

# INF 5490 RF MEMS

## **LN12: RF MEMS inductors**

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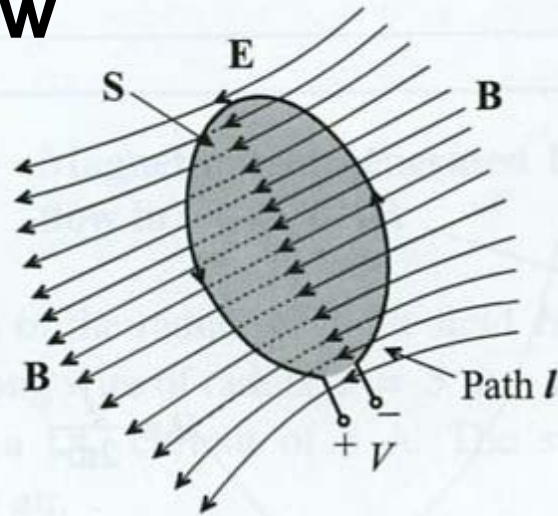
# Today's lecture

- What is an inductor?
- MEMS -implemented inductors
- Modeling
- Different types of RF MEMS inductors
  - **Horizontal plane** inductors
  - Real **solenoids**
- How to increase performance
  - Q-value, Inductance (L), Self resonance frequency ( $f_{\max}$ )
- Elevated inductors
- Inductor banks

# What is an inductor?

- Inductor = a component with interaction between **magnetic** and **electric flux**
  - Magnetic field  $\leftrightarrow$  current
- Two basic laws
  - Faraday's law
    - Varying **magnetic field** induces **current**
  - Ampere's law
    - **Current** flowing sets up a **magnetic field**

# Faraday's law



**Figure 2-15** The time rate of change of the magnetic flux density induces a voltage.

$$\oint \vec{E} \cdot d\vec{l} = - \frac{d}{dt} \iint \vec{B} \cdot d\vec{S}$$

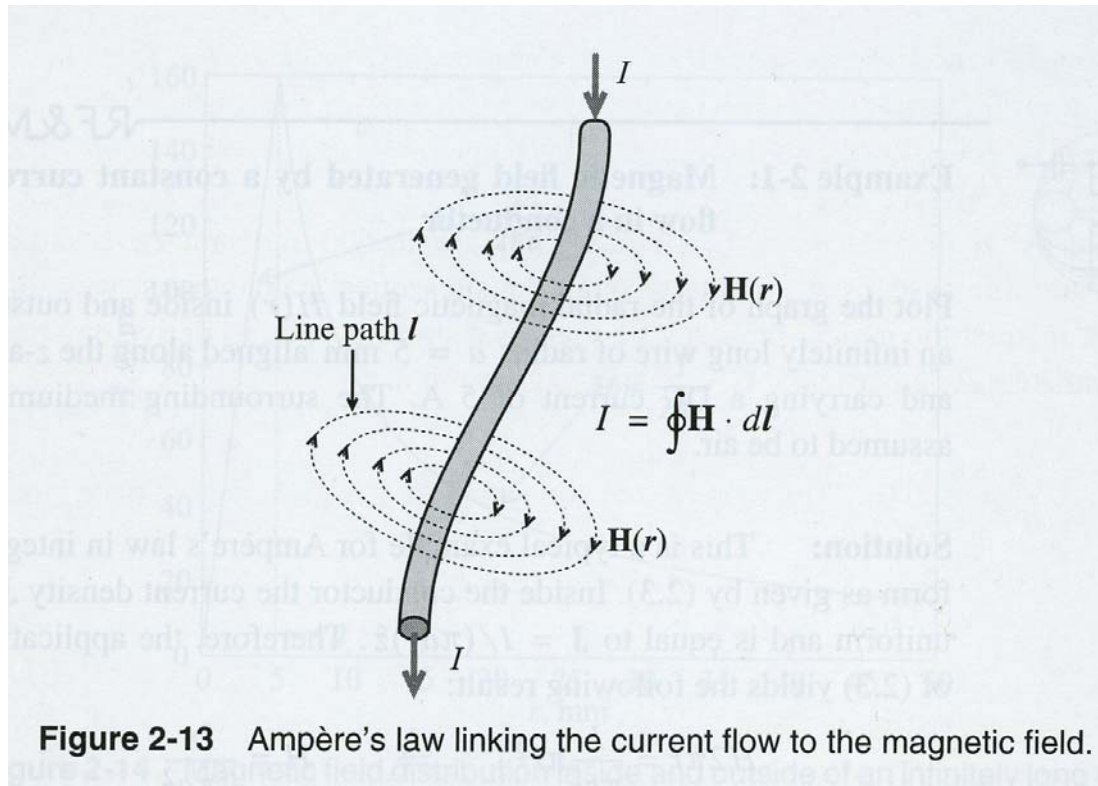
$\vec{B}$  = magnetisk flukso-tetthet      magnetic flux density

$$\vec{B} = \mu \cdot \vec{H}$$

$\mu$  = permeabilitet =  $\mu_0 \cdot \mu_r$       permeability

$\vec{H}$  = magnet felt      magnetic field

# Ampere's law



$$I = \oint \vec{H} \cdot d\vec{l} = \iint \vec{J} \cdot d\vec{S}$$

# Inductors follow **Faraday's/Ampere's laws**

- Change of current in inductor →
- Change of magnetic field (Ampere's law) →
- Electric field induced (Faraday's law) →
- The induced electric field opposes further change in current (Lenz law)
  - Inertia with respect to changing: **"reactance"**
  - Mechanical analogy: **mass!**

# Inductance

- Implemented as **solenoids**
  - 2D (in plane) or 3D
  - Several turns used to increase magnetic flux density
    - May give large inductance,  $L$ , for a small area
- Basic equations
  - $V = L \, di/dt$
  - $V = L_s * I$  (Laplace)
- Solenoids in **plane** are typical for IC and MEMS

metal
dielectric
substrate

# Competition from IC

- Standard **CMOS, SiGe-technology** has given good results!
  - F.ex.  $Q = 12-18 @ 2 \text{ GHz}$ ,  $16-22 @ 6 \text{ GHz}$  (2003)
- Reasons for the increased IC-component performance during the years
  - Optimizing **inductor geometry** using good CAD tools
  - Use of **thick metal layers** of gold ( $3 \mu\text{m}$ )
  - **Thick dielectric** ( $3-6 \mu\text{m}$  oxide over substrate)
  - Use of **high resistivity substrates**,  $10-2000 \text{ ohm-cm}$ , reducing "eddy currents" – substrate loss below the inductor (= magnetic induced currents)



# Possibilities for RF MEMS inductors

- Micromachined inductors should have better performance than today's CMOS inductors
  - MEMS can give **higher Q-values!**
    - **Q>30**
  - MEMS may give higher **L** and self resonance-frequency
- Should be CMOS compatible
  - F.ex. post processing CMOS
- Micromachined inductances not yet a commercial product

L → L, C, R -circuit



# Applications of (RF MEMS) inductors

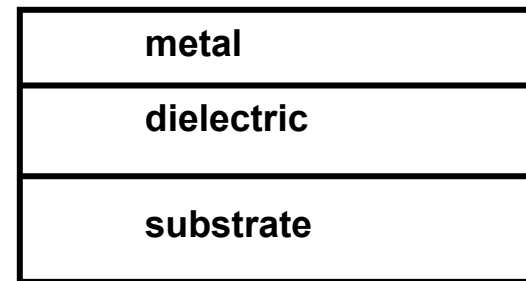
- Replacement components in
  - Low noise oscillators
  - Integrated LC-filters
  - Amplifiers
  - On-chip "matching" networks
  - Impedance transformers
  - Phase shifters

# RF MEMS inductors

- Two-dimensional (**planar**) inductors
- Three-dimensional inductors, **solenoids**
- Only **fixed-value** inductors can be implemented
  - No practical implementation of tunable inductors exist
- Variable inductance values: implemented as an **inductor bank**
  - Many inductors with fixed, high Q-values
  - In combination with MEMS contact switches

# Planar inductors, in general

- Implemented in a single plane
- One **metal layer** patterned by etching
- Inductor rest on a **substrate** covered by a **dielectric**
- **Loss** in inductor due to:
  - Finite metal conductivity
  - Loss in dielectric
  - Loss in substrate
- Area limitations for RF
  - Total length of an inductor has to be significantly shorter than the wavelength
    - This will give negligible phase shift of signal



# Different planar geometries

- Simple **line sections**
  - Each one has a low inductance value,  $nH$
- **Meander**
  - Coupling by negative mutual inductances
- **Spiral inductors**
  - Higher L, higher Q
  - **Problem:** connecting to the **inner winding**
    - Wire bonding
    - Separate structure layer
    - Flip-chip methods

# Contribution to inductance

- **Self inductance** from own winding
- **Mutual inductance** from neighbouring windings
  - Mutual coupling between neighbour lines
- Total inductance is the sum of self inductance and mutual inductance
  - In some elements current flows in the **same** direction, in others **opposite**

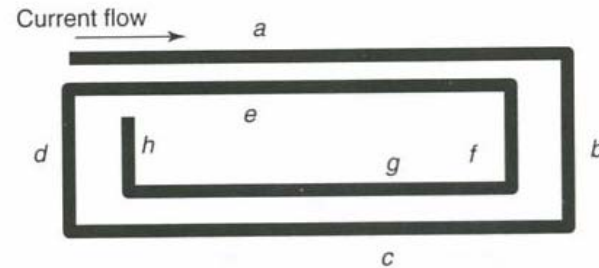
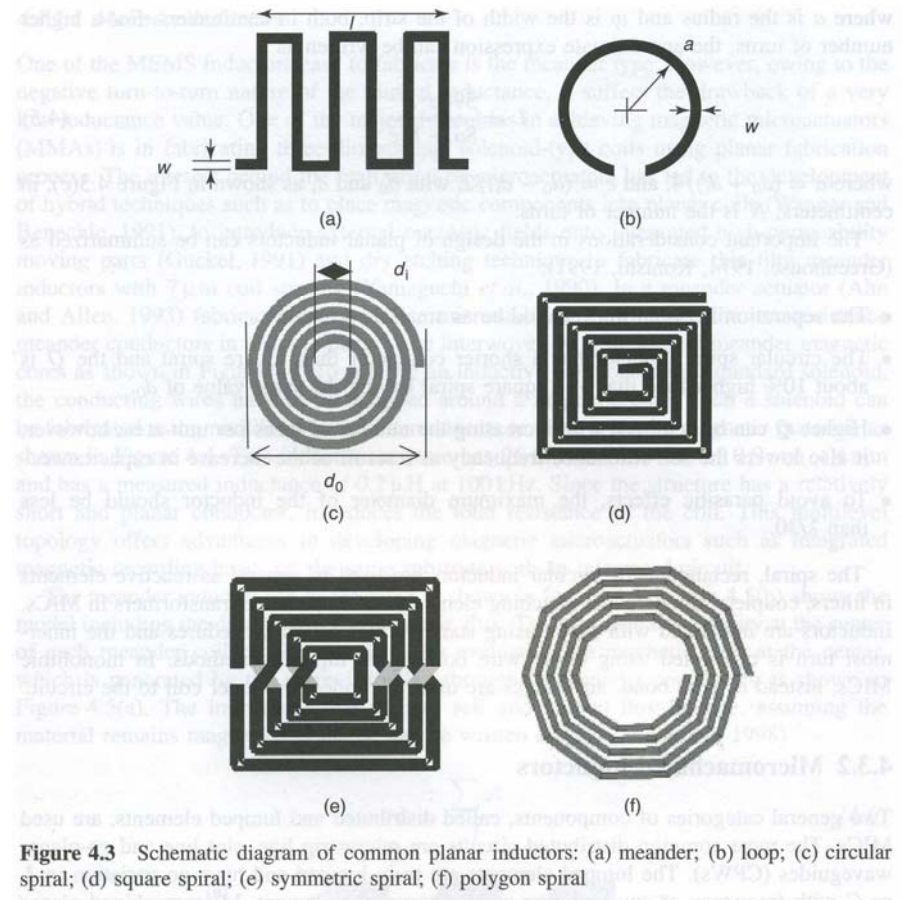


Figure 4.2 Spiral inductor and the effect of current flow in nearby segments

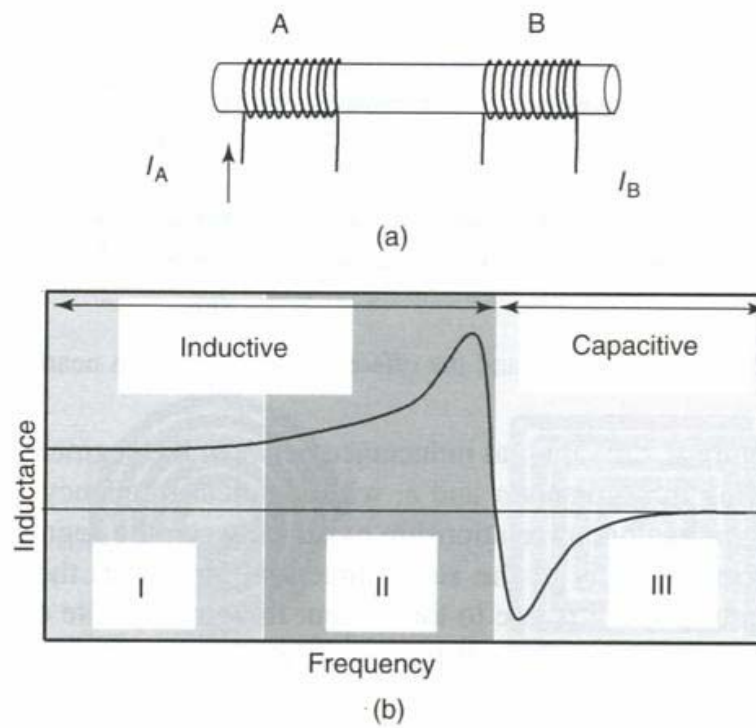
# Different planar geometries

- Distance between lines is critical
- Circular spiral has a shorter length than a quadratic spiral
  - $\rightarrow$  Lower R
  - Q is about 10% higher with same "diameter",  $d_0$
- Higher Q achieved by increasing number of turns per area
  - Self resonance frequency decreases due to the increase in capacitance  $\rightarrow$  limits the region of use



# Inductor is a non-ideal component

- Changes its value versus frequency
  - Becomes capacitive at high frequencies



**Figure 4.1** (a) Self-inductance and mutual inductance due to a change in current; (b) typical operational regions of an inductor. Note:  $I_A$  and  $I_B$ , current in coils A and B, respectively



# General model for a planar inductor

$L_s$  is low frequency inductance

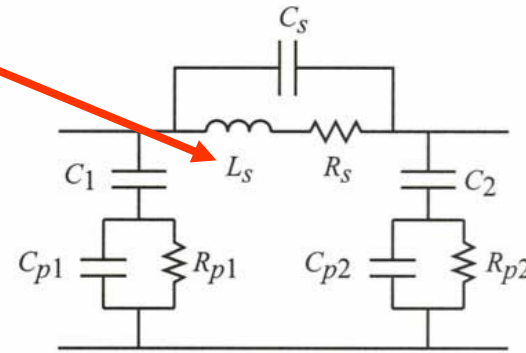
$R_s$  is series resistance

$C_s$  is capacitance between windings

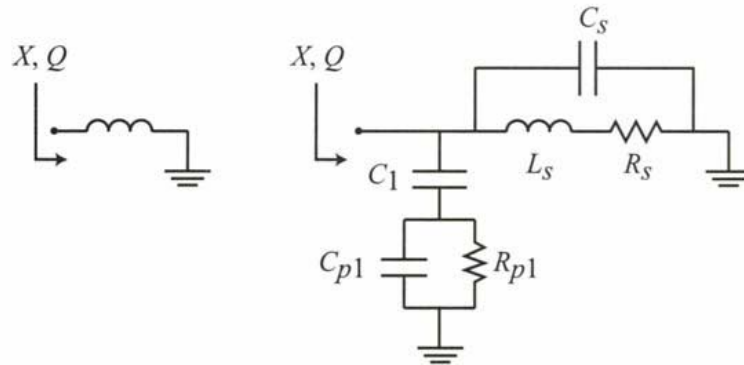
$C_1$  is capacitance in oxide layer between inductor and substrate

$C_p$  is capacitance to ground through substrate

$R_p$  is "eddy current" loss in substrate



(a)



(b)

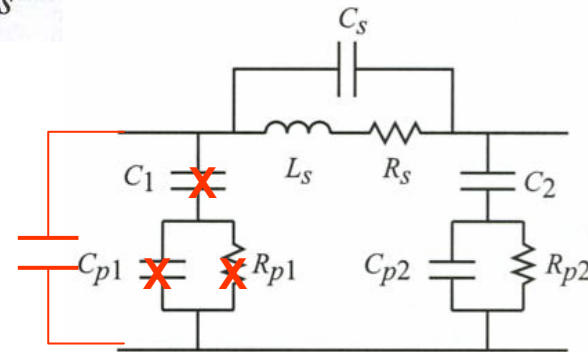
**Figure 12.1.** (a) The equivalent LRC model of a planar inductor. (b) A short-circuited inductor model typically used in  $S$ -parameter and  $Q$  measurements.  $C_{p1}$  and  $C_{p2}$  are often assumed identical and equal to  $C_p$ .

