INF5490 RF MEMS

L7: RF MEMS switches, I

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Today's lecture

- Switches for RF and microwave
  - Examples
  - Performance requirements
  - Technology
  - Characteristics of RF MEMS switches
- Basic switch structures
  - Working principles
- Important switch parameters
- Design of RF MEMS switches
  - Electromechanical design, I

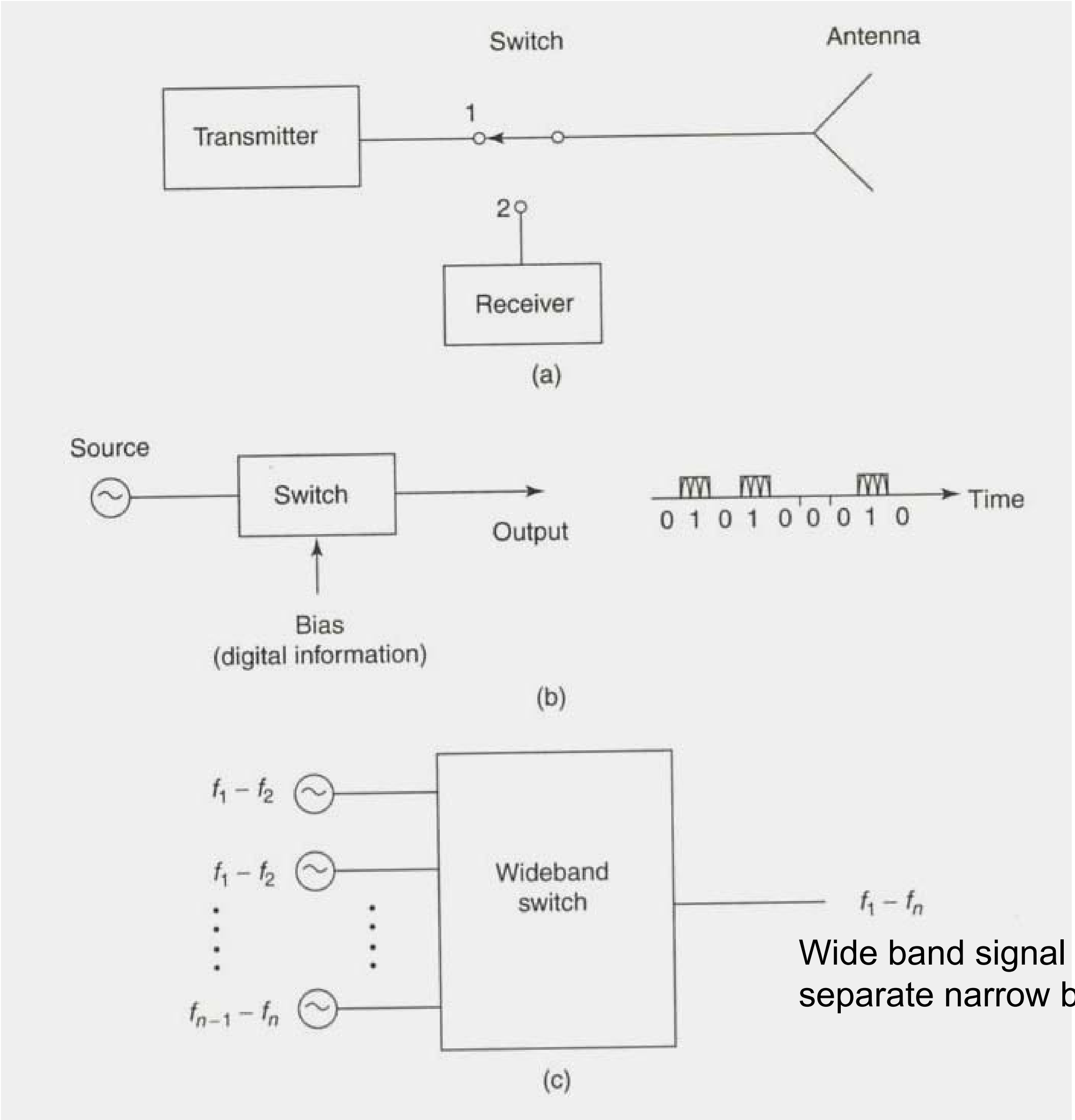
Next lecture, L8

- Design of RF MEMS switches, contd.
  - Electromechanical design, II
  - RF design
- Ex. of implementations
  - Structure
  - Fabrication
  - Performance
- Special structures and actuation mechanisms
- Some challenges

Background

- **Switch - relay**
- Important component for RF systems
  - – Signal routing
    - Re-directing of signals: antennas, transmitter/receiver
  - – Connecting / selecting various system parts
    - Choice of filter in filter bank
    - Choice of network for impedance matching
    - Choice of matching circuitry for amplifier
- Telecom is a dominant user

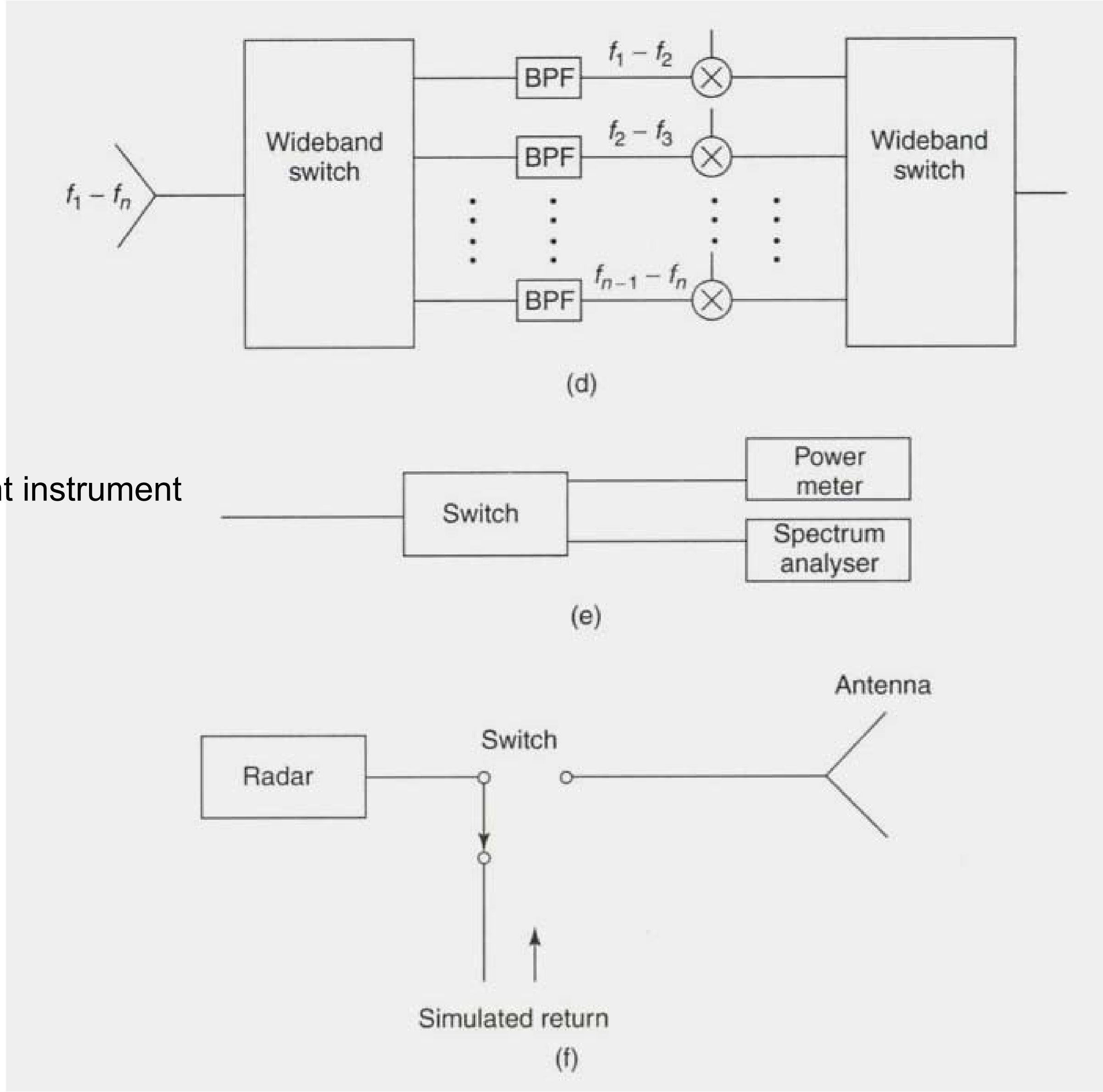
Ex. of switch applications



Wide band signal generator from separate narrow band sources

Varadan, fig. 3.1

Applications, contd.



Choose channel

Choose measurement instrument

Varadan fig. 3.1

Performance requirements

- Good **performance parameters** are desired
  - Low loss
  - Good isolation
  - Low cross-talk
  - Short switching time
  - Long lifetime
- Choice of **switch technology** is dependent of
  - RF-signal frequency
  - Signal level
  - “Large power” capability
  - Speed requirements

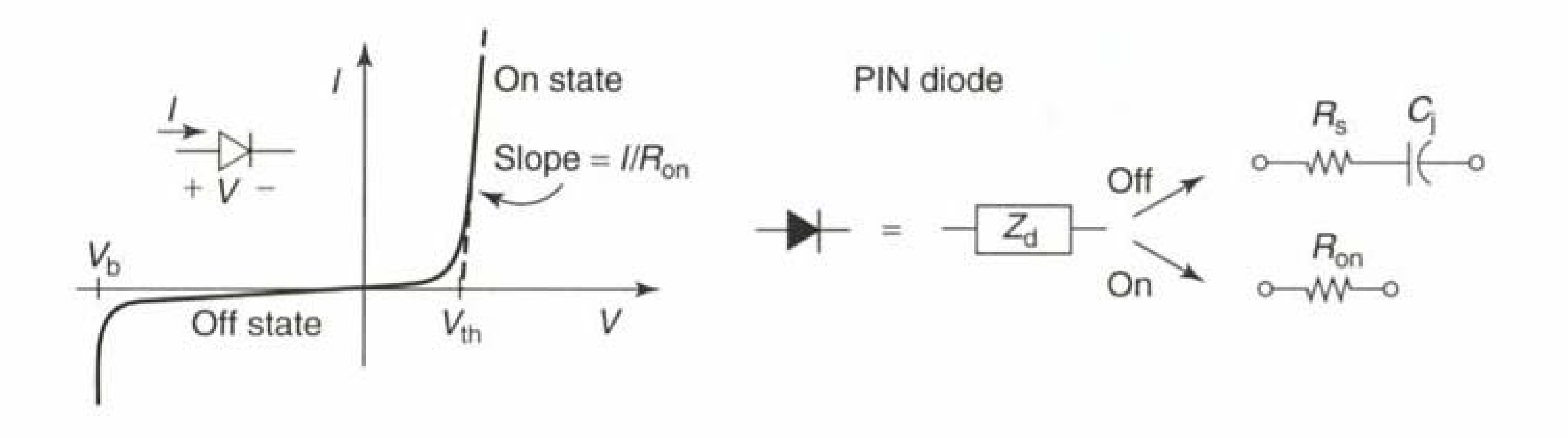
Technology choice

- Traditional mechanical switches **(relays)**
  - ala light switch
    - Low loss, good isolation (+)
    - Can handle high power (+)
    - Slow (-)
    - Mechanical degradation (-)
    - Contact degradation, reduced lifetime (-)

