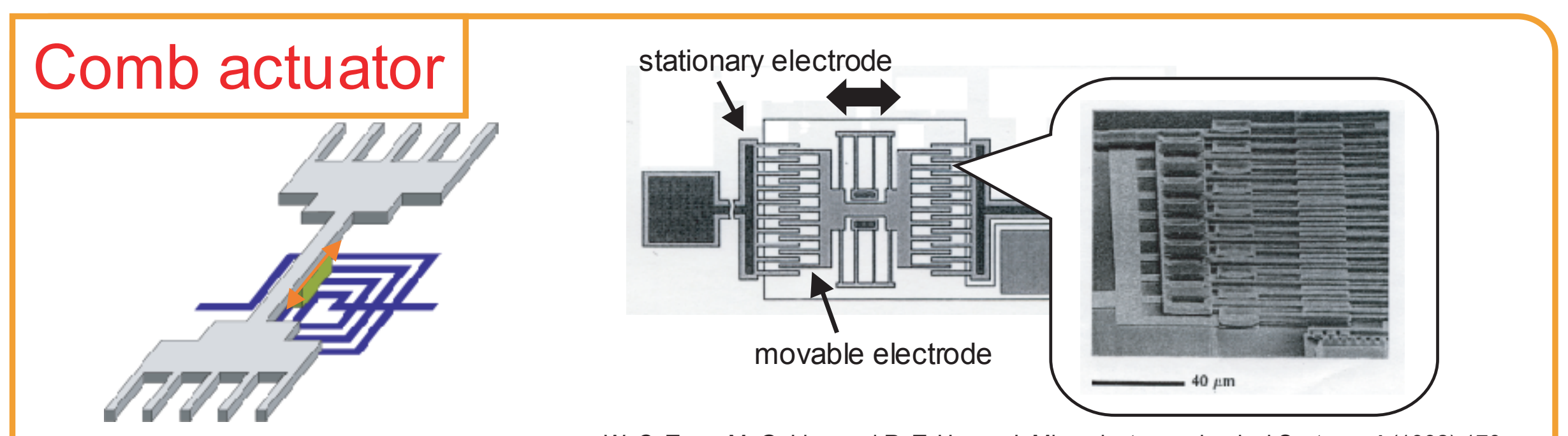
- ■Wide-range oscillation of VCO
- ■Wide-tunable impedance matching

MEMS Actuator

The actuators are driven by electrostatic force. By generating DC bias between the stationary electrode and the movable electrode.

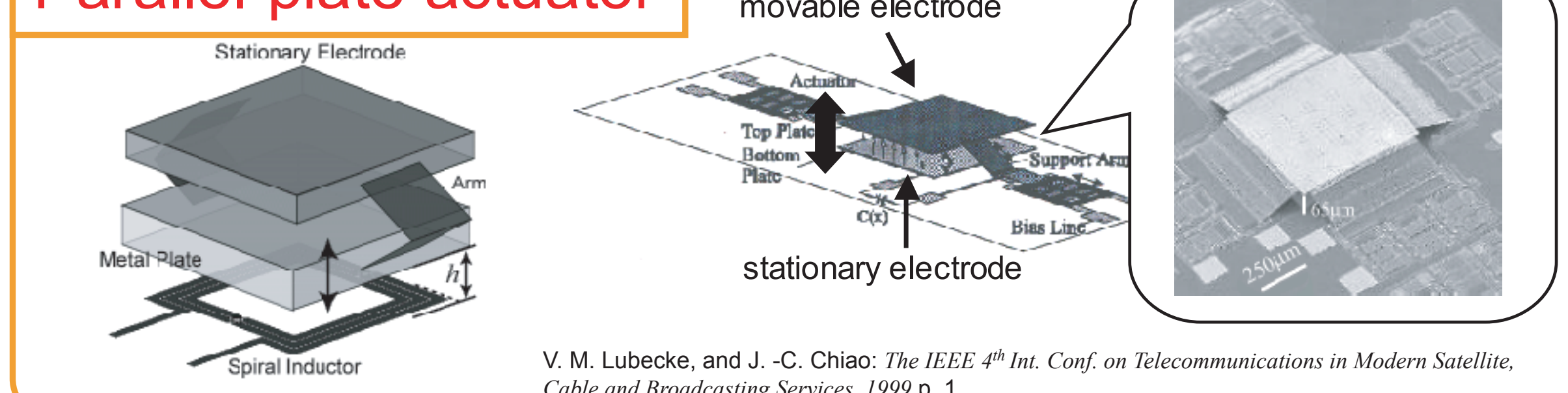
`MEMS actuator is used for moving the metal plate above the spiral inductor`