# Frequency response for a planar inductor

- At low frequencies we have

$$Z = R_s + j\omega L_s \quad (12.1)$$

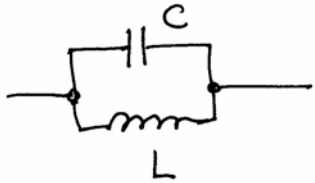
- At high frequencies:
  - $R_{p1}$  is negligible
  - $C_1$  and  $C_{p1}$  combined  $\rightarrow C_p$



$$Z = (R_s + j\omega L_s) \parallel \left( \frac{1}{\omega C_s} \right) \parallel \left\{ \frac{1}{\omega C_1} + \left( \frac{1}{\omega C_{p1}} \parallel R_{p1} \right) \right\} \quad (12.2)$$

# Parallel resonator

Parallell resonans



$$Z = \frac{\frac{1}{j\omega C} \cdot j\omega L}{\frac{1}{j\omega C} + j\omega L}$$

Resonans när

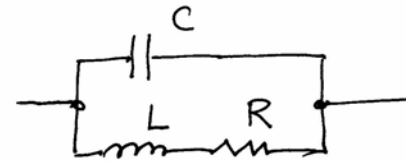
$$\frac{1}{\omega C} = \omega L$$

$$\frac{1}{j\omega C} + j\omega L = 0$$

$$Z = \infty$$

Due to parasitic capacitances a specific self resonance frequency is obtained

$$Q_{ind} = \omega L / R$$



$$Z = \frac{\frac{1}{j\omega C} \cdot (R + j\omega L)}{\frac{1}{j\omega C} + R + j\omega L} = \frac{-j\omega L (R + j\omega L)}{R}$$

$$\approx -j\omega L$$

At resonance:

$$Z = \frac{\omega^2 L^2}{R} - j\omega L \approx \frac{\omega^2 L^2}{R}$$

# Ex.: Inductor reactance

Resistance is here defined at 2 GHz

R is supposed to vary as **sqrt (f)** over 2 GHz due to the skin effect

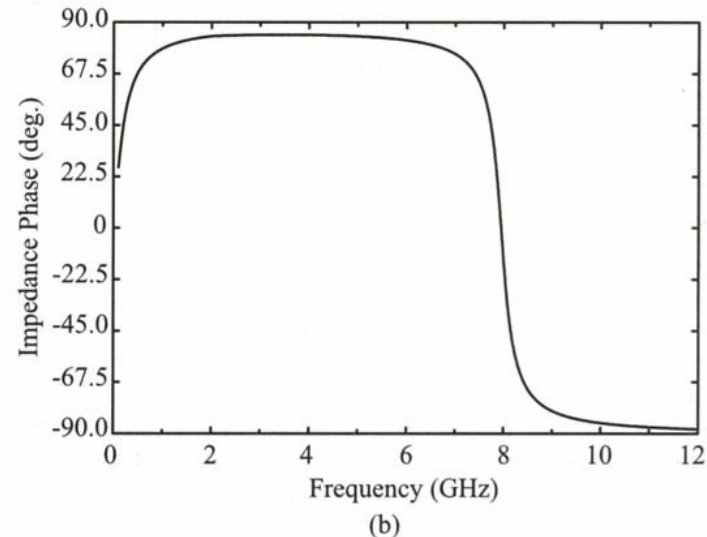
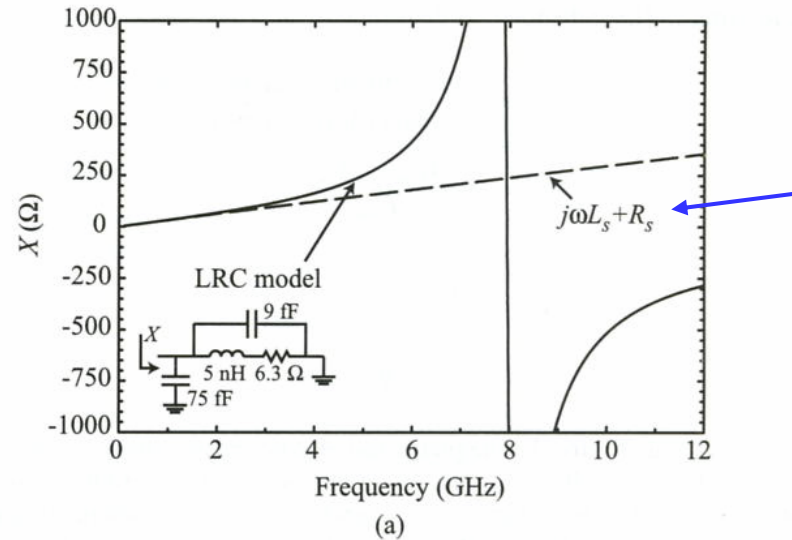
Parallel-type resonance at 8 GHz, phase also changes

At resonance the input impedance of a parallel resonator is real and given by:

$$Z_{res} = \frac{(\omega L_s)^2}{R_s} \quad (12.3)$$

Figure shows that simple L, R – model is valid to 0.5 f\_resonance

Phase properties show that the component is inductive also for higher frequencies →



**Figure 12.2.** The calculated  $X$  (a) and phase (b) of a planar 5-nH inductor. The resonant frequency is 8 GHz and the resistance is assumed constant up to 2 GHz and then increases as  $\sqrt{f}$ .

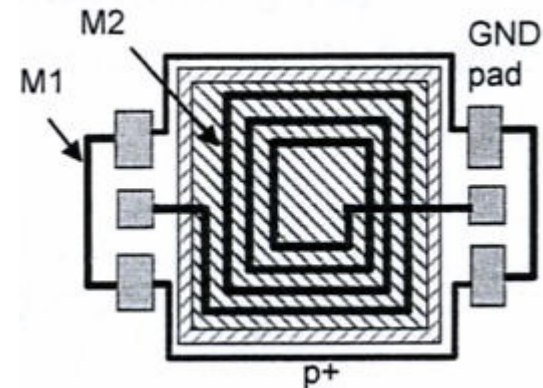
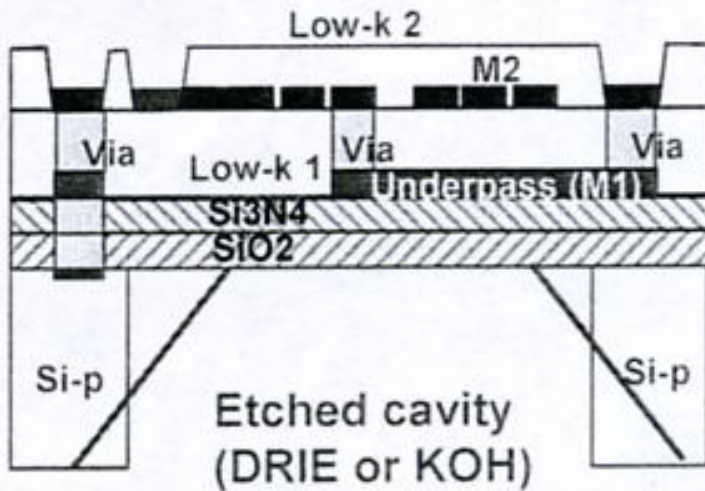
# Today's lecture

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# Example: Thick copper/polyimide horizontal-plane inductor

## Process (EPF Lausanne, WIDE-RF):

- 4-8 $\mu\text{m}$  electroplated Cu in polyimide mold using Ta barriers



”Form” (”mold”) of organic material

# Ex. CMOS – MEMS inductor

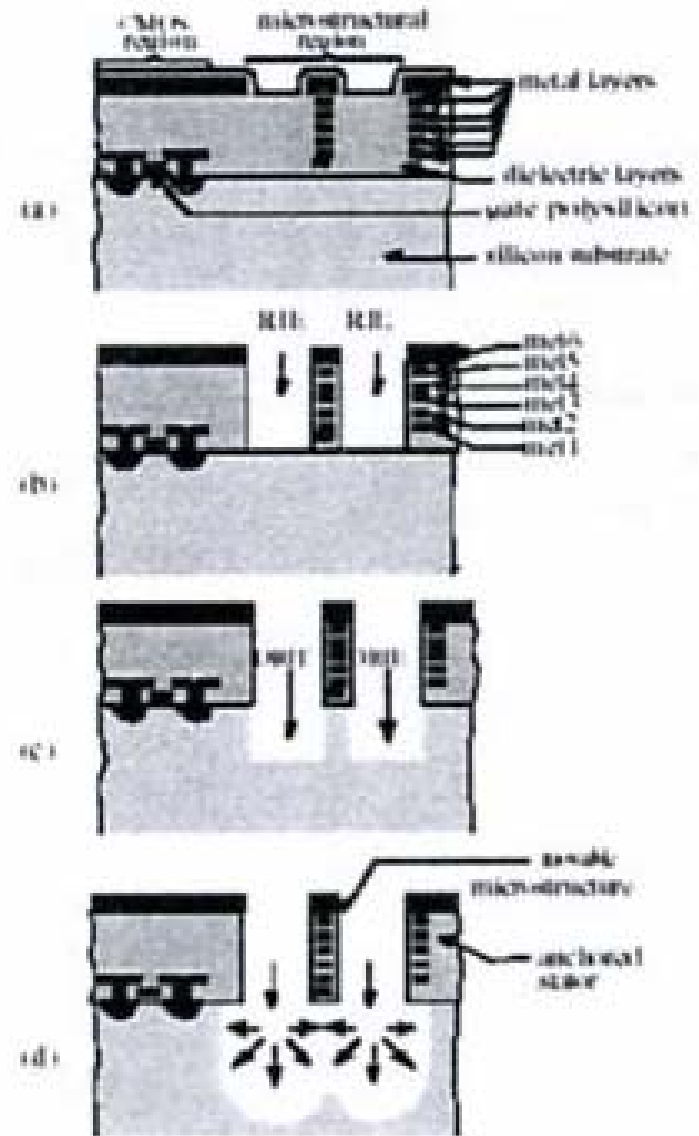
- High Q, 6 Cu layers
- Low- $\epsilon$  dielectric
- Post-CMOS processing
  - Standard CMOS + RIE post processing + isotropic etch
- X. Zhu et al

**Carnegie Mellon University**

Ex. from Transducers 2001

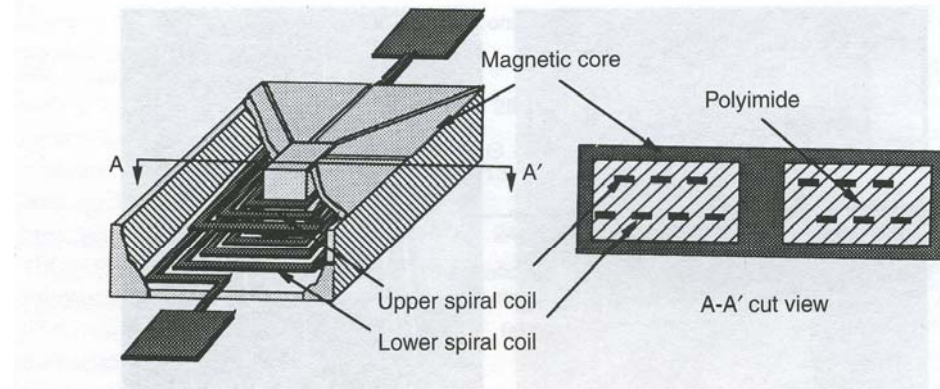
**Anisotropic etching followed by isotropic etching**

**Top metal layer is mask**



# Ex. Spiral inductor (Ahn & Allen)

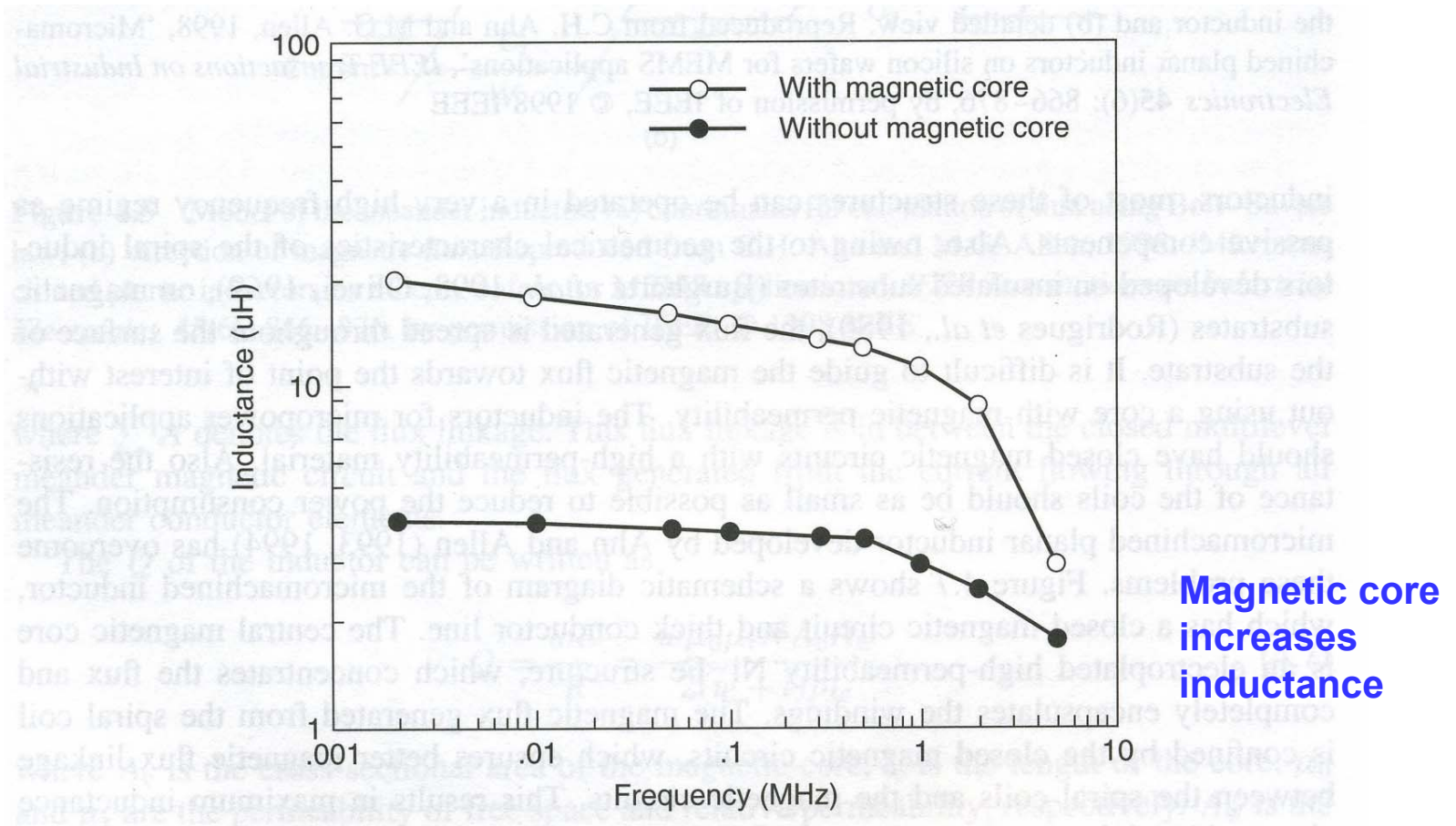
- Two solenoids
- **Magnetic core** used for trapping magnetic flux
  - Must be a high permeability material
  - Ex. Varadan fig. 4.7 (Ahn & Allen) →
- Conductor from centre needed!



