INF5490 RF MEMS

LN11: RF MEMS capacitors

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Today's lecture

- Passive components in RF circuits
  - Capacitors, C
  - Inductors, L
- Tunable **RF MEMS capacitors**
  - **Vertical** tunable capacitors
  - **Lateral** tunable capacitors
  - **Thermal** tunable MEMS capacitance
  - **Piezoelectric** actuator tunable capacitors
  - Tuning by changing of **dielectric** material
- RF MEMS **capacitance banks**

Passive components in RF circuits

- → **MEMS capacitors and inductors**
  - Relevant as **replacements** for traditional ”off-chip” passive components
  - Tuneability and programability are desired
- **MEMS capacitors**
  - Simple, tunable capacitances
    - **= varactor** (”variable reactor”)
  - Programable capacitance banks with fixed C
- **MEMS inductors** (LN12)
  - Simple, fixed inductors
  - Programable inductance banks with fixed L

Use of tunable capacitors

- VCO = ”Voltage controlled oscillator”
  - Value of C determines the frequency
  - Voltage tuned
  - VCO has strict requirements on
    - Stability
    - Low phase noise
    - Wide frequency bandwidth
- Tunable filters
- Tunable network
- Impedance matching
- Phase shifters

MEMS compete with commercial semiconductor technologies

- Many discrete Si and GaAs varactors exist
  - → 30 GHz
  - Ex. Q = 30-60 for 0.5-5 GHz (SiGe)
  - MEMS varactors not mature enough to replace GaAs varactors, especially for frequencies below 5 GHz
- MEMS varactors have not developed as fast as MEMS switches
  - But: is the RF MEMS component closest to commercial applications
  - Relative mature technology
  - Already, many replacements using MEMS have been demonstrated, DC → 100 GHz

Typical characteristics for MEMS varactors

- + Potentially **high Q-values**
  - High Q-value (>100) over a wide frequency band
    - Ex. Q = 100 – 400 for mm-frequencies
- + Simple, compared to alternative technologies
- + Capable of sustaining large RF voltages
- + Low cost fabrication
  - On glass, ceramic, high-resistivity Si-substrate
  - Ex. ”low-cost” 3 – 60 GHz tunable networks and filters
- + More reliable
- + Simple and low-cost packaging

Why high Q-values?

- 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)

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

Characterize power loss due to dissipation mechanisms in reactive elements.

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

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

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

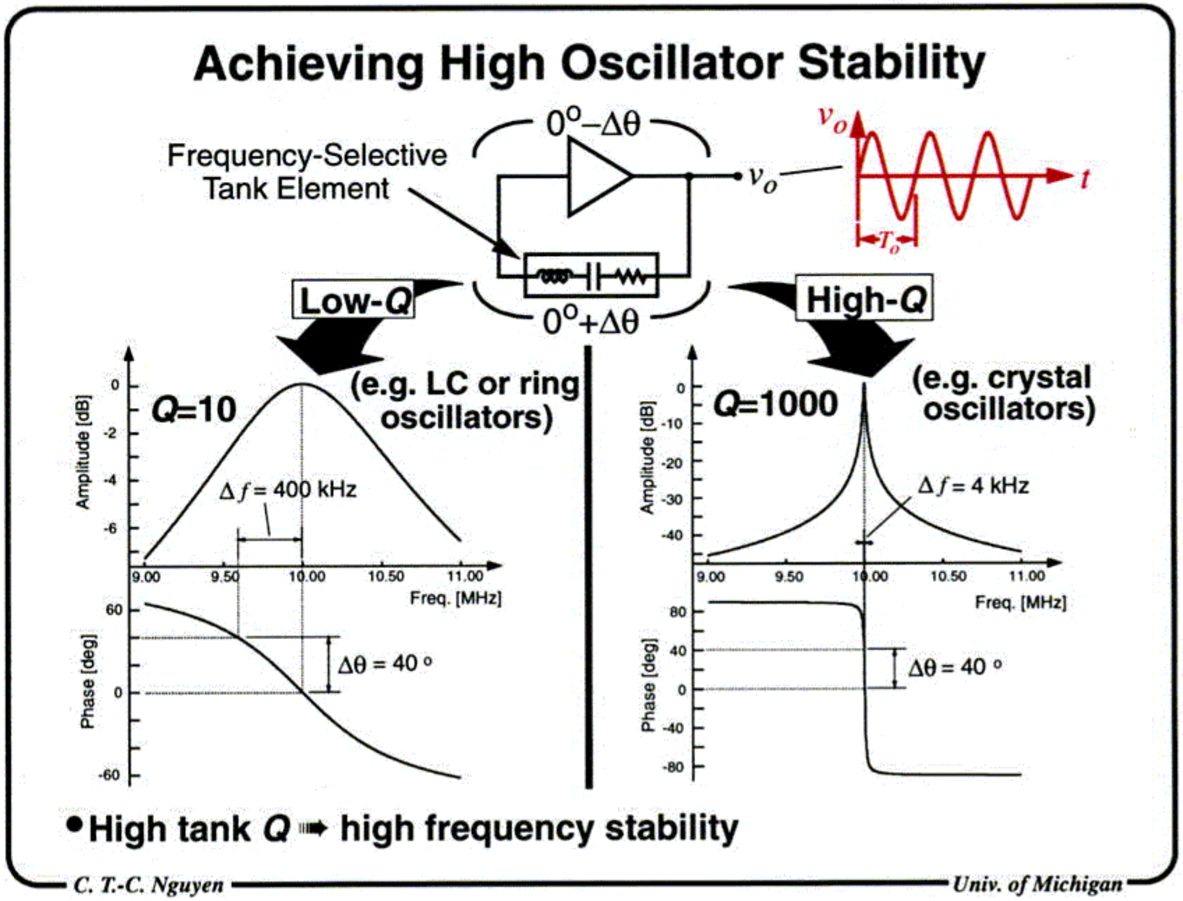
Unloaded : Q (intrinsic)

Loses due to external load : Q_L

→ Insertion loss at resonance: $IL(dB) = 20 \log (1 + \frac{Q_L}{Q})$

Relation between Q-factor and oscillator stability

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



Equivalent circuit for capacitor

- At high frequency → inductance
  - has a characteristic self resonance frequency
  - Inductance should be as low as possible so the self resonance frequency is much higher than the frequency used in normal operation