- **Semiconductor switches** (solid-state)
  - Most used today
  - FET (Field Effect Transistors), CMOS, PIN-diodes etc.
    - High reliability (+)
    - Integration with Si (+)
    - FET degrades at high frequency (-)
    - Large insertion loss, high resistive loss (-)
    - Limited isolation (-)
    - Limited “high power” capability (-)

High reliability technology: PIN-diode

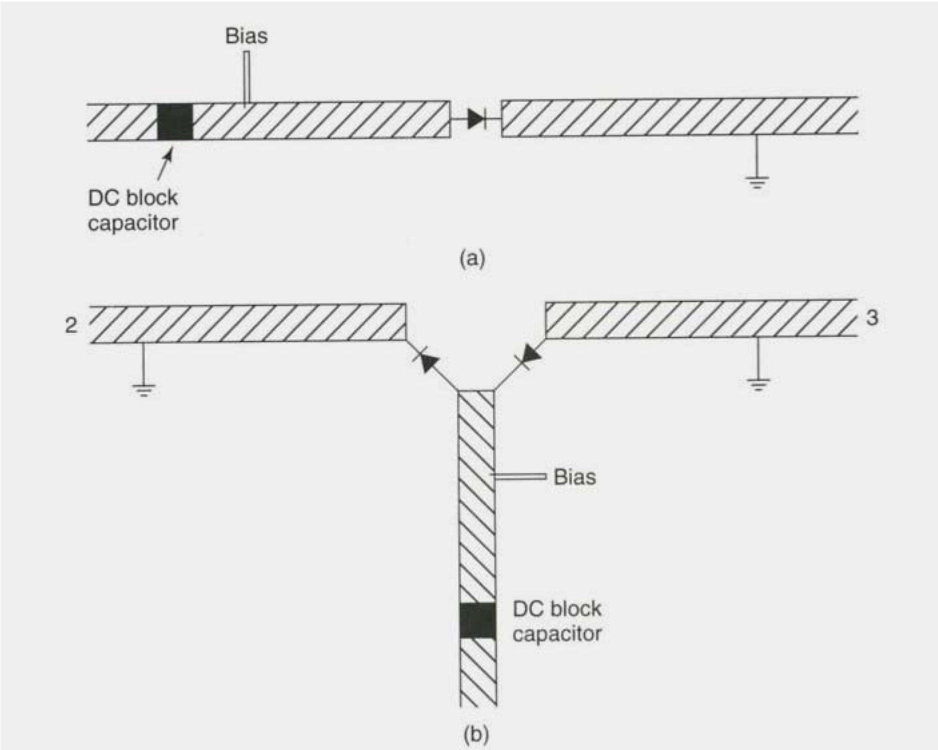
- Varadan fig. 3.6
  - PIN: p – insulator - n
  - **Forward** biased: low R
  - **Reverse** biased: low C due to isolator layer → high impedance Z



PIN-diode used in system

- The biasing of the PIN-diode determines the switching
  - Forward bias: low R
  - Reverse bias: high Z

- Typical terms
  - Single-pole single-throw, **SPST**
  - Single-pole double-throw, **SPDT**
    - Varadan fig. 3.8



RF MEMS switches

- **A great need exists for having switches with better performance!**
  - → MEMS switches:
    - The first ex. of RF MEMS-components (78→)
    - Many implementations exist
      - *F.ex. in Gabriel M. Rebeiz: "RF MEMS – Theory, Design and Technology" (Wiley 2003)*
      - Publications
    - Most mature RF MEMS field

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) ~10^9-10^{10} cycles; no reliable switch to handle ~few Watts
- • **Packaging**: needs inert ambient & low humidity & **low cost**

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Comparing performance

TABLE 1.2. Performance Comparison of FETs, PIN Diode, and RF MEMS Electrostatic Switches

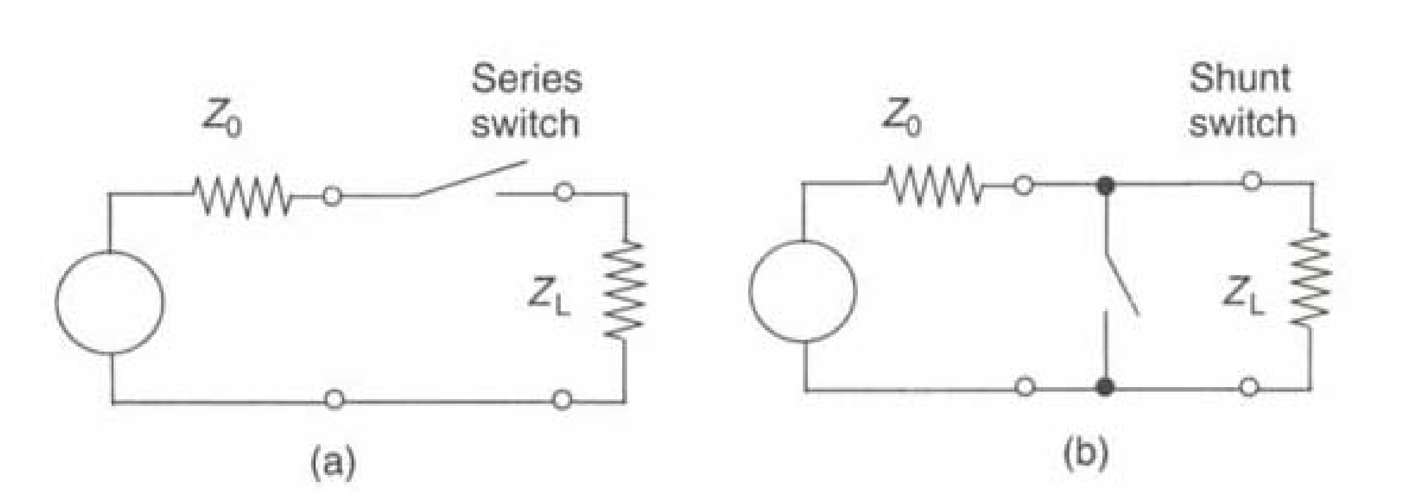
Parameter	RF MEMS	PIN	FET
Voltage (V)	20–80	±3–5	3–5
Current (mA)	0	3–20	0
Power consumption[a] (mW)	0.05–0.1	5–100	0.05–0.1
Switching time	1–300 μs	1–100 ns	1–100 ns
C_{up} (series) (fF)	1–6	40–80	70–140
R_s (series) (Ω)	0.5–2	2–4	4–6
Capacitance ratio[b]	40–500[b]	10	n/a
Cutoff frequency (THz)	20–80	1–4	0.5–2
Isolation (1–10 GHz)	Very high	High	Medium
Isolation (10–40 GHz)	Very high	Medium	Low
Isolation (60–100 GHz)	High	Medium	None
Loss (1–100 GHz) (dB)	0.05–0.2	0.3–1.2	0.4–2.5
Power handling (W)	<1	<10	<10
Third-order intercept point (dBm)	+66–80	+27–45	+27–45

[a] Includes voltage upconverter or drive circuitry.

[b] Capacitive switch only. A ratio of 500 is achieved with high-ε_r dielectrics.