Comb actuator



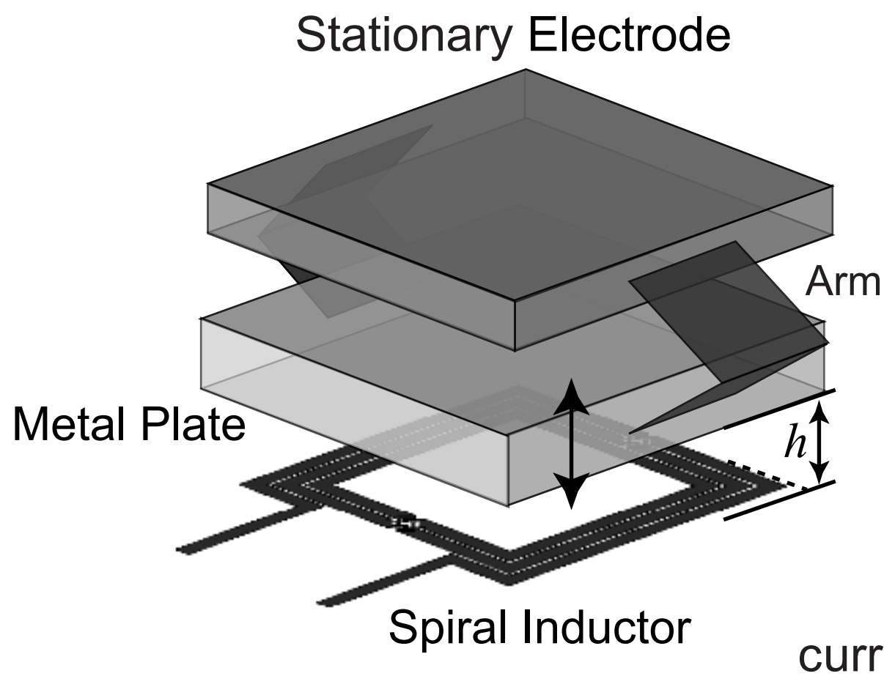
W. C. Tang, M. G. Lim, and R. T. Howe: J. Microelectromechanical Systems **4** (1992) 170.

Parallel-plate actuator



V. M. Lubecke, and J. -C. Chiao: *The IEEE 4th Int. Conf. on Telecommunications in Modern Satellite, Cable and Broadcasting Services, 1999* p. 1

Parallel-plate Actuator



The metal plate is moved by DC bias between the stationary electrode and the movable electrode

Lower Power Consumption

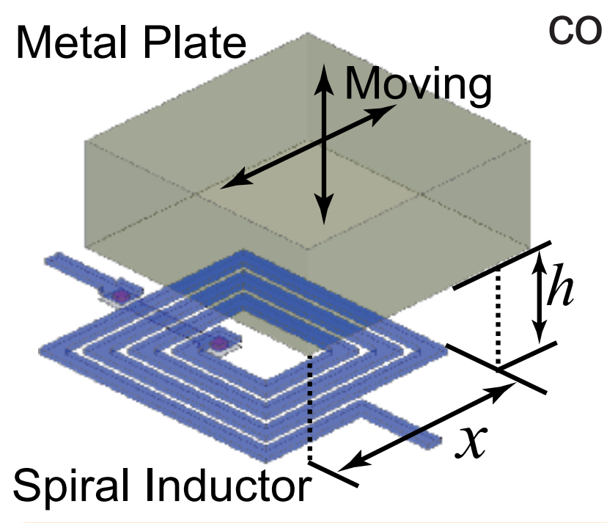
current does not flow between the electrodes

The variable inductor is an indispensable device for high-frequency and multi-band circuits.

MEMS actuator requires high manufacturing cost, and the reliability is not so high at the present time.

2. Principle of Variable Inductor

Variable Inductor



consists of a planar-type spiral inductor and a metal plate.

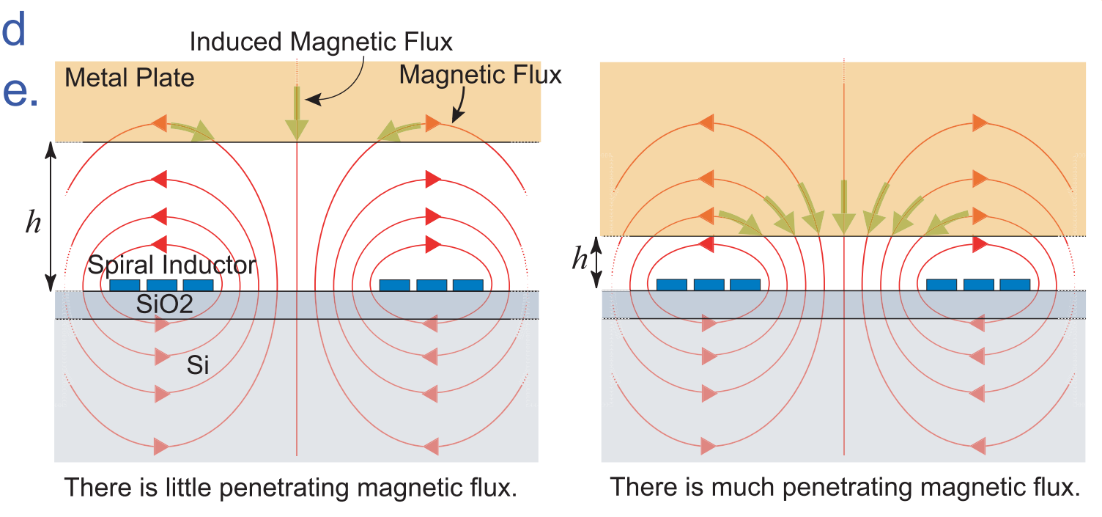
The metal plate shields the magnetic flux which penetrate the inductor.

The inductance continuously varies depending on the position of the metal plate.

The inductance value can be also varied by changing the height of the metal plate.