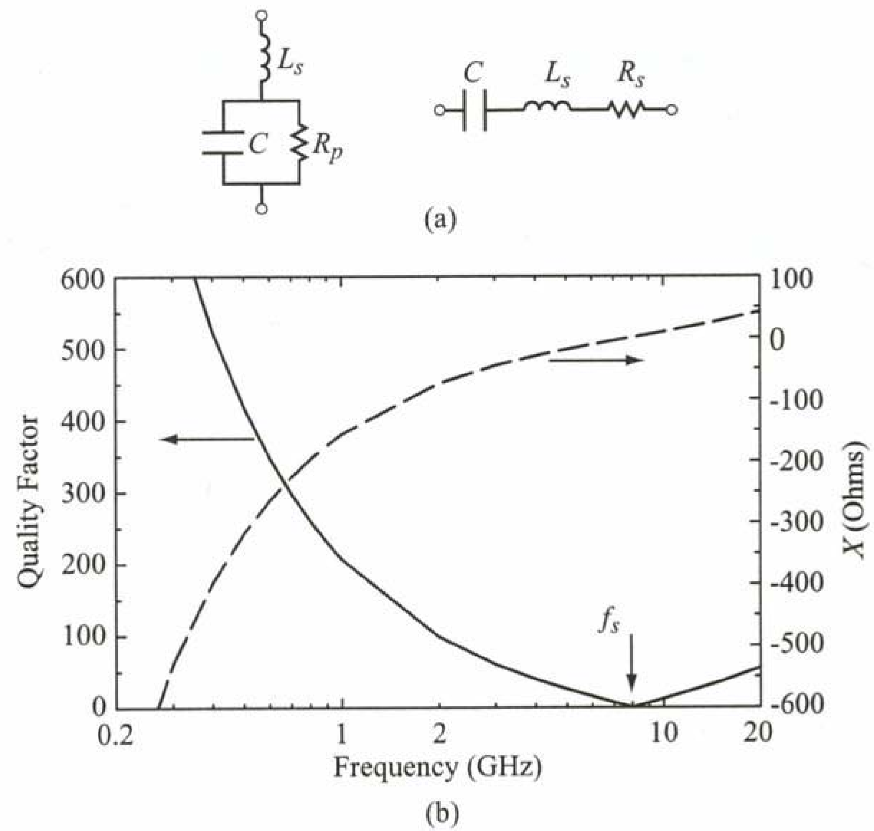


Figure 11.1. (a) Capacitor models. (b) Calculated reactance and Q of a 1-pF capacitor with $L_s = 0.4$ nH and $R_s = 0.83\ \Omega$ ($f_s = 8$ GHz).

Impedance and Q-factor for a discrete capacitor

Q-factor given for ωL<<1/ωC

$$Z = R_s + j\left(\omega L_s - \frac{1}{\omega C}\right) \qquad \text{for a series model}$$

$$\simeq \frac{1}{\omega^2 C^2 R_p} + j\left(\omega L_s - \frac{1}{\omega C}\right) \qquad \text{for a parallel model} \qquad (11.2)$$

The capacitor quality factor, Q, is derived to be

$$Q = \frac{|\mathrm{Im}(Z)|}{\mathrm{Re}(Z)} = \frac{1}{\omega C R_s} \qquad \text{for a series model}$$

$$= \omega C R_p \qquad \text{for a parallel model} \qquad (11.3)$$

Calculations shown next →

Rebeiz

Calculations I:

SERIE (series)

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

Selvresonans : $\mathrm{Im}(Z) = 0$ $\qquad \omega_0 = \frac{1}{\sqrt{LC}}$

(Self resonance)

Under selvresonans

Below self resonance)

$$\omega^2 << \frac{1}{LC}$$

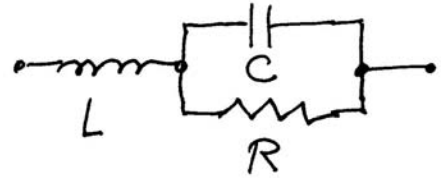
$$\omega L << \frac{1}{\omega C}$$

$$Q = \frac{|\mathrm{Im}(Z)|}{\mathrm{Re}(Z)} \approx \frac{\frac{1}{\omega C}}{R} = \frac{1}{\omega C R}$$

Calculations II

PARALLELL

(parallel)



$$Z = sL + (C // R) = sL + \frac{\frac{1}{sC} \cdot R}{\frac{1}{sC} + R} = sL + \frac{1}{sC + \frac{1}{R}}$$

$$z = sL + \frac{1}{sC} + t$$

$$t = \frac{1}{sC + \frac{1}{R}} - \frac{1}{sC} = \frac{-\frac{1}{R}}{s^2C^2 + sC\frac{1}{R}} = \frac{-1}{s^2C^2R + sC}$$

$$t = \frac{1}{\omega^2C^2R - j\omega C} \approx \frac{1}{\omega^2C^2R}$$

↑ Dominerende ved lave frekvenser (dominating term at low frequencies)

$$z = j\left(\omega L - \frac{1}{\omega C}\right) + t = j\left(\omega L - \frac{1}{\omega C}\right) + \frac{1}{\omega^2C^2R}$$

$$Q = \frac{|\mathrm{Im}(z)|}{\mathrm{Re}(z)} = \frac{\frac{1}{\omega C}}{\frac{1}{\omega^2C^2R}} = \frac{\omega^2C^2R}{\omega C} = \underline{\underline{\omega CR}}$$

Challenges for RF MEMS capacitors

- ÷ Tuning ratio for MEMS varactors is small
  - 1.2 – 2.5
  - For semiconductor varactors: 4 – 6
  - → Obtain required **Tuning Ratio (TR)**
    - Definition TR: C_{max} / C_{min}
    - Should be > 2
- ÷ MEMS is sensitive to various noise effects present for low spring constant, k
  - Low k is desired for 3 – 5 V applications
  - A low k-value is a challenge due to
    - Acceleration, RF power self actuation, noise effects

Parallel plate capacitor

- Basic equations
  - $Q = V C$, $I = C\, dV/dt$
  - $C = \varepsilon A / g$

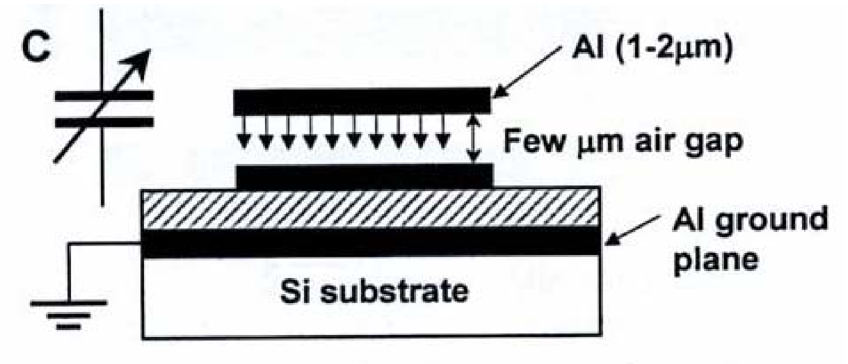
- NB! C generally tuned by 3 parameters
  - g, gap
  - A, area
  - ε, dielectric constant

Tunable RF MEMS capacitors

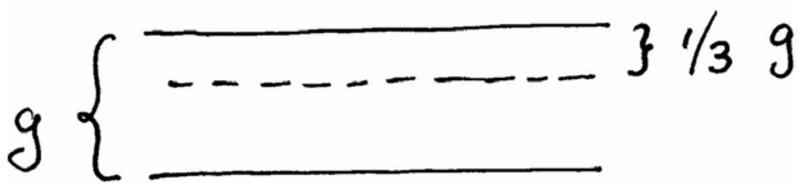
- Electrostatic actuation is a dominating mechanism for tuning
  - Low power consumption, simple
- **Vertical** electrostatic displacement
  - Tuning the gap (**non-linear** change) in parallel plate capacitor
    - 2-plate capacitance
    - 3-plate capacitance
    - Double air-gap capacitance
    - Other examples
- **Horizontal** (lateral) displacement
  - Tuning of area (**linear** change)
- **Thermally** tunable MEMS capacitance
- **Piezoelectric** actuator tunable capacitance
- Tuning by change of **dielectric** material