**Figure 4.7** Schematic diagram of a micromachined spiral inductor. Reproduced from C.H. Ahn and M.G. Allen, 1993, 'A planar micromachined spiral inductor for integrated magnetic microactuator applications', *Journal of Micromechanics Microengineering* 3: 37–44, by permission of the Institute of Physics



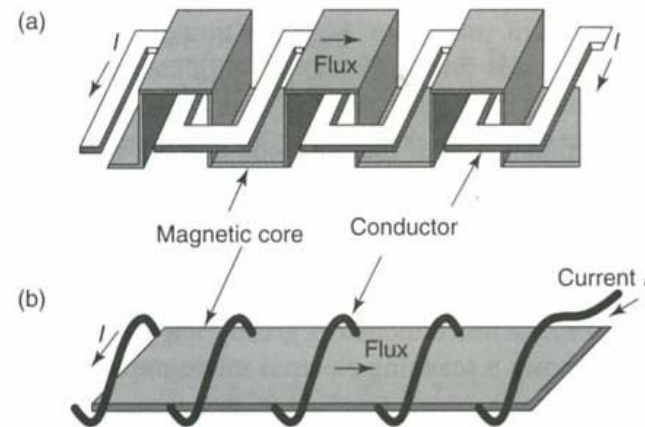
# Effect of magnetic core



**Figure 4.8** Measured inductance with and without magnetic core. Reproduced from C.H. Ahn and M.G. Allen, 1993, 'A planar micromachined spiral inductor for integrated magnetic microactuator applications', *Journal of Micromechanics Microengineering* **3**: 37–44, by permission of the Institute of Physics

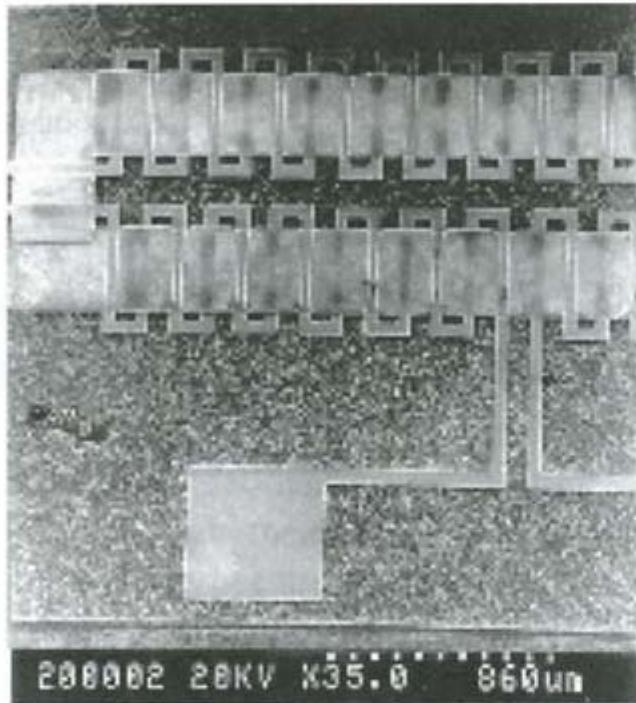
# Meander inductors

- Meander has lower inductance than spiral inductor
- Meander fabricated by surface processing
  - a) Metal conductor in one layer
    - Penetrated by multilevel magnetic core
  - b) Schematic of principle →
    - Ala magnetic core in one layer surrounded by metal turns

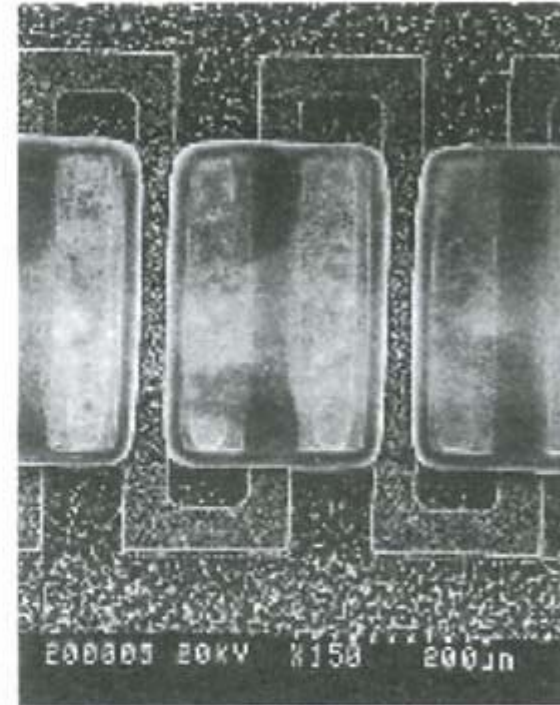


**Figure 4.4** Schematic diagram of the micromachined multilevel meander inductor. Reproduced from C.H. Ahn and M.G. Allen, 1998, 'A fully integrated surface micromachined microactuator with a multilevel meander magnetic core', *Journal of Microelectromechanical Systems* 2(1): 15–22, by permission of IEEE, © 1998 IEEE

# Meander fabricated (SEM picture)



(a)



(b)

**Figure 4.6** Scanning electron micrograph of the fabricated toroidal-meander inductor: (a) half of the inductor and (b) detailed view. Reproduced from C.H. Ahn and M.G. Allen, 1998, 'Micromachined planar inductors on silicon wafers for MEMS applications', *IEEE Transactions on Industrial Electronics* **45**(6): 866–876, by permission of IEEE, © 1998 IEEE

# Meander: effect of different line widths

- Influence of the **line width** (C vs width)
  - "sheet resistance" is inverse proportional to  $w$  → decreases!
  - Resistance decreases if  $w$  increases, but the **capacitance increases**

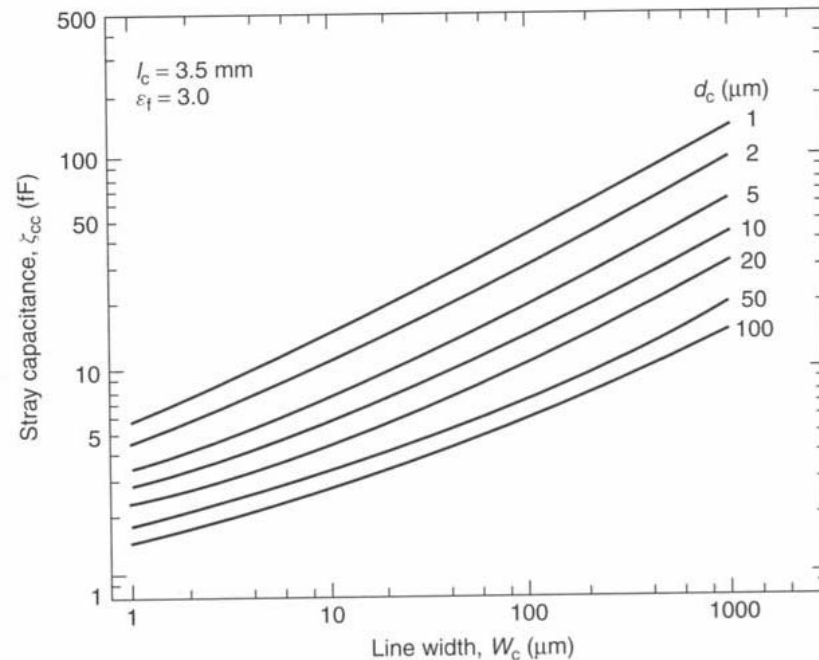
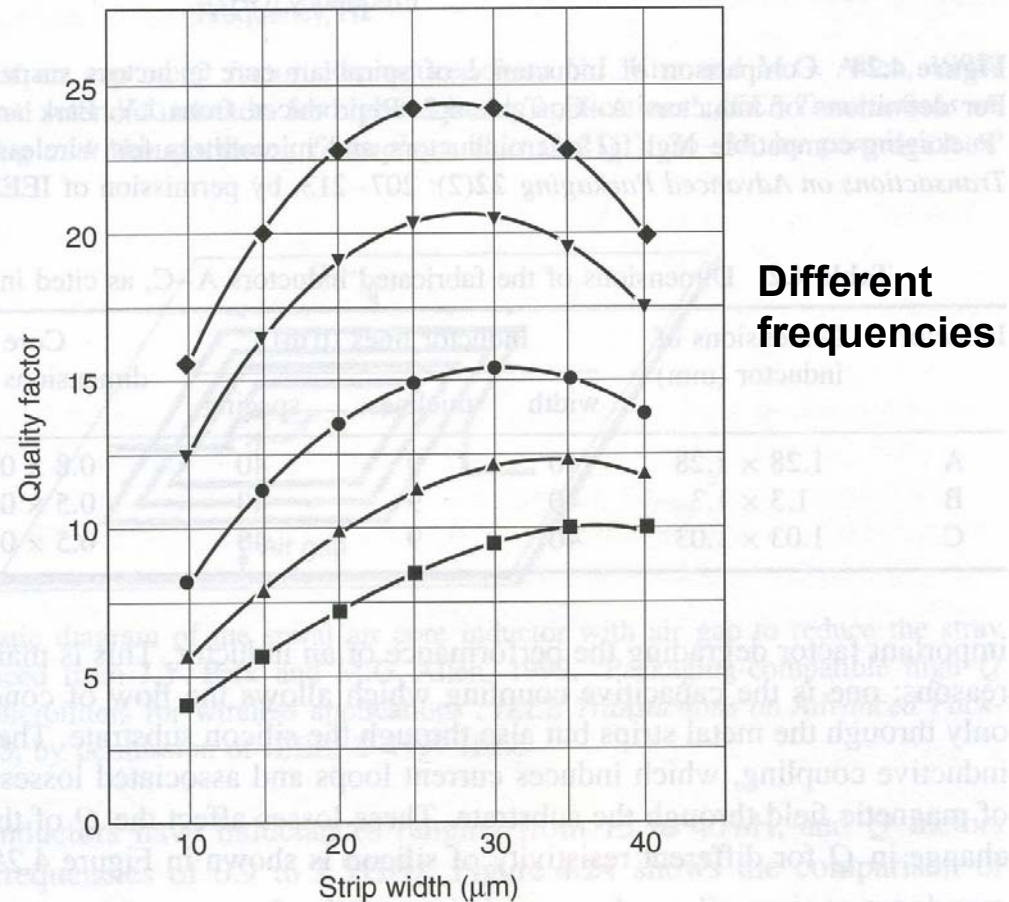


Figure 4.11 Computed stray capacitance due to change in line width  $W_c$ . Reproduced from M. Yamaguchi, M. Mastumo, H. Ohzeki and K.I. Arai, 1991, 'Analysis of the inductance and the stray capacitance of the dry-etched micro inductors', *IEEE Transactions on Magnetics* 27(6): 5274–5276, by permission of IEEE, © 1991 IEEE

dc = distance between conductors



# Effect of **stripe width $w$** on Q-factor

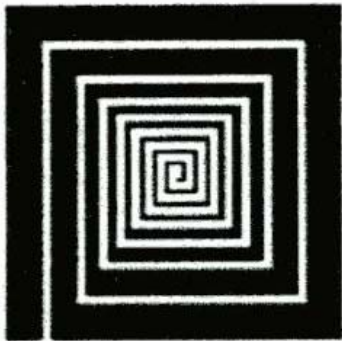


Optimal values of  $w$  exist for minimizing series resistance and maximizing  $Q$

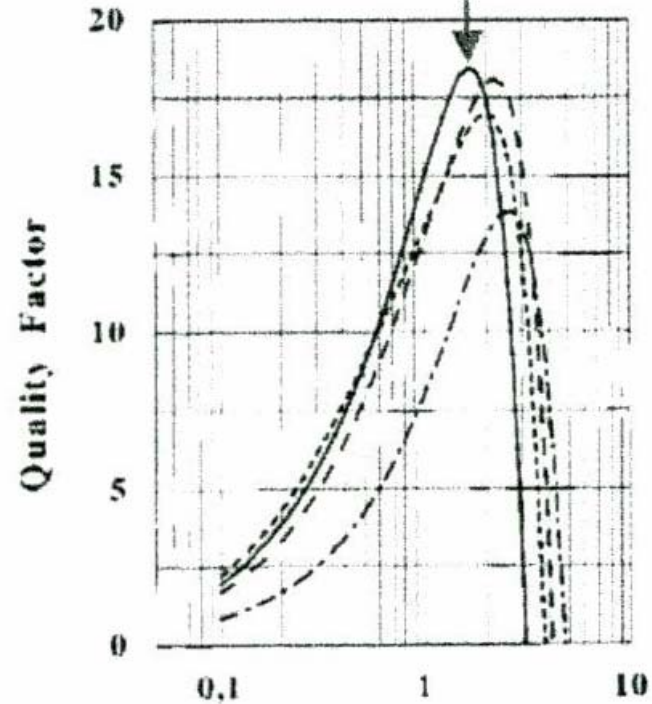
**Figure 4.26** Change in  $Q$  due to change in strip width for 20-nH inductors for different frequencies: ■, 7 GHz; ▲, 1 GHz; ●, 1.5 GHz; ▼, 2.5 GHz; and ◆, 3.5 GHz. Reproduced from I.J. Bahl, 1999, 'Improved quality factor spiral inductors on GaAs substrates', *IEEE Microwave and Guided Wave Letters* 9(10): 398–400, by permission of IEEE, © 1999 IEEE

# Optimization

- Width of each turn can be optimized
  - Each turn has a **constant resistance**

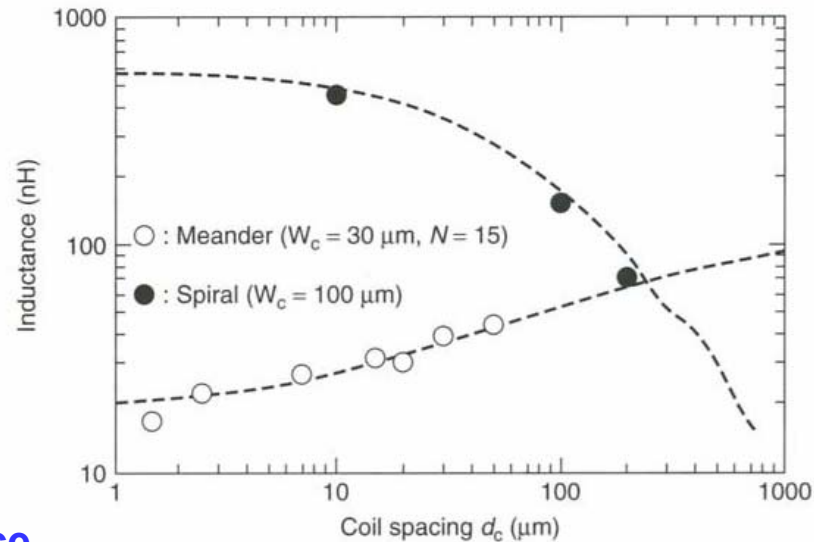


Optimized (**width of each turn**) inductor design



# Effect of different implementations

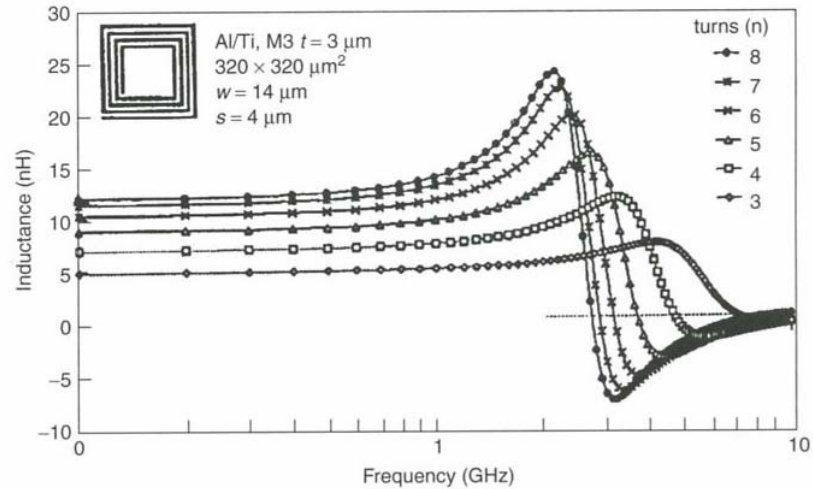
- How **line spacing** influences L



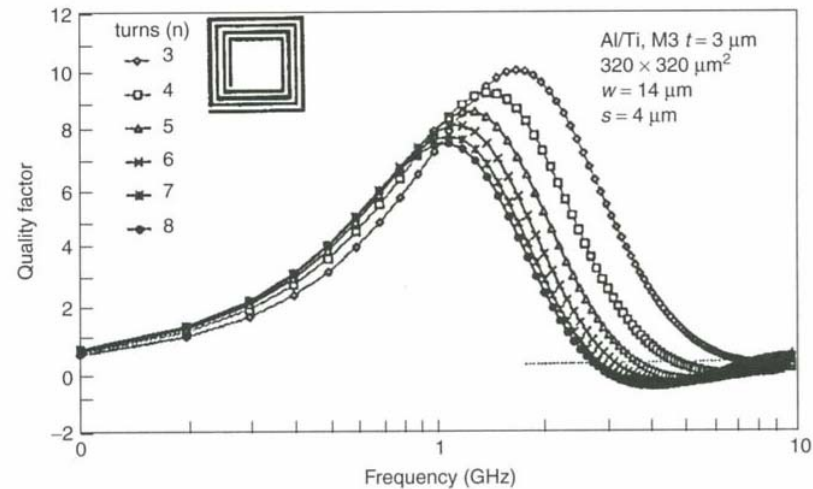
Different effect for spiral and meander: constructive versus destructive mutual inductance