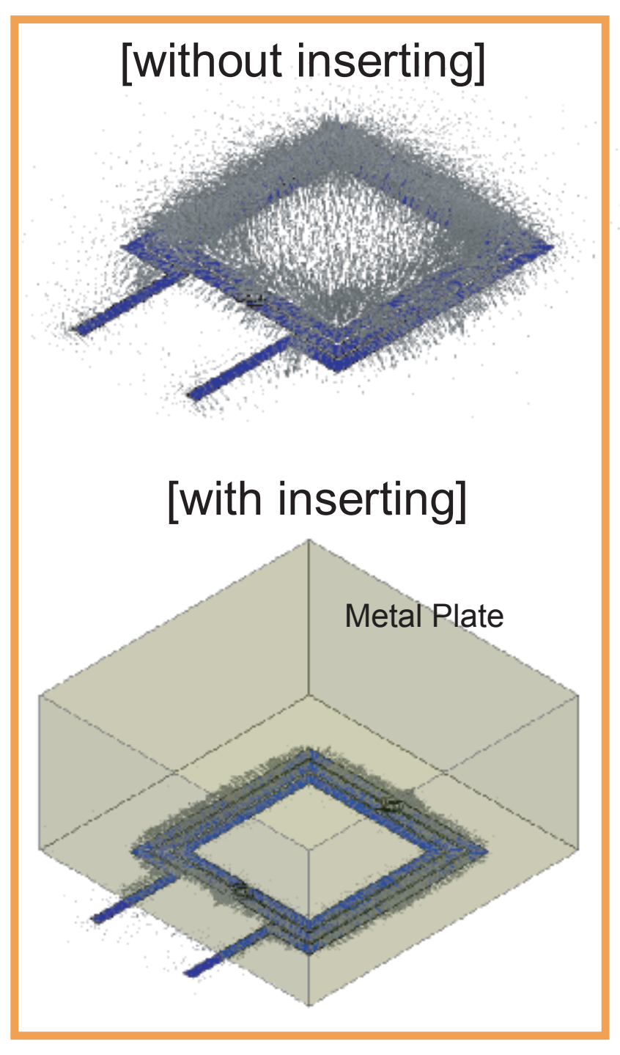
Small h

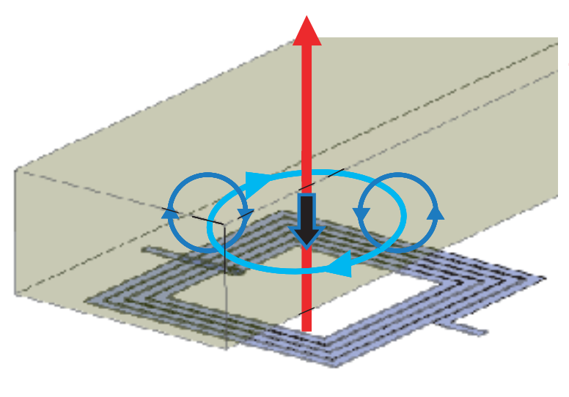
- Variable range of inductance increases.
- Parasitic Capacitance increases.



There is little penetrating magnetic flux. There is much penetrating magnetic flux.

Shielding Magnetic Mechanism





The magnetic flux penetrates the metal plate.

Eddy current flows in the metal plate.

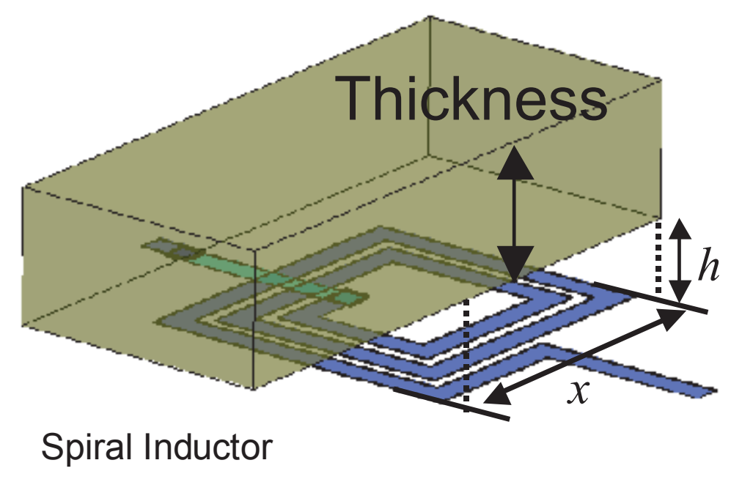
Induced a counteractive magnetic field according to Lenz's Law.

The metal plate shields the magnetic flux.

Change of the magnetic flux

Inductance change

Metal Plate



Spiral Inductor
Turns : 2.5
Line width W : 20 μm
Line space S : 10 μm
Outer dimension D : 250 μm
L=1.8 nH