Two-plate tunable MEMS capacitance

- Young & Boser, Berkeley
- Gap-tuning
- One plate can move by electrostatic actuation
- Equilibrium between elastic and electrical forces



Calculation of TR for 2-plate capacitance



$$C_{min} = \varepsilon \frac{A}{g} \qquad C_{max} = \varepsilon \frac{A}{\frac{2}{3} g} = 1.5\, C_{min}$$

$$C_{max} = 150\% \cdot C_{min} \Rightarrow TR = 150\%$$

Theoretical TR = 150%. Limited by the pull-in effect

Young & Bover, Berkeley

- Etching a hole in capacitance plate
  - For decreased squeezed-film damping
  - Positive for "release"-step in the process

- Theoretical tuning range: 50% (limited by pull-in effect)
- Practical tuning range (demonstrated): TR=16%, C_{max}=2.46pF, C_{min}=2.11pF, V_A=5V
- RF performance: Q=62 @ 1GHz

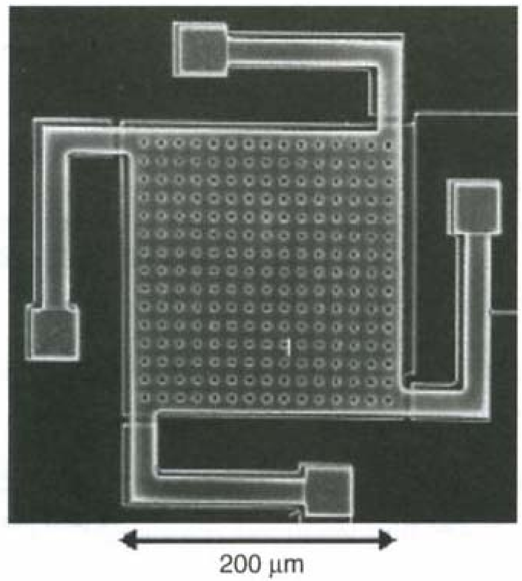
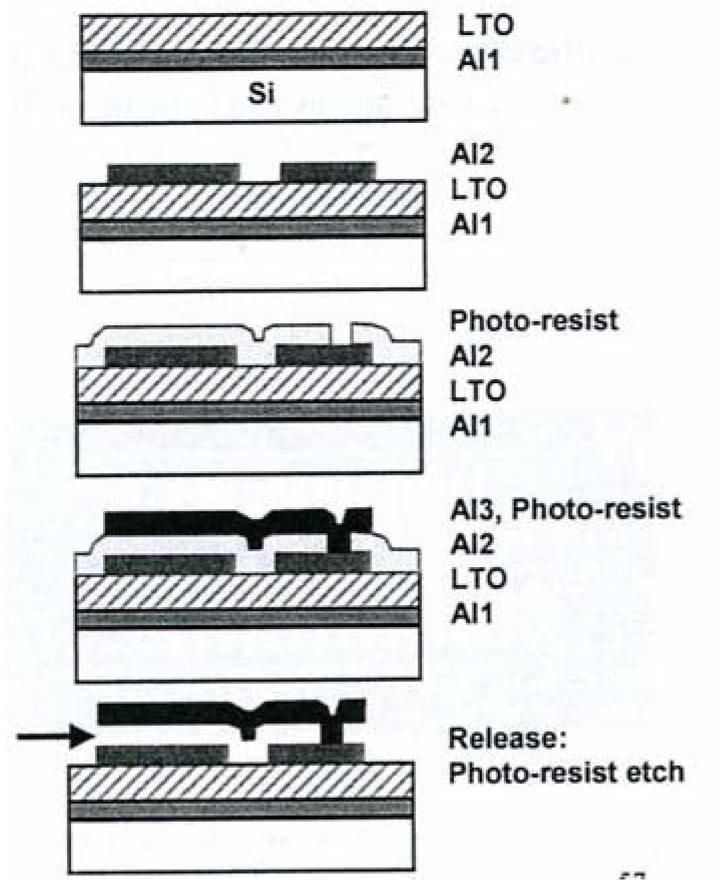


Figure 4.33 Top view of a micromachined variable capacitor. Reproduced from D.J. Young and B.E. Bover, 1996, 'A micromachined variable capacitor for monolithic low-noise VCOs', in *Proceedings of the International Conference on Solid-state sensors and Actuators*, IEEE, Washington, DC: 86–89, by permission of IEEE, © 1996 IEEE

Implementation

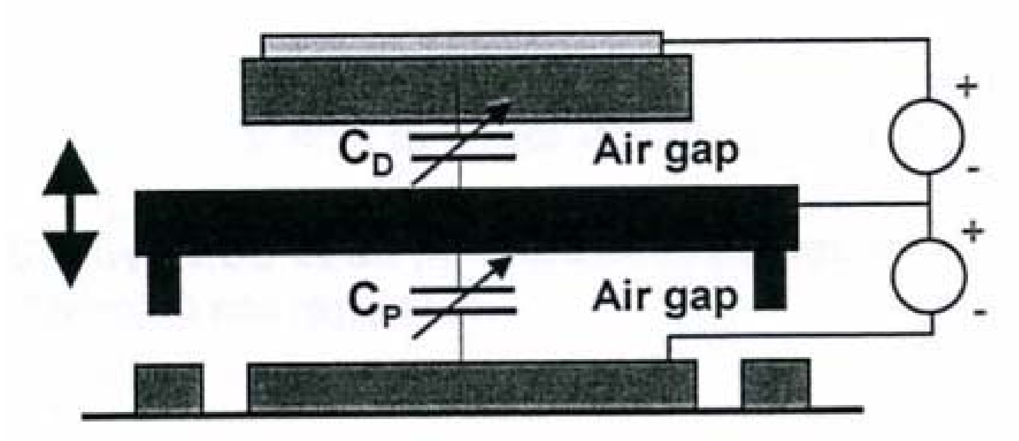
- Typical features for a Berkeley implementation →
- Surface micromachining
  - 2 metal layers + Al gnd-plane



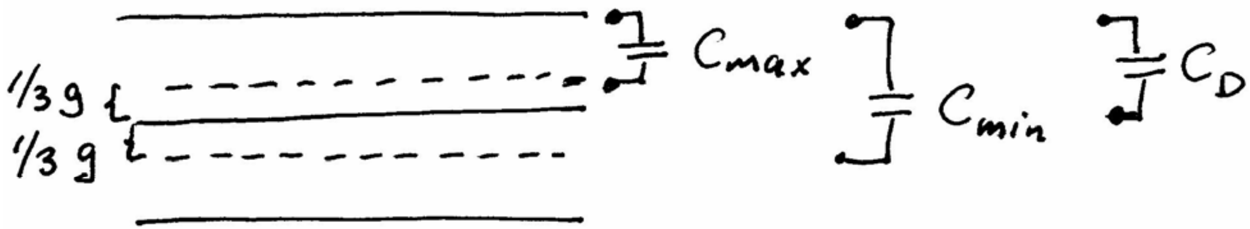
LTO = Low temperature oxide

3-plate tunable MEMS capacitance

- TR can be increased by introducing a 3rd plate
  - A. Dec & K. Suyama: ”Micromachined Electro-Mechanically Tunable Capacitors and Their Applications to RF IC´s” 1998. **Columbia University**