**Figure 4.10** Change in inductance arising from changes in spacing between the conductors for meander and spiral inductors. Reproduced from M. Yamaguchi, M. Mastumo, H. Ohzeki and K.I. Arai, 1991, 'Analysis of the inductance and the stray capacitance of the dry-etched micro inductors', *IEEE Transactions on Magnetics* **27**(6): 5274–5276, by permission of IEEE, © 1991 IEEE

- Effect of number of turns on L and Q
- **Spiral** inductors with same dimensions
- $n: 3 \rightarrow 8$ :
  - L increases
  - Q decreases (due to increase in C)



(a)



(b)

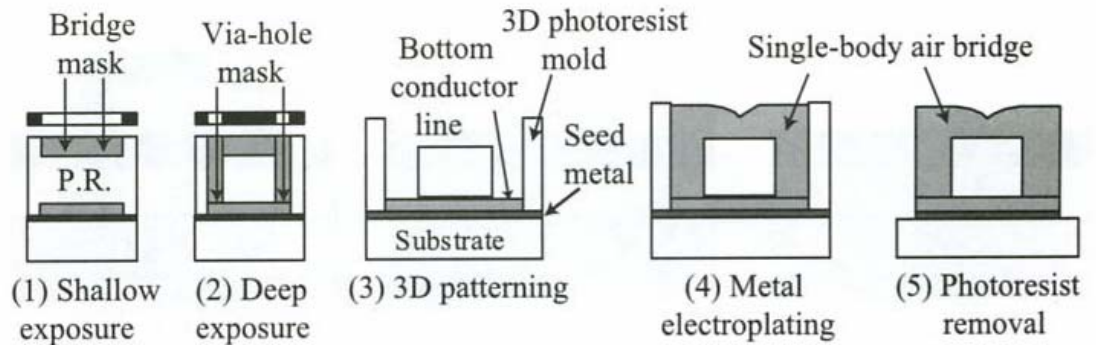
**Figure 4.12** Effect of number of turns on (a) the inductance value and (b)  $Q$  factor. Reproduced from Y.K. Koutsoyannopoulos and Y. Papananos, 2000, 'Systematic analysis and modeling of integrated inductors and transformers in RF IC design', *IEEE Transactions on Circuits and Systems II* 47(8): 699–713, by permission of IEEE, © 2000 IEEE



# Solenoid-type inductors

- Classical example
- Process using thick **photo resist form**

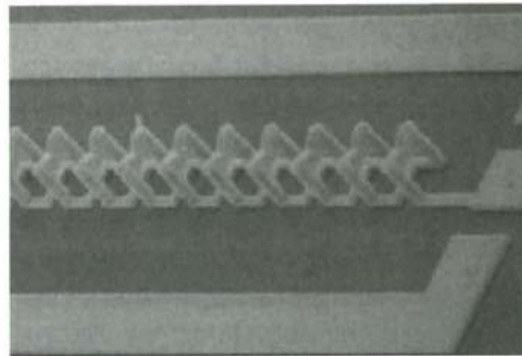
– 45 – 60  $\mu\text{m}$  deep



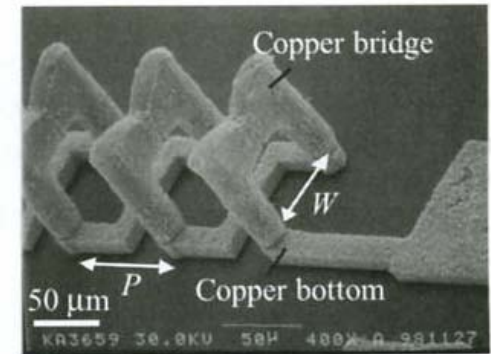
(a)

- Top fabricated using copper: **electroplating**
- seed + 20 – 30  $\mu\text{m}$  copper layer on top

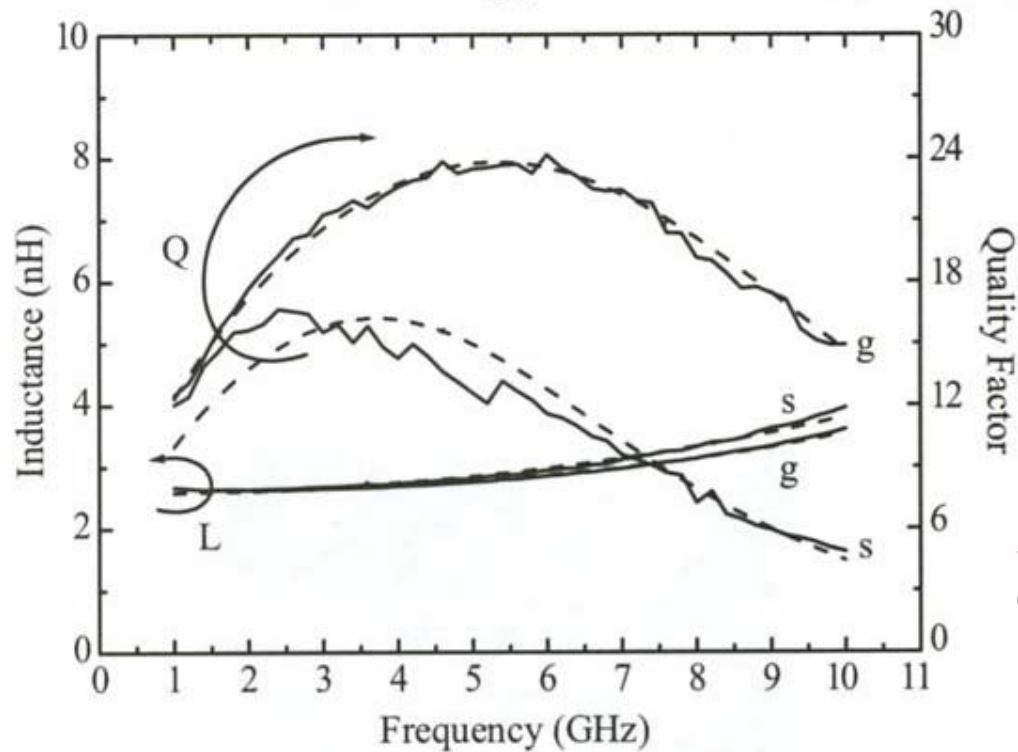
- Result: "loops" formed



(b)



# Solenoid-type copper inductors



(c)

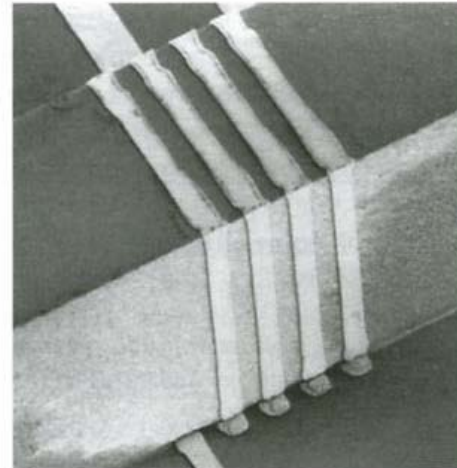
**Figure 12.14.** Fabrication process (a), picture (b), and measured performance (c) of a 2.4-nH all-copper solenoid inductor on silicon and glass substrates [24, 25] (Copyright IEEE).

**Si or glass substrate give different values**

Results from Yoon et al.

# Extreme type

- Solenoid-type inductor with large alumina core
  - Placed **manually** on a Si-substrate, fig. →
    - Cross section  $650 \times 500 \mu\text{m}^2$
  - Photo resist on alumina core
  - Direct write laser, 3D
  - Electroplating
    - 5-10  $\mu\text{m}$  copper
  - **Not practical!**

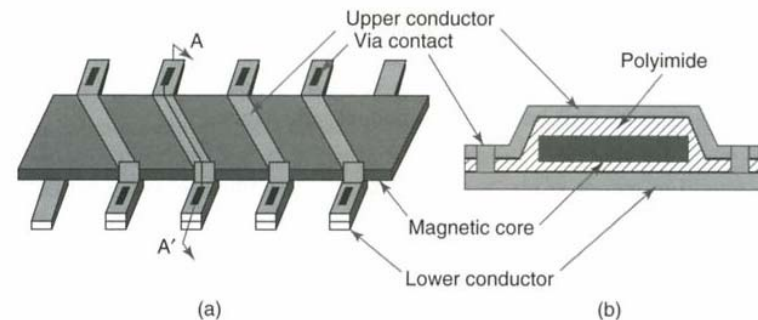


**Figure 12.16.** A solenoid-type four-turn inductor using a large alumina core [28] (Copyright IEEE).

Young et al., 1997

# Example of 3-D structure

- Difficult to produce
  - Nickel-iron (permalloy) magnetic core
  - Multilevel copper + via-contacts
  - Contacts have high contact resistance
  - Need of many turns to get high L
    - More contacts → higher resistance
    - Electroplating of metal lines and via holes may reduce resistance and increase performance



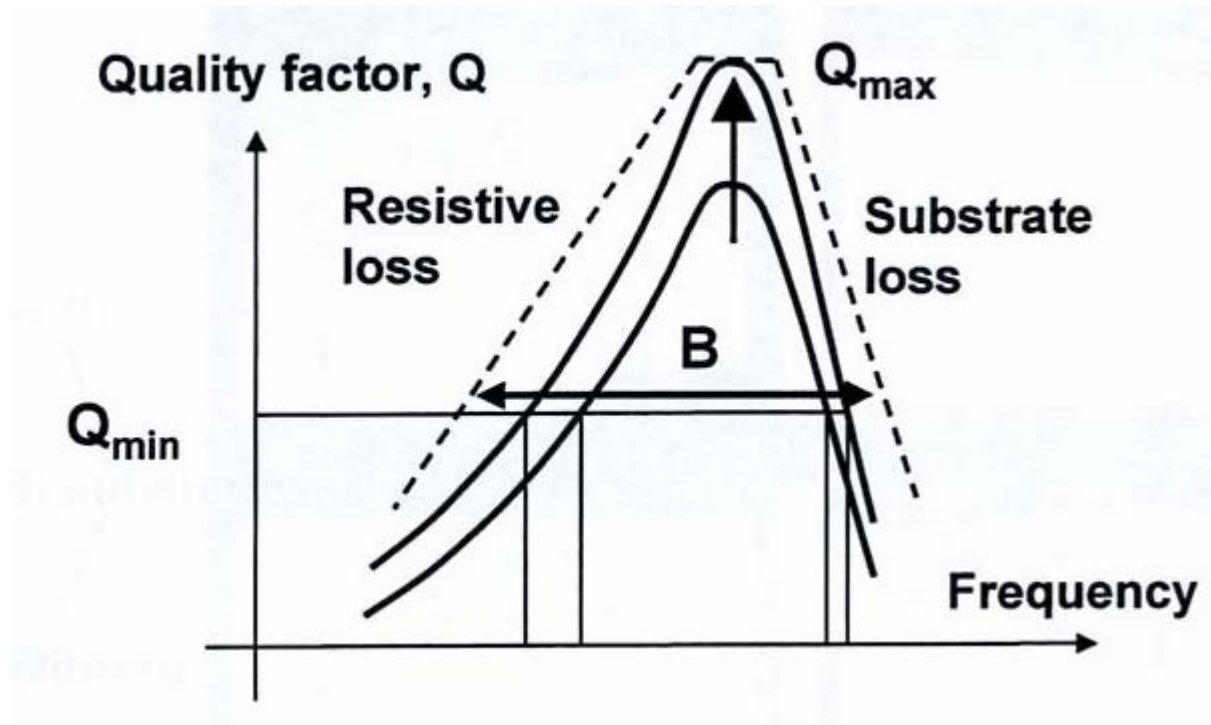
**Figure 4.9** Schematic diagram of a solenoid-type inductor: (a) schematic view; (b) cross-sectional view at AA'. Reproduced from C.H. Ahn and M.G. Allen, 1998, 'Micromachined planar inductors on silicon wafers for MEMS applications', *IEEE Transactions on Industrial Electronics* 45(6): 866–876, by permission of IEEE, © 1998 IEEE

Ahn & Allen, 1998

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Q-factor depends on resistive loss and substrate loss



For low frequencies: [resistive loss](#) limits Q

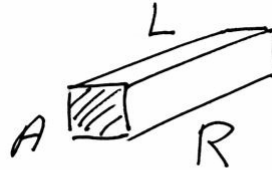
For high frequencies: [substrate loss](#) limits Q

# Improving Q-factor

- Metallization is important
  - Reduction of resistive loss!
  - Use metals with **higher conductivity**
    - Use copper, Cu, instead of Al
  - Use **thicker** structures

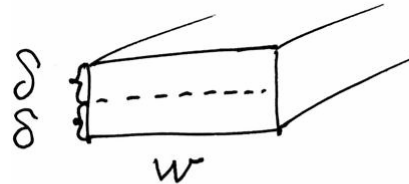
# Effect of metal thickness

- Series resistance limits performance
- Simulations show that minimum thickness of **2 x "skin depth"** is needed to obtain minimum resistance



