

# INF5490 RF MEMS

## **LN15: Summary, repetition**

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# Overview

- Motivation
- Micromachining
- Modeling
- Specific features for RF systems
- Q-factor
- RF MEMS components
  - Switches
  - Phase shifters
  - Resonators
  - Micromechanical filters
  - Capacitors
  - Inductors
- Integration and packaging
- RF MEMS in wireless systems
- Conclusion and future prospects

# Choice of focus → RF MEMS

- MEMS is a broad field of research
  - Need of focus in NANO group → RF MEMS!
- ***”RF MEMS refers to the design and fabrication of dedicated MEMS for RF (integrated) circuits”***
  - 1a) Components **operate** micromechanical  
and/or
  - 1b) Components **fabricated** using micromachining
  - 2) Components are used in **RF systems**

# Typical RF MEMS components

- Switches
- Variable capacitors
- Inductors
- Resonators
- Micromechanical filters
- Phase shifters

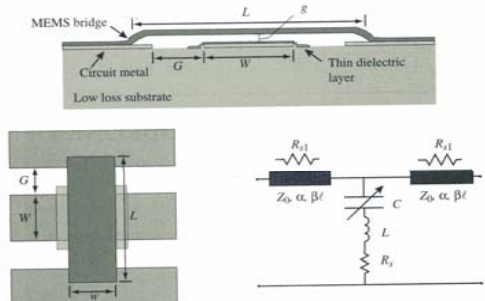
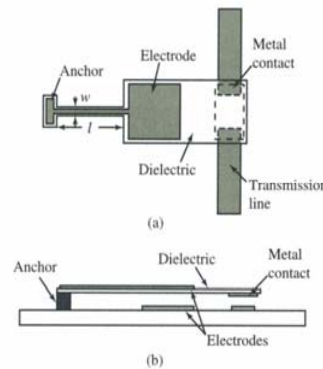
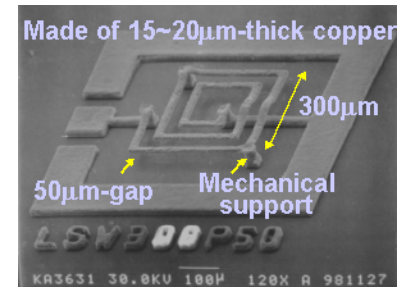
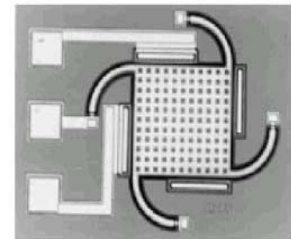
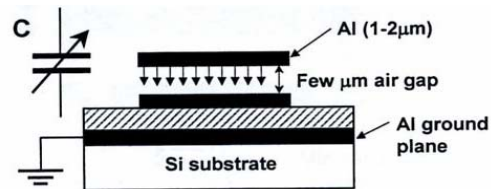


Figure 4.1. Illustration of a typical MEMS shunt switch shown in cross section and plan view. The equivalent circuit is also shown [6] (Copyright IEEE).



# Benefits of RF MEMS

- Higher **performance**
  - Increased selectivity: sharp filters
  - Increased Q-factor: stable "tank" frequency
  - Reduced loss
  - Higher isolation, reduced cross talk
  - Reduced signal distortion
  - Larger bandwidth
- Lower **power consumption**
- **Reduced cost**
  - Batch processing
- Circuit and system **miniaturization**
  - System integration ( $\mu$ electronics + MEMS)
    - Packaging: Multi-chip module
    - Monolithic integration: SoC (System-on-Chip)

# Micromachining

- Micromachining, definition:
  - *Accurately, to **define and implement** any microscopic mechanical structure **out of or on** a material*
- **Silicon micromachining is mature**
  - Si processes also used by IC industry
    - "grown out of" IC-processing
  - New specific MEMS processes also developed
    - A lot of variants, - **few standards!**

# Important process steps

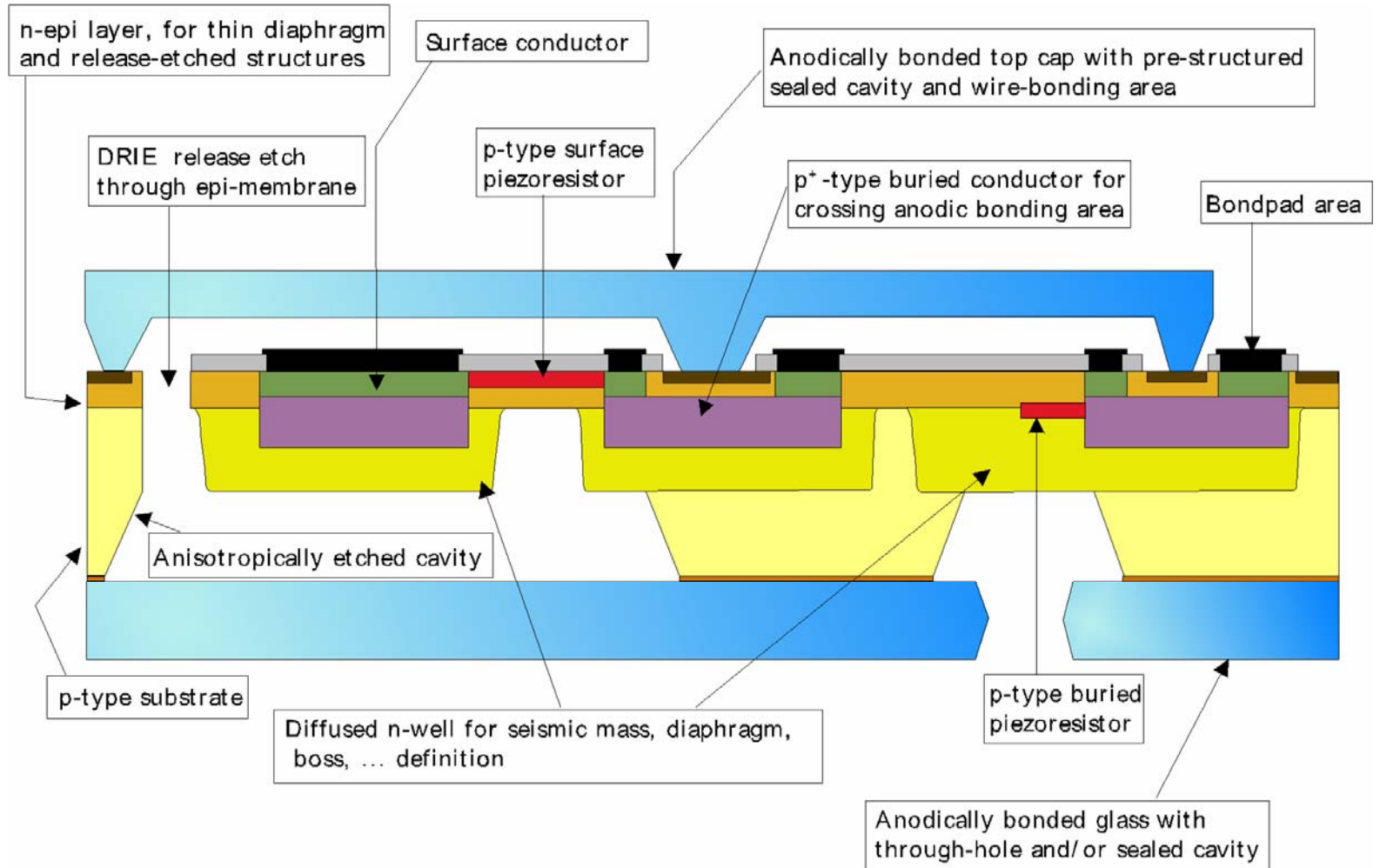
- Define patterns
  - *Photolithography*
- Modify semiconductor material properties
  - *Diffusion*
- Remove material
  - *Ething*
- Adding material – build structures
  - *Deposition*

# Bulk micromachining

- Selective etching and diffusion into well defined areas **of a substrate**
  - Etching of the substrate → membranes
  - Etching from back side (wet etching: liquid is used)
  - Possibly combined with dry etching on the front side
- More mature than surface micromachining
- Typical examples
  - Pressure sensor, accelerometer
- "Wafer-bonding" may be necessary
  - Interconnect whole wafers