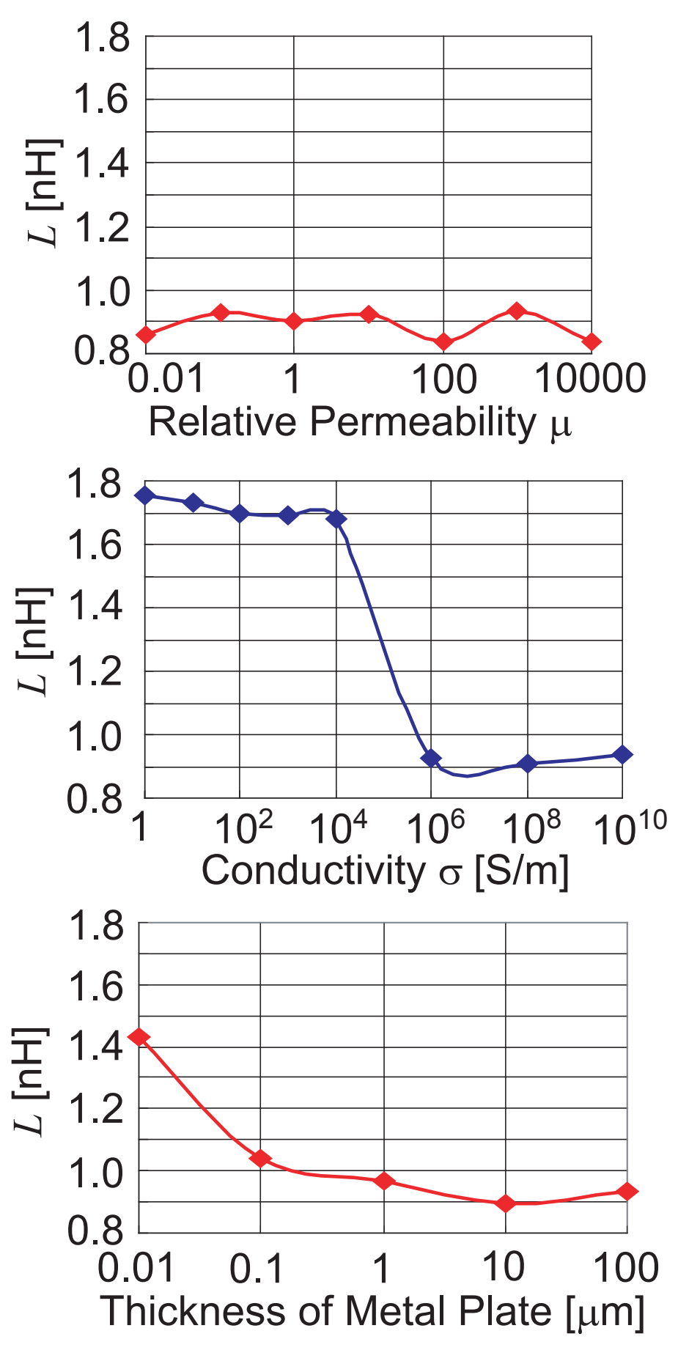
$$\text{Skin Depth} = \sqrt{\frac{2}{\omega\sigma\mu}}$$

Skin Depth≒2μm @1GHz

Metal Thickness of over Skin Depth

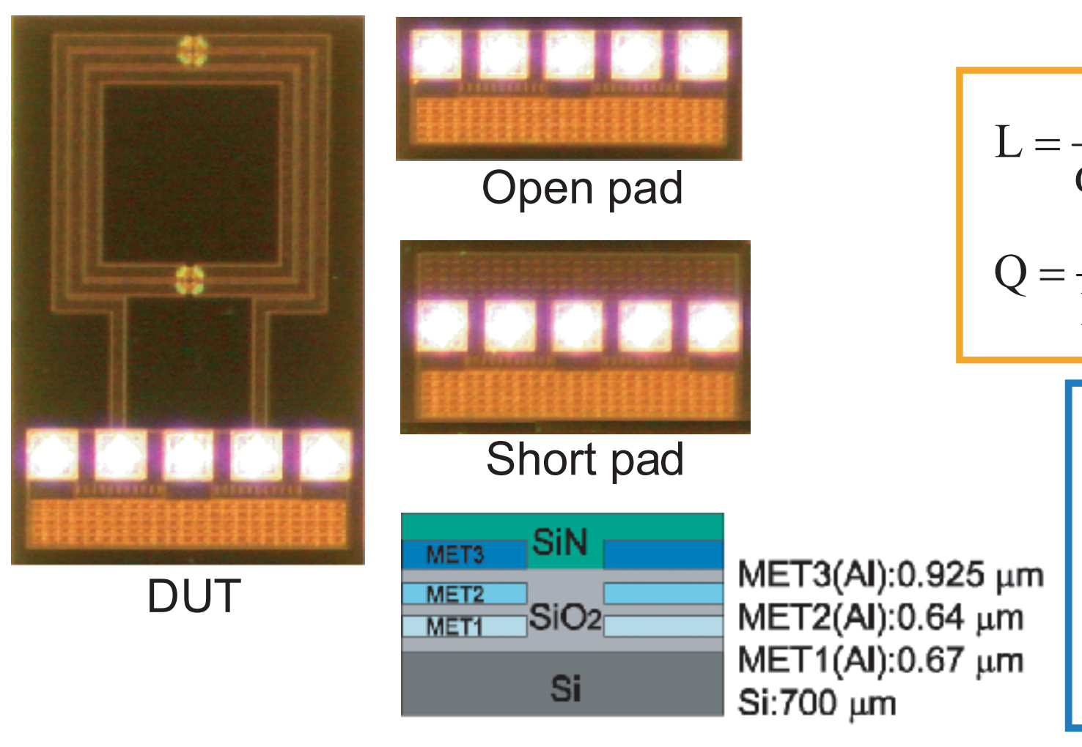
Magnetic flux can be shielded by the metal plate

Simulated by HFSS (Ansoft)