Rebeiz

Two basic switch configurations

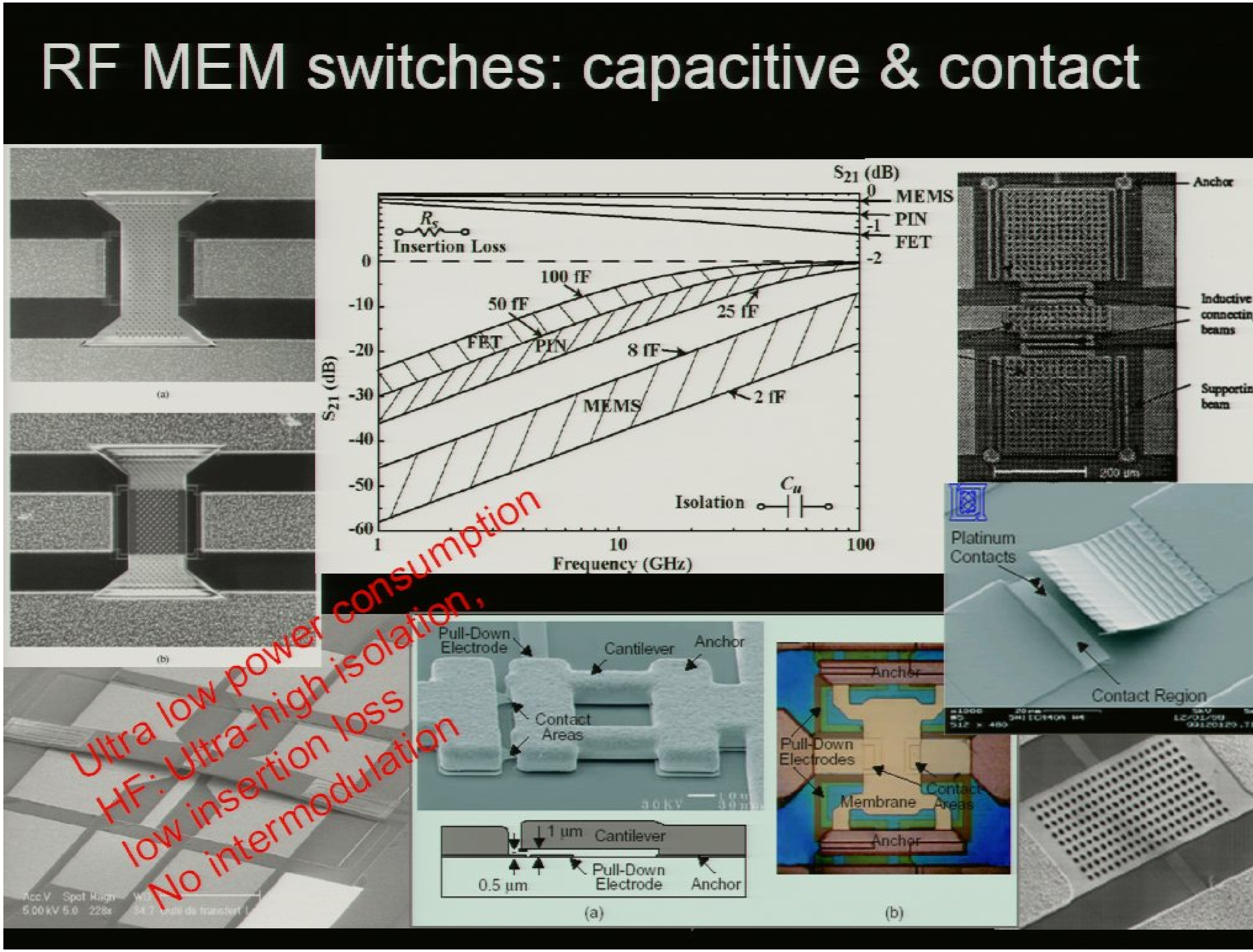


Varadan fig. 3.2

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

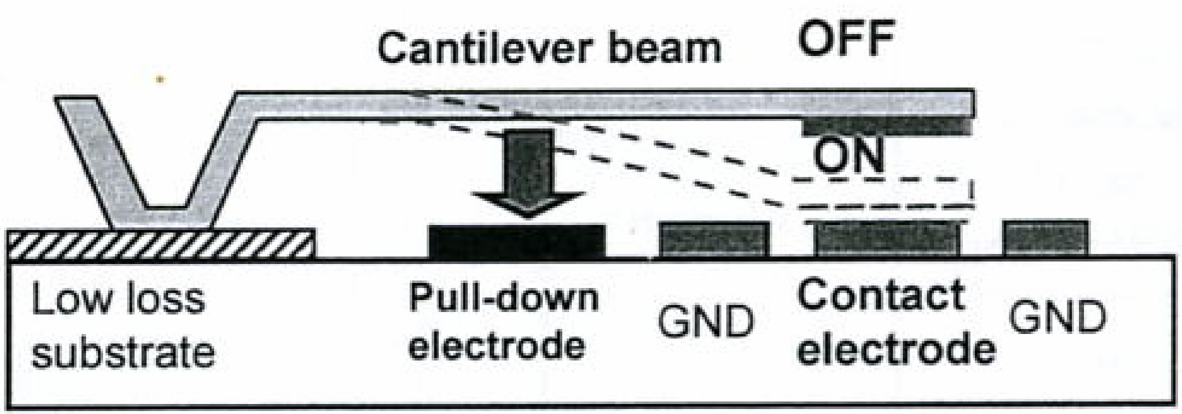
* most used



Adrian Ionescu, EPFL. Europractice – STIMESI, Nov 2007

Series contact switch

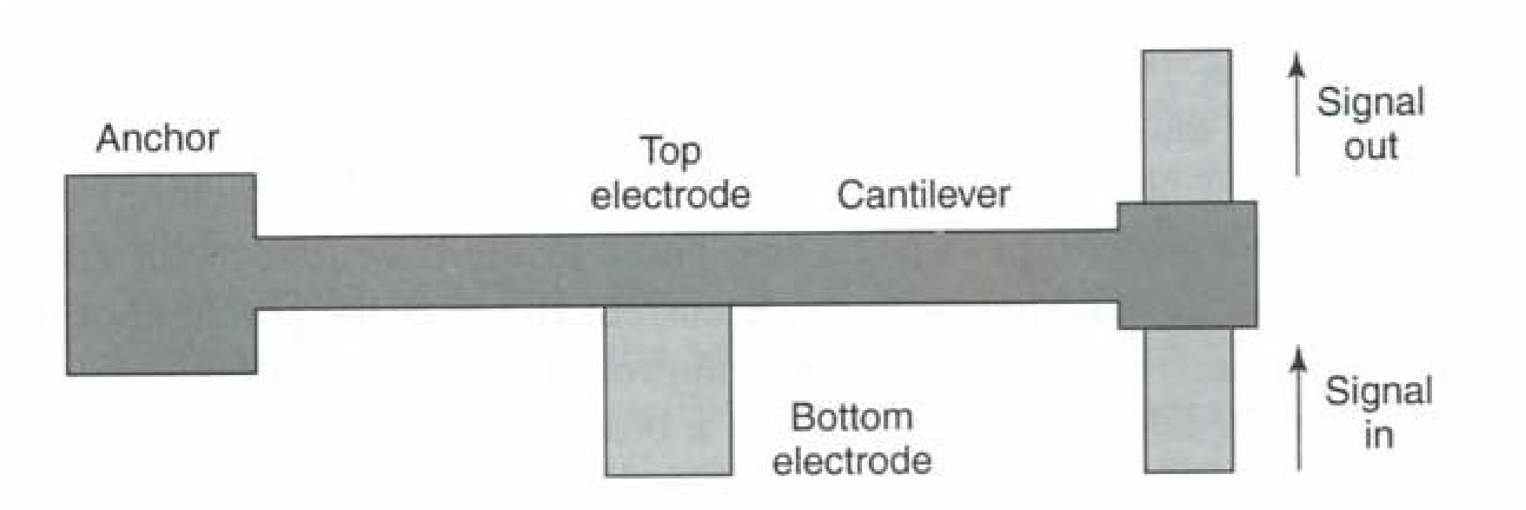
- Cantilever beam switch



coplanar waveguide

Signal propagation **into** the paper plane

Signal propagates perpendicular to cantilever

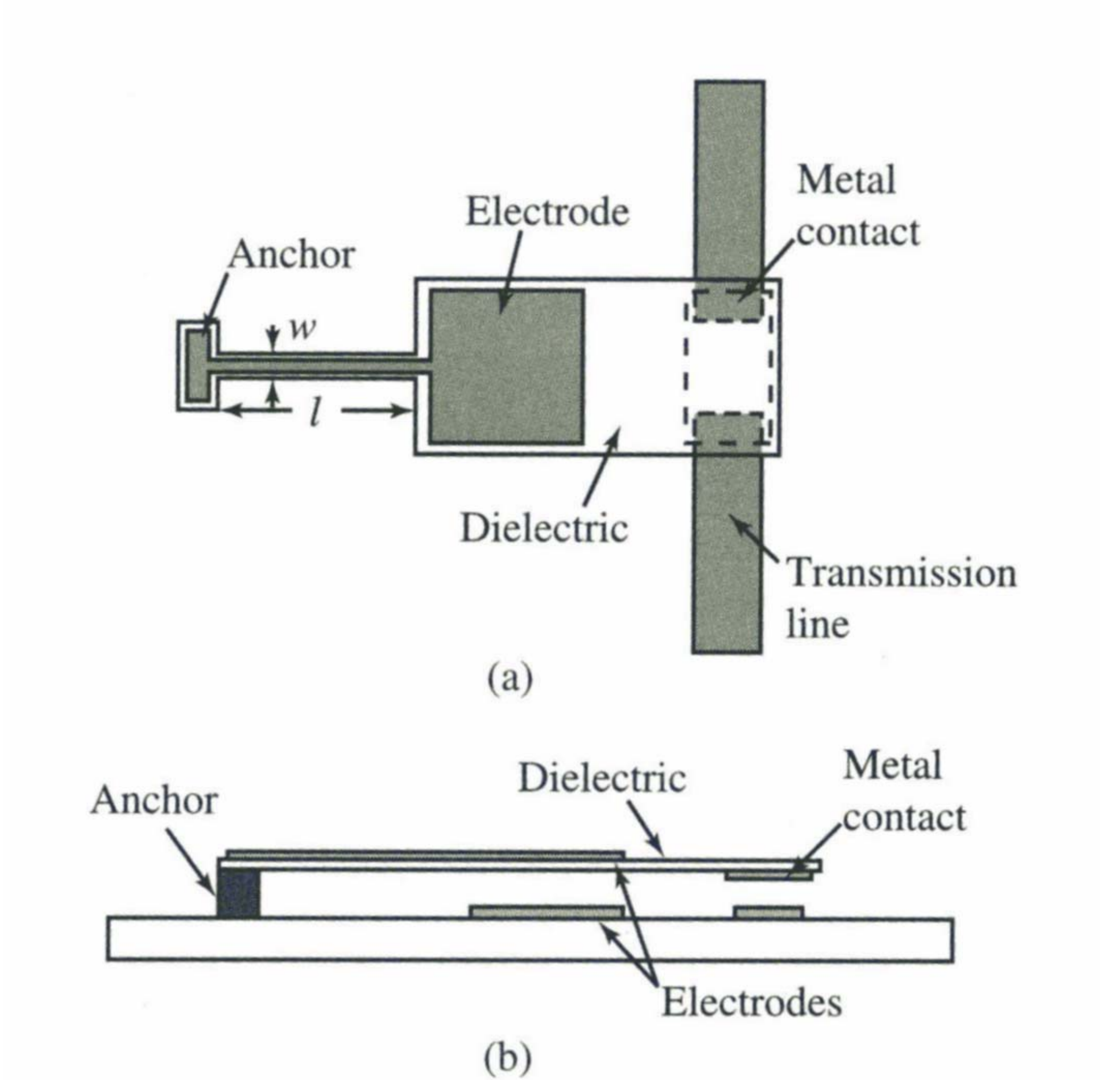


Separate pull-down electrode

- Actuation voltage between beam and bottom electrode
- Separate "contact metal" at beam end