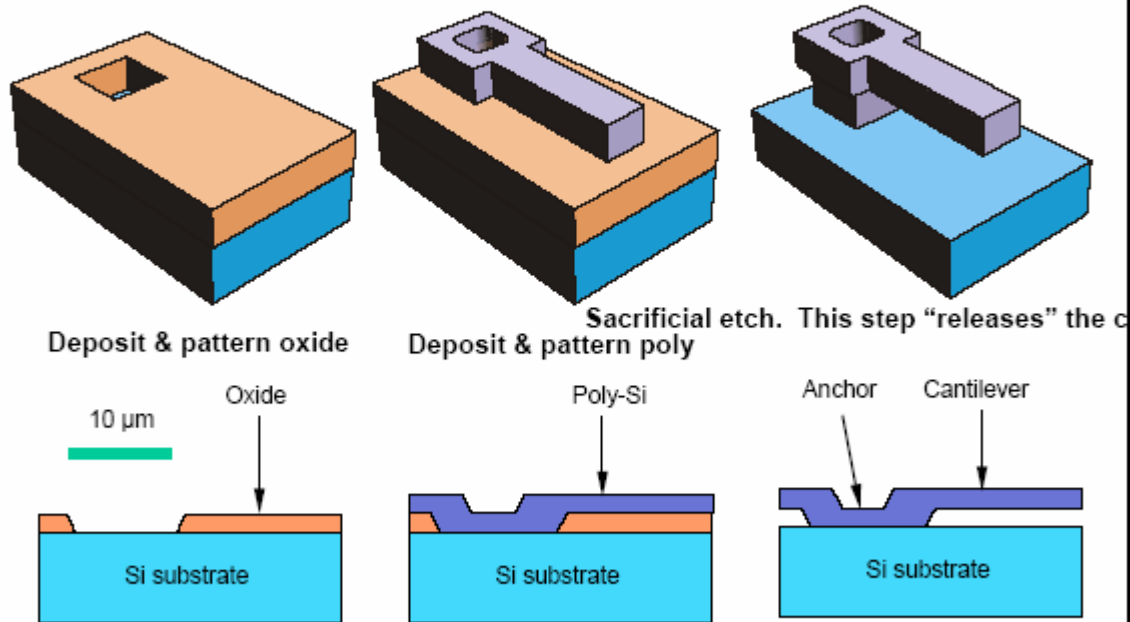
# Cross section overview



# Surface micromachining

- **"Surface"** micromachining
  - Deposit layers
    - **Structural layer**
    - **Sacrificial layer** = "distance-keeping" layer
  - Selective etching of structural layers
  - Removing sacrificial layers

## Micromachining a Cantilever

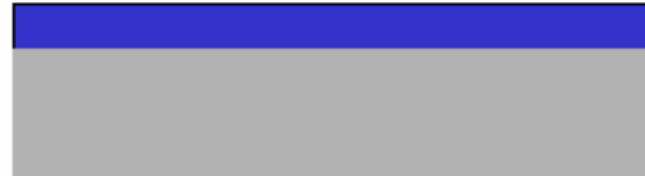


# Additive process steps

- Techniques
  - a. Epitaxial growth
  - b. Oxidation
  - c. Vaporization
  - d. CVD, Chemical Vapor Deposition
  - e. Sputtering
  - f. Moulding
- When depositing, stress may be built into the structures

# Residual Stress in Thin Films

- Residual film stress
  - Microstructure
  - Thermal mismatch



- Compressive vs. tensile stress



Under **compressive stress**,  
film wants to expand.  
Constrained to substrate,  
bends it in convex way.



Under **tensile stress**, film  
wants to shrink  
Constrained to substrate,  
bends it in concave way.

# Removing material: Etching

- **Wet-etching** or **dry-etching**
- **Wet-etching**
  - **Deep etching** of Si is essential in micromachining
  - Using liquids
  - Depends of:
    - Concentration of liquid, time, temperature
  - Low cost batch processing
  - Both **isotropic** or **anisotropic**

# Wet-etching

- **Isotropic** = uniform etching in all directions
  - HF or blends are usual
  - 0.1 – 100  $\mu\text{m}/\text{min}$  etch speed
- **Anisotropic** = etching faster along some directions
  - Etch speed depends of **crystal orientation**
  - NaOH, KOH used
  - Silicon nitride used as mask for **KOH**

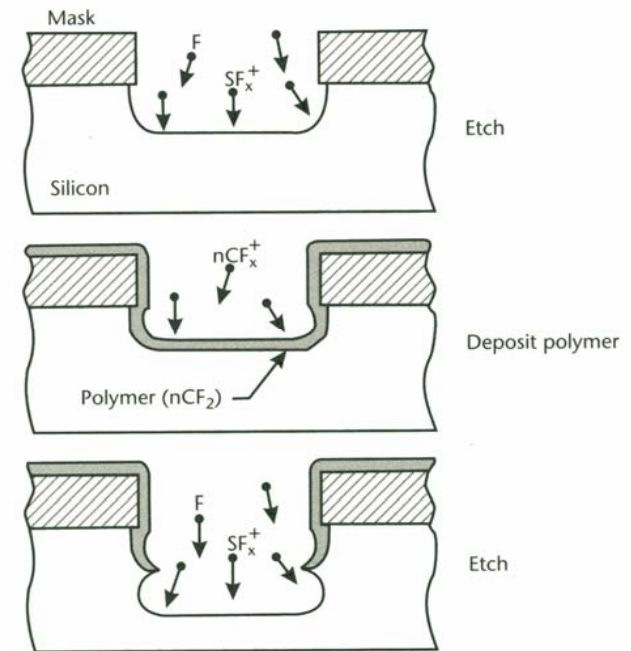
# RIE - DRIE

- **DRIE** – Deep Reactive Ion Etching (1995-)

- Vertical etching
- Can etch deep holes ( $> 500 \mu\text{m}$ ) with almost perfect vertical sidewalls

- **Bosch-process**

- Figure  $\rightarrow$
- High "aspect-ratio"
- Etching and deposition every second step
  - **etch**:  $\text{SF}_6$ , mostly at the bottom!
  - **deposit**:  $\text{C}_4\text{F}_8$ , polymer





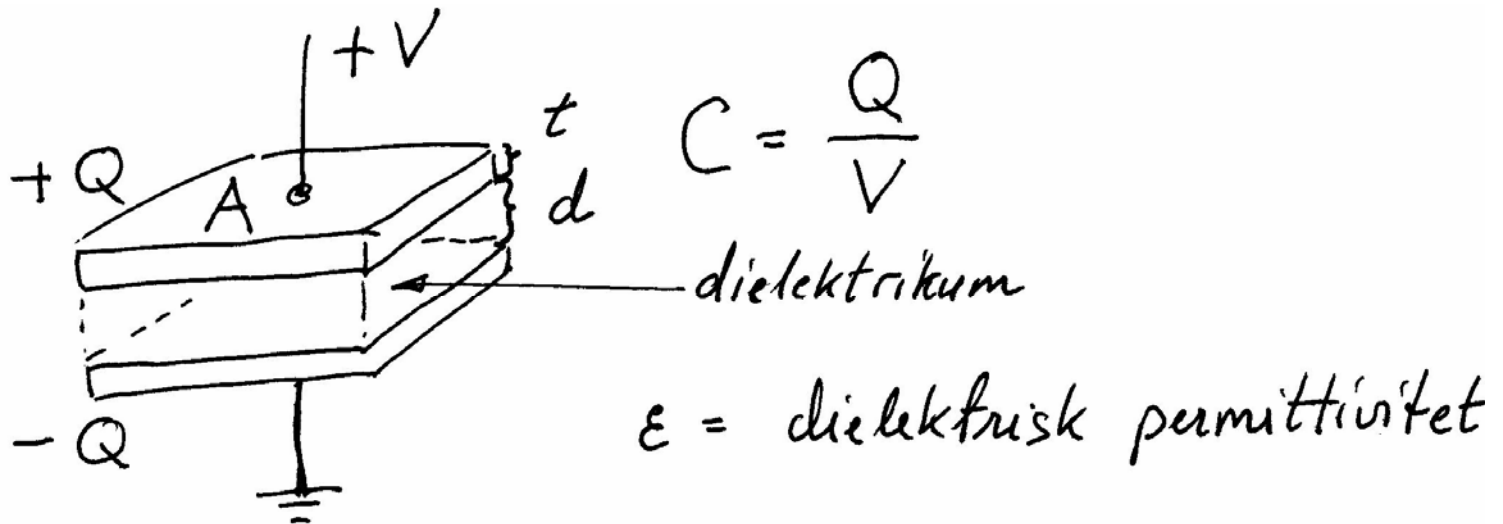
# Transducers for (RF) MEMS

- **Electromechanical transducers**
  - Transforming  
**electrical energy  $\leftrightarrow$  mechanical energy**
- Transducer principles
  - Electrostatic
  - Electromagnetic
  - Electro thermal
  - Piezoelectric

# Methods for modeling RF MEMS

- **1. Simple mathematical models**
  - Ex. parallel plate capacitor
- **2. Converting to electrical equivalents**
- **3. Analysis using Finite Element Methods**

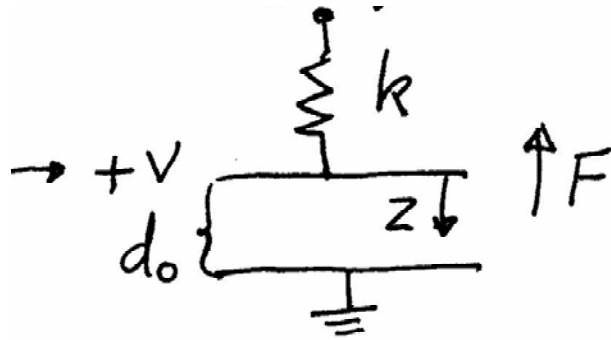
# Parallel plate capacitor



Attractive force between plates

$$F = -\frac{\partial U}{\partial d} = -\frac{\partial}{\partial d} \left( \frac{\epsilon A}{2d} V^2 \right) = \frac{\epsilon A V^2}{2d^2}$$

# Force balance



k = spring constant

$$F_{\text{spring}} = k \cdot x$$

deflection from start position

$d_0$  = gap at 0V and zero spring strain

$$d = d_0 - z$$

$$z = d_0 - d$$

Force on upper plate at V and d:

$$F_{\text{net}} = - \frac{\epsilon A V^2}{2 d^2} + k (d_0 - d) = 0 \text{ at equilibrium}$$