$\rho =$  resistivity

$$R = \frac{\rho \cdot L}{A}$$



Resistance per length

$$\frac{R}{L} = \frac{\rho}{A} = \frac{\rho}{2\delta \cdot w}$$

skin depth  $= \delta$

$$\delta = \sqrt{\frac{\rho}{\pi \mu \cdot f}} \sim \frac{1}{\sqrt{f}}$$

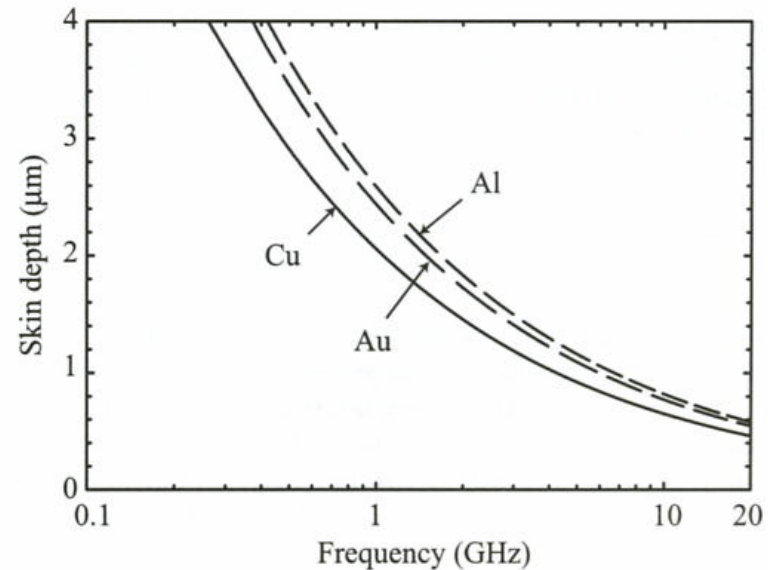
$\mu =$  permeability  
 $\rho =$  resistivity

$$\frac{R}{L} \sim \frac{1}{\delta} \sim \sqrt{f}$$



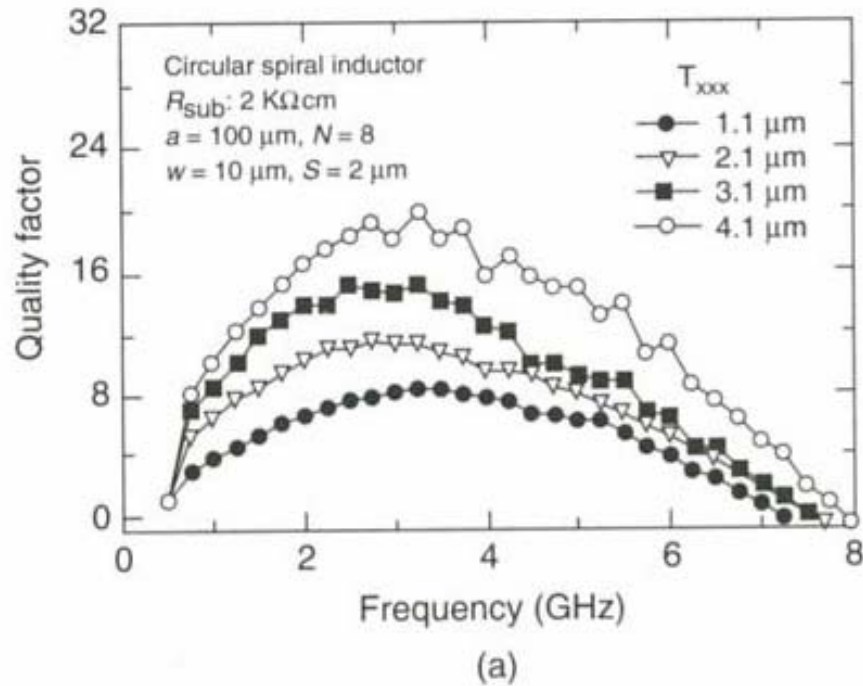
# Thick conductors needed

- For copper at 1 GHz: skin depth is about 2  $\mu\text{m}$
- One should have conductors of min 2 x skin depth thickness
  - E.g. about 4 - 5  $\mu\text{m}$  for Cu
  - Thick layer!
  - Typically obtained by **electroplating**



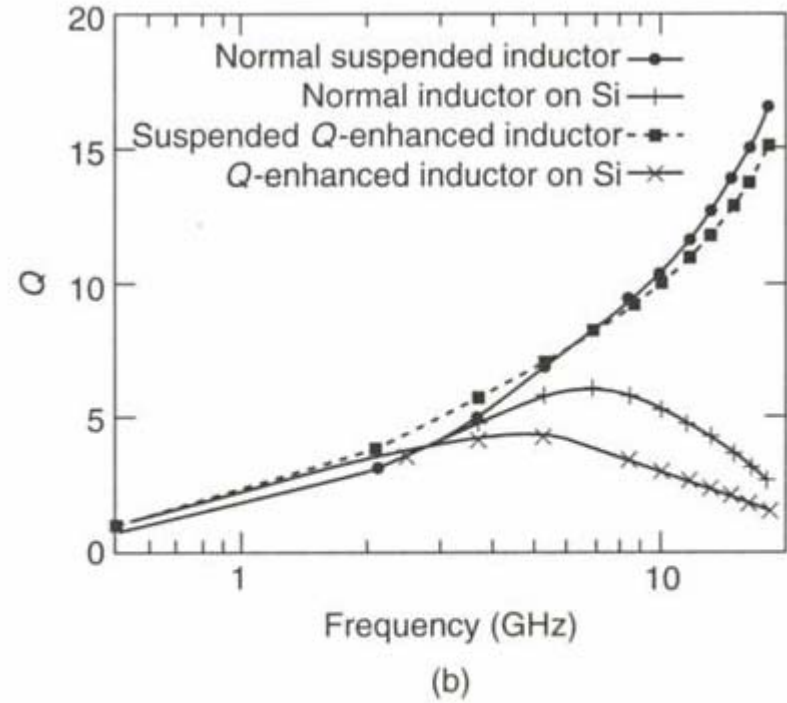
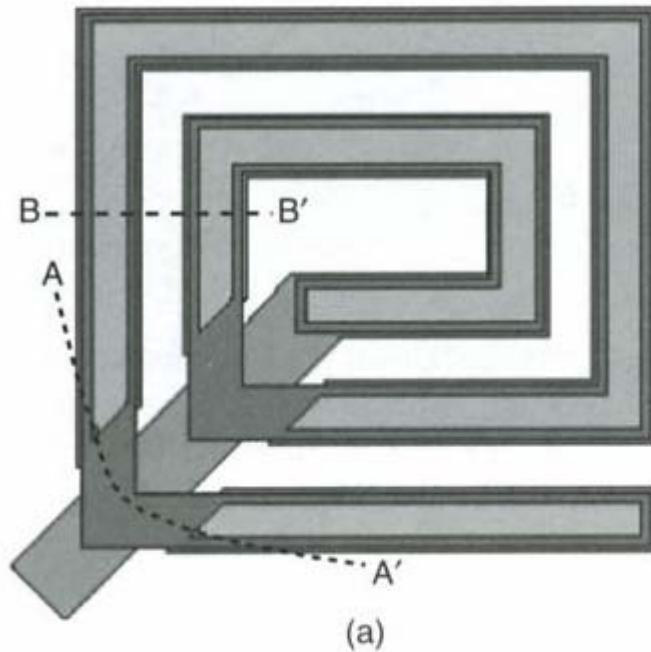
**Figure 12.4.** Skin depth versus frequency for copper, gold, and aluminum metal layer (bulk values of resistivities are assumed).

## Change of Q versus metal thickness



**Figure 4.29** Change in  $Q$  of an inductor for (a) different metal thickness; (b) for substrates with different resistivity. Reproduced from M. Park, C.S. Kin, J.M. Park, H.K. Yu and K.S. Nam, 1997b, 'High  $Q$  microwave inductors in CMOS double metal technology and its substrate bias effects for 2 GHz RF IC application', in *Proceedings of IEDM 97*, IEEE, Washington, DC: 59–62, by permission of IEEE, © 1997 IEEE

# Double level metallization



**Figure 4.27** (a) Schematic diagram of a  $Q$ -enhance inductor; (b) measured results of normal and  $Q$ -enhanced inductors. Reproduced from Y. Sun, J.L. Tauritz and R.G.F. Baets, 1999, 'Micromachined RF passive components and their applications in MMICs', *International Journal of RF and Microwave CAE* 9: 310–25, © Wiley (1999), by permission of Wiley

4.5  $\mu\text{m}$   $\rightarrow$  9  $\mu\text{m}$ , on/without 10  $\mu\text{m}$  polyimide layer

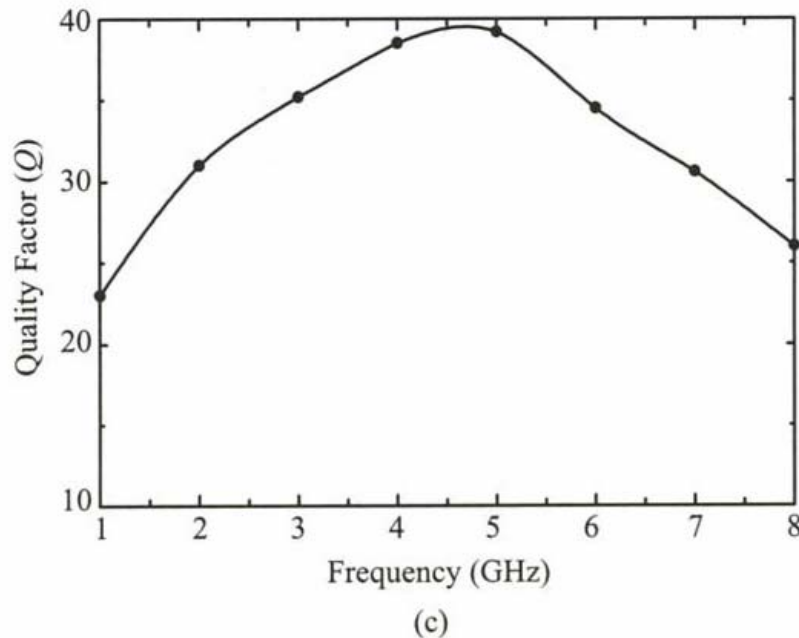
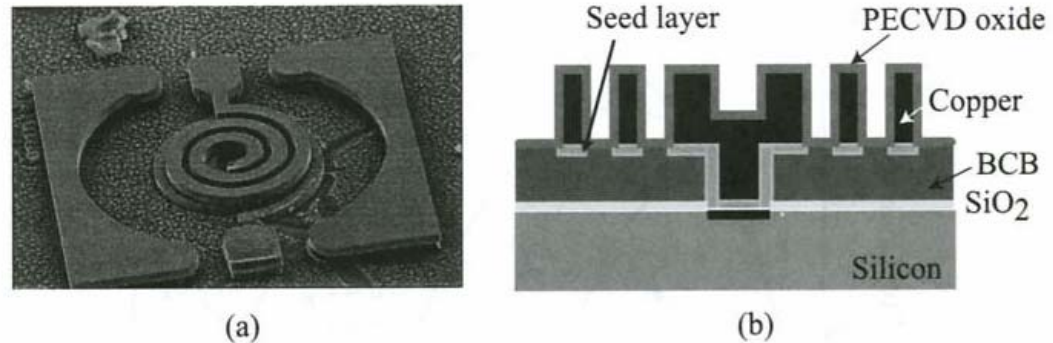
## Example:

Micromachining using  
**thick metal layers**

Thick **BCB layer**  
(Benzocyclobutene, low  $\epsilon$   
dielectric, polymer)  
10  $\mu\text{m}$  thick copper-layer

Post-CMOS, low-  
temperature processing

The thick copper layer is  
beneficial due to the large  
surface of the copper  
inductor relative to skin  
depth



**$Q_{\text{max}} = 40$**

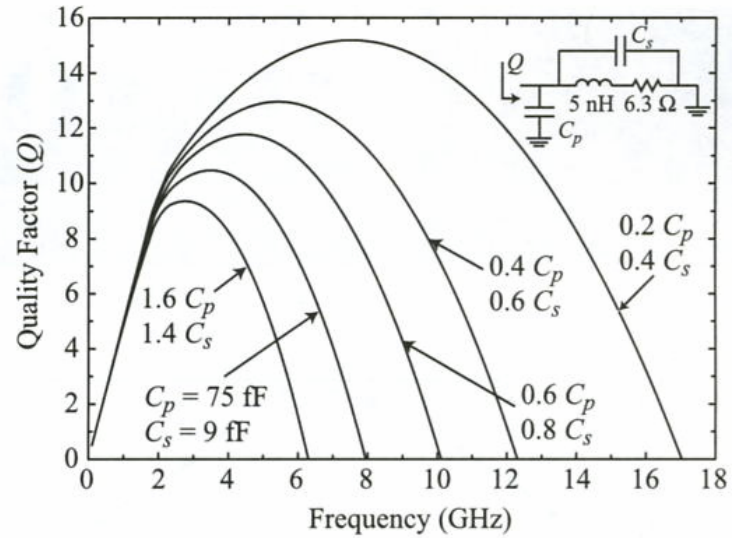
**Figure 12.7.** The electroplated copper MEMSCAP inductor (a), cross-sectional view (b), and the measured  $Q$  of a 1.5-nH inductor [12] (Copyright IEEE).

# Substrate etching

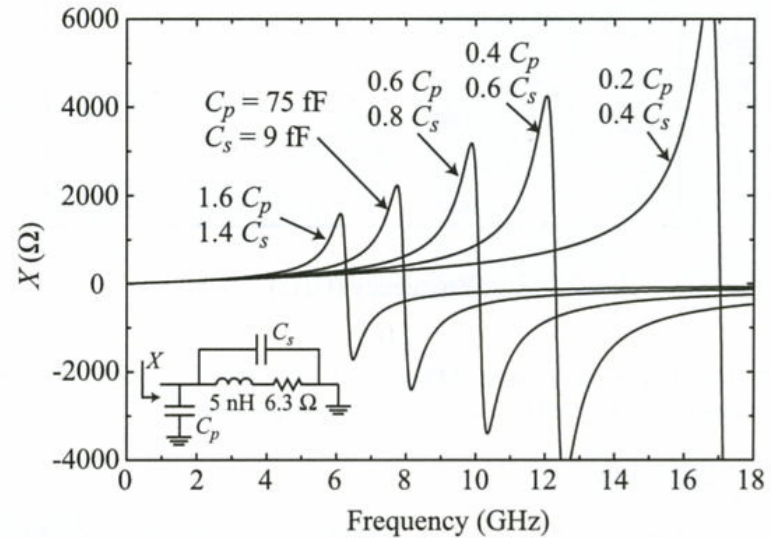
- Parasitic capacitance between inductor and ground plane is a problem
  - Depends on type and thickness of dielectric
  - Depends on type and thickness of substrate
- Solution: **etching of substrate**
  - Reduction of parasitic capacitance
  - Q increases
  - Resonance frequency is shifted to higher frequency
    - Increases the useful bandwidth of the inductor
  - High L can be implemented without having too low  $f_{\max}$

**Substrate capacitance** effect on  $Q$  and reactance  $X$

At 1 – 4 GHz series resonance limits



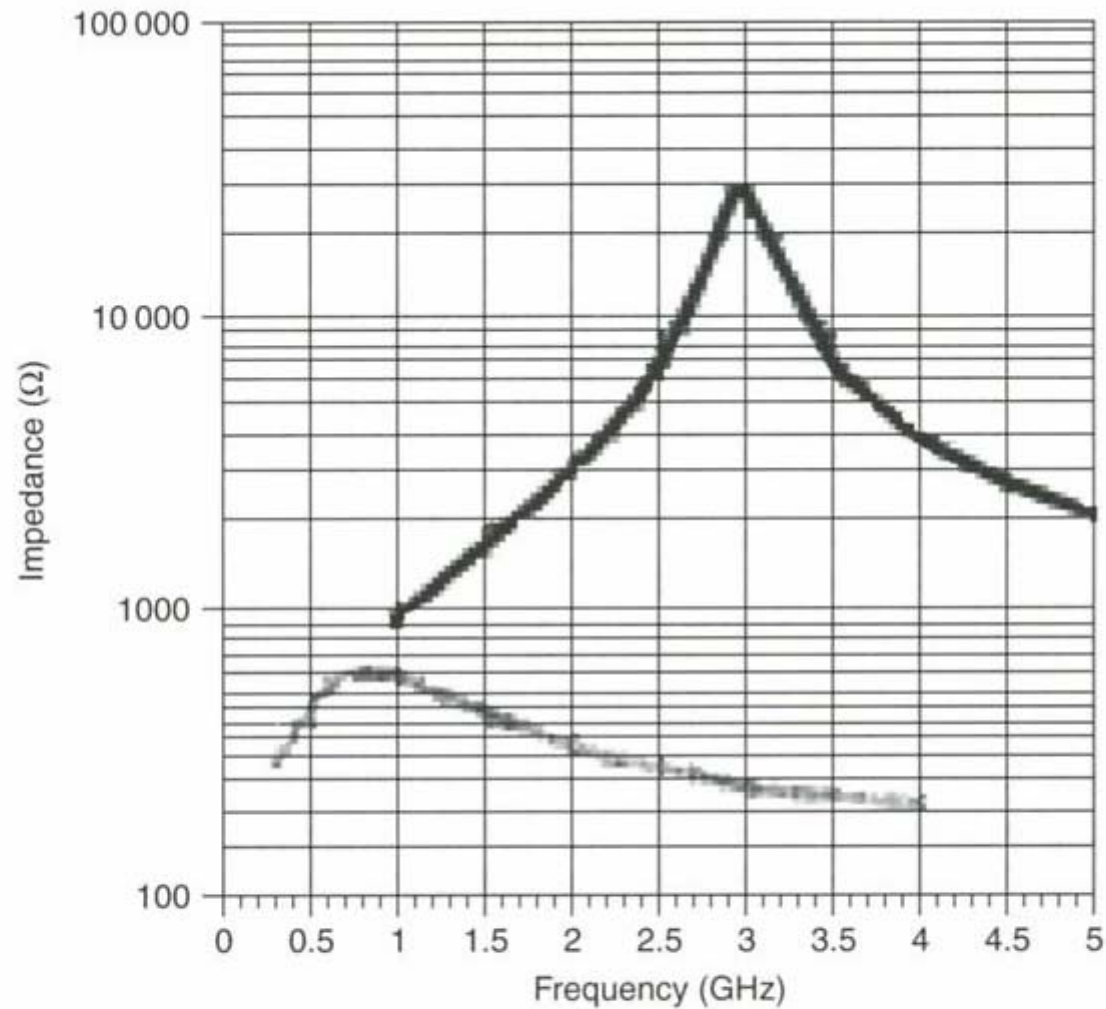
(a)



(b)

Figure shows that higher  $Q$  also gives a higher self resonance frequency

**Figure 12.6.** The effect of the substrate capacitance on the  $Q$  (a) and  $X$  (b) of a 5-nH inductor. The resistance is assumed constant up to 2 GHz and then increases as  $\sqrt{f}$ .