3. Measurement Results

Measurement Method



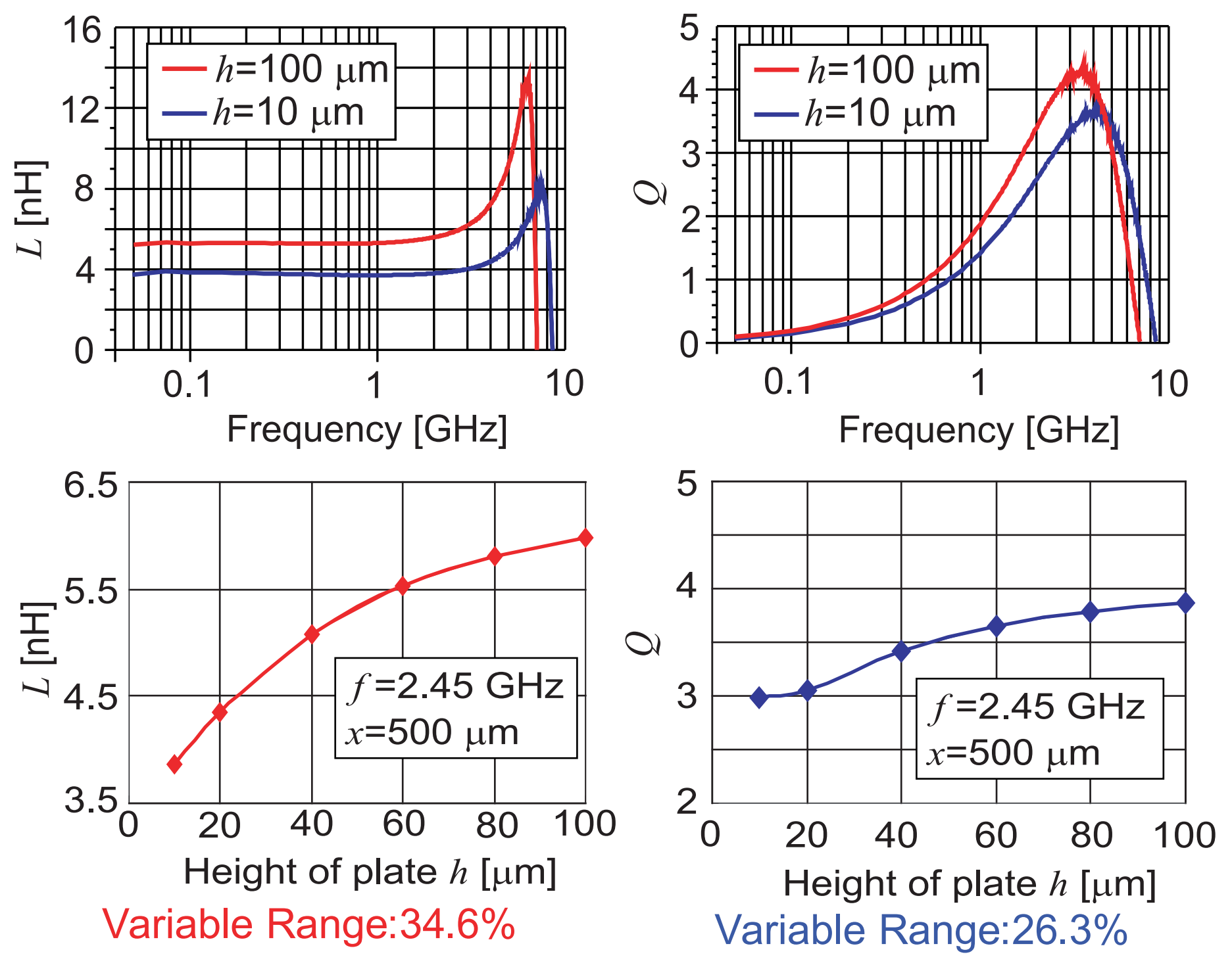
MET3(Al):0.925 μm
MET2(Al):0.64 μm
MET1(Al):0.67 μm
Si:700 μm

$$L = \frac{1}{\omega} I_m(Z_d) \qquad Q = \frac{I_m(Z_d)}{R_e(Z_d)} \qquad Z_d = \frac{Y_{11}^{ind} + Y_{12}^{ind} + 2Y_{12}^{ind}}{Y_{11}^{ind} Y_{22}^{ind} - (Y_{12}^{ind})^2}$$

De-embedding

- Open and short pad are used

$$Y^{ind} = \frac{1}{\dfrac{1}{Y^{meas} - Y^{open}} - \dfrac{1}{Y^{short} - Y^{open}}}$$

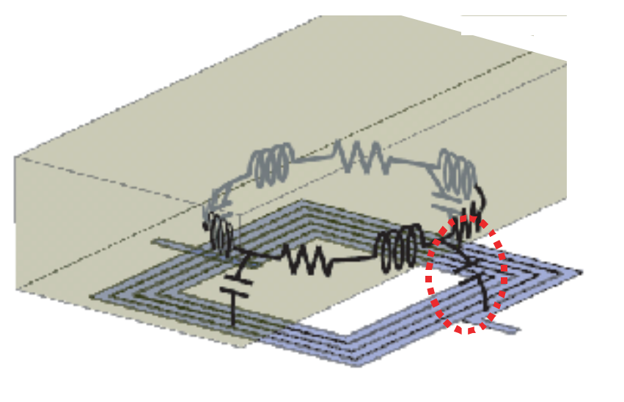


Variable Range:34.6%

Variable Range:26.3%

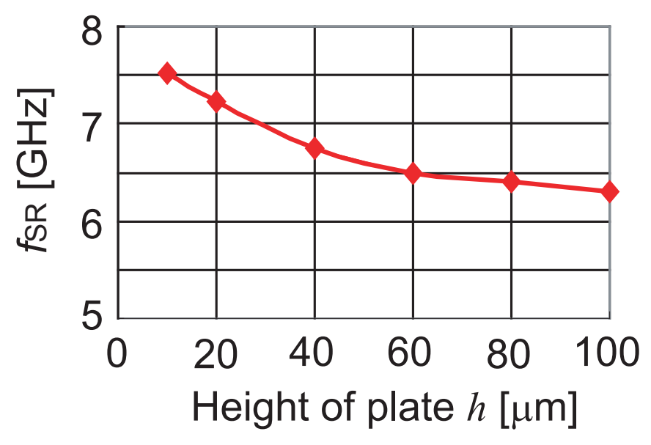
The variation Q is smaller than that of L