# Two equilibrium positions

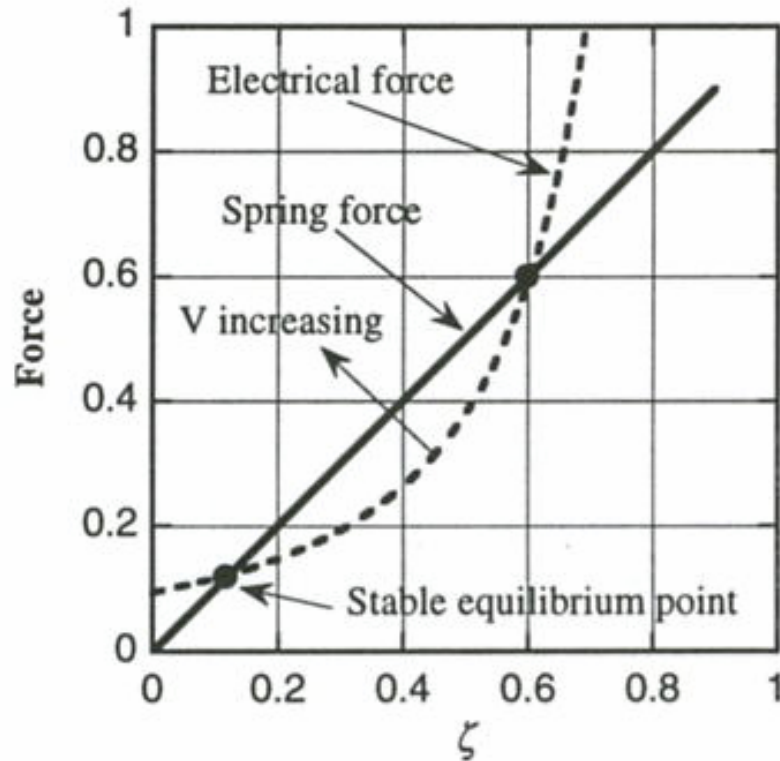


Figure 6.7. Electrical and spring forces for the voltage-controlled parallel-plate electrostatic actuator, plotted for  $V/V_{PI} = 0.8$ .

$$\zeta = 1 - d/d_0$$

Senturia

# Pull-in

$$F_{net} = 0$$

$$\frac{\epsilon A V_{PI}^2}{2 d_{PI}^2} = k (d_0 - d_{PI})$$

↑  
=  $\frac{\epsilon A V_{PI}^2}{d_{PI}^3}$

Pull-in when:

$$d_{PI} = \frac{2}{3} d_0$$

$$V_{PI} = \sqrt{\frac{8 k d_0^3}{27 \epsilon A}}$$



## 2. Converting to electrical equivalents

- Mechanical behavior can be modeled using **electrical circuit elements**
  - Mechanical structure → simplifications → equivalent electrical circuit
    - ex. spring/mass → R, C, L
  - Possible to “interconnect” electrical and mechanical energy domains
    - Simplified modeling and co-simulation of electronic and mechanical parts of the system
  - Proper **analysis-tools** can be used
    - Ex. SPICE

# $e \rightarrow V$ - convention

- **Senturia and Tilmans** use the  **$e \rightarrow V$  -convention**
- Ex. electrical and mechanical circuits
  - $e \rightarrow V$  (voltage)      equivalent to  $F$  (force)
  - $f \rightarrow I$  (current)      equivalent to  $v$  (velocity)
  - $q \rightarrow Q$  (charge)      equivalent to  $x$  (position)
  - $e * f =$  "power" injected into the element

H. Tilmans, Equivalent circuit representation of electromagnetical transducers:  
I. Lumped-parameter systems, J. Micromech. Microeng., Vol. 6, pp 157-176, 1996



# Ex. of interconnection:

## ”Direct transformation”

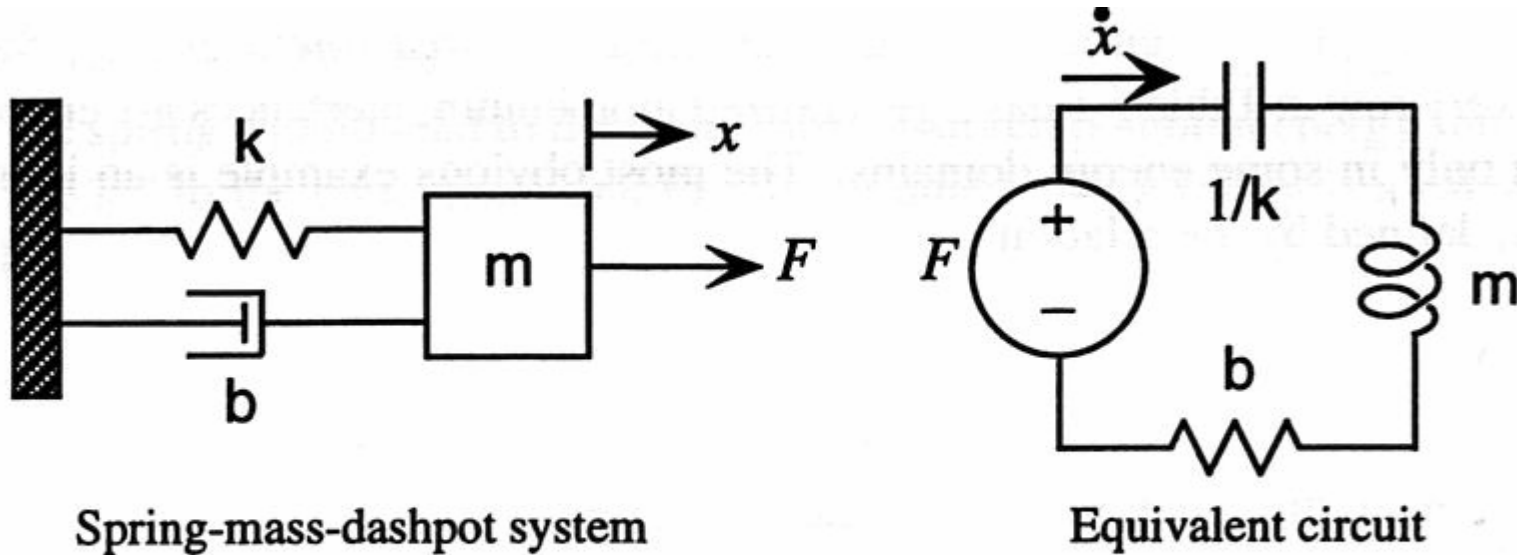
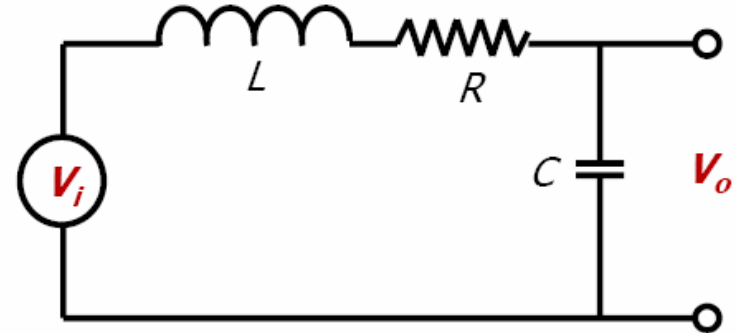
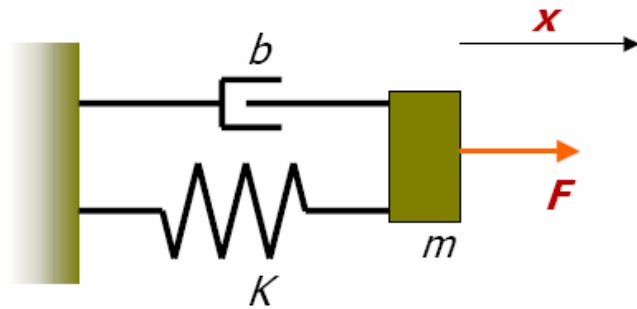


Figure 5.9. Translating mechanical to electrical representations.

# Mechanical / Electrical Systems



Input : external force  $F$

Output : displacement  $x$

$$m\ddot{x}(t) + b\dot{x}(t) + Kx(t) = F$$

$m$  mass,  $b$  damping,  $K$  stiffness

Transfer function :

$$H(s) = \frac{x}{F} = \frac{\frac{1}{m}}{s^2 + \frac{b}{m}s + \frac{K}{m}}$$

Input : voltage  $V_i$

Output : voltage  $V_o$

$$L\ddot{q}(t) + R\dot{q}(t) + \frac{1}{C}q(t) = V_i$$

$L$  induct.,  $R$  resist.,  $C$  capacit.