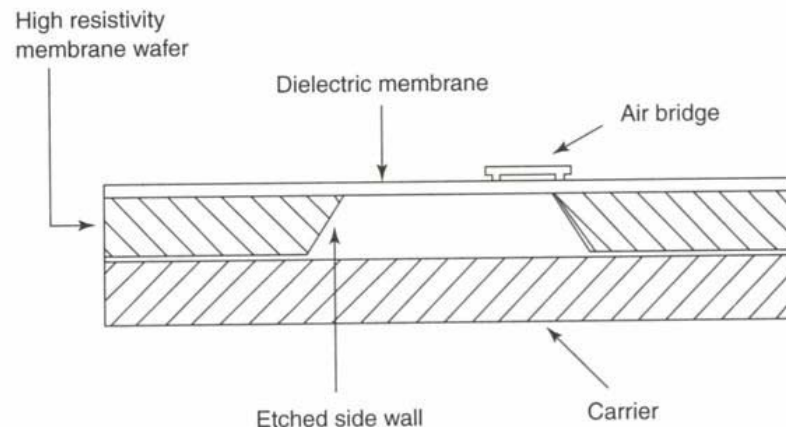
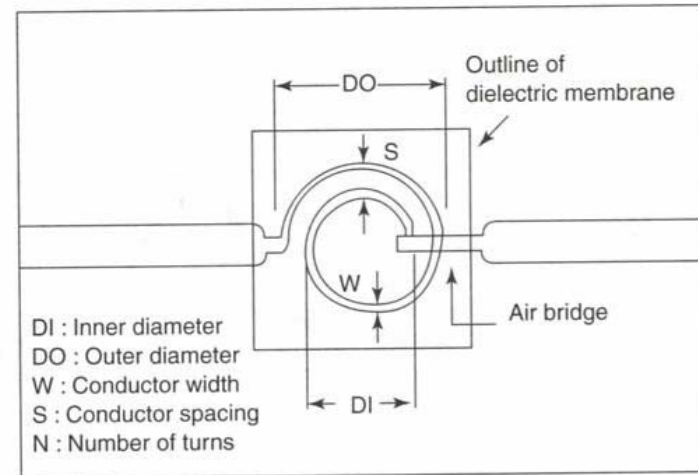
**With and without substrate**

**Figure 4.13** Simulated change in resonant frequency of 100 nH inductor with (gray) and without (black) underlying substrate. Reproduced from J.Y.-C. Chang, A.A. Abidi and M. Gaitan, 1993, 'Large suspended inductors on silicon and their use in a 2 mm CMOS RF amplifier', *IEEE Electron Device Letters* **14**(5): 246–248, by permission of IEEE, © 1993 IEEE



# Test system

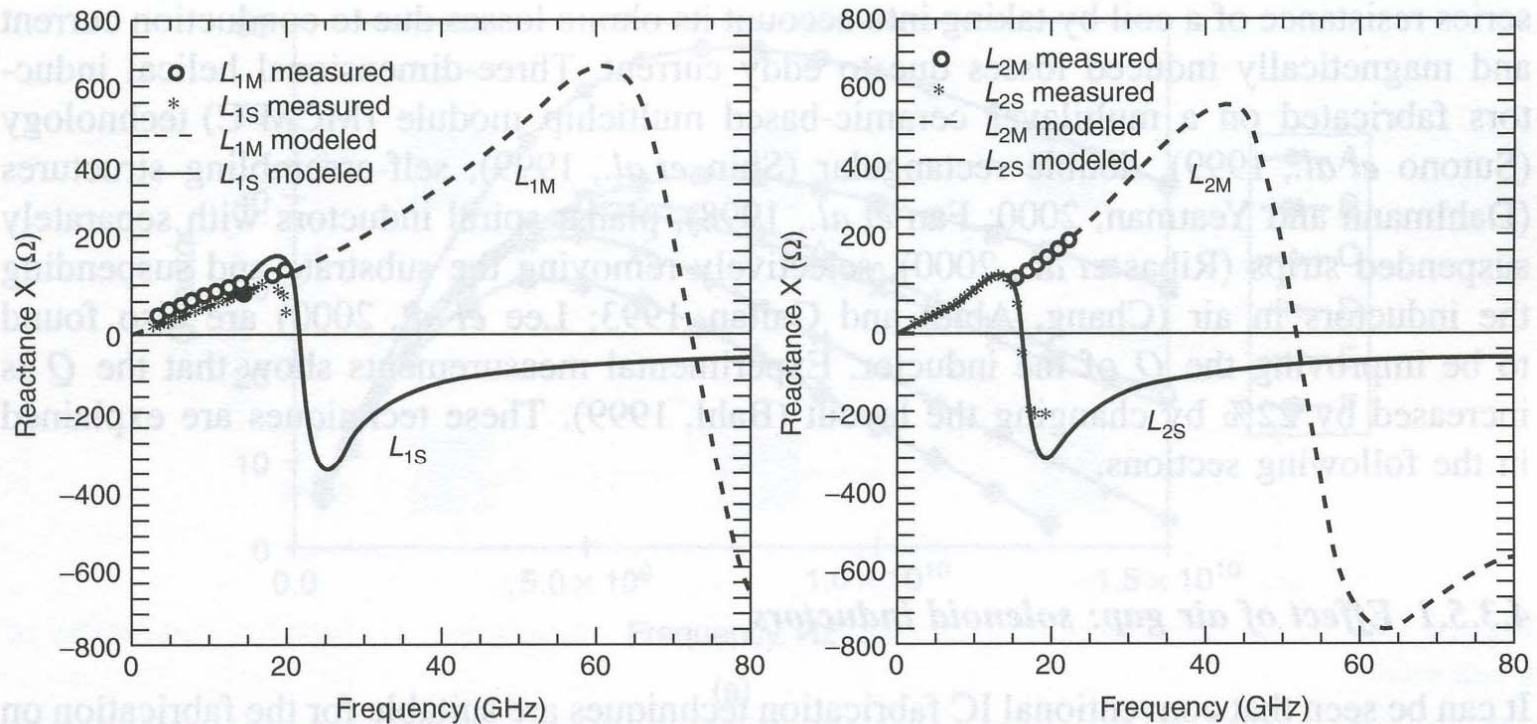
- Example system for testing the effect of having a solenoid on a **membrane** or on **Si**



**Figure 4.14** Schematic diagrams of the planar inductor and the membrane outline. Reproduced from C.-Y. Chi and G.M. Rebeiz, 1995, 'Planar microwave and millimeter wave lumped elements and coupled line filters using micromachining technique', *IEEE Transactions on Microwave Theory and Techniques* **43**(4): 730–738, by permission of IEEE, © 1995 IEEE



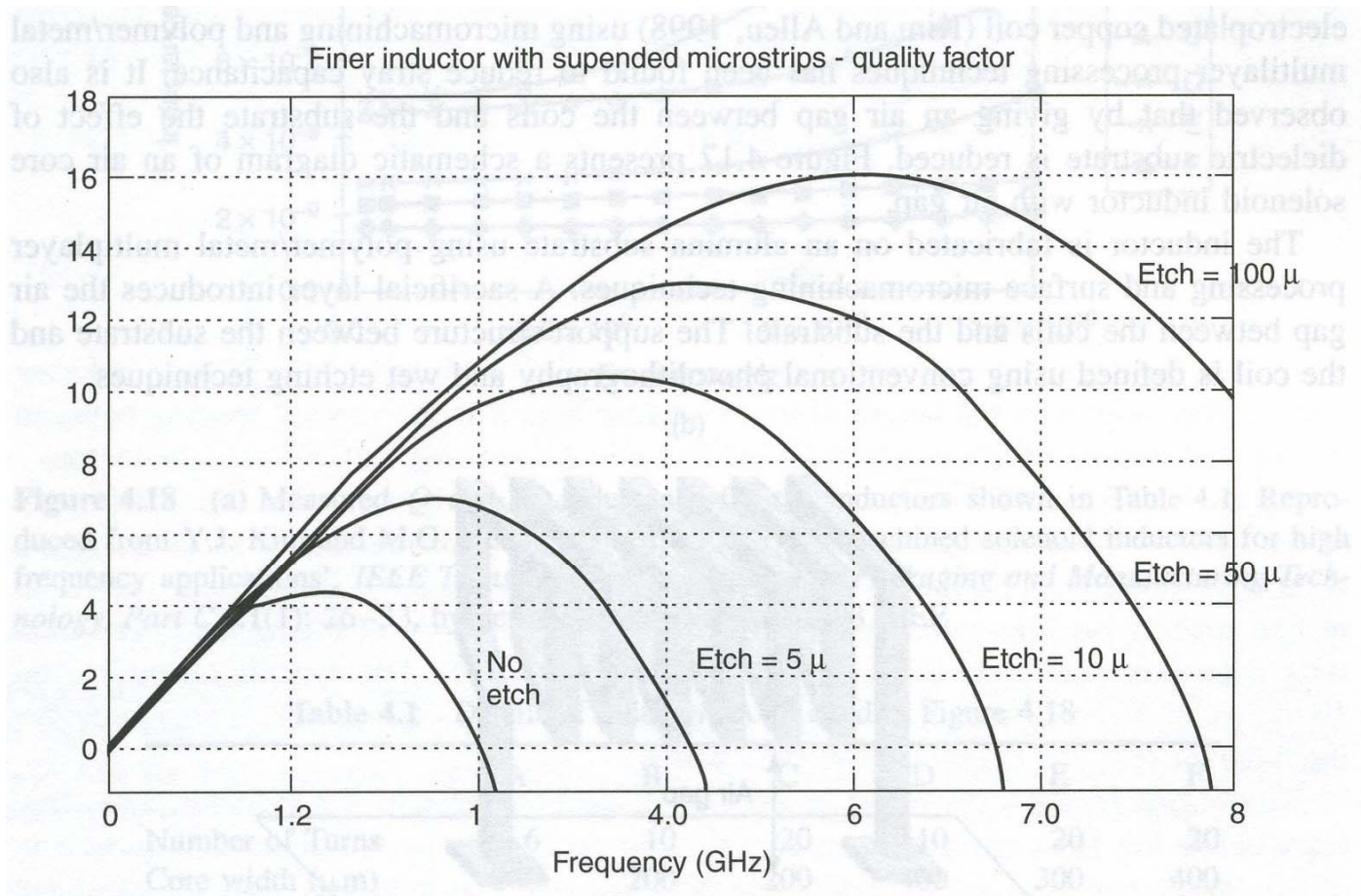
## Achieved L on Si and membrane



**Figure 4.15** Measured and modeled reactance for inductors on silicon ( $L_{1S}$ ,  $L_{2S}$ ) and on membrane ( $L_{1M}$ ,  $L_{2M}$ ). Reproduced from R. Rodrigues, J.M. Dishman, F.D. Dickens and E.W. Whelan, 1980, 'Modeling of two-dimensional spiral inductors', *IEEE Transactions Components, Hybrids, Manufacturing Technology* **5**: 535–541, by permission of IEEE, © 1980 IEEE

**M = membrane, S = Si**

# Ex.: Q for different etch depths



**Figure 4.16** The change in  $Q$  for a suspended planar inductor for different etch depth. Reproduced from R.P. Ribas, N. Bennouri, J.M. Karam and B. Courtois, 1997, 'GaAs MEMS design using  $0.2\mu\text{m}$  HEMT MMIC technology', in *Proceedings of the 19th Annual IEEE Gallium Arsenide Integrated Circuit Symposium*, IEEE, Piscataway, NJ, USA: 127–130, by permission of IEEE, © 1997 IEEE

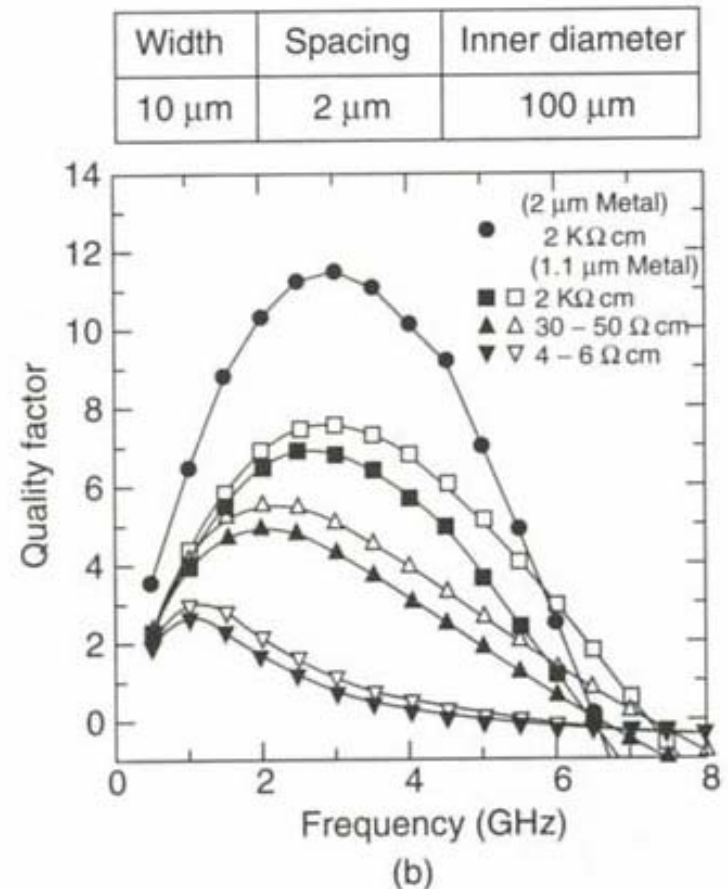
# Different substrate materials

- Substrate etching has no effect on Q for low frequencies
  - $R_s$  is the limitation
  - $R_s$  is prop with  $\sqrt{f}$
- Look at the effect of **different substrate materials**  
→
  - Different resistivity