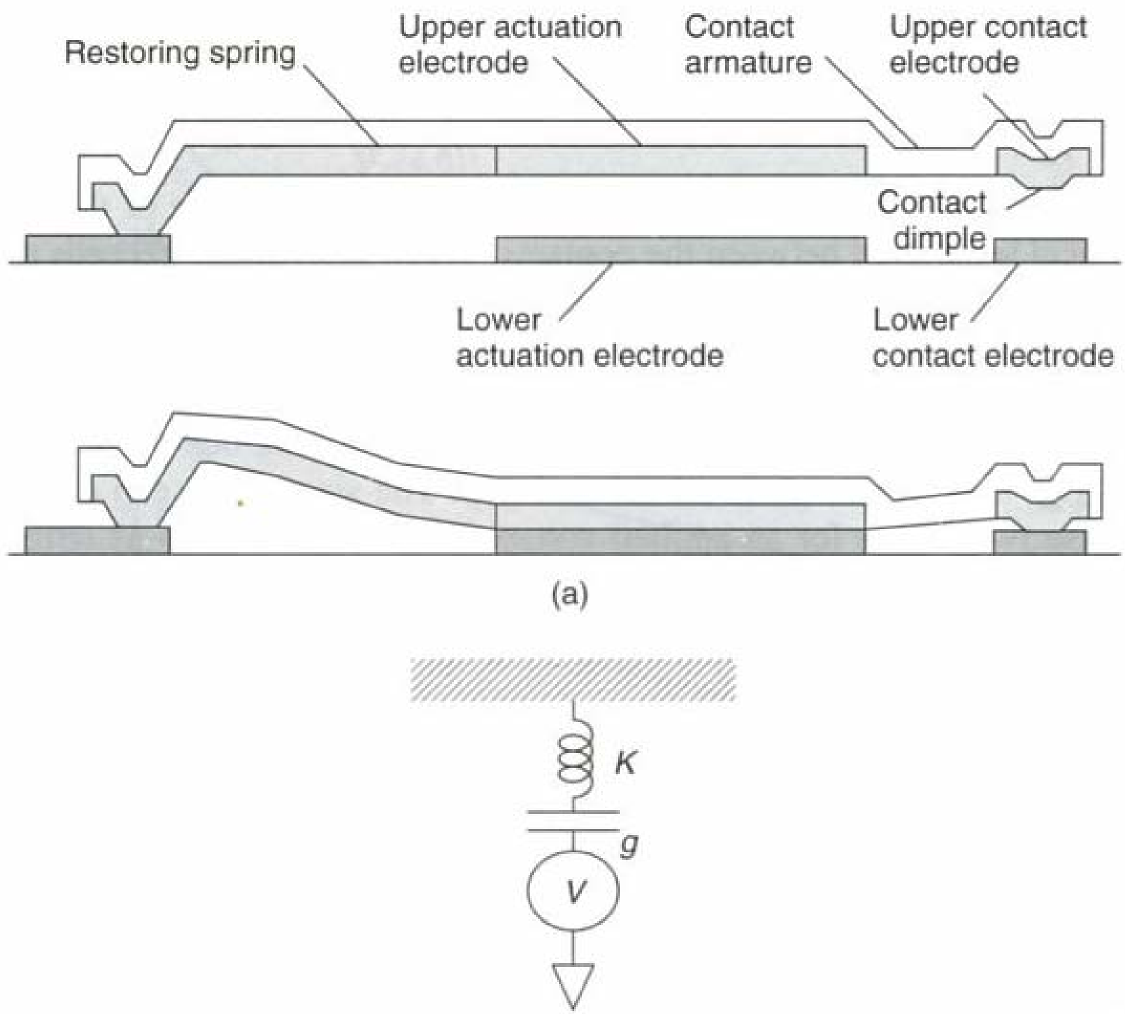
Varadan fig. 3.14, top view

Working principle



Rebeiz fig.2.12

More realistic structure

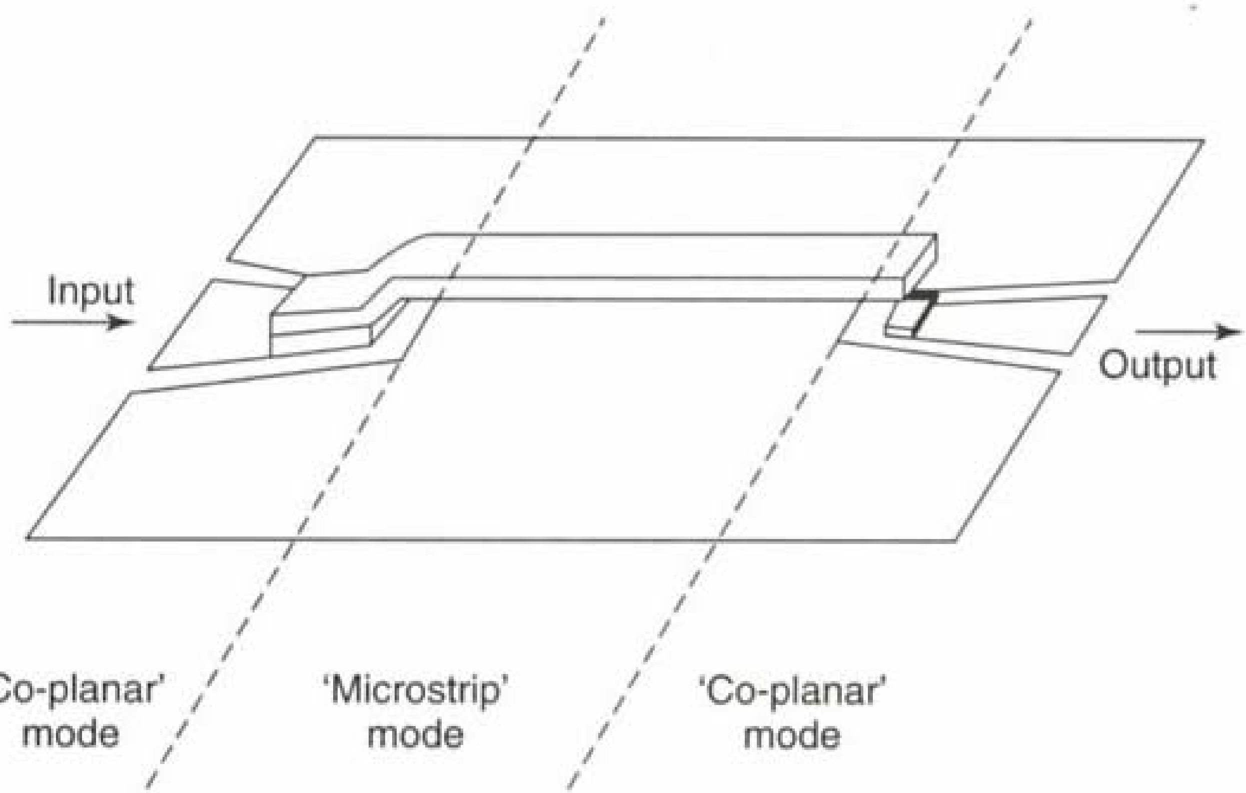


(a)

(b)

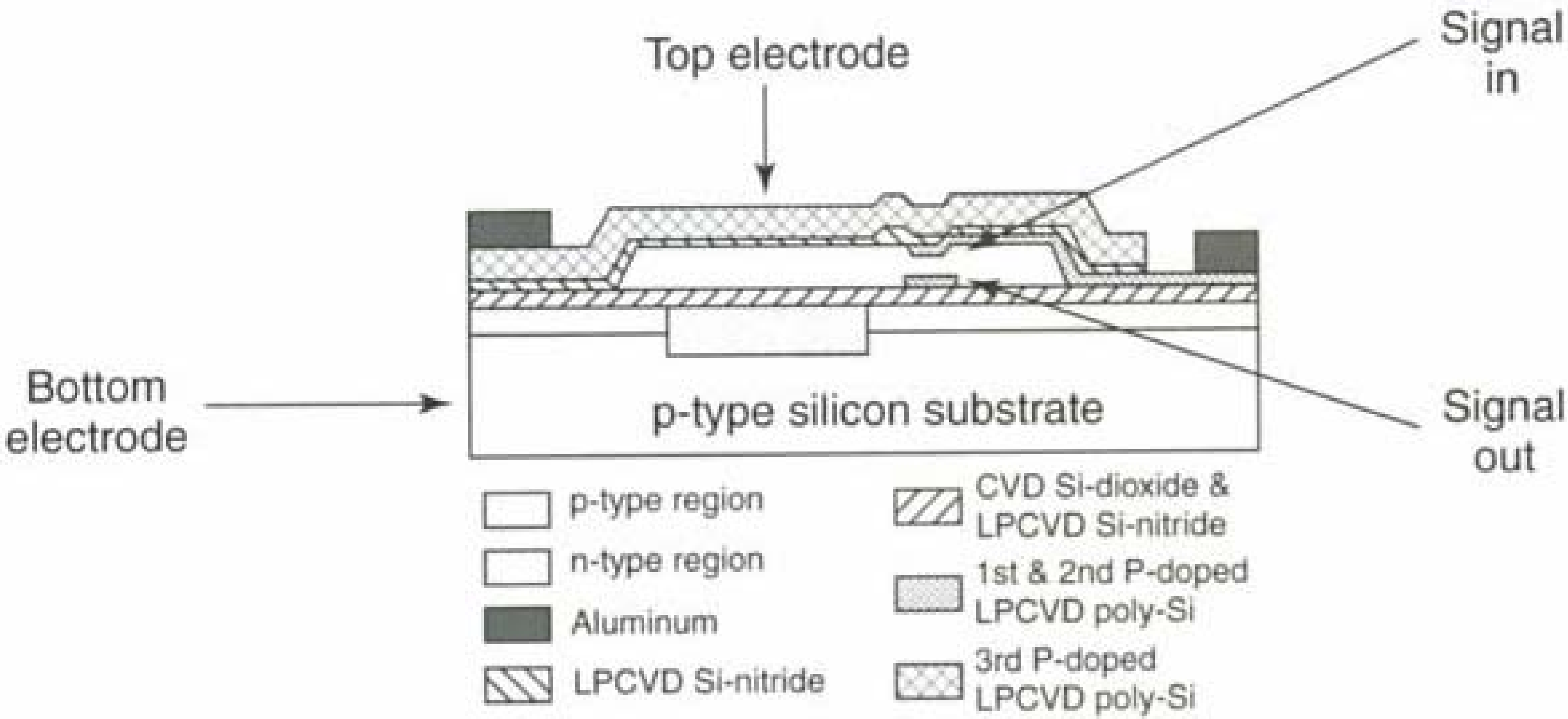
Varadan fig 3.16

Signal propagation along beam



Varadan fig. 3.13

Doubly supported cantilever beam



Varadan fig. 3.15

Cantilever beam switch: critical parameters

- **Contact resistance** for metal – metal
  - Contact pressure
  - Surface roughness
  - Degradation due to increased resistance
    - Soft vs hard metals (gold vs alloys)
- Actuation voltage vs spring constant
- Possibility of **”stiction”** (”stuck-at”)
  - Restoring spring force vs adhesion forces
- **Reliability**
  - Aging
  - Max. number of contact cycles
  - High current is critical (”hot switching”)
    - melting, conductive metal damp → ”microwelding”
- **Self actuation**
  - V_{RF} (RMS) > $V\_{actuation}$

Series switch

- Ideal requirements – typical parameters
  - ”Open/short” transmission line (t-line)
    - 0.1 to 40 GHz
  - ”Infinite” isolation (up)
    - -50 dB to -60 dB at 1 GHz
  - ”Zero” insertion loss (down)
    - -0.1 dB to -0.2 dB