Transfer function :

$$H(s) = \frac{V_o}{V_i} = \frac{\frac{1}{LC}}{s^2 + \frac{R}{L}s + \frac{1}{LC}}$$

# Resonators

- Analogy between mechanical and electrical system:
  - Mass  $m$  - inductivity  $L$
  - Spring  $K$  - capacitance  $C$
  - Damping  $b$  - resistance  $R$  (depending where  $R$  is placed in circuit)
- Solution to 2nd order differential equation:

$$H(s) = \frac{\omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2}$$

$$\omega_0 = 2\pi f_0 \text{ natural frequency}$$

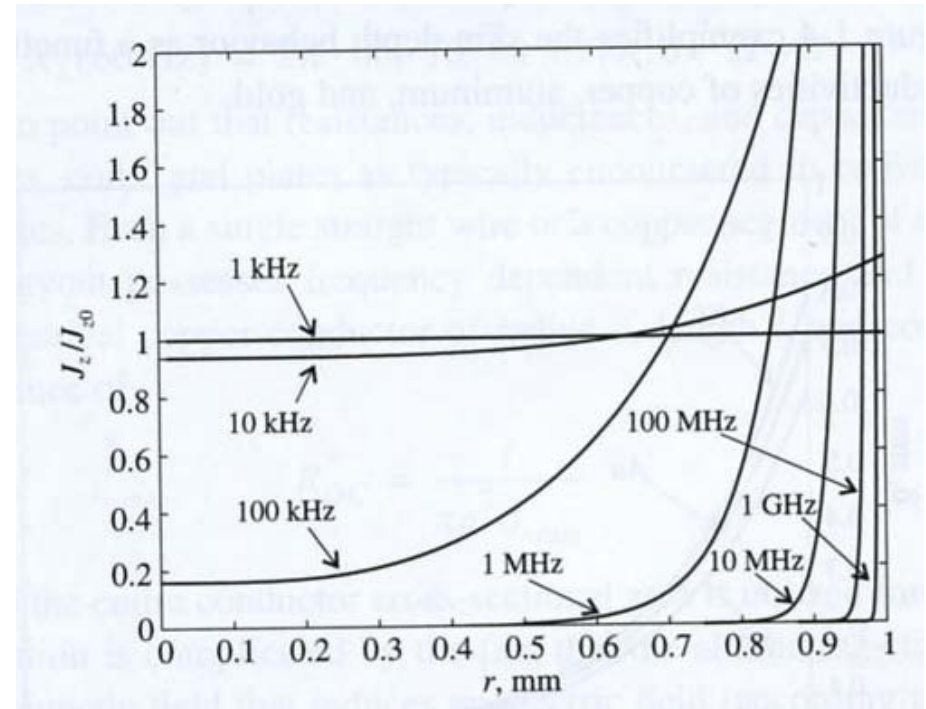
$$\omega_0 = \sqrt{\frac{K}{m}} \text{ mechanical system, } \omega_0 = \sqrt{\frac{1}{LC}} \text{ electrical system}$$

$$Q \text{ quality factor}$$

# Skin depth

- Resistance R increases towards centre of conductor
  - Current close to **surface** at increasing frequency
  - Formula: "skin-depth" →
    - Current density reduced by a factor 1/e

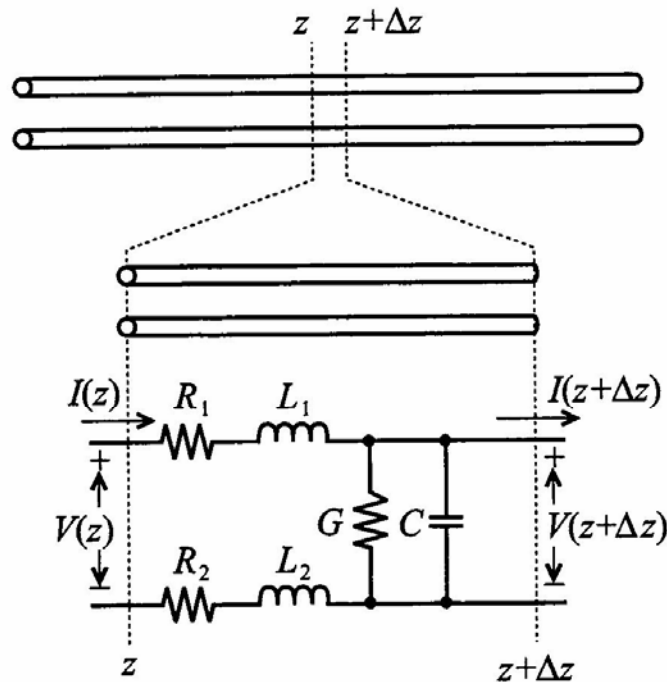
$$\delta = (\pi f \mu \sigma_{\text{cond}})^{-1/2}$$



- What does this mean for practical designs?

# Transmission line

- A conductor has to be modeled as a transmission line



**Figure 2-3** Partitioning an electric line into small elements  $\Delta z$  over which Kirchhoff's laws of constant voltage and current can be applied.

# Solution: 2 waves

- The solution is waves in a **positive** and **negative** direction

$$V(z) = V^+ e^{-kz} + V^- e^{+kz} \quad (2.34)$$

$$I(z) = I^+ e^{-kz} + I^- e^{+kz} \quad (2.35)$$

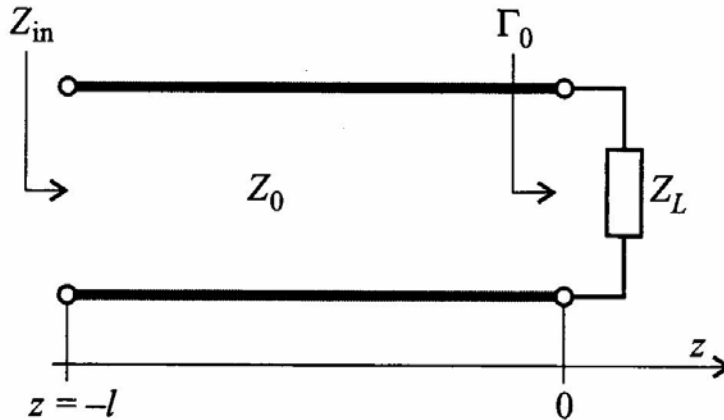
$$I(z) = \frac{k}{(R + j\omega L)} (V^+ e^{-kz} - V^- e^{+kz}) \quad (2.36) \quad (\text{Jmfr.2.27})$$

**Characteristic line-impedance:**  $Z_0 = \frac{V^+}{I^+} = -\frac{V^-}{I^-}$

$$Z_0 = \frac{(R + j\omega L)}{k} = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}} \quad (2.37)$$

# Impedance for **lossless** transmission line

$$Z_0 = \sqrt{L/C}$$



**Figure 2-23** Terminated transmission line at location  $z = 0$ .

How to avoid reflections and have good signal propagation?

# Reflection coefficient

$$\Gamma_0 = \frac{V^-}{V^+} \quad \leftarrow \text{definition of reflection coefficient for } z = 0$$

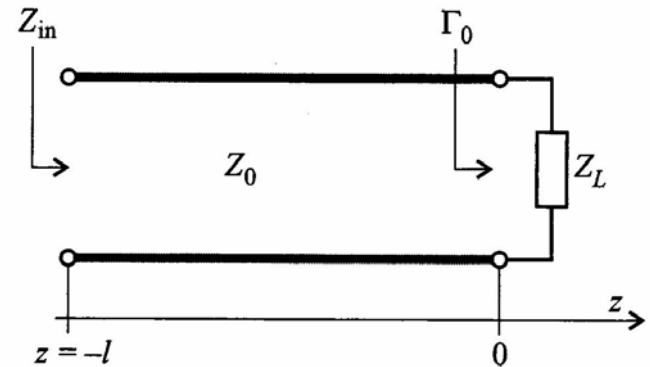
$$V(z) = V^+ (e^{-kz} + \Gamma_0 \cdot e^{+kz})$$

$$I(z) = \frac{V^+}{Z_0} (e^{-kz} - \Gamma_0 \cdot e^{+kz})$$

Impedance for  $z = 0$ :

$$Z(0) = \frac{V(0)}{I(0)} = Z_0 \frac{1 + \Gamma_0}{1 - \Gamma_0} = Z_L \quad = \text{load impedance}$$

$$\Gamma_0 = \frac{Z_L - Z_0}{Z_L + Z_0}$$





# Various terminations

$$\Gamma_0 = \frac{Z_L - Z_0}{Z_L + Z_0}$$

## Open line

→ reflection with equal polarity

$$Z_L = \infty \Rightarrow \Gamma_0 = 1$$

## Short circuit

→ Reflection with inverse polarity

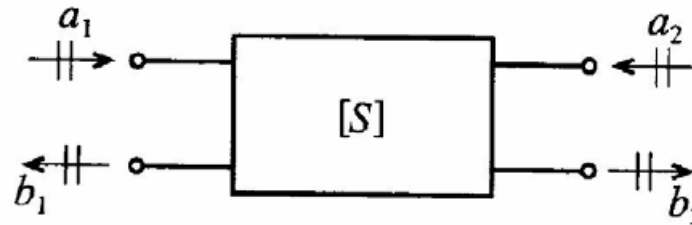
$$Z_L = 0 \Rightarrow \Gamma_0 = -1$$

No reflection when:

$$Z_0 = Z_L \Rightarrow \Gamma_0 = 0$$

→ "MATCHING"