Effect of Parasitic Capacitance



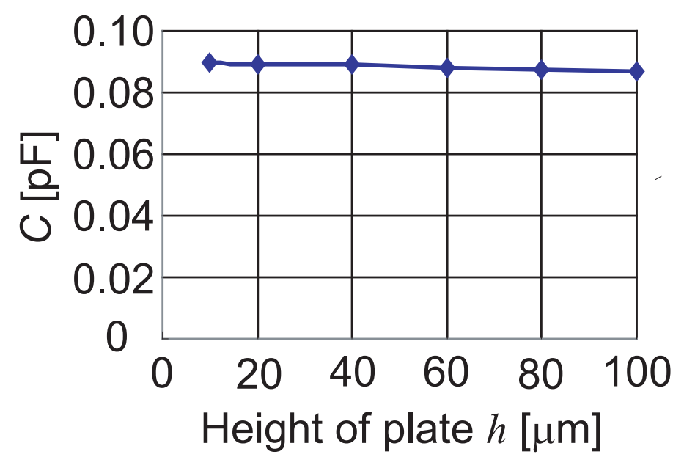
The parasitic capacitance is induced between the spiral inductor and the metal plate

⇒Degrade the inductor characteristics



h decreases⇒f_{SR} decreases

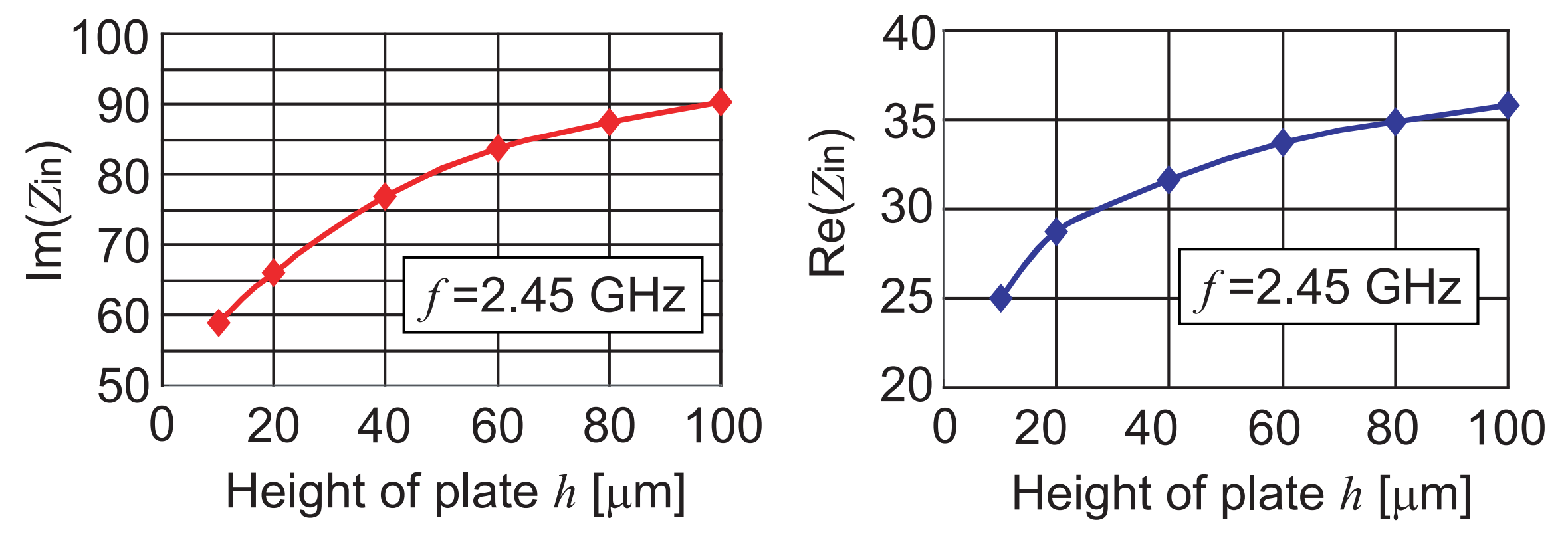
Effect of parasitic capacitance is not dominant