## Q-factor for substrates with different resistivities

”Eddy current”-effects present at high frequency

High resistivity substrate increases performance

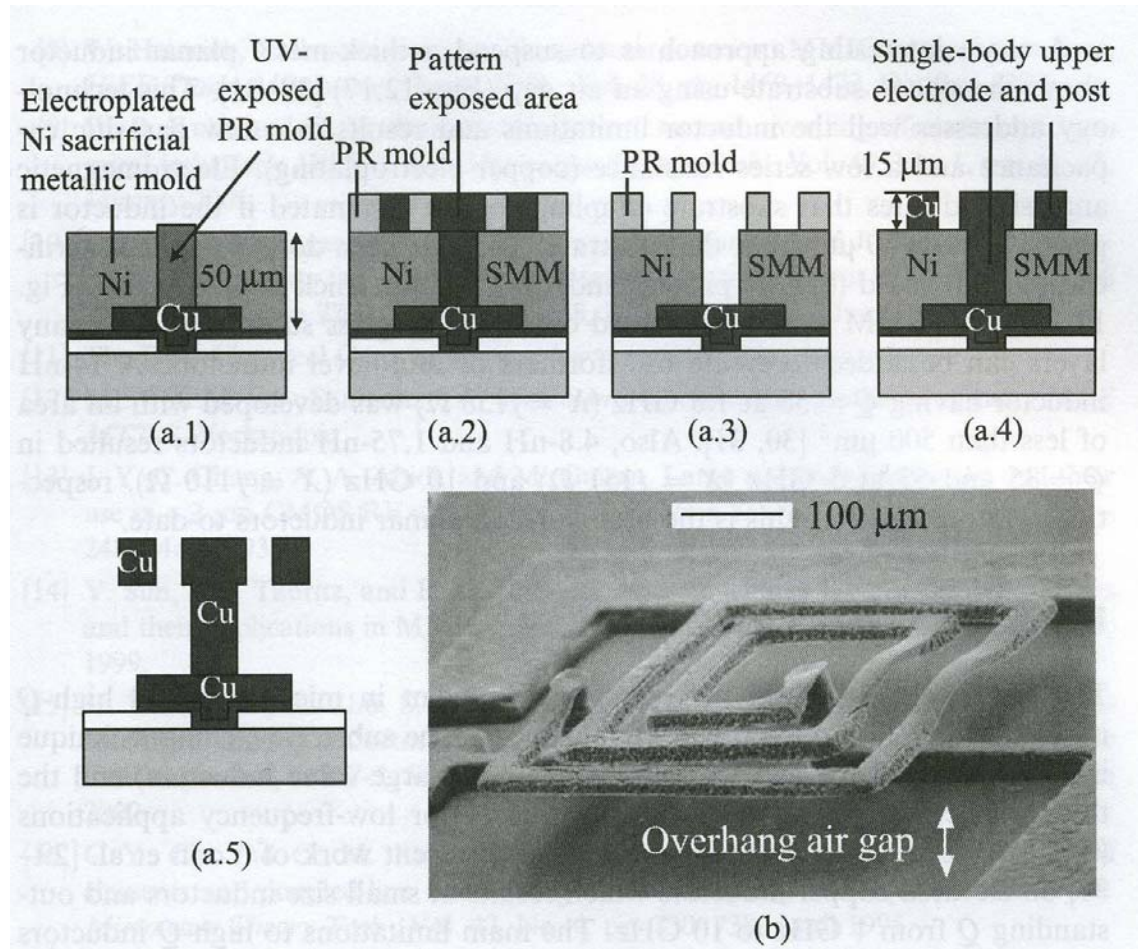


**Figure 4.29** Change in  $Q$  of an inductor for (a) different metal thickness; (b) for substrates with different resistivity. Reproduced from M. Park, C.S. Kin, J.M. Park, H.K. Yu and K.S. Nam, 1997b, 'High  $Q$  microwave inductors in CMOS double metal technology and its substrate bias effects for 2 GHz RF IC application', in *Proceedings of IEDM 97*, IEEE, Washington, DC: 59–62, by permission of IEEE, © 1997 IEEE

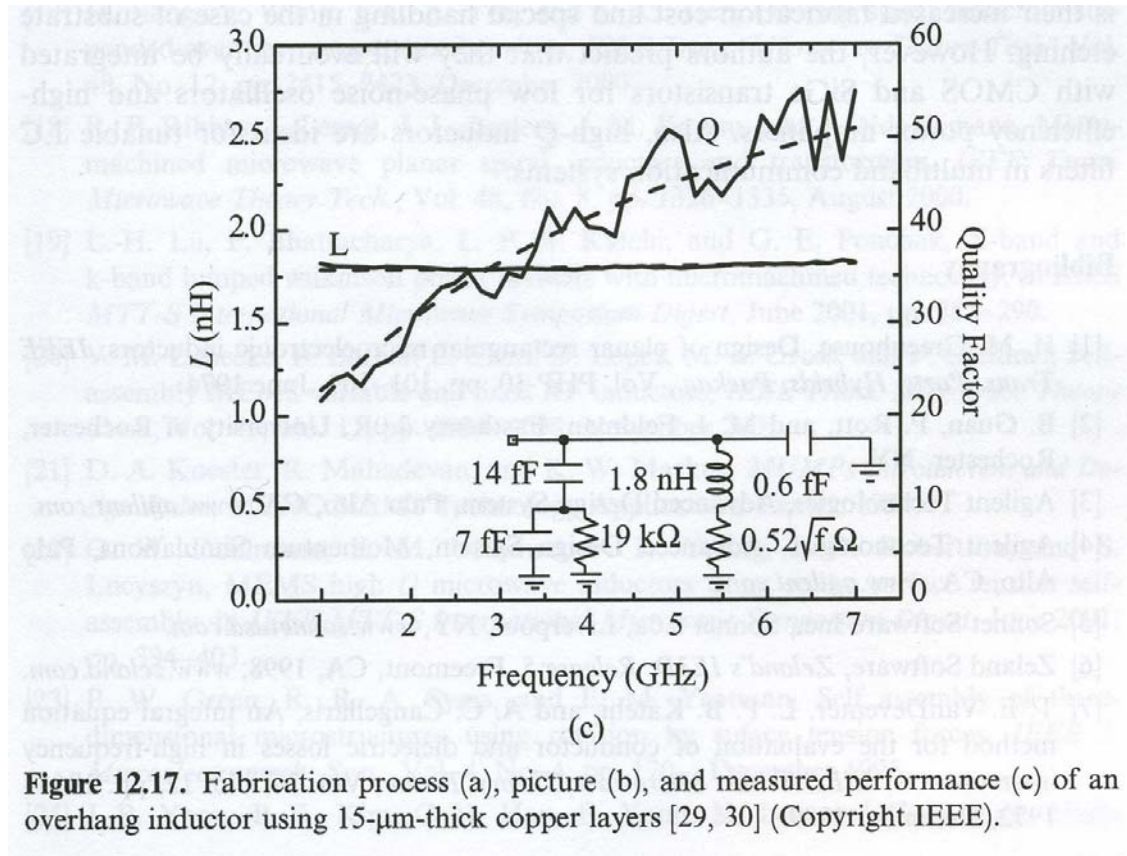


# "Air gap" - inductor

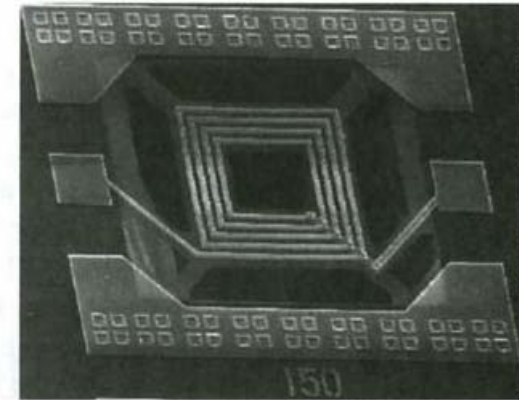
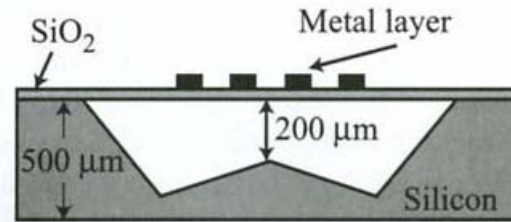
- **Thick metal** planar inductor over substrate with an **air gap** in-between
  - Elimination of substrate coupling: 30  $\mu\text{m}$  elevation
  - "Sacrificial metallic mold" (SMM) process used + 10-15  $\mu\text{m}$  copper layer



# Performance to inductor above air gap

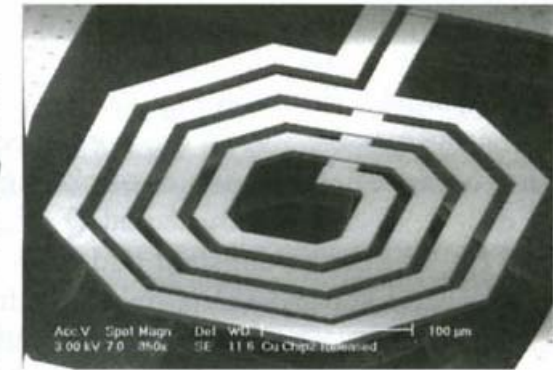
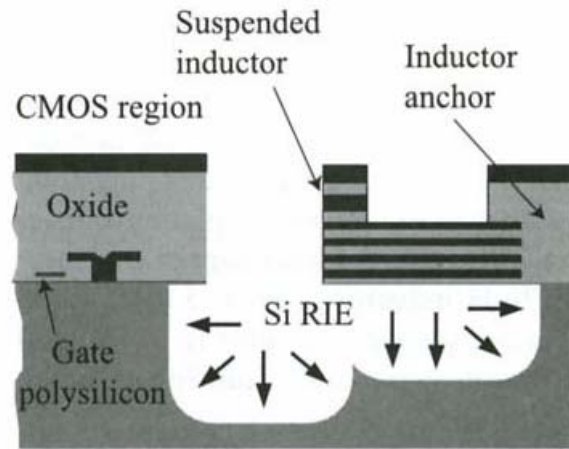


- Ex. from the first known work, fig 12.8 a: anisotropic etching



(a)

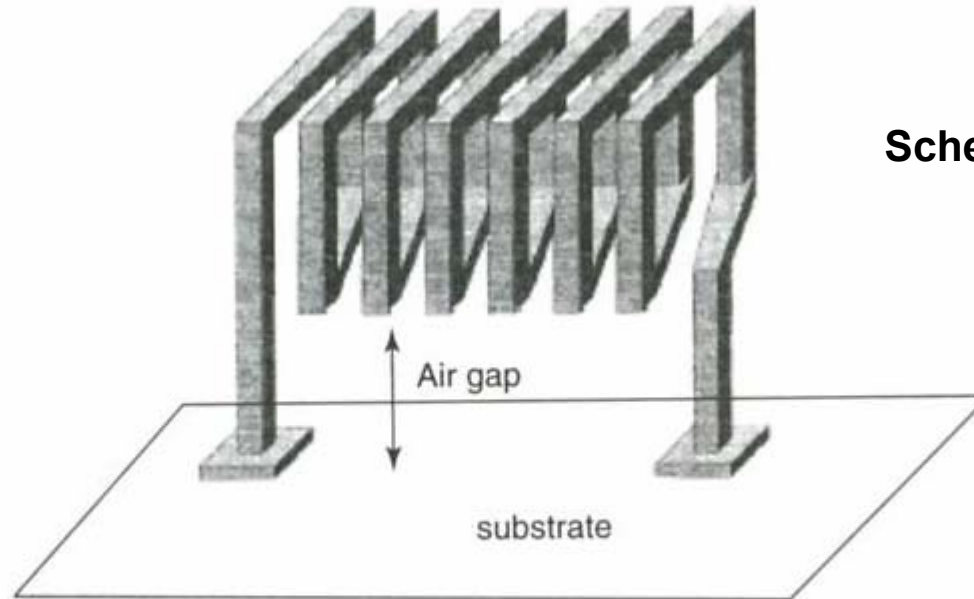
- Fig 12.8 b: suspended inductor
  - One anchor, sensitive to mechanical vibrations
  - $Q = 17$  at 8.6 GHz



(b)

**Figure 12.8.** Suspended inductors using front-etching techniques and compatible with CMOS processing: UCLA and Delft [13, 14] (a), Carnegie Mellon (b), effort [15] (Copyright IEEE).

# Air-gap for solenoids

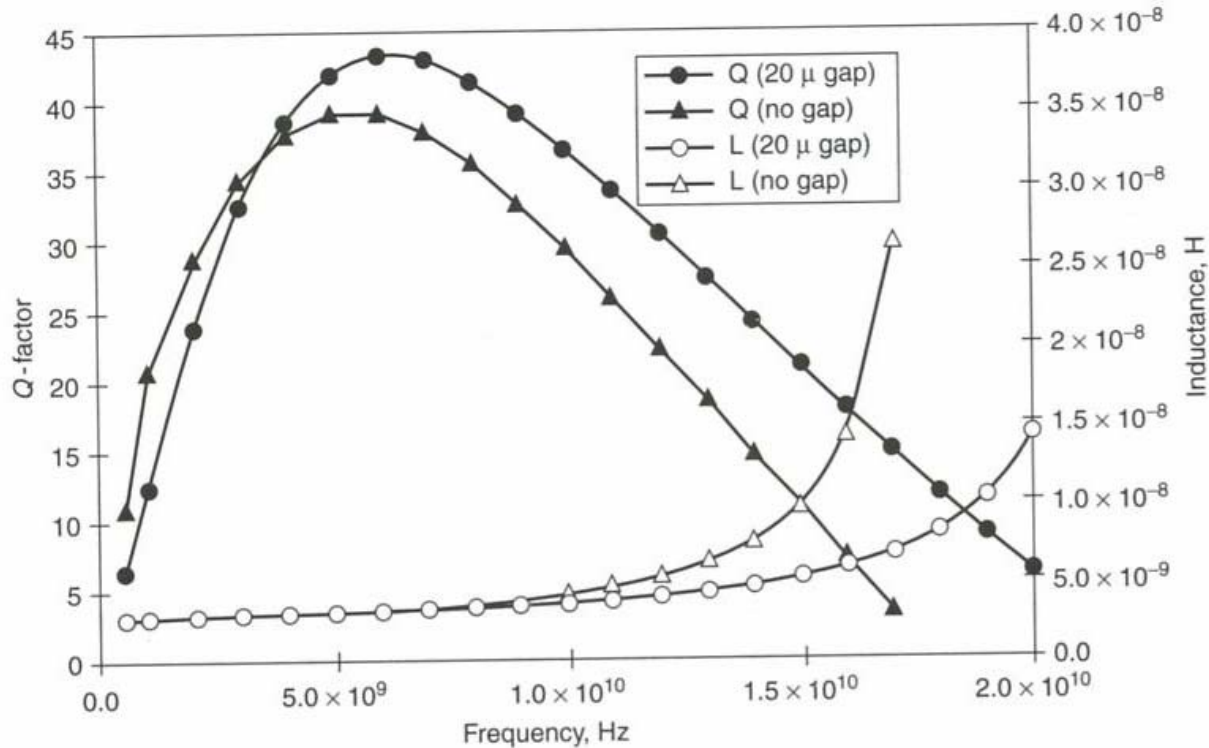


**Schematic figure!**

**Figure 4.17** Schematic diagram of a solenoid inductor with an air gap. Reproduced from Y.J. Kim and M.G. Allen, 1998, 'Surface micromachined solenoid inductors for high frequency applications', *IEEE Transactions on Components, Packaging and Manufacturing Technology, Part C* **21**(1): 26–33, by permission of IEEE, © 1998 IEEE



# Effect of air-gap for spiral inductors



**Figure 4.22** Effect of air gap on  $Q$  factor. Reproduced from Y.J. Kim and M.G. Allen, 1998, 'Surface micromachined solenoid inductors for high frequency applications', *IEEE Transactions on Components, Packaging and Manufacturing Technology, Part C* **21**(1): 26–33, by permission of IEEE, © 1998 IEEE

**L benefits from "no-gap", Q benefits from air-gap**

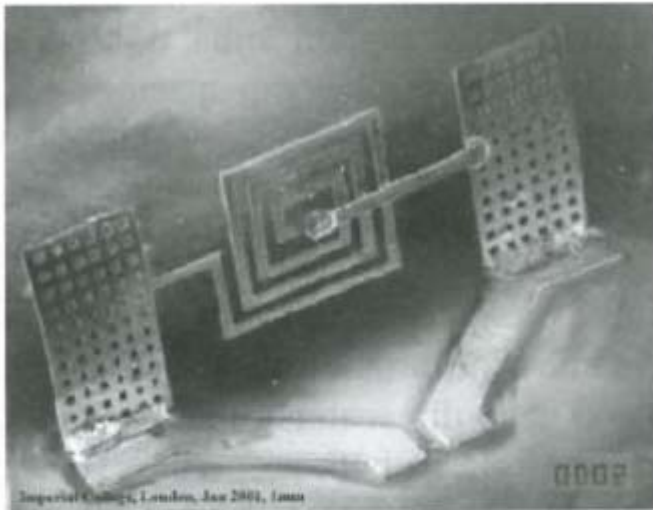
# Summary: How to increase performance?