Typical shunt switch

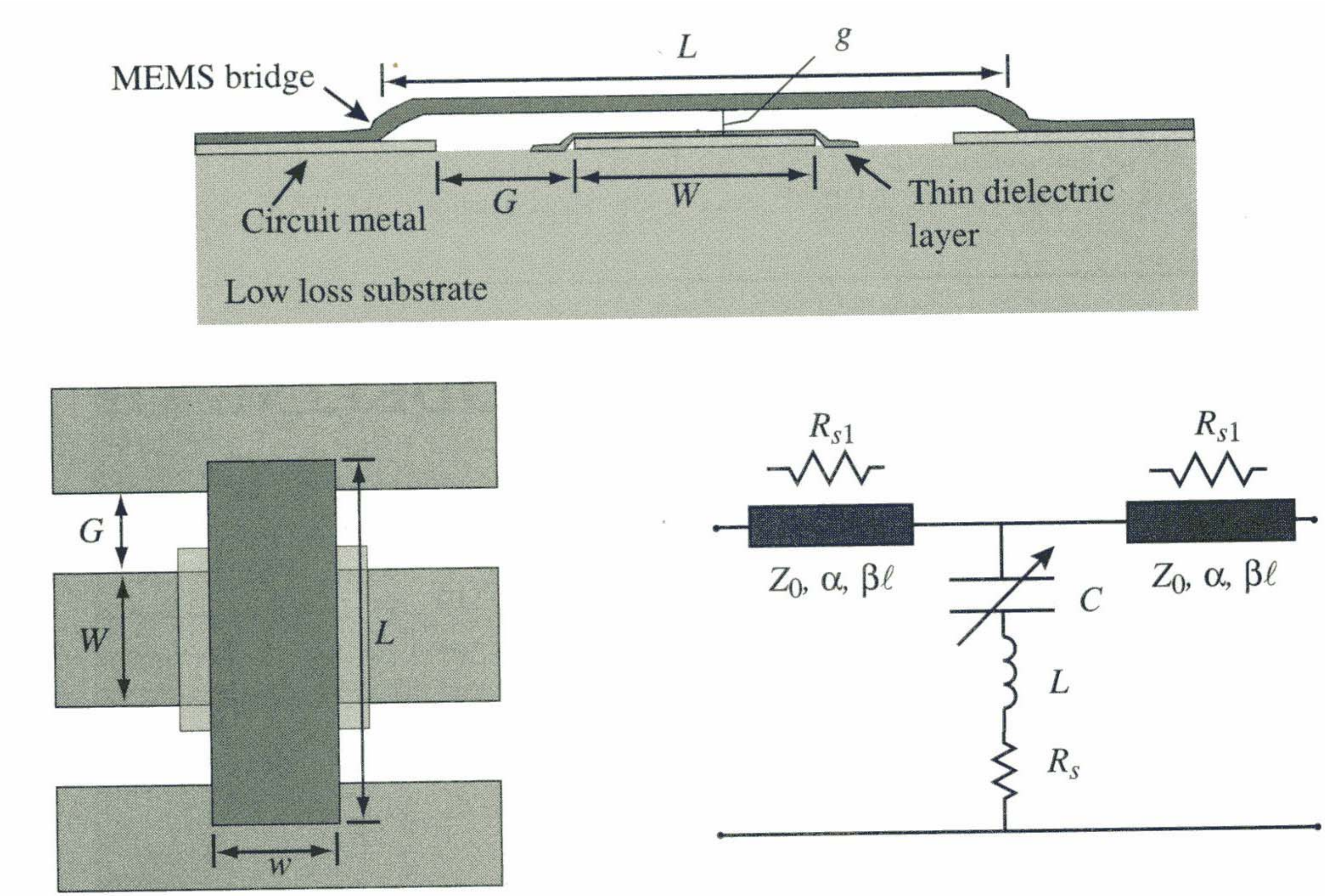
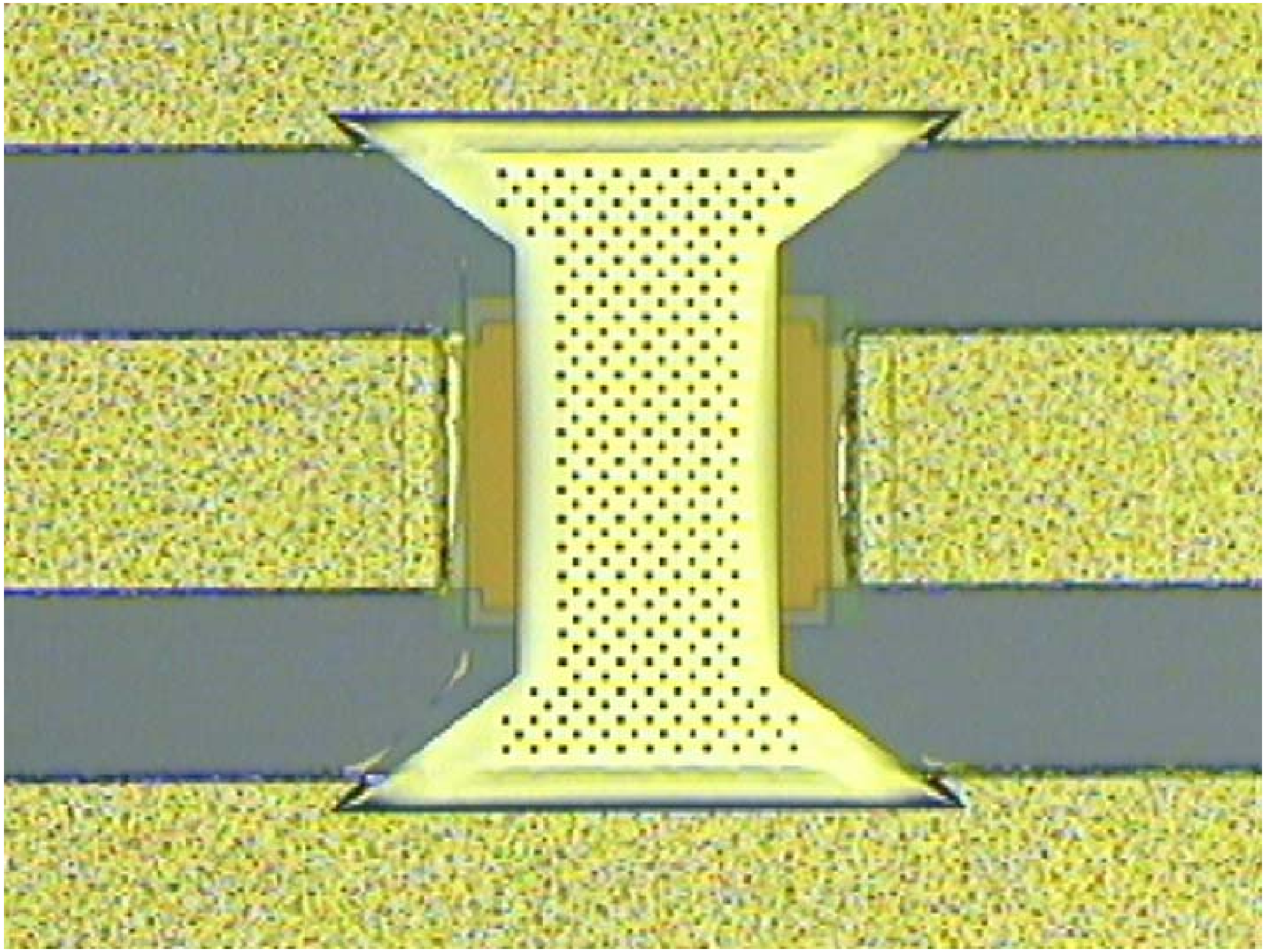


Figure 4.1. Illustration of a typical MEMS shunt switch shown in cross section and plan view. The equivalent circuit is also shown [6] (Copyright IEEE).

RF MEMS switch

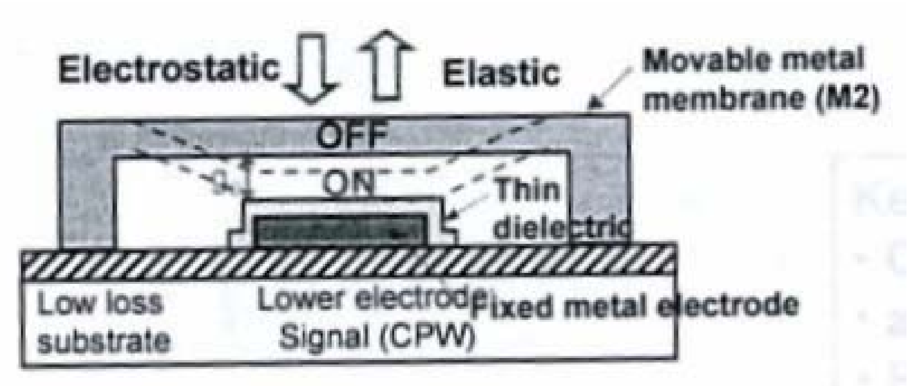
Signal



Coplanar waveguide

Shunt capacitive switch, contd.

- Clamped-clamped beam (c-c beam)
  - **Electrostatic actuation** ←→ beam elasticity
- RF signal is **modulating** actuation voltage
  - ”overlaying”
- No direct contact between metal regions
  - Dielectric (isolator) in-between
  - C_up / C_down important!



Shunt capacitive switch, contd.

- C_down / C_up should be > 100
    - C= εA/d
    - C_down = C_large
    - C_up = C_small
- Impedance Z ~ 1/j ωC
    - For a given ω:
        - C_small→ Z_large = **Z_off**
            - → **isolation**
        - C_large → Z_small = **Z_on**
            - → **short circuiting of RF-signal to GND**

Capacitive switch: design parameters

- Signal lines and switches must be designed for RF
  - Suitable layouts
    - ”CPW – coplanar waveguide” (horizontal)
    - ”microstrip lines” (vertical)
- Switches should be compatible with IC-technology
  - Not too high actuation voltage
  - Proper spring constant
- Alternatives to electrostatic actuation:
  - **Piezoelectric actuation**
- Reliability > 10E9 switching cycles before failure
  - 10E9 is demonstrated

Capacitive switch: critical parameters

- Thickness and quality of dielectric
- Choice of dielectric material
  - High dielectric constant:
  - Gives high ratio C_{down} / C_{up}

- Charging of the surface of the dielectric
  - C -degradation
  - Possible ”stiction”
- ”Breakdown” of dielectric
  - Becomes conductive → disaster!

Shunt switch

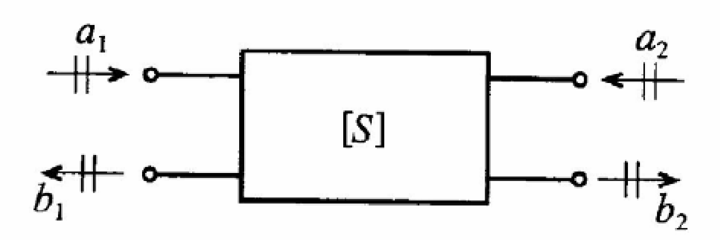
- Ideal requirements – typical parameters
  - Shunt between t-line and GND
    - 5 to 100 GHz
  - ”Zero” insertion loss (up)
    - -0.04 dB to -0.1 dB at 5-50 GHz
  - ”Infinite” isolation
    - -20 dB to -30 dB at 10-50 GHz

Important switch parameters (Var p.111)

- **Actuation voltage**
  - Important parameter for electromechanical design!
    - Desired: VLSI compatibility
    - No problem for semiconductor components
- **Switch speed**
  - 50% control voltage → 90% (10%) of RF-output port envelope
- **Switch transients**
  - Voltage transients at input/output due to changes in actuation voltage
- **Transition time**
  - Output RF signal 10 → 90% or 90 → 10%

Important switch parameters, contd.

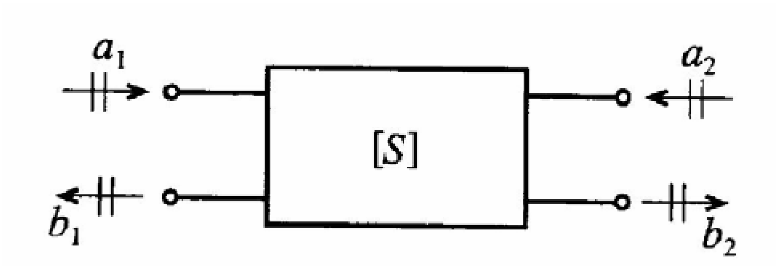
- **Impedance matching**
  - Avoid reflections at both input and output port (for on or off)
- **IL = ”insertion loss”**
  - Defined for **”on-state”**
  - Ratio between signal out (b2) versus signal in (a1)
  - IL = inverse transmission coefficient = 1/S21 in dB
    - S21 = b2/a1 when a2 = 0
  - Design goal: minimize!
    - RF MEMS has low IL at several GHz
    - Much better than for semiconductor switches
    - ”Skin-depth” effect – increased loss, IL, at high frequencies



- **Series resistance**
  - Relevant when interconnecting switches in series
  - Gives lower signal level

Important switch parameters, contd.