# Interpretation of S-parameters



$$S_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0} \equiv \frac{\text{reflected power wave at port 1}}{\text{incident power wave at port 1}} \quad (4.42a)$$

$$S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0} \equiv \frac{\text{transmitted power wave at port 2}}{\text{incident power wave at port 1}} \quad (4.42b)$$

$$S_{22} = \left. \frac{b_2}{a_2} \right|_{a_1=0} \equiv \frac{\text{reflected power wave at port 2}}{\text{incident power wave at port 2}} \quad (4.42c)$$

$$S_{12} = \left. \frac{b_1}{a_2} \right|_{a_1=0} \equiv \frac{\text{transmitted power wave at port 1}}{\text{incident power wave at port 2}} \quad (4.42d)$$

# Q-value

- Q-factor characterizes loss due to power dissipation in elements
- Q should be as high as possible to reduce Insertion loss
- Quality factor fundamentals (definition)

$$Q = 2\pi \frac{\text{maximum instantaneous energy stored in circuit}}{\text{energy dissipated per cycle}}$$

Characterize power loss due to dissipation mechanisms in reactive elements.

$$Q_{\text{Tuned Circuit}} = \frac{f_0}{B}$$

Unloaded : Q (intrinsic)

Losses due to external load :  $Q_L$

$$Q_{\text{Capacitor}} = \frac{\omega_0 C}{G}$$

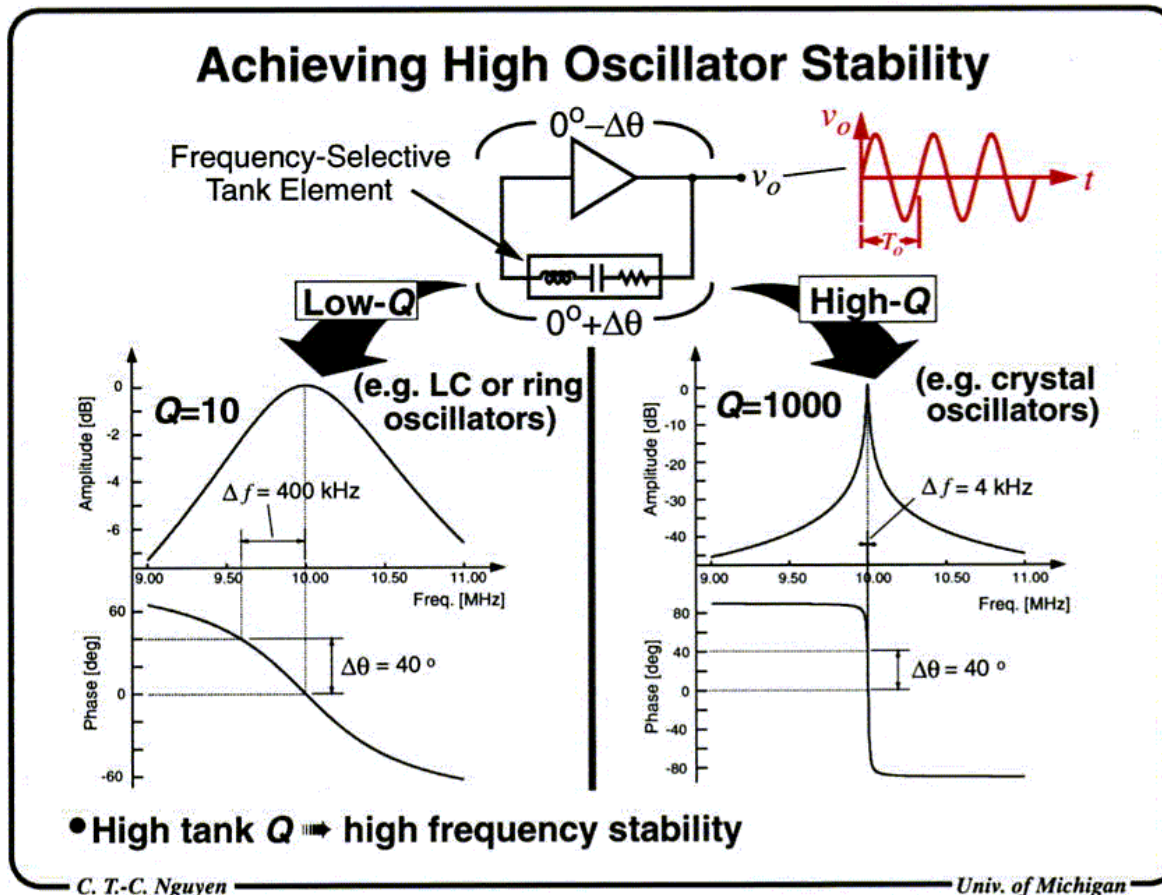
$$Q_{\text{Inductor}} = \frac{\omega_0 L}{R}$$

→ Insertion loss at resonance:

$$IL(\text{dB}) = 20 \log \left( 1 + \frac{Q_L}{Q} \right)$$

# Relation between Q-factor and oscillator stability

- **Q-factor is critical for RF circuit performance!**



# Benefits and typical characteristics of RF MEMS switches

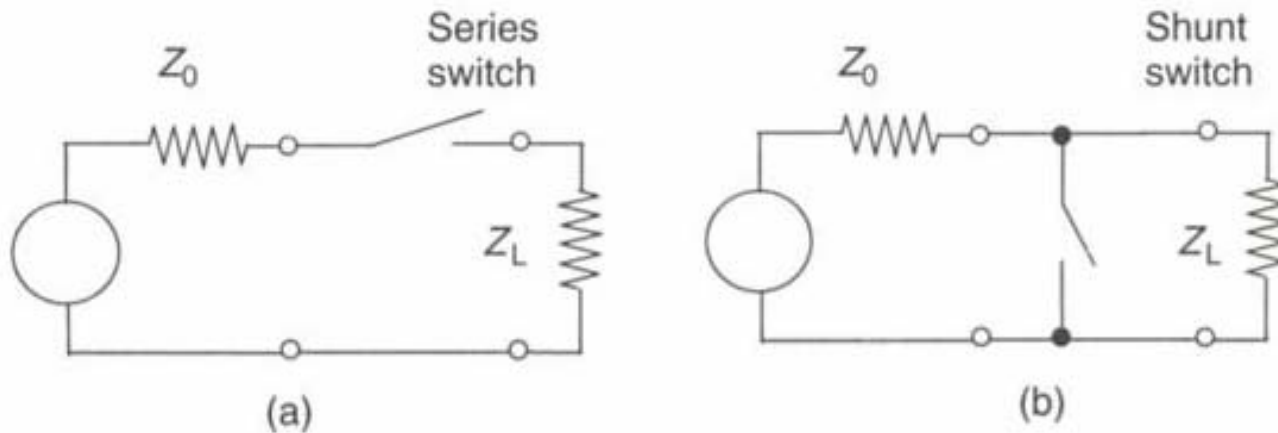
FSRM



## RF MEMS switch: key advantages and issues

- + • **Ultra low power** consumption: 10-100nW
- + • **Ultra-high isolation** → airgap: low state C ~fF, 0.1-40GHz
- + • **Low insertion loss** → ~ -0.1dB, 0.1-40GHz
- + • **Practically no intermodulation**: very linear
- + • **Low cost** ~ simple technology, integrable with RF ICs  
(problem → cost & performance of the full packaged structure)
  
- • **Speed limited** by mechanical nature: 1-100μs
- • **Power handling limited**: <100mW
- • **Reliability**: limited (today) ~10<sup>9</sup>-10<sup>10</sup> cycles  
no reliable switch to handle ~few Watts
- • **Packaging**: needs inert ambient & low humidity & **low cost**

# Two basic switch configurations



# Basic switch structures

- **Series switch**

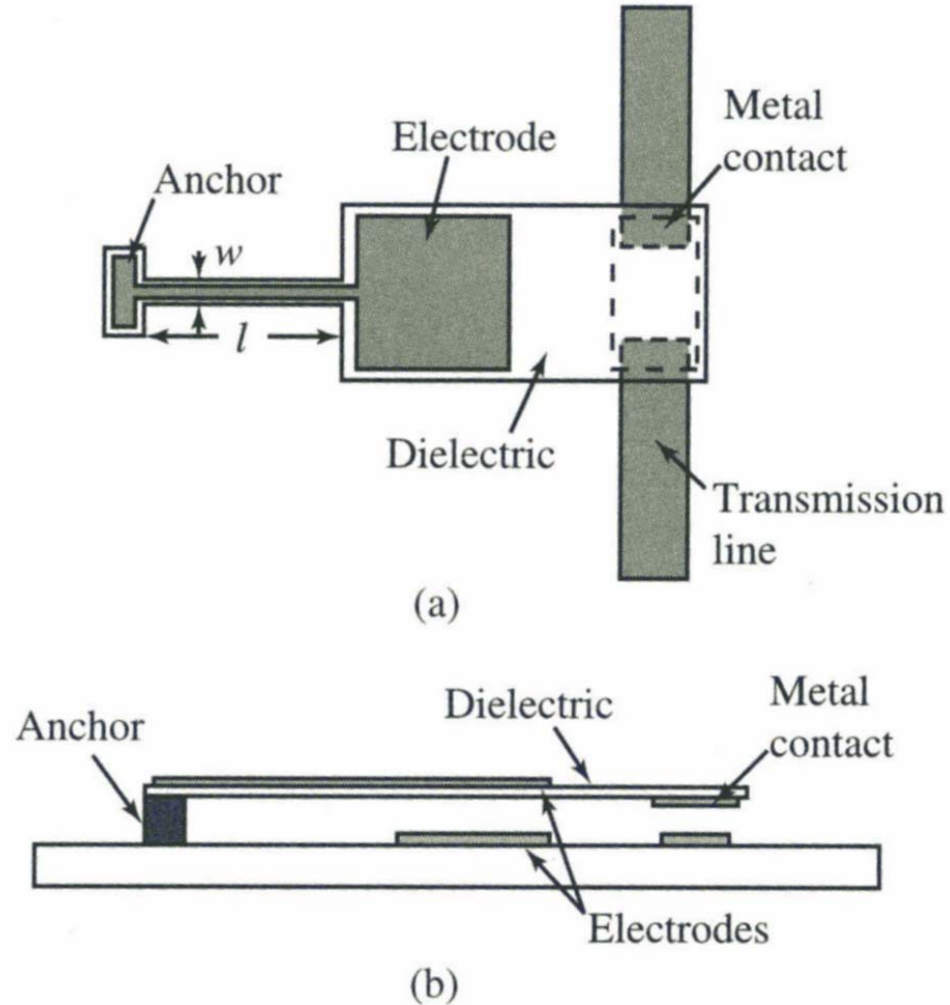
- Contact switch, ohmic (relay) \*
- Cantilever beam
- Capacitive switch (“contact less”)
  - RF-signals short-circuited via C (  $Z=1/j\omega C$  )
    - Impedance depends on value of C