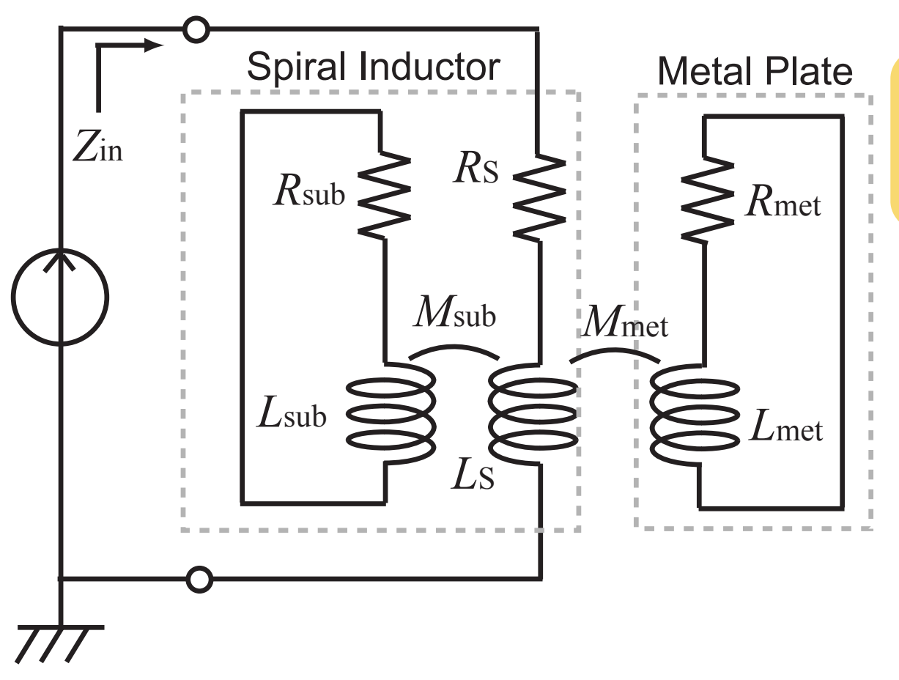
$$f_{SR} = \frac{1}{2\pi\sqrt{LC}}$$

Parasitic capacitance is not increased so much by metal plate

Input Impedance



Equivalent circuit model



$$Zin = Rs + j\omega Ls + \frac{(\omega M_{met})^2}{R_{met} + j\omega L_{met}} + \frac{(\omega M_{sub})^2}{R_{sub} + j\omega L_{sub}}$$

$$= Rs + \frac{(\omega M_{met})^2 R_{met}}{R_{met}^2 + (\omega L_{met})^2} + \frac{(\omega M_{sub})^2 R_{sub}}{R_{sub}^2 + (\omega L_{sub})^2} + j\left(Ls - \frac{(\omega M_{met})^2 \omega L_{met}}{R_{met}^2 + (\omega L_{met})^2} - \frac{(\omega M_{sub})^2 \omega L_{sub}}{R_{sub}^2 + (\omega L_{sub})^2} \right)$$

h decreases

M_{met} increases⇒Im(Zin) decreases

M_{sub} decreases⇒ Re(Zin) decreases

$$Q = \frac{\mathrm{Im}(Zin)}{\mathrm{Re}(Zin)}$$ ⇒Variation of Q is small

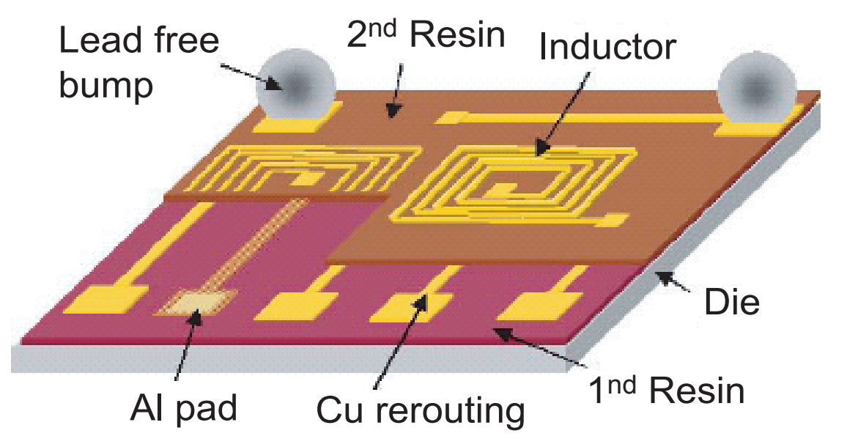
Appendix. Redistributed Layers

WL-CSP

wafer-level chip-scale packages

WL-CSP

The CMOS chip's pads are connected to the board's pads through lead free bumps and redistributed layers.



K. Itoi, M. Sato, H. Abe, H. Sugawara, H. Ito, K. Okada, K. Masu, and T. Ito: *IEEE MTT-S Int. Microwave Symp. Digest, Fort Worth, 2004* p. 197.

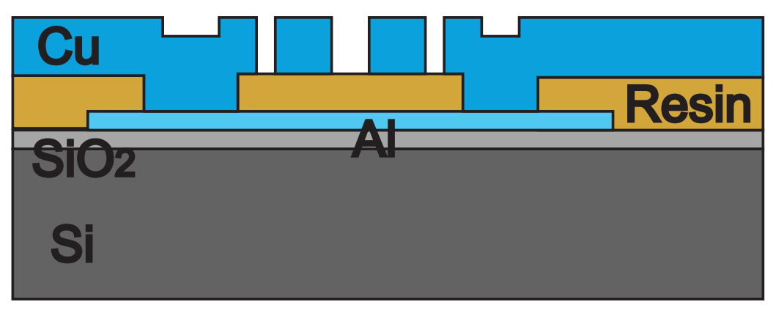
Inductance is implemented using redistributed layer

WL-CSP Advantages

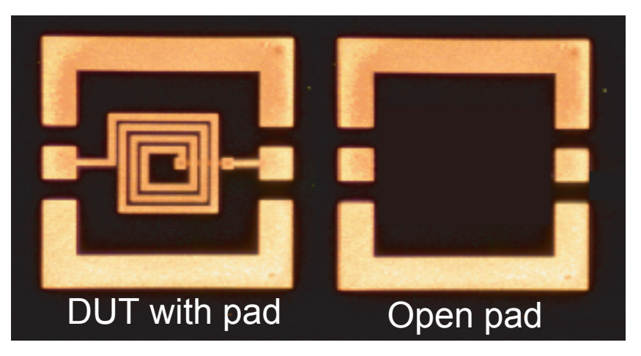
- Thick Cu conductor
- Resin layer between the conductor and Si substrate