Calculating TR for 3-plate



$$C_{max} = \frac{3}{2} C_D \qquad C_{min} = \varepsilon \frac{A}{\frac{4}{3} g} = \frac{3}{4} C_D$$

$$TR = \frac{C_{max}}{C_{min}} = \frac{\frac{3}{2} C_D}{\frac{3}{4} C_D} = 2 = 200\%$$

TR = 200%, e.g.: can be tuned 100%

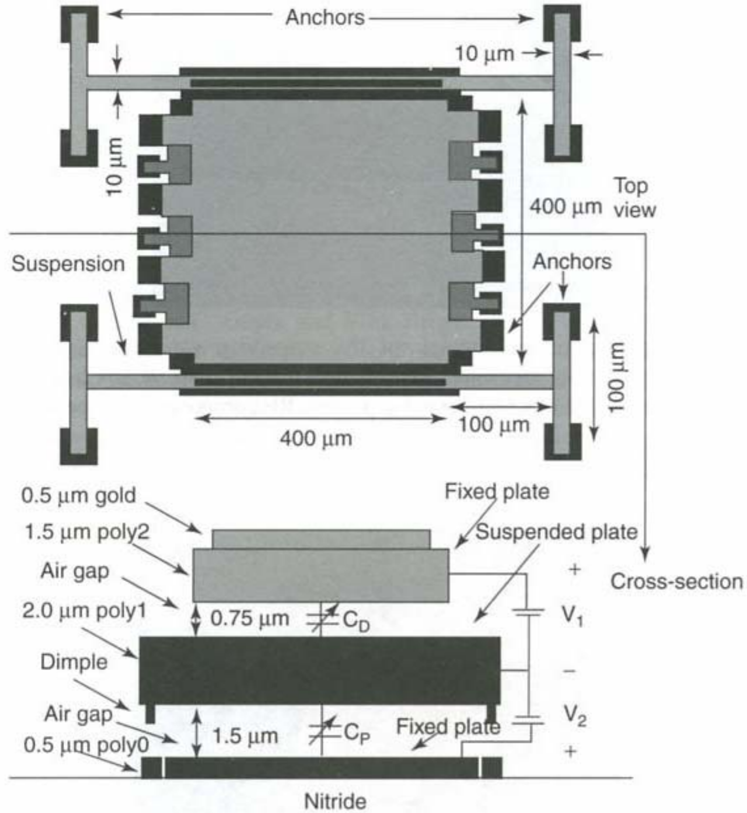


Figure 4.35 Top and cross-sectional views of three-plate varactor. Reproduced from A. Dec and K. Suyama, 1998b, 'Micromachined electromechanically tunable capacitors and their applications to RF IC's', *IEEE Transactions on Microwave Theory and Techniques* **46**(12): 2587–2596, by permission of IEEE, © 1998 IEEE

Demonstrated values, Dec & Suyama:

- **Theoretical tuning range: 100%**
- **Practical tuning range:** **TR=87%, C_{min}=3.4pF, C_{max}=6.4pF, V~4V**
- **RF performance: Q = 15.4 @ 1GHz, 7.1 @ 2GHz**

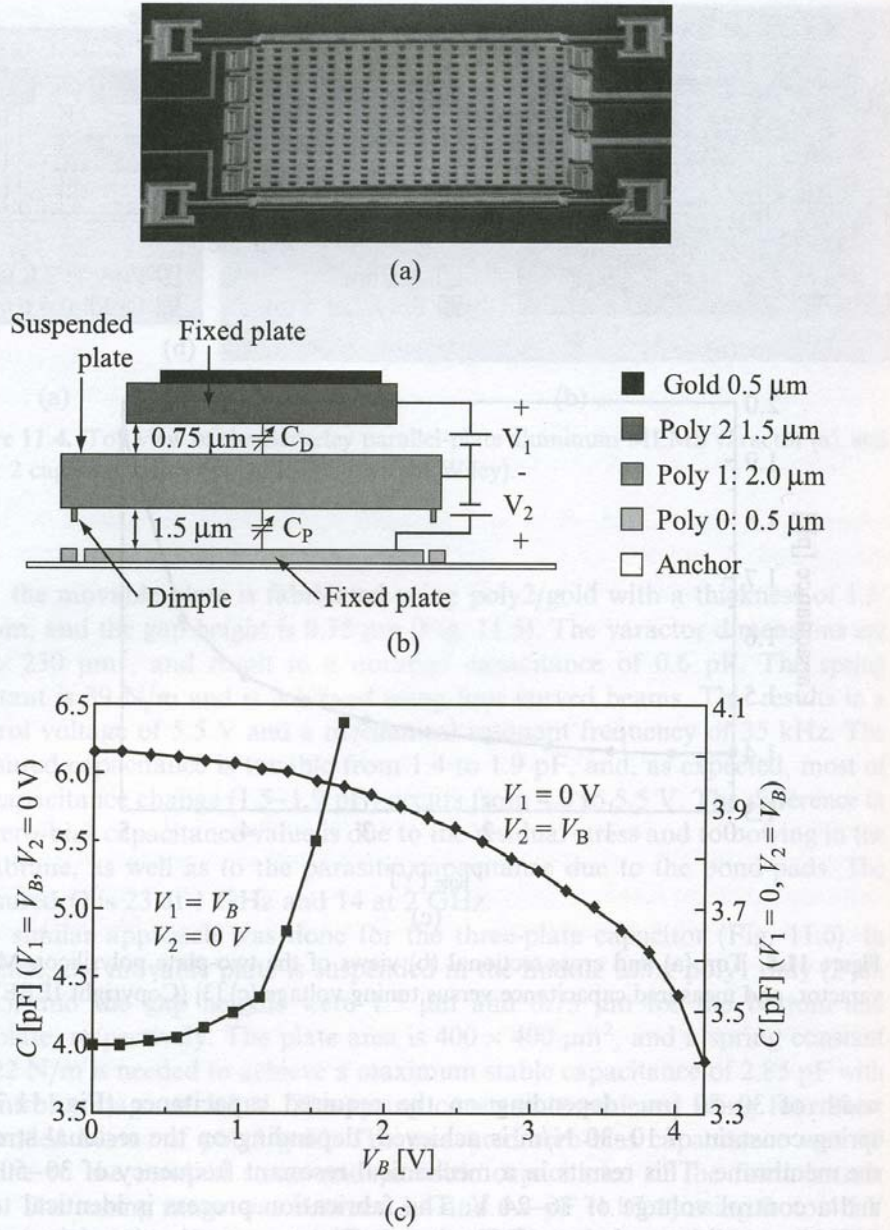


Figure 11.6. Top (a) and cross-sectional (b) view of the three-plate polysilicon MEMS varactor, and measured capacitance versus tuning voltage (c) [2] (Copyright IEEE).

Rebeiz:
Dec & Suyama

Dec & Suyama, contd.