- **Shunt switch**

- Shunt capacitive switch \*
- clamped-clamped beam (c-c beam)
- Shunt contact switch

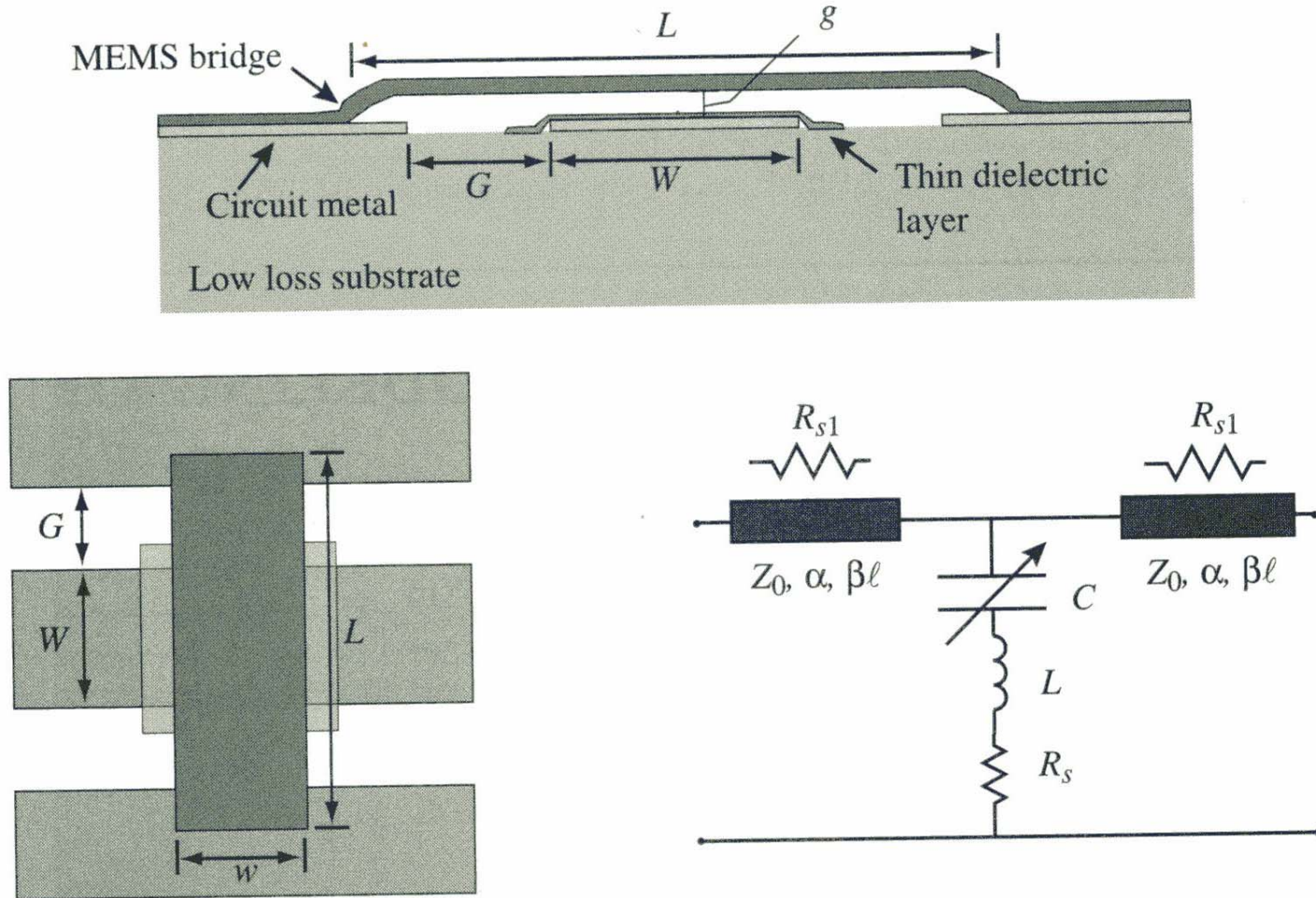
\* most used

# Series switch





# Typical shunt switch



**Figure 4.1.** Illustration of a typical MEMS shunt switch shown in cross section and plan view. The equivalent circuit is also shown [6] (Copyright IEEE).

# Electromechanical operation

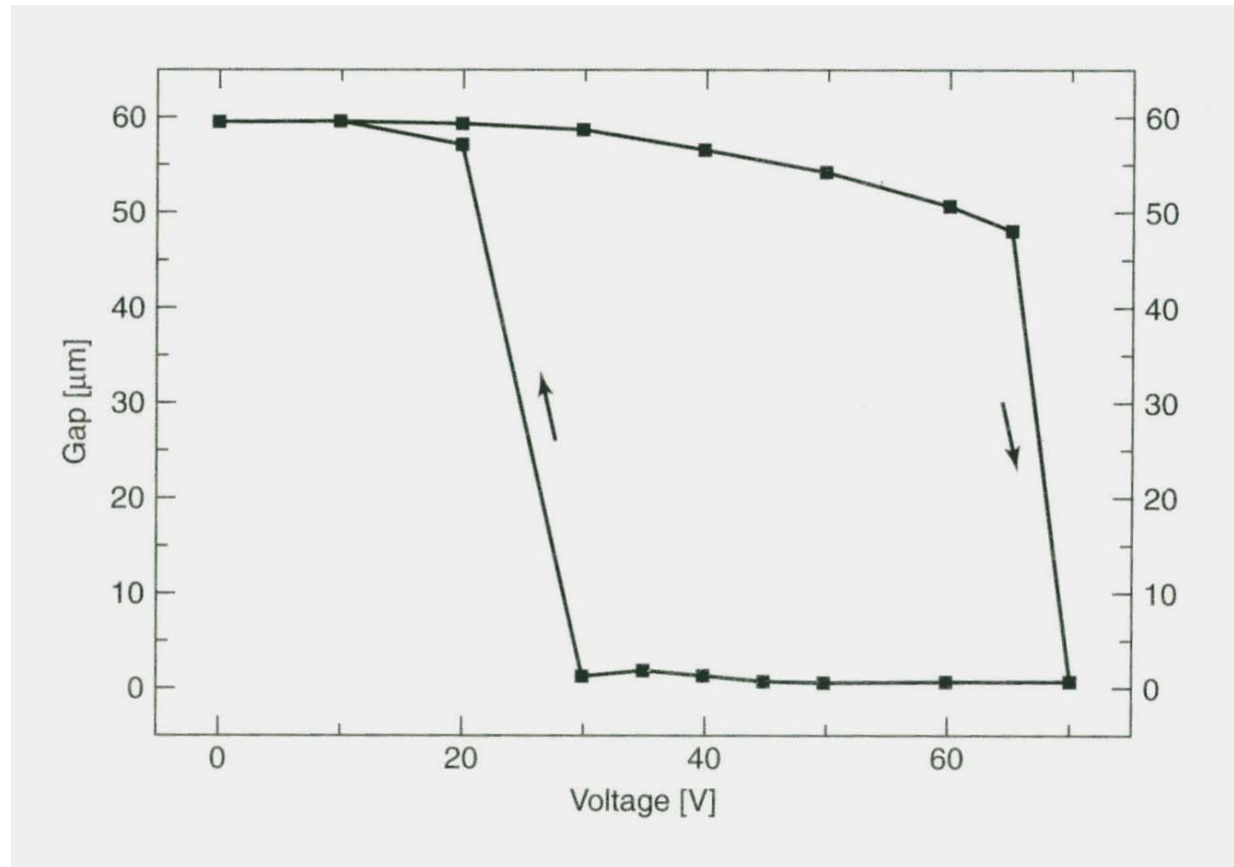
- The operation is based on the **pull-in** effect
  - Characteristics at pull-in
    - Membrane/beam pulls in at 1/3 of gap
    - Pull-in voltage:

$$V_{PI} = \sqrt{\frac{8K}{27\epsilon_0 W w}} g_0^3$$

- Definition of parameters:
  - K spring constant
  - $g_0$  initial gap
  - $A=W*w$  = area