- **Isolation**
  - Defined in **”off-state”**
  - The **inverse** ratio between signal out (b2) versus signal in (a1)
    - Defined as 1/S21 i dB
  - Alternatively: The inverse ratio between signal transmitted back to the input (b1) versus signal in on the output port (a2)
    - Defined as 1/S12 i dB
  - Large value → low coupling between terminals



Important switch parameters, contd.

- **Bandwidth**
  - An upper limit is usually specified
    - Resistances and parasitic reactances influence the value
- **Resonance frequency**
  - Specifies the frequency where the switch “resonates”
  - Resonance when potential and kinetic energy are “equal”
    - $j\omega L = - 1/ j\omega C$
    - Reactances are of equal magnitude
    - Frequency depends on k and m → 1/C og L

    - Operational bandwidth should be **outside** the frequency of natural resonance mode
    - → Limits minimum or maximum switching speed

Important switch parameters, contd.

- **RF power capability**
  - Specifies **linearity** between output power and input power
  - Possible degradation of switch for high power
- **Phase and amplitude ”tracking” and ”matching”**
  - Specifies how well the signal keeps the ”shape”
  - Important for ”multi-throw” switches
  - Each branch may have different length and loss, giving phase and amplitude differences
- **”Intercept” point**
  - Specifies when distortion of output power versus input power “starts”

Important switch parameters, contd.

- **Life cycle** and degradation
  - Influences from the environment
  - Fatigue fracture
  - This aspect is important for all parts containing **movable structures!**

Design of RF MEMS switches

- **Electromechanical** design, I
- Remaining contents of today´s lecture
  - Design parameters determining pull-in
  - Effect of dielectric
  - Roughness
  - Simplified analysis of cantilever beam
    - Elasticity
    - Deflection of beam
  - Mechanical anchoring
    - Folded springs
    - Material choice

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:

$$\boxed{V_{PI} = \sqrt{\frac{8K}{27\varepsilon_0 W w} g_0^3}}$$

    - Definition of parameters:
      - K spring constant
      - g0 initial gap
      - A=W*w = area

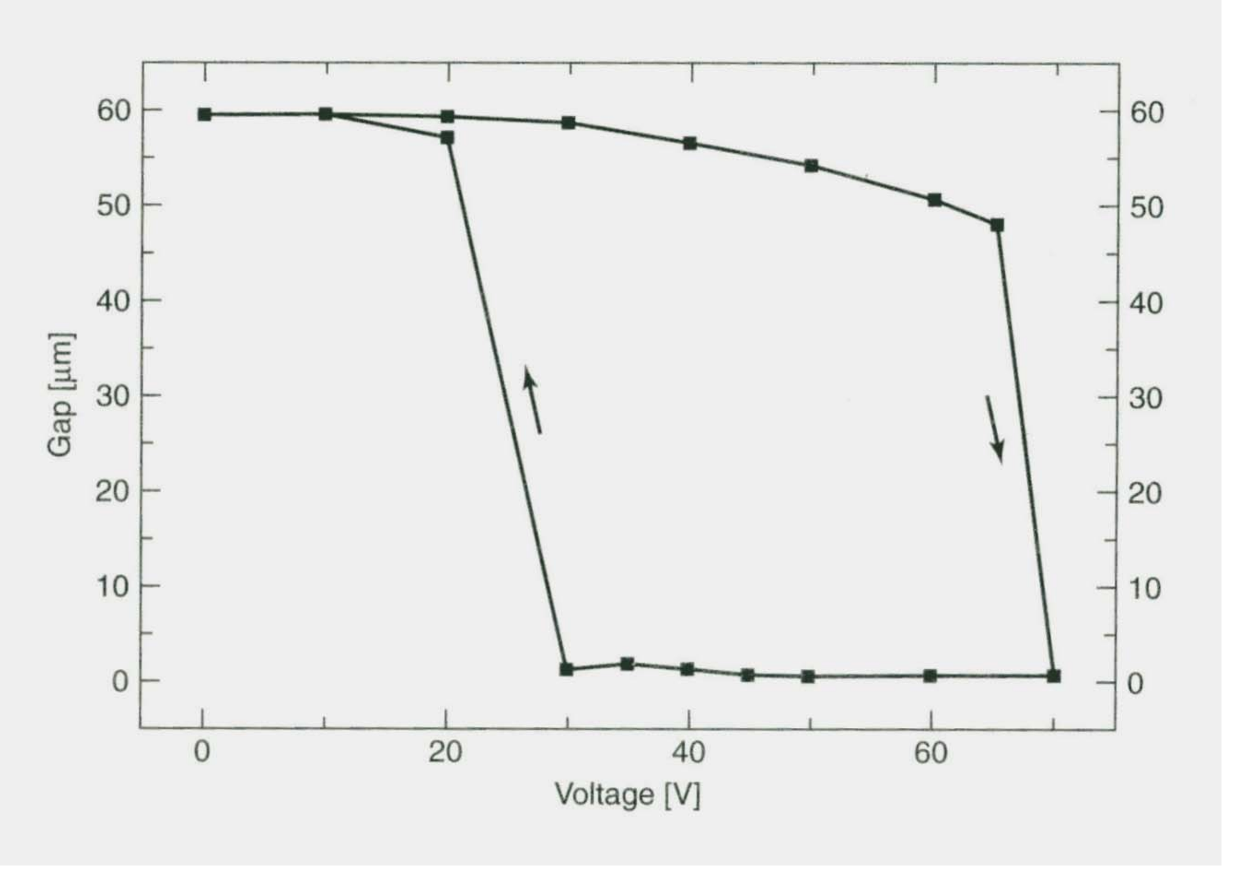
Discussion of design parameters

- Vpi
  - Should be low for CMOS compatibility
- A=W*w
  - Should be large. Size requirement is a limitation (→ compactness)
- g0
  - Should be small. Depending of fabrication yield. Must be traded against RF performance (return loss and isolation)
- K
  - Low voltage when soft spring. Dependent on proper mechanical design. Make sure that the beam can be “released”!

$$V_{PI} = \sqrt{\frac{8K}{27\varepsilon_0 W w} g_0^3}$$

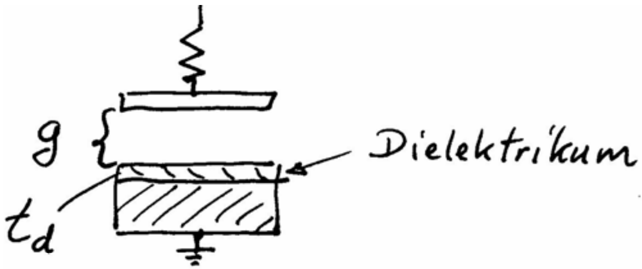
Hysteresis

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

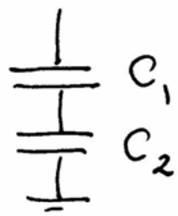


Varadan fig. 3.18

Parallel plate capacitance for shunt switch



(Dielectric)



$$C_1 = \varepsilon_0 \frac{A}{g}, C_2 = \varepsilon_0 \varepsilon_r \frac{A}{t_d}$$

$$Z = \frac{1}{sC_{up}} = \frac{1}{sC_1} + \frac{1}{sC_2}$$

$$C_{up} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}}$$

$$C_{up} = \frac{1}{\frac{g}{\varepsilon_0 A} + \frac{t_d}{\varepsilon_0 \varepsilon_r A}} = \frac{\varepsilon_0 A}{g + \frac{t_d}{\varepsilon_r}} \approx \frac{\varepsilon_0 A}{g_{eff}}$$

Down-state

$$C_d = \frac{\varepsilon_0 \varepsilon_r A}{t_d}$$ Fringe field negligible

Down-state / up-state

$$\frac{C_d}{C_{up}} = \frac{\dfrac{\varepsilon_0 \varepsilon_r A}{t_d}}{\dfrac{\varepsilon_0 A}{g_{eff}} + \underset{\uparrow}{C_f}} \approx \frac{\varepsilon_r g_{eff}}{t_d} \approx \frac{\varepsilon_r g}{t_d}$$

Fringe field effect

Typical value 60 - 120

Electromechanical design of RF MEMS switch (2)

Hysteresis of capacitive switch (*source: H. Tilmans*)

$g_o = \textit{zero-voltage gap spacing}$

$g = g_o - x$

$g_{eff} = g_o + \dfrac{g_\varepsilon}{\varepsilon_r} \approx g_o$

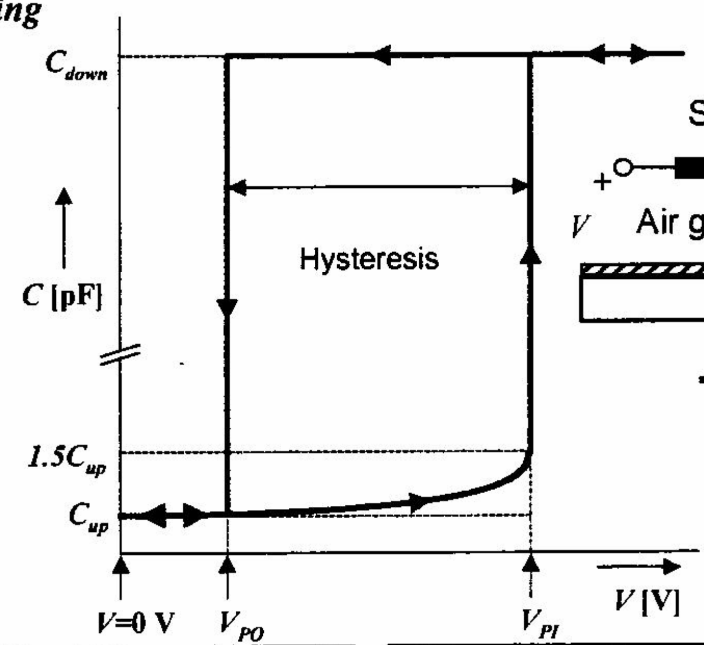
$F_{el} = \dfrac{\varepsilon_0 A V^2}{2g^2}$

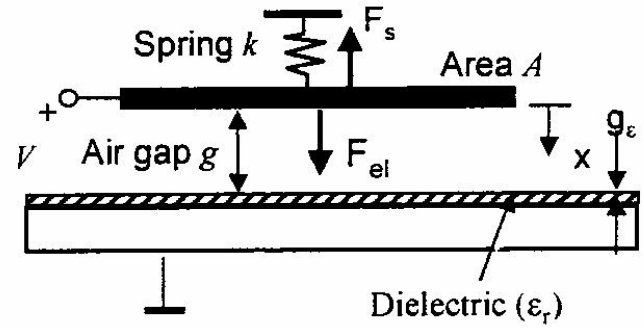
$F_s = k(g_o - g)$

$C_{up} = C(V=0) = \varepsilon_0 \dfrac{A}{g_{eff}}$

$C_{down} = C(V > V_{PI}) = \varepsilon_0 \varepsilon_r \dfrac{A}{g_\varepsilon}$