- Process
  - Standard 3-layer poly surface micromachining (MUMP´s) with HF etching and ”supercritical drying”
  - Poly often used as parallel plate due to superior mechanical properties instead of Al (in spite of Al having better conductivity)

TABLE I
SUMMARY OF SELECTED MUMP'S PROCESS PARAMETERS

Layer	*Thickness*	*Sheet Resistance*
Poly0	0.5 μm	30 Ω/sq
Poly1	2.0 μm	10 Ω/sq
Poly2	1.5 μm	20 Ω/sq
Gold	0.5 μm	0.06 Ω/sq

Dec & Suyama, ex.2

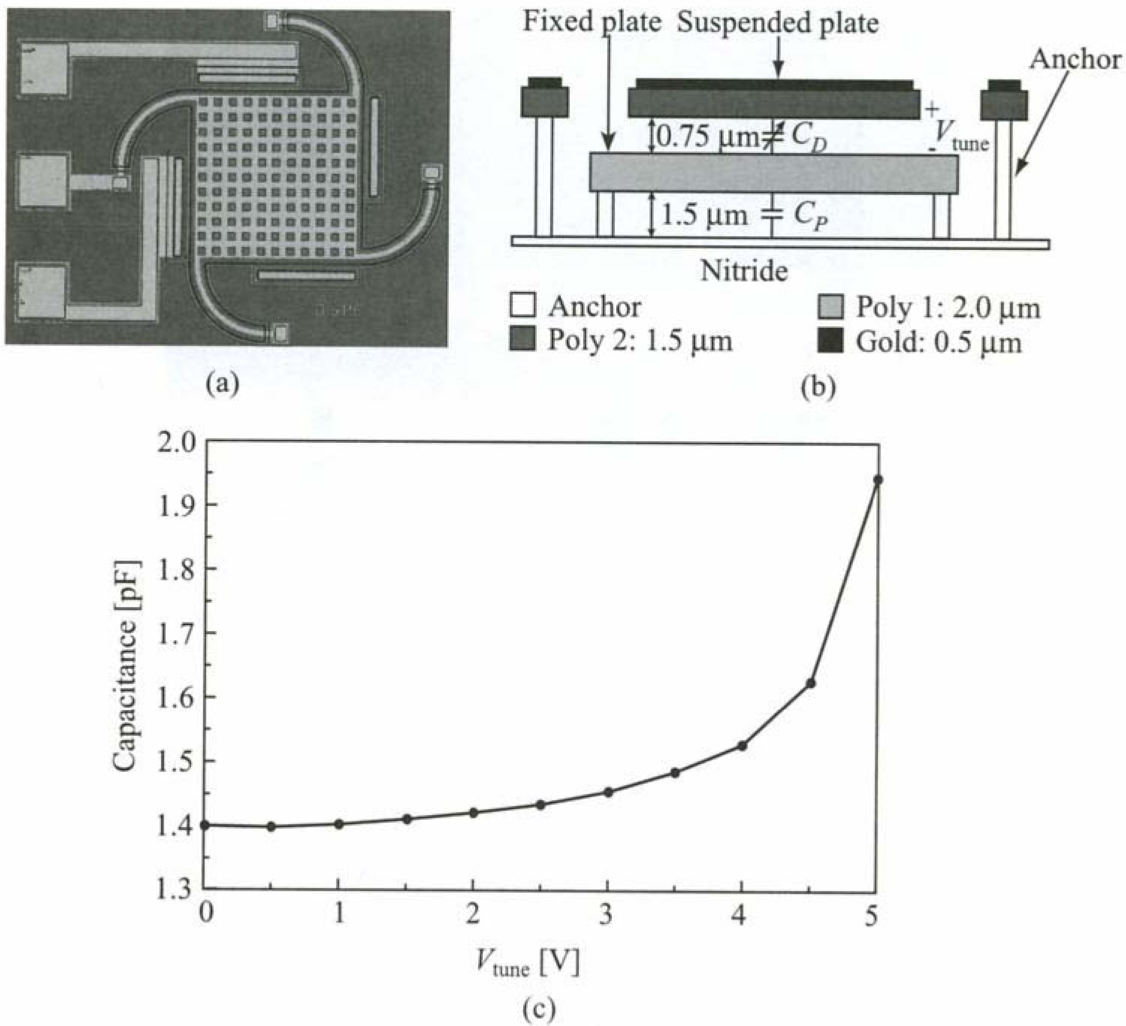
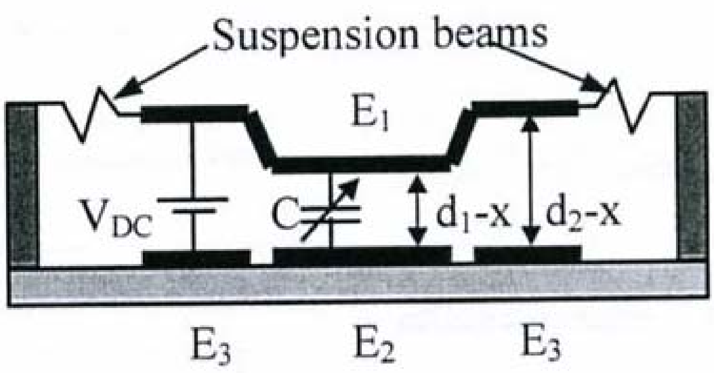


Figure 11.5. Top (a) and cross-sectional (b) views of the two-plate polysilicon MEMS varactor, and measured capacitance versus tuning voltage (c) [3] (Copyright IEEE).

Double air-gap capacitance

- J. Zou et al, 2000, Univ of Illinois
- Why double air-gap?
  - Increase TR
    - Eliminate pull-in effect
  - May deflect down to 1/3 d_2 before pull-in
  - TR may increase significantly if $1/3 * d_2 > d_1$
    - Eg. **centre electrode can be fully deflected without pull-in!**



Univ of Illinois, contd.