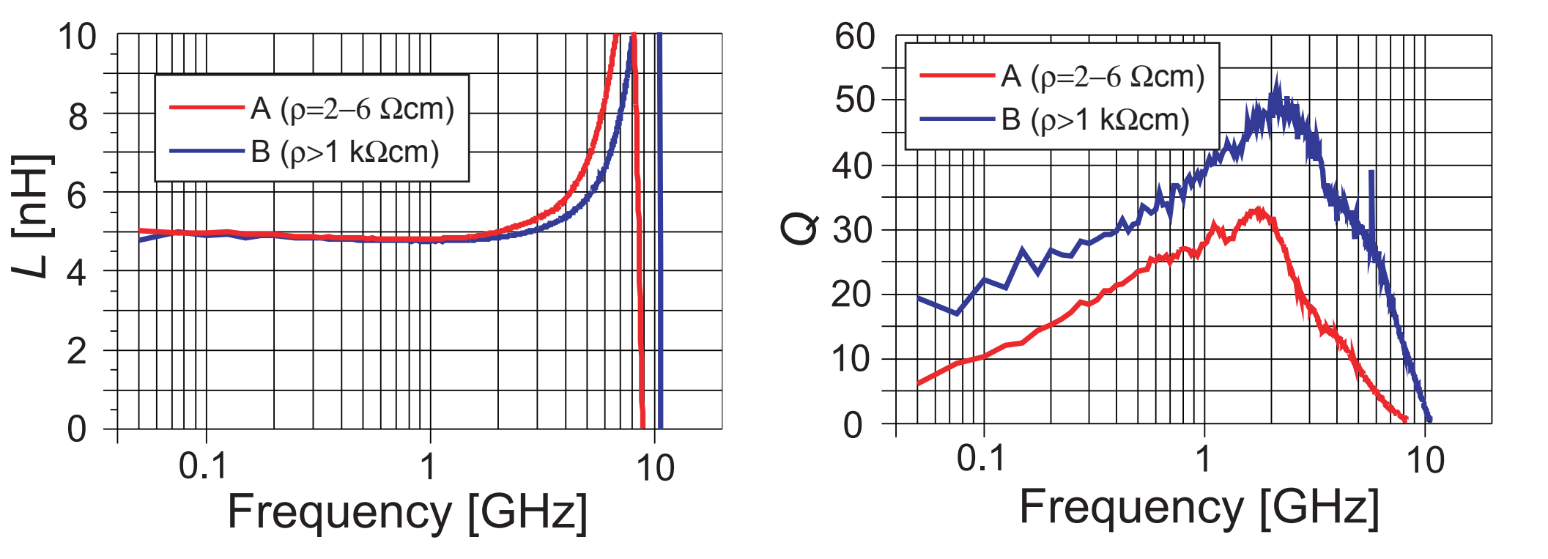
Reduction in substrate loss

⇒High-Q

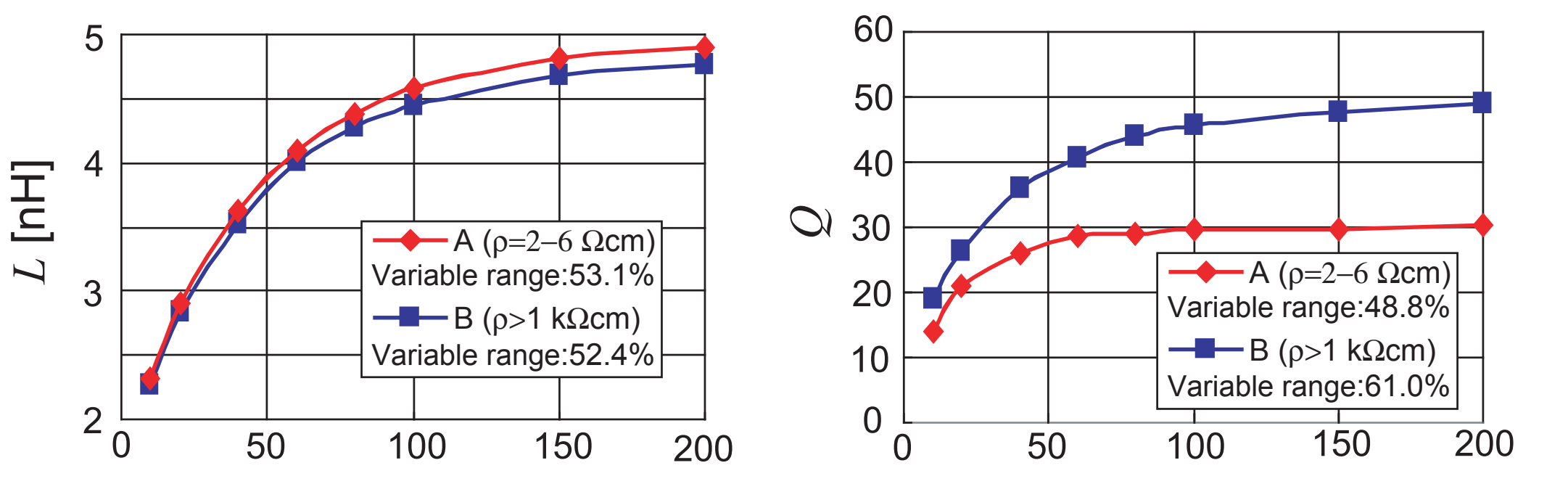


Cu:10 μm
Resin:10 μm
Al:1.5 μm
SiO2 :0.5 μm
Si:525 μm
Si resistivity
A: 2-6 Ωcm
B: 1k Ωcm





@ f=2 GHz



The variable range of L

53 % in Inductor A 52 % in Inductor B

The variable range of Q

50 % in Inductor A 62 % in Inductor B