$\dfrac{C_{down}}{C_{up}} = \dfrac{\varepsilon_r g_{eff}}{g_\varepsilon} \approx \dfrac{\varepsilon_r g_o}{g_\varepsilon}$





$$\boxed{V_{PO} = \sqrt{\frac{2kg_0 g_\varepsilon^2}{\varepsilon_r^2 \varepsilon_0 A}}}$$

$$\boxed{V_{PI} = \sqrt{\frac{8}{27}\frac{kg_{eff}^3}{\varepsilon_0 A}}}$$

Ionescu, EPFL

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Thickness off dielectric

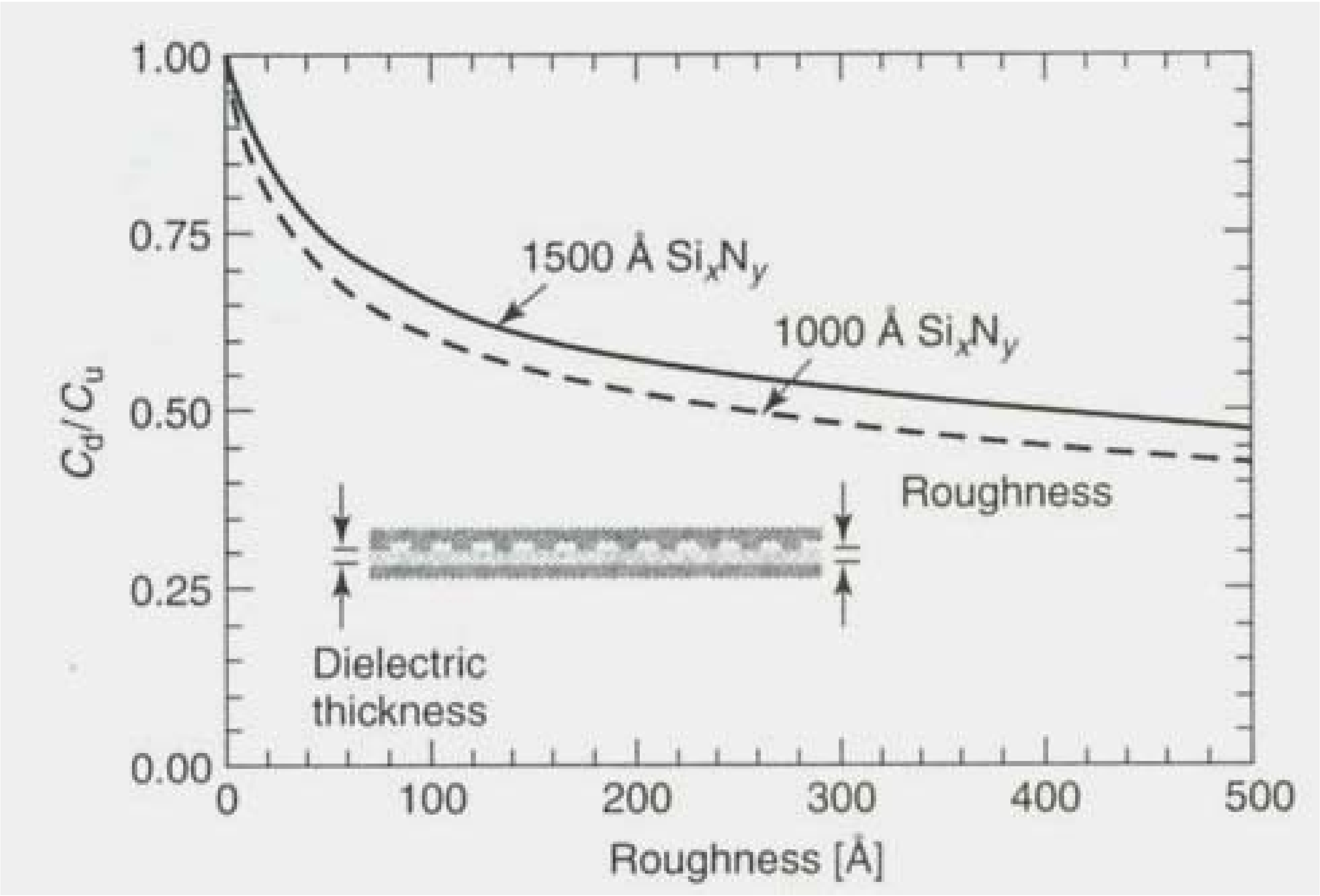
- Thickness of dielectric controls the capacitance ratio C_{down}/C_{up}
  - Thin layer may give high Cd / Cu –ratio
    - Beneficial for performance
  - Problem with thin layer
    - Difficult to deposit: ”pinhole” problem
    - In real life: min 1000 Å,
    - Should sustain high voltage without breakdown, 20 – 50V

  - Dielectric materials with higher ε_r give higher Cd/Cu-ratio
    - ε_r from 7.6 for SixNy → 40-200 for strontium-titanate-oxide
    - **PZT: ε_r >1000!**

Roughness

- Cd/Cu may decrease due to roughness
  - Increased roughness reduces the ratio
- Metal-to-metal: roughness degrades contact
  - Increased resistance in contact interface
- Var fig 3.26 shows effect of roughness →

Effect of roughness



Varadan fig. 3.26

Simplified analysis of cantilever beam

- Look at interaction between **elastic** and **electrostatic** properties

- Starting with some **elasticity** →
  - Slides from Arlington

Axial Stress And Strain

Stress: force applied to surface

$\sigma = F/A$

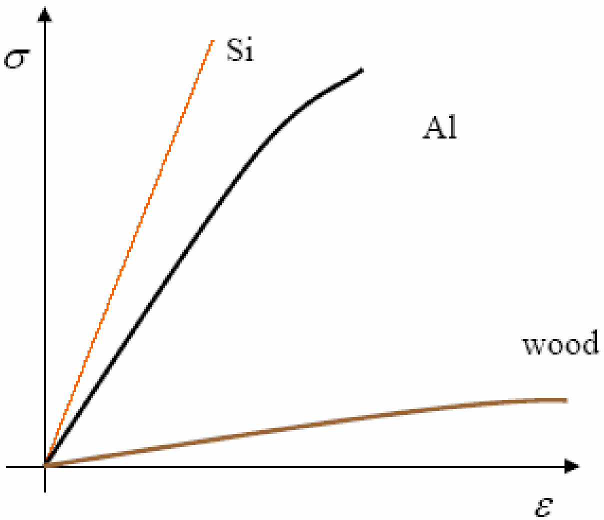
measured in N/m^2 or Pa

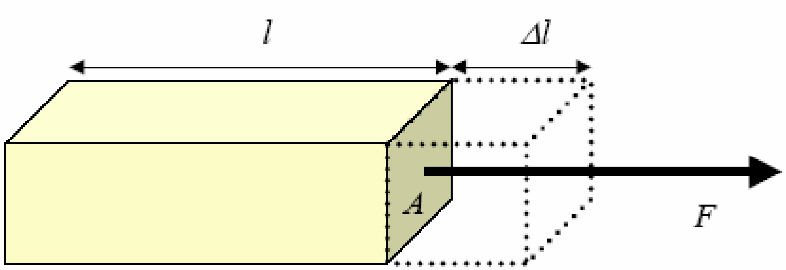
compressive or tensile

Strain: ratio of deformation to length

$\varepsilon = \Delta l \,/\, l$

measured in %, ppm, or microstrain





Young's Modulus:

$E = \sigma/\varepsilon$

Hooke's Law:

$K = F/\Delta l = E\,A/l$

Shear Stress And Strain

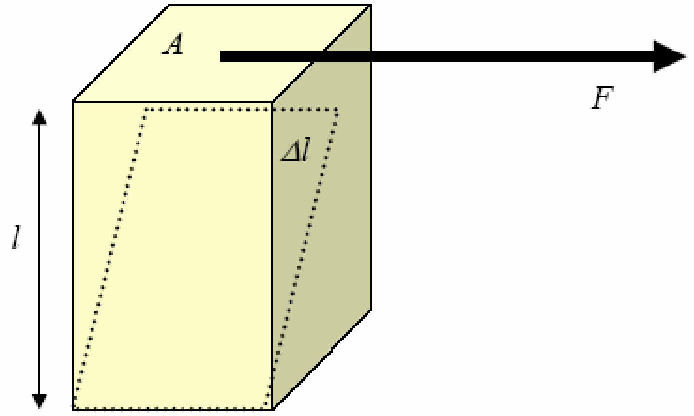
Shear Stress: force applied parallel to surface

$\tau = F/A$

measured in N/m^2 or Pa

Shear Strain: ratio of deformation to length

$\gamma = \Delta l / l$



Shear Modulus:

$G = \tau / \gamma$

Poisson's Ratio

Tensile stress in x direction results in compressive stress in y and z direction (object becomes longer and thinner)

Poisson's Ratio:

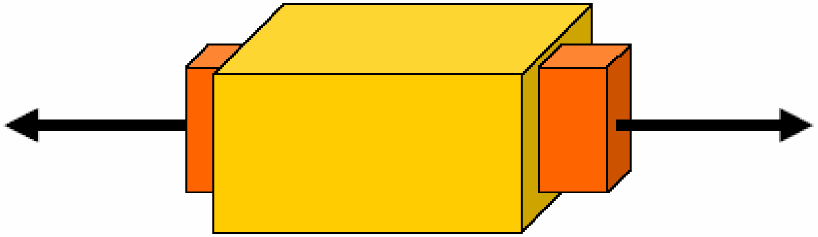
$\nu = -\varepsilon_y / \varepsilon_x$

$=$ - transverse strain / longitudinal strain

Metals: $\nu \approx 0.3$

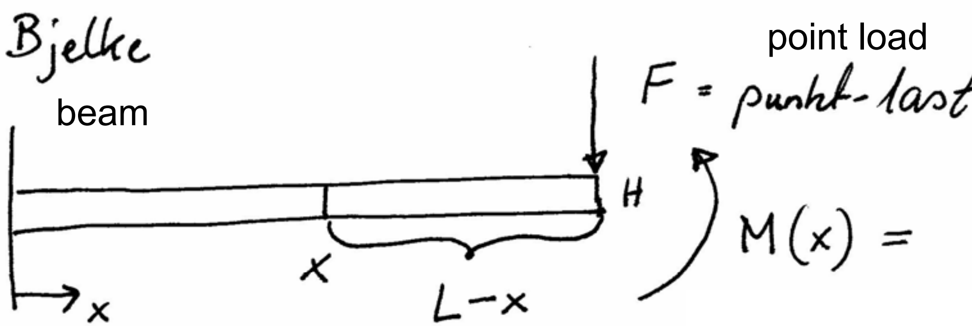
Rubbers: $\nu \approx 0.5$

Cork: $\nu \approx 0$



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



Bending moment in x

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

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

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

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

Bending moment
(force * arm)