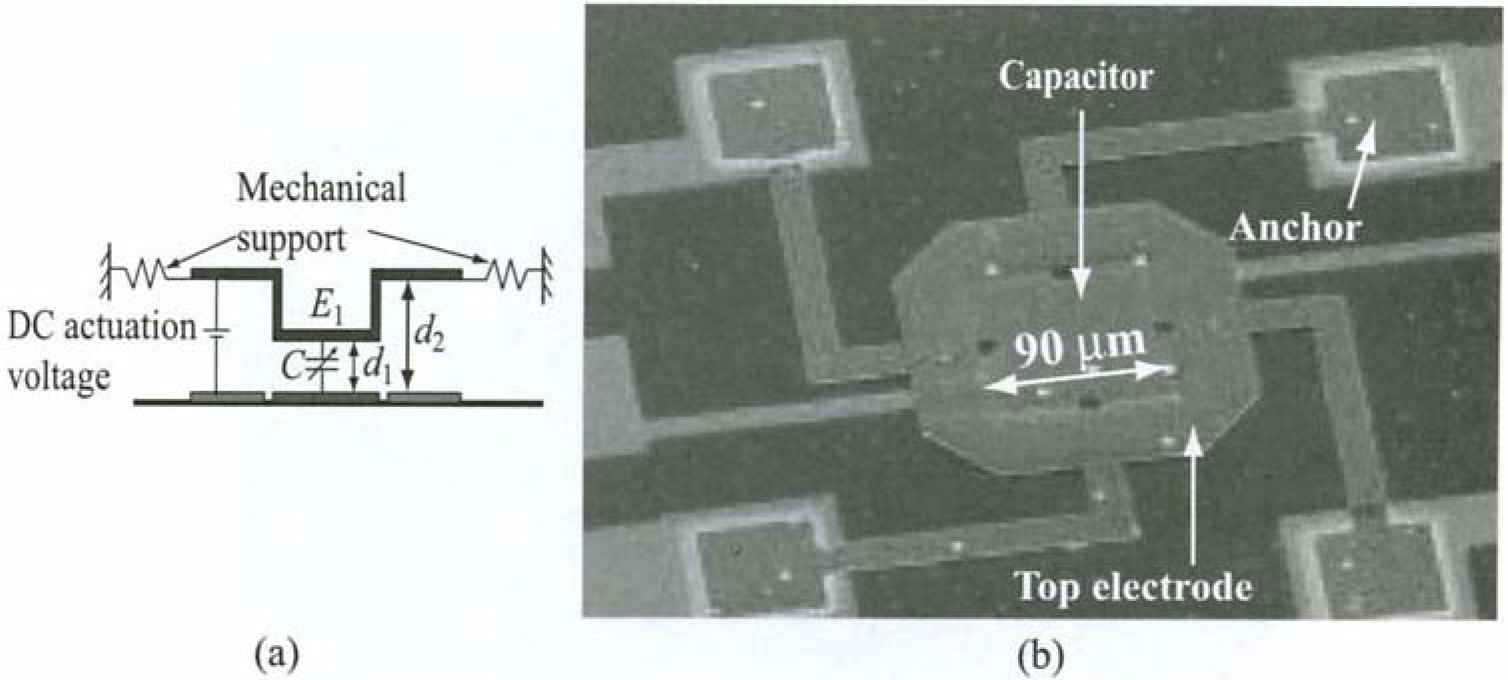


Figure 11.12. Cross-sectional (a) and top (b) view of the University of Illinois wide-tuning-range varactor [11] (Copyright Wiley).

Univ of Illinois, contd.

Simplified fabrication process

- Cu as sacrificial layer
- Metals: gold & permaloy (Ni-Fe)
- Air-gap: d_1 = 2 μm, d_3 = 3 μm

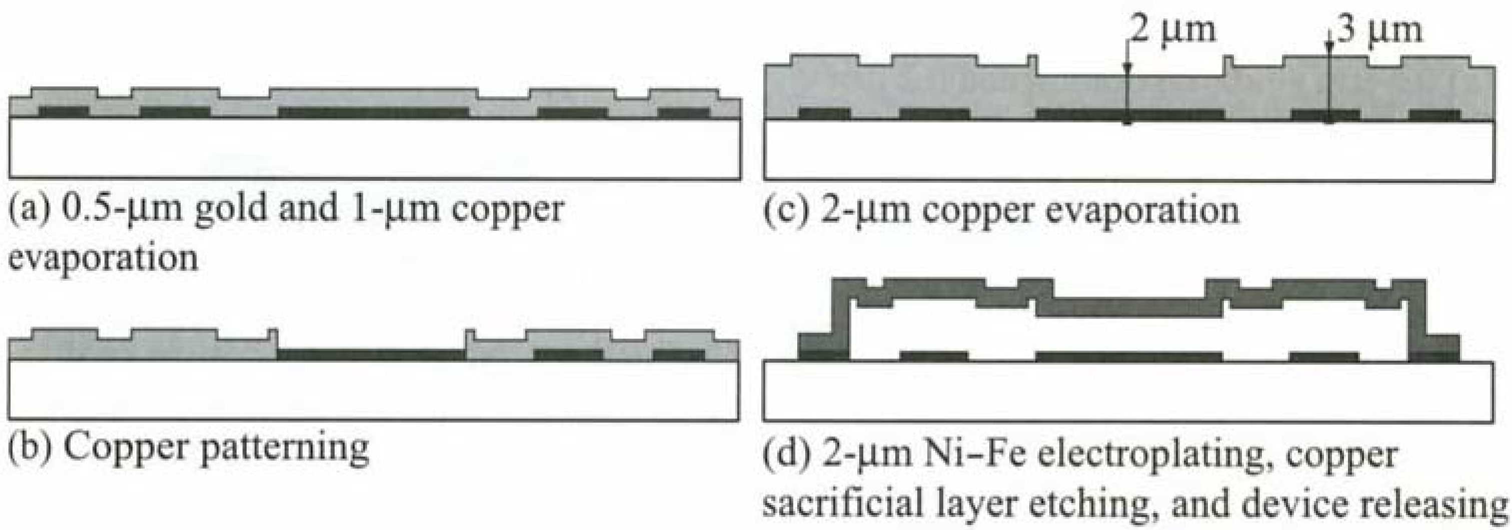


Figure 11.13. Fabrication process of the University of Illinois wide-tuning-range varactor [11] (Copyright Wiley).

Ex. from Univ of Michigan

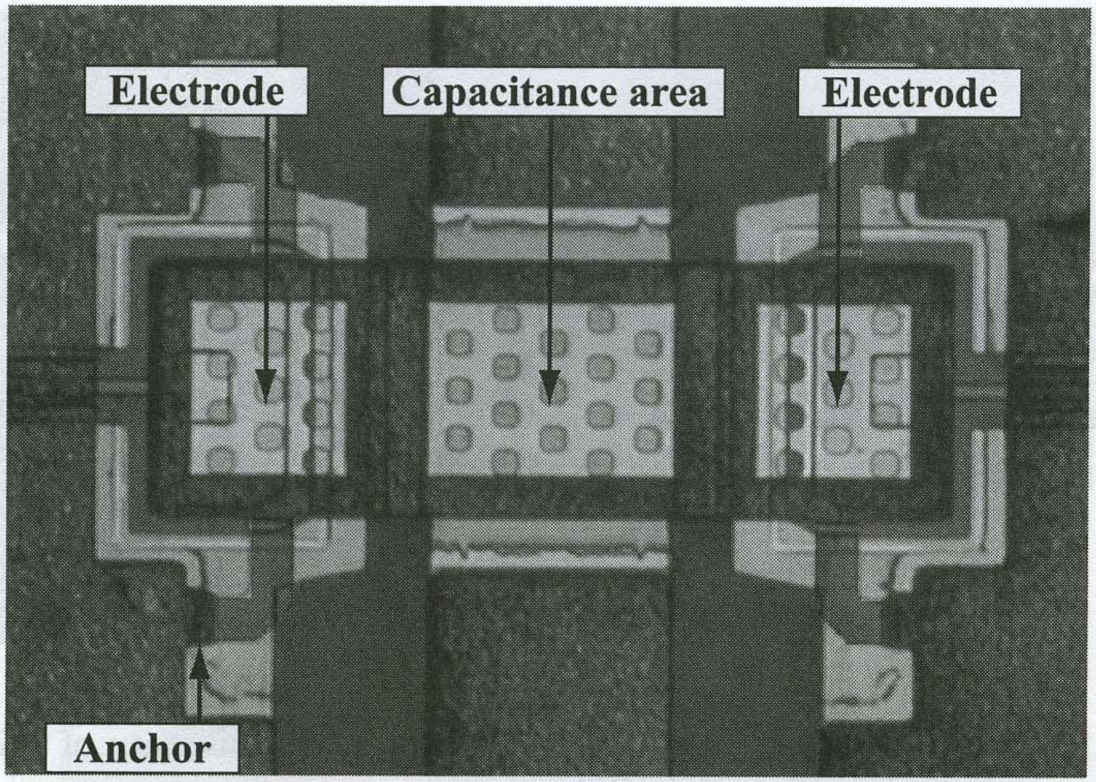
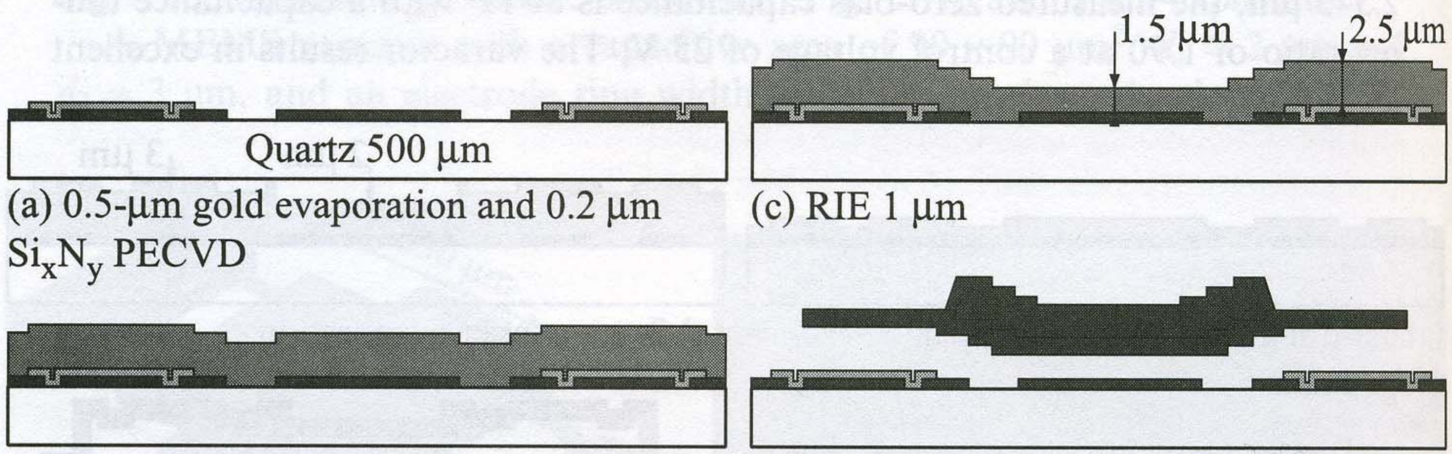