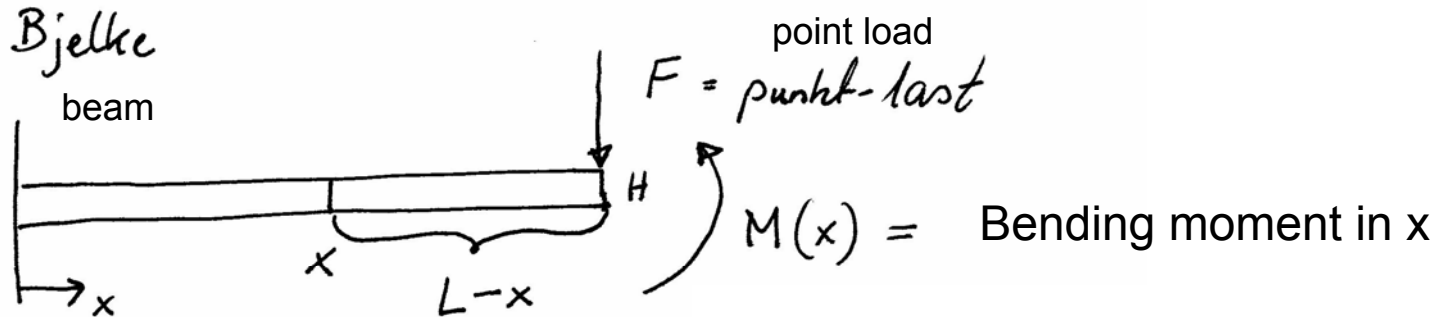
# Hysteresis

- A capacitive switch shows hysteresis when being switched on/off



# Deflection of beam

- Suppose the following approximations:
  - Actuation electrode is not deflected
  - Electrostatic force concentrated at the end of the flexible beam with length L



$w(x)$  = vertical displacement

$W$  = width

**Euler beam equation**

$$\frac{d^2 w}{dx^2} = - \frac{M}{E \cdot I}$$

$I$  = (area) moment of inertia

$$I = \frac{1}{12} W \cdot H^3$$

$$w(x) = \frac{FL}{2EI} x^2 \left(1 - \frac{x}{3L}\right)$$

Max. deflection at  $x = L$

$$w(L) = \frac{L^3}{3EI} \cdot F$$

Beam stiffness represents a spring with spring constant  $k_{\text{cantilever}}$

Compare with

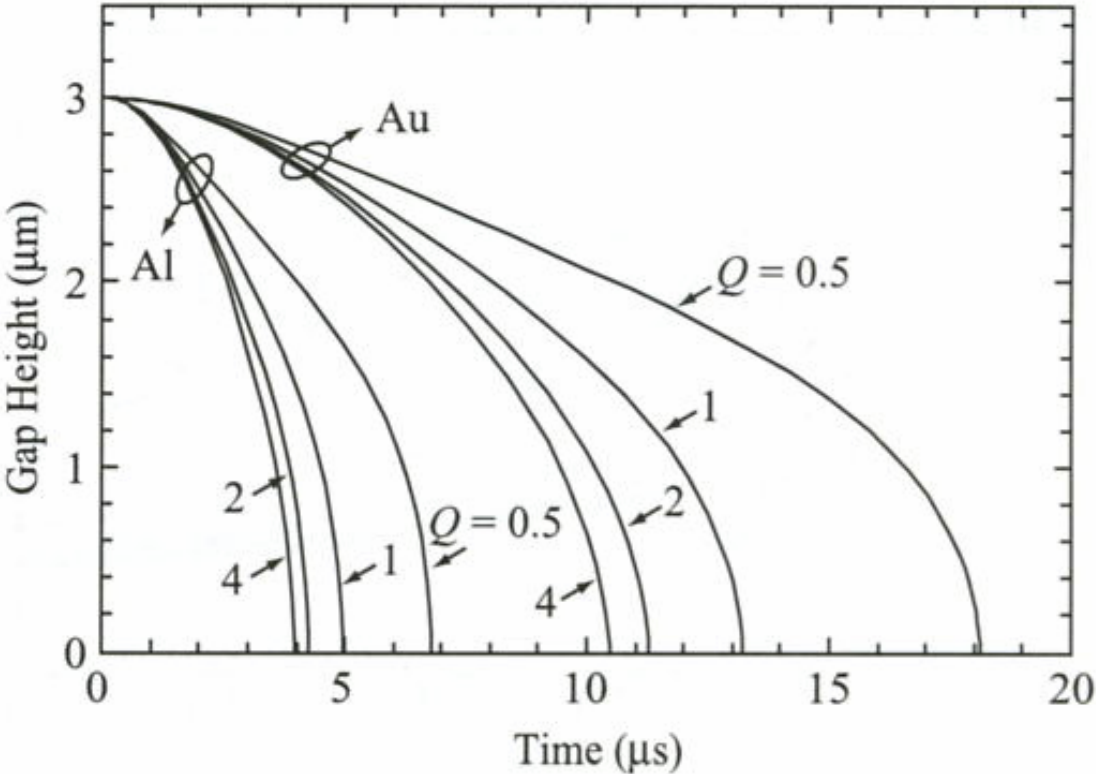
$$F = k_{\text{cantilever}} \cdot \underbrace{\Delta W}_{w_{\text{max}}}$$

$$k_{\text{cantilever}} = \frac{F}{w(L)} = \frac{3EI}{L^3} = \frac{1}{4} E \cdot W \left(\frac{H}{L}\right)^3$$

# Switch speed and damping

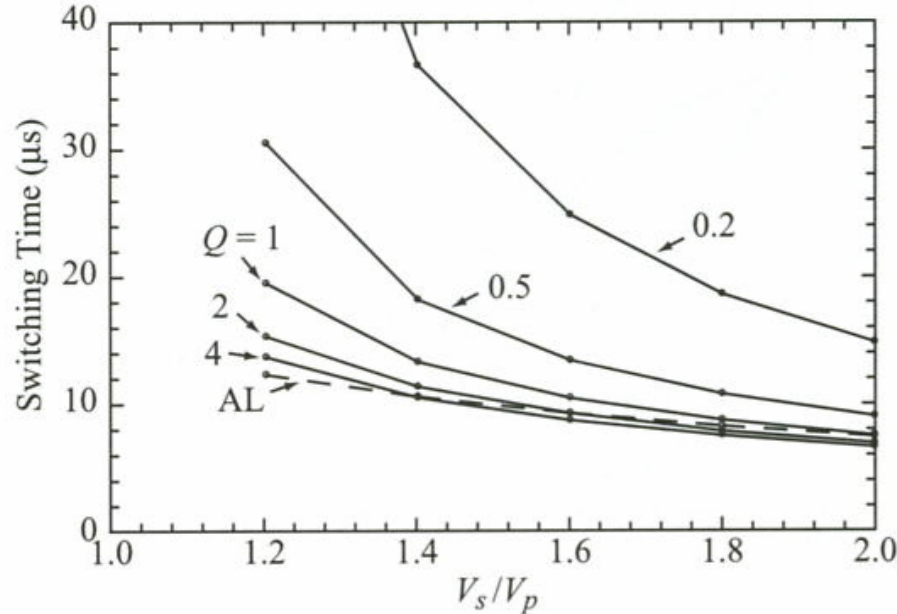
- Switch speed depends of **damping**
  - Air, gas must be pushed/pulled
  - **”squeezed-film damping”**
  - Method of modeling from fluid dynamics
- How to reduce damping?
  - Operate in vacuum
    - Hermetic sealed packages
  - Make holes in membrane
    - Perforated membrane

# Gap vs. Time for various Q-factors



**Figure 3.3.** Pull-down simulations for the Au and Al beams of Table 3.1 for an applied voltage of 42 V ( $V_s = 1.4V_p$ ).

# Acceleration limited switch



**Figure 3.5.** Simulated switching times for the Au beam given in Table 3.1. “AL” means acceleration-limited and is given by Eq. (3.23).