- Have **thick metal layer** with good conductivity
  - To reduce series resistance
- Use **substrate etching**
  - Reduce substrate parasitic capacitance
- Use **3-D** structures
  - For vertical plane solenoids the L-value may increase
- Use of **core material**

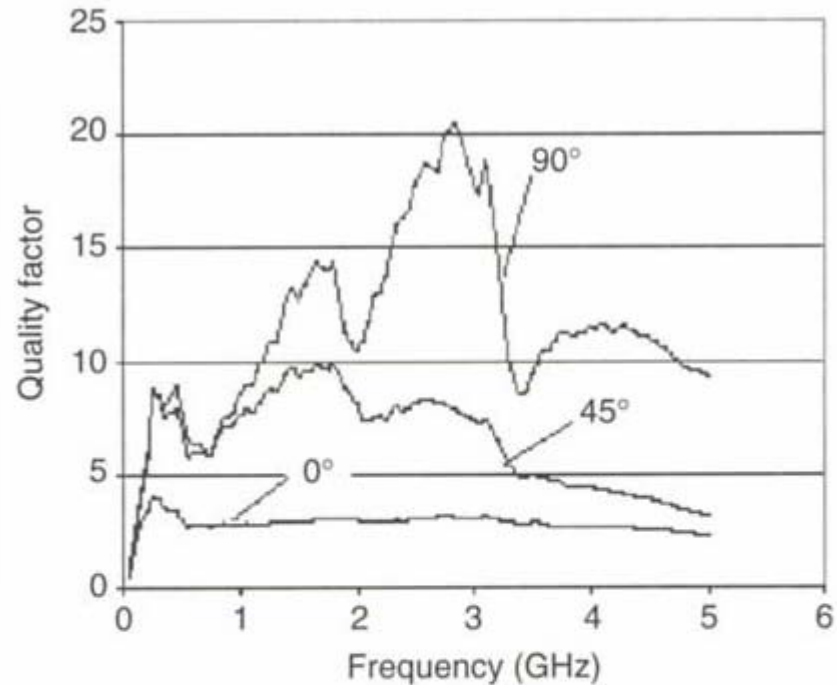
# Basic implementation technologies

- Thick metal **electroplating**
  - 0.2 – 6 GHz
- **Substrate etching**
  - 1 – 100 GHz
- Three-dimensional **solenoid type** inductors
  - High L and Q-values
  - 0.2 – 6 GHz
- **“Self-assembly” (elevation)** of inductor →
  - Elevate inductor **above substrate** to reduce parasitic capacitance to substrate, 1 – 100 GHz

# Folded and elevated inductors



(a)



(b)

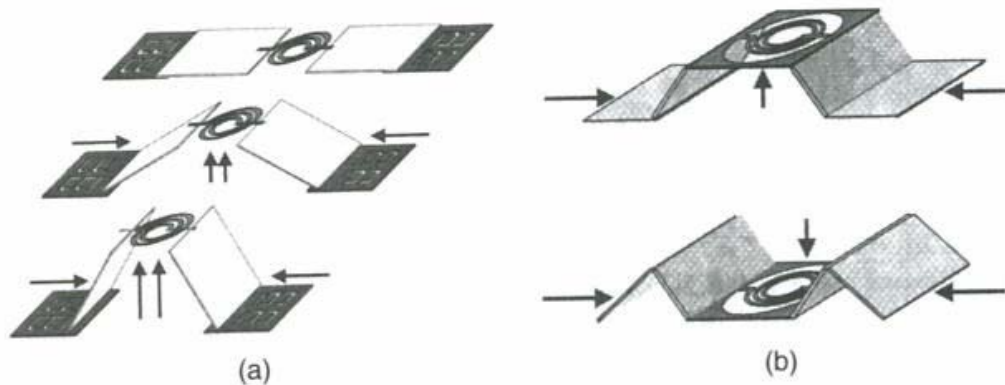
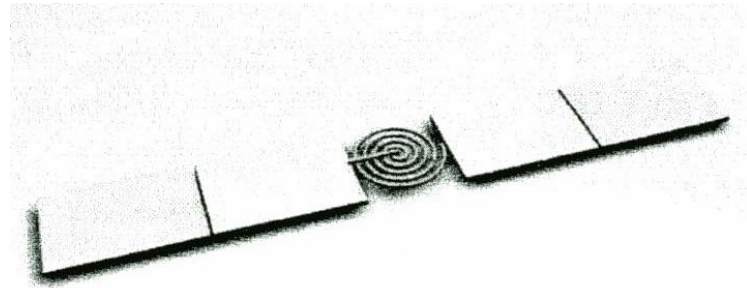
## Solder surface tension

**Figure 4.30** (a) Three-turn spiral folded inductor after self-assembly; and (b) change in  $Q$  against frequency for different angles between coil and substrate. All devices are  $4\frac{1}{2}$ -turn meander inductors ( $L = 2$  nH). Reproduced from G.W. Dahlmann and E.M. Yeatman, 2000, 'High  $Q$  microwave inductors on silicon by surface tension self-assembly', *Electronics Letters* **36**(20): 1707–1708, by permission of IEEE, © IEEE 2000

Eric. Yeatman, Imperial College, London

# Out of plane inductors

- Inductor can be elevated by "scratch actuators"
  - L. Fan et al, MEMS 1998
  - Elevated 250  $\mu\text{m}$  over Si substrate
  - Resonance at 1.8 – 6.6 GHz after elevation of solenoid



**Figure 4.31** (a) Schematic diagram of the MESA micro-elevator by self-assembly structure; (b) the center platform can move upward or downward. Reproduced from L. Fan, R.T. Chen, A. Nepolsa and M.C. Wu, 1998, 'Universal MEMS platforms for passive RF components: suspended inductors and variable capacitors', in *Proceedings of 11th Annual International Workshop on MEMS '98*, IEEE, Washington, DC: 29–33, by permission of IEEE, © 1998 IEEE

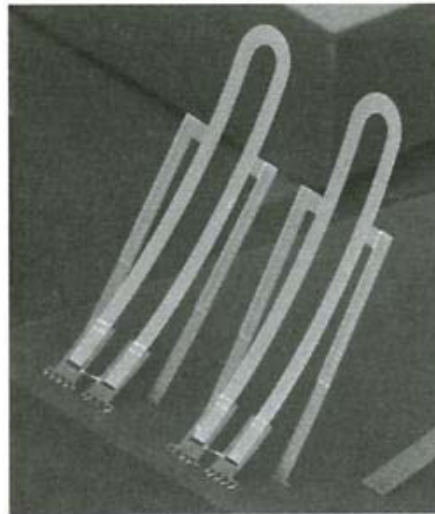
# Micromachining using self-assembly

Elevate inductor above substrate to reduce parasitic capacitance

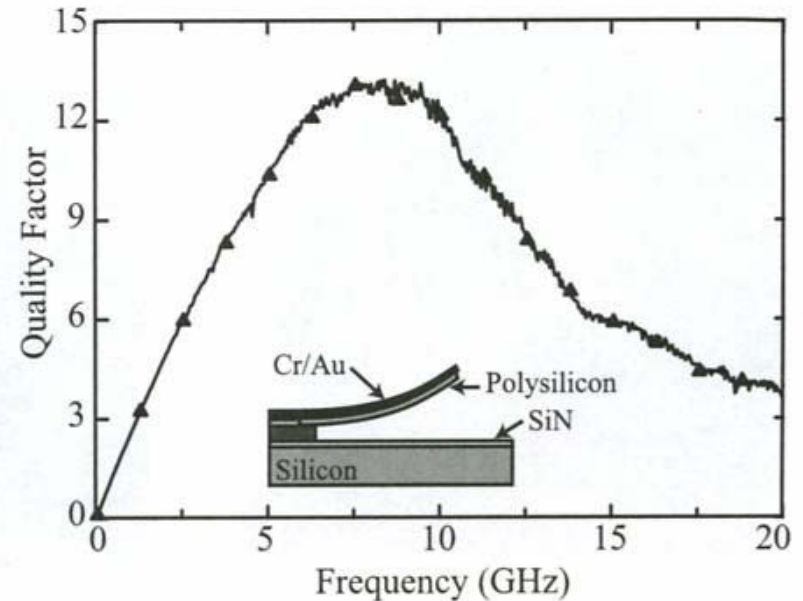
Cr-Au layer over poly-layer

Different residual **stress** in materials make the inductor **"curl"** above substrate

Anchor causes a significant parasitic capacitance



(a)



(b)

**Figure 12.12.** Picture (a) and measured  $Q$  (b) of a self-assembled 1.2-nH inductor [20] (Copyright IEEE).

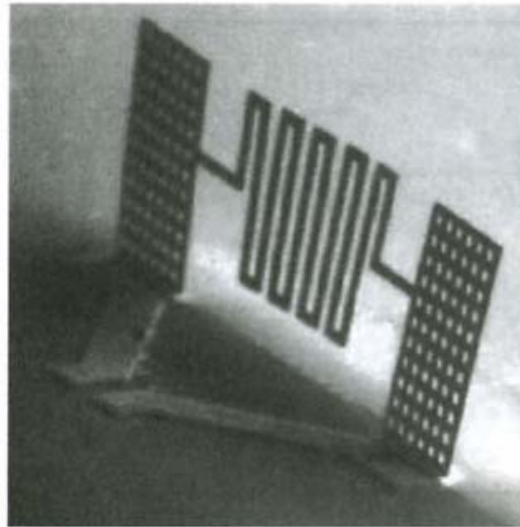
# Solder surface tension used

Photo resist as sacrificial layer

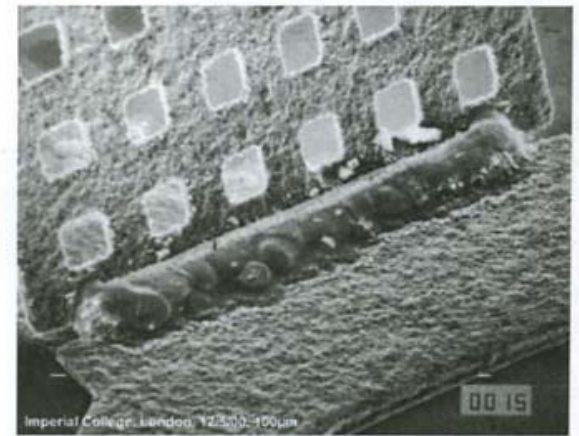
Copper structure with solder pads between anchor and a free movable structure

Heating to  $185\text{ }^{\circ}\text{C}$   $\rightarrow$  solder pads melt and pull, due to **surface tension force**, the structure to a vertical position

Cooling  $\rightarrow$  solder hardens



(a)



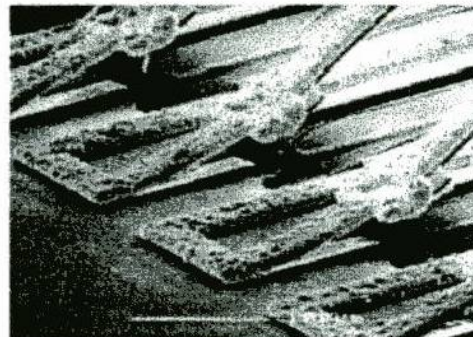
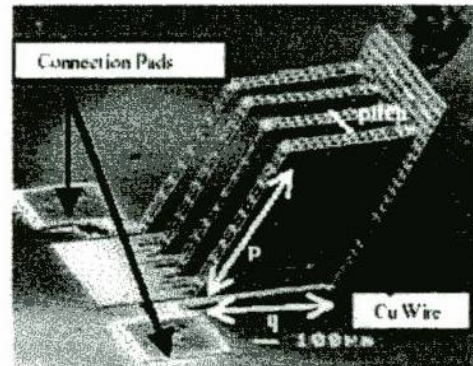
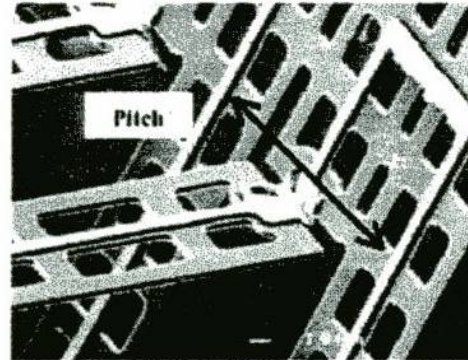
(b)

**Figure 12.13.** (a) Out-of-plane meander-type inductors after self-assembly, and (b) a blow-up of the solder hinges after heating [22, 23] (Copyright IEEE).



# Structure with suspension hinges

- Copper structure can **manually** be folded and glued
- Typical "turns" with large dimensions  $\sim 100 \mu\text{m}$
- M. Gel et al, Transducers 2001





# Today's lecture

- What is an inductor?
- MEMS -implemented inductors
- Modeling
- Different types of RF MEMS inductors
  - **Horizontal plane** inductors
  - Real **solenoids**
- How to increase performance
  - Q-value, Inductance (L), Self resonance frequency ( $f_{\max}$ )
- Elevated inductors
- **Inductor banks**

# Programmable inductor banks

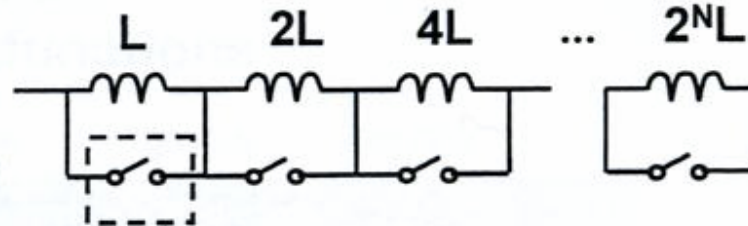
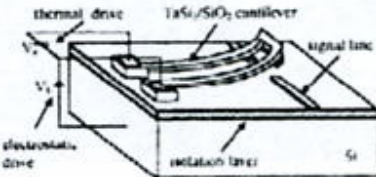
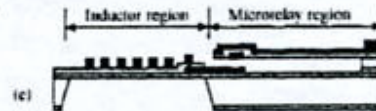
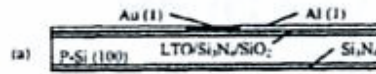


## Micromachined digitized high-Q inductor banks

### Design and process

(New jersey Institute of Technology)

- micro-relays made on  $TaSi_2/SiO_2$  bimorph cantilever beam, gold-to-gold electrical contact, Al as sacrificial layer and thermal actuation
- gold inductors and pads



Contact switch (micro-relay)

Thermal actuation!

### Performance:

- $L = 2.5$  up to  $162.4$  nH
- $Q=3.3$  @  $1.6$ GHz
- electro-thermal relays with  $R_{on}=0.6-0.8\Omega$
- thermal power= $8$ mW,  $V=20$ V
- contacts fails after  $10^6$  cycles (!!)

$D_1 D_2 D_3 D_4$	L (nH)	$D_1 D_2 D_3 D_4$	L (nH)
0000	324.8	1000	162.4
0001	277.9	1001	105.7
0010	223.2	1010	67.4
0011	185.0	1011	45.9
0100	166.9	1100	60.5
0101	127.3	1101	31.5
0110	103.8	1110	16.2
0111	83.1	1111	2.5

S. Zhou, X.-Q. Sun, W.N. Carr, TRANSDUCERS '97, Vol. 2, June 1997, pp. 1137-1140.

# How different design parameters influence performance

- $Q_{\max}$  and  $f_{\text{rez}}$  decrease when area and number of turns increase

## Integrated inductor performance versus design space

After Varadan et al. [3]

		$Q_{\max}$	L	$f_{\text{rez}}$
<b>Conductor thickness</b>	↗	↗	-	-
<b>Sheet resistance</b>	↗	↘	-	-
<b>Insulator thickness</b>	↗	↗	-	↗
<b>Substrate resistivity</b>	↗	↘ ↗	-	↗
<b>Area</b>	↗	↘	↗	↘
<b>Number of turns</b>	↗	↘	↗	↘
<b>Track width</b>	↗	↗	↘	↘
<b>Multilayer inductor (extra layer)</b>	↗	↘	↗	↘

(Double arrow: less influence)