Figure 11.14. Top view of the University of Michigan wide-tuning-range varactor [12] (Copyright IEEE).

Ex. from Univ of Michigan, contd.

- Implemented on quartz substrate
- SiO2 sacrificial layer partly etched → 2-steps Au membrane
- Q = 120 @ 34 GHz



(a) 0.5-μm gold evaporation and 0.2 μm Si_xN_y PECVD

(b) 2.5-μm SiO_2 PECVD

(c) RIE 1 μm

(d) 0.8-μm gold sputtering, 2.5-μm gold electroplating, SiO_2 sacrificial layer etching and critical point drying

Figure 11.15. Fabrication process of the University of Michigan wide-tuning-range varactor [12] (Copyright IEEE).

Univ of Michigan, discrete 2-valued

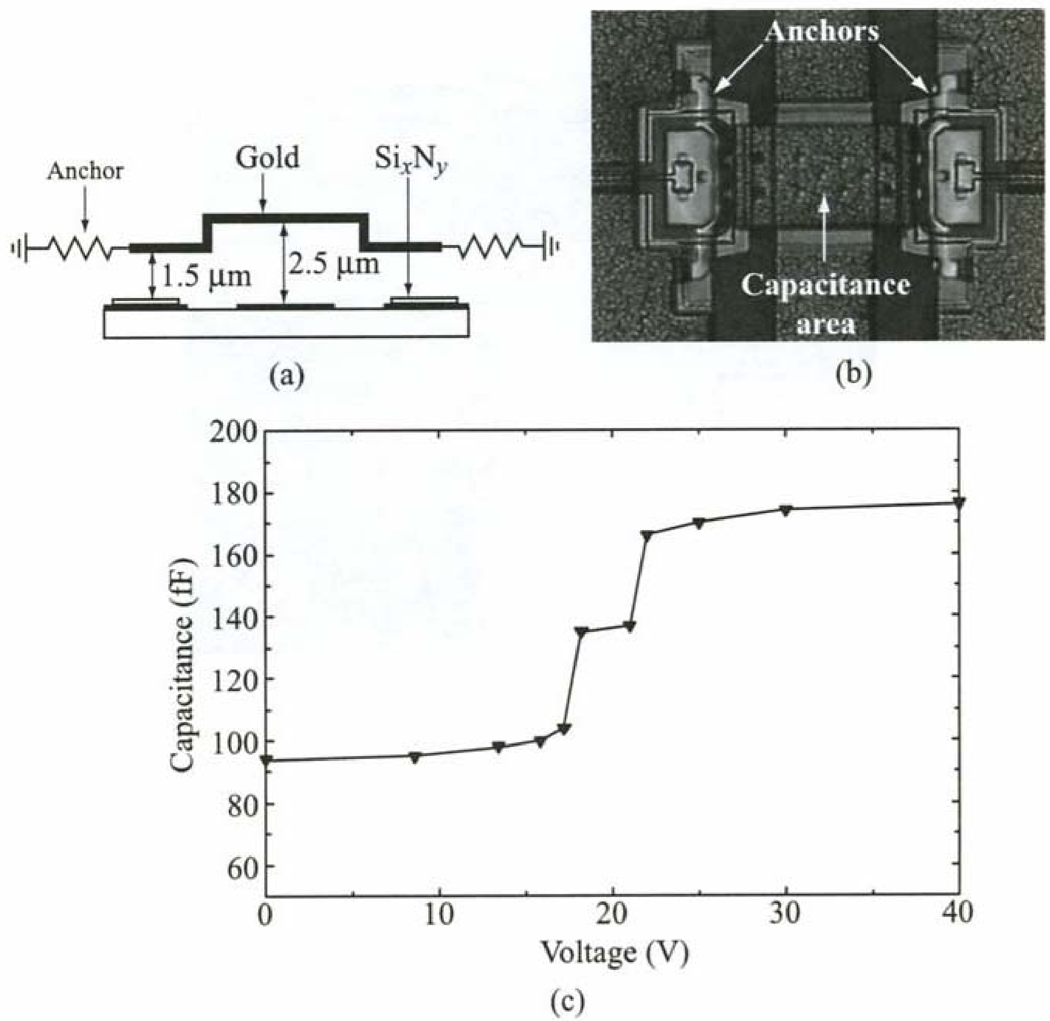
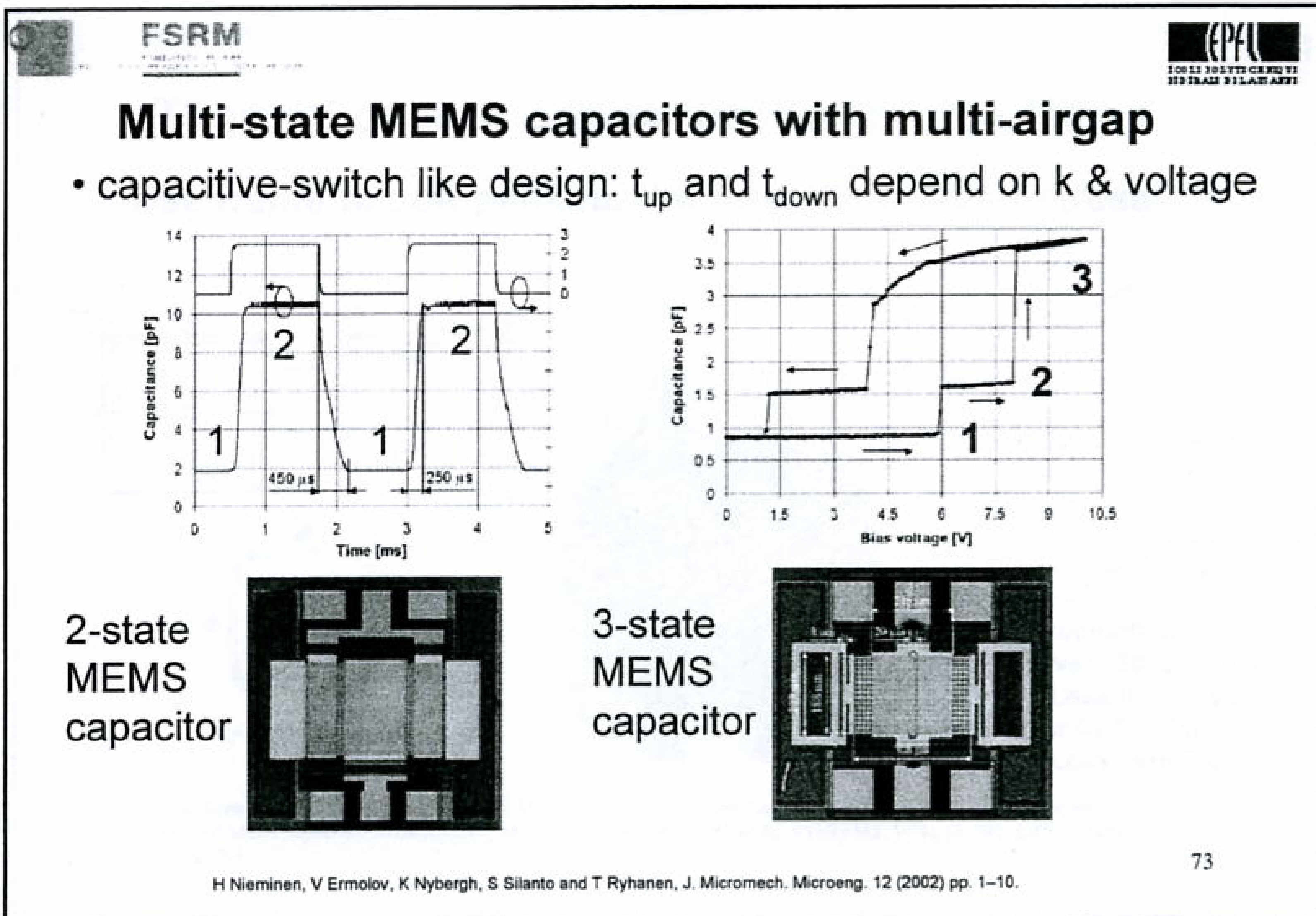
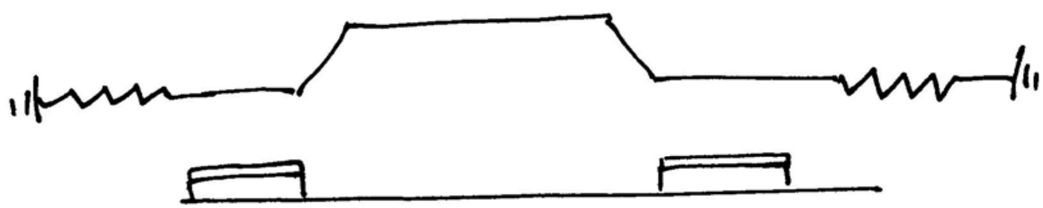