$$M(x) = -F(L-x)$$

$$\frac{d^2 w(x)}{dx^2} = \frac{F}{E \cdot I}(L-x)$$

$$w(0) = 0$$

Boundary conditions

$$\frac{dw(0)}{dx} = 0$$

Suppose a solution

$$w(x) = A + Bx + Cx^2 + Dx^3$$

$$\frac{dw(x)}{dx} = B + 2Cx + 3Dx^2$$

$$\frac{d^2w(x)}{dx^2} = 2C + 6Dx$$

Boundary conditions

$$w(0) = 0 \quad \Rightarrow \quad A = 0$$

$$\frac{dw(0)}{dx} = 0 \quad \Rightarrow \quad B = 0$$

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

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

Max. deflection at x = L

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

Beam stiffness represents a spring with spring constant k_cantilever

Compare with

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

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

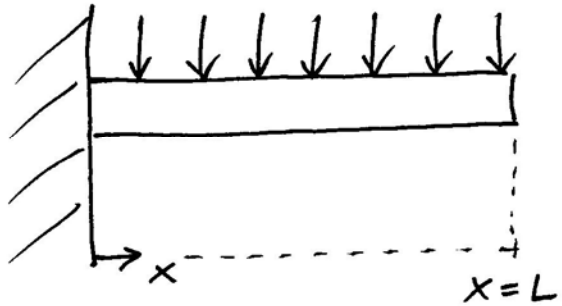
Spring constant

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

For a **double clamped** beam we have (Varadan p. 132)

$$k_{cc} = 16\, E \cdot W \left(\frac{H}{L}\right)^3$$

Beam equation for distributed force



$$q_0 = \frac{F}{L}$$

$$EI \cdot \frac{d^4 w(x)}{dx^4} = q_0$$

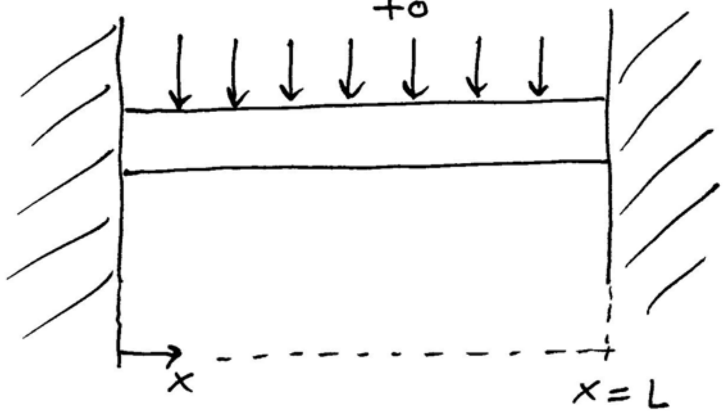
$$w(0) = w'(0) = 0$$
$$w''(L) = w'''(L) = 0$$

$$\Rightarrow \quad w(x) = \frac{q_0}{24EI} x^2 \left(x^2 + 6L^2 - 4Lx \right)$$

$$w(L) = \frac{q_0}{8EI} L^4 = \frac{F}{8EI} L^3$$

$$k_{cantilever} \approx \frac{F}{w(L)} = \frac{8EI}{L^3} = \frac{2}{3} E W \left(\frac{H}{L} \right)^3$$

c-c-beam



$$EI \cdot \frac{d^4 w(x)}{dx^4} = q_0$$

$$w(0) = w'(0) = 0$$
$$w(L) = w'(L) = 0$$

$$\Rightarrow w(x) = \frac{q_0}{24EI} x^2 \left(x^2 - 2Lx + L^2 \right)$$

$$w\left(\frac{L}{2}\right) = \frac{q_0}{24EI} \cdot \frac{L^4}{8} = \frac{F}{24EI} \cdot \frac{L^3}{8}$$

$$k_{c\text{-}c} \approx \frac{F}{w\left(\frac{L}{2}\right)} = \frac{24 \cdot 8 \cdot EI}{L^3} = 16 E W \left(\frac{H}{L}\right)^3$$

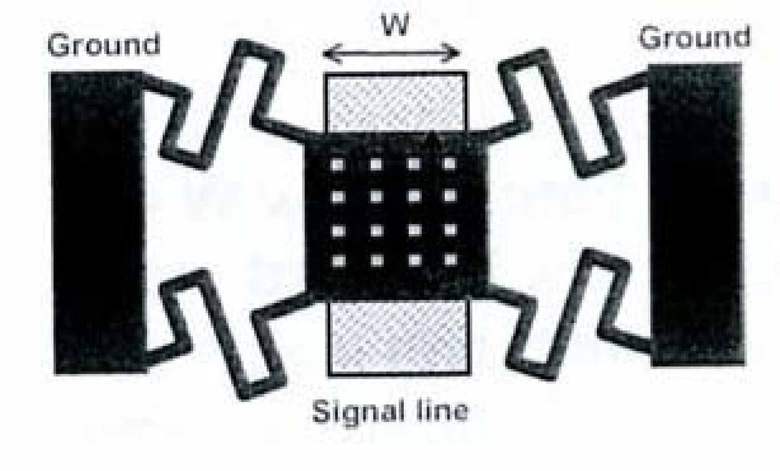
Mechanical anchoring

- Folded springs are often used
- Why?
  - To obtain low actuation voltage (< 5V) for mobile communication systems

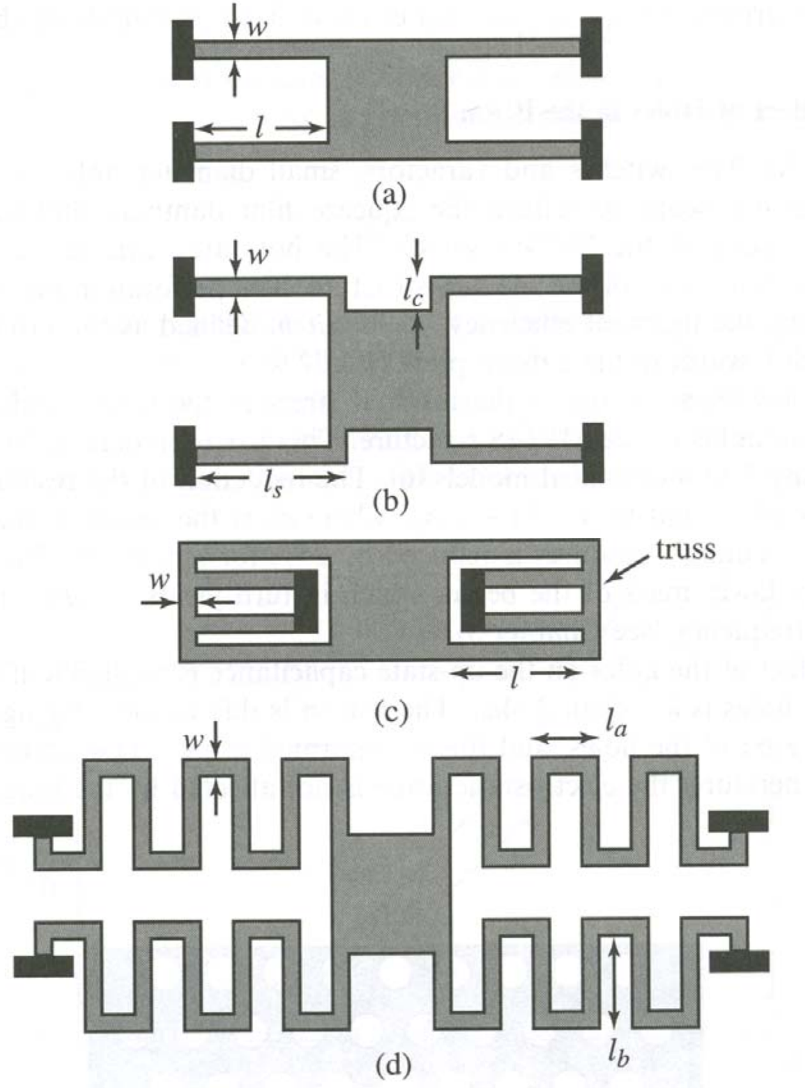
- → **Folded spring gives low K on a small area**

Reduced actuation voltage

- Actuation voltage
  - ”pull-down” needed
  - Should be < tens of V
- Membrane should not be too stiff
  - **Use meanders**
  - Folded spring has lower k
  - **Area effective!**



Different folded springs

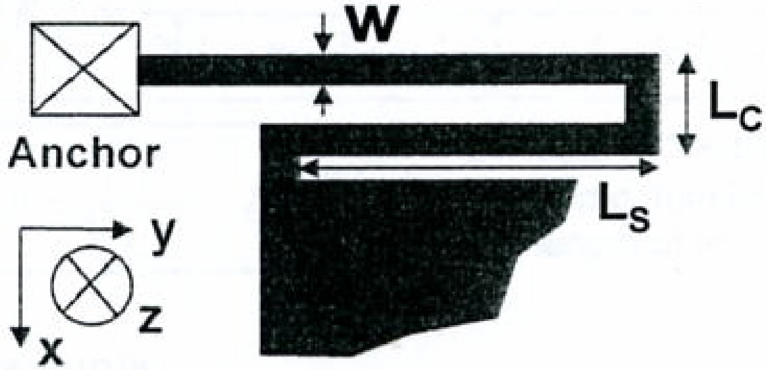


Rebeiz fig. 2.10

Electromechanical design of RF MEMS switch (3)

- **Suspension (arm) folded design**

Low voltage operation (<5V) for mobile communication applications requires folded suspension design: low-k in small area



L_S: span beam length
L_C: connector beam length
w : width
t : metal thickness
E: Young's modulus
ν: Poisson's ratio

$$k_z = \frac{\left(\frac{Ew}{2}\right)\left(\frac{t}{L_C}\right)^3}{1+\frac{L_S}{L_C}\left[\left(\frac{L_S}{L_C}\right)^2+12\frac{1+\nu}{1+(w/t)^2}\right]}\Bigg|_{L_S>>L_C} \rightarrow 2Ew\left(\frac{t}{L_S}\right)^3$$

Approximation

Independent of ν

$$k_x = 2Et\left(\frac{w}{L_c}\right)^3$$

$$k_y = 2Et\left(\frac{w}{L_S}\right)^3$$

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Ionescu, EPFL

Spring materials?

- **<u>Metal or polysilicon</u>: case study (one) serpentine spring**

Ls=220um, Lc=18um, t=2um, w=6um

Au	**Al**	**Polysilicon**
E_{Au}~80GPa	E_{Al}~70GPa	$E_{Si\text{-}poly}$~170GPa
ν_{Au} ~0.22	ν_{Al}~0.3	$\nu_{Si\text{-}poly}$~0.3

Elastic constant K_z(= $4k_z$)

K_{zAu}=0.721N/m **K_{zAl}=0.631N/m** **K_{zpoly}=1.533N/m**

Elastic constant K_x

$K_{xAu}=1.19\times10^4$N/m $K_{zAl}= 1.04\times10^4$N/m $K_{zpoly}= 2.52\times10^4$N/m

Elastic constant K_y

K_{yAu}=6.49N/m K_{zAl}=5.68N/m K_{zpoly}=13.79N/m

Estimated V_{PI} (area = 100x100 / 20x20 um^2, 2um-gap):

V_{PIAu}= 4.4V/21.9V V_{PIAl}=4.1V/20.6V V_{PIpoly}=6.4V/32V

Spring materials, contd.

- Summary
  - Metal seems to be a better choice for RF MEMS spring structures than polySi
    - Low actuation voltage (+)
    - Metal has lower resistivity (+)
  - BUT: PolySi is stiffer
    - Higher actuation voltage (÷)
    - Mechanical release force larger (+)
      - **Avoids ”stiction”**