**Note: The system becomes more acceleration limited when damping decreases (eg. Q-factor increases). High  $V_s/V_p$  is good.**



# Switch speed for increased $V_s$

- Switch-speed strongly depends on **actuation voltage,  $V_s$** 
  - $V_s$  is usually larger than  $V_{pi}$
  - $V_s = \text{const} * V_{pi}$  (pull-in) = ("actuation voltage")
  - Larger voltage gives larger electrostatic force
    - → increased switch speed

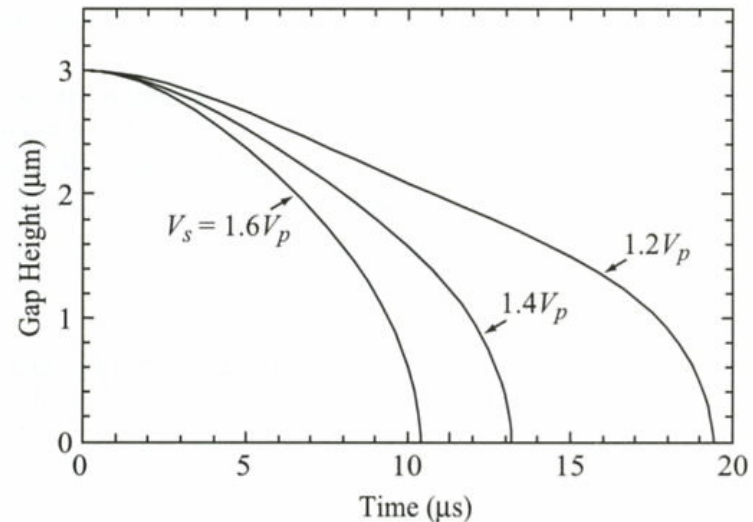
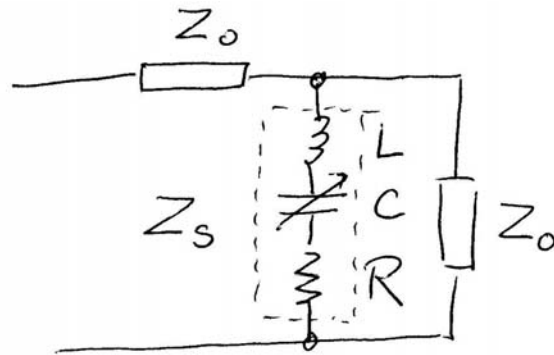


Figure 3.4. Pull-down simulations for the Au beam of Table 3.1 versus the applied voltage, and  $Q = 1$ .

# RF modeling: Shunt configuration



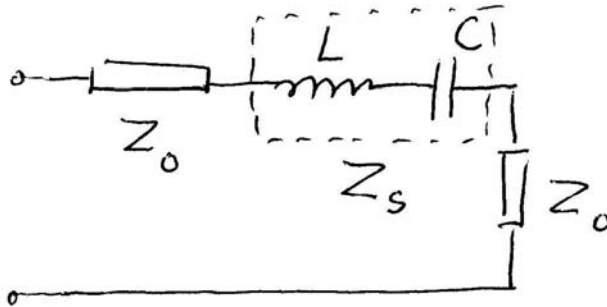
$$Z_s = R + j\omega L + \frac{1}{j\omega C}$$

$$S_{11} = S_{22} = \Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{Z_s // Z_0 - Z_0}{Z_s // Z_0 + Z_0} = \frac{-Z_0}{2Z_s + Z_0}$$

$$S_{12} = S_{21} = 1 + \Gamma = 1 + \frac{-Z_0}{2Z_s + Z_0} = \frac{2Z_s}{2Z_s + Z_0}$$

## Series contact cantilever switch

OFF (up-state)



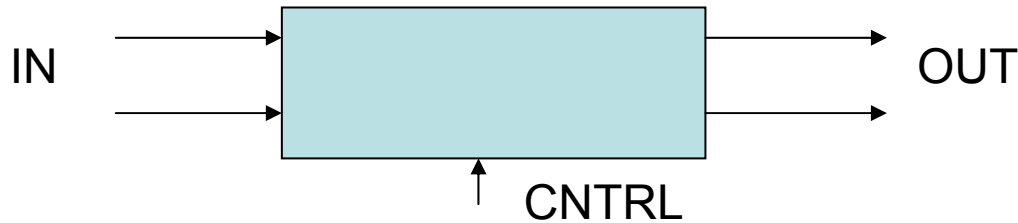
$$Z_s = j\omega L + \frac{1}{j\omega C}$$

$$S_{11} = S_{22} = \Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{(Z_s + Z_0) - Z_0}{(Z_s + Z_0) + Z_0} = \frac{Z_s}{2Z_0 + Z_s}$$

$$S_{12} = S_{21} = 1 - \Gamma = 1 - \frac{Z_s}{2Z_0 + Z_s} = \frac{2Z_0}{2Z_0 + Z_s}$$

# Phase shifter

- A phase shifter is a 2-port



- Output signal is delayed relative to the input signal
- The effective "path-length" of the transmission line can be changed
  - Signal propagates a longer distance → "delayed" → phase change
  - Phase difference can be controlled by a DC bias

# Analog phase shifters

- Phase velocity for a transmission line

$$v_p = \frac{1}{\sqrt{L_t \cdot C_t}}$$

- Variables are inductance and capacitance per unit length
- Idea: C-value can be controlled by a bias voltage
  - For example by **shunt capacitive loaded line**

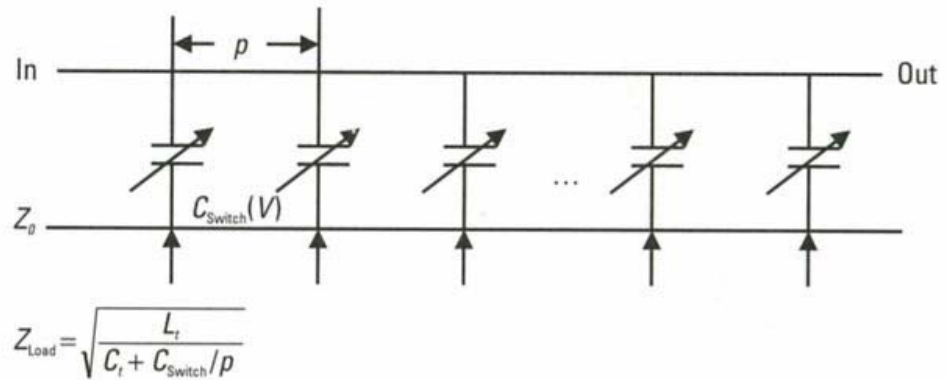
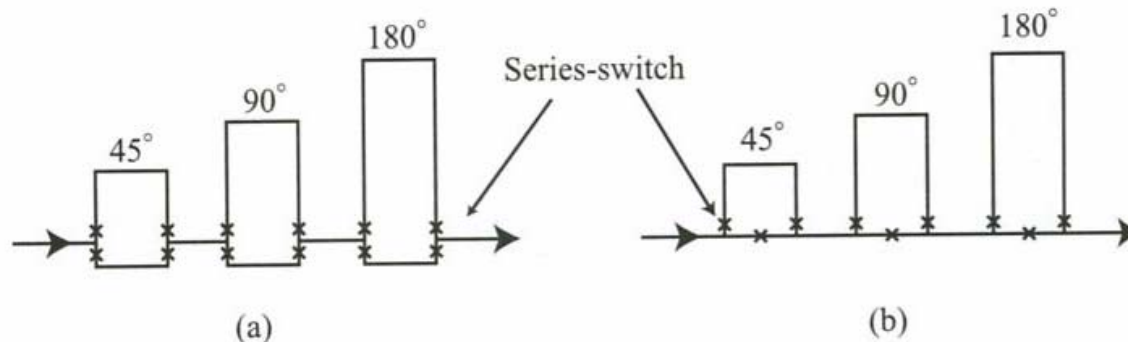


Figure 5.1 Schematic of analog phase shifter.

$C_t$  = line capacitance

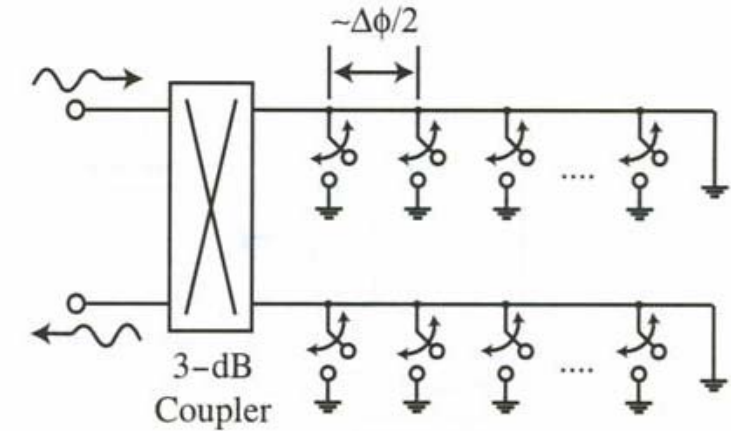
De Los Santos

# Digital phase shifters with series-switches

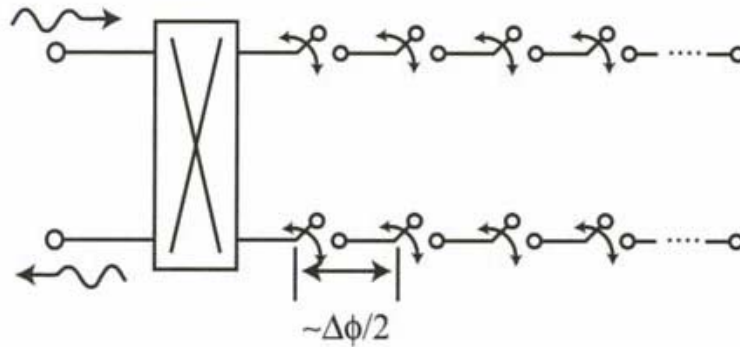


- Working principle
  - Different line paths connected in/out
  - Interconnections through switches
- Switches for "180°, 90°, 45°, 22.5°, 11.25° -sections in a cascade arrangement
- Several bits used
  - Controlling line sections individually
  - F.ex. 3 bits: 45/90/180° give phase shift 0, 45, 90, 135, ... , 315°
  - 3 bit and 4 bit phase shifters have been demonstrated

# Reflection type phase shifter, N-bit



(a)



(b)

Figure 9.1. A reflect-line  $N$ -bit phase shifter using (a) shunt and (b) series switches.