Figure 11.29. Cross section (a), top view (b), and measured capacitance (c) of the Michigan discrete two-value MEMS varactor [12] (Copyright IEEE).



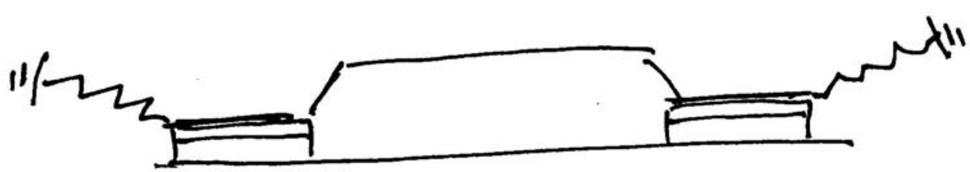
Different segments with multi-gap. May be tuned to 2 or 3 levels. Hystereses properties

Working principle:



C_0

C_1

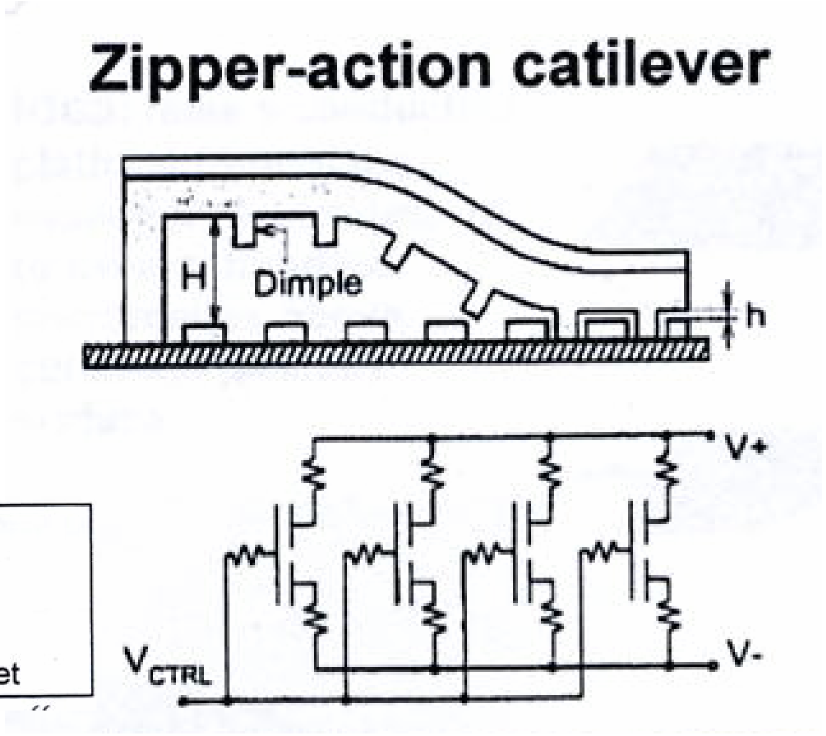


C_2

"Zipper" capacitance

- Ex. zipper cantilever capacitance
- Design and fabrication at Columbia University
  - Long, thin beam deflected gradually from one edge
  - Small capacitances added in parallel

Performance:
- **TR: 46%** with voltage~35V
- **Q=6.5 @1.5GHz**
- a CMOS VCO with this capacitor exhibited TR of 4.8% with center frequency of 1.5GHz and phase noise of –131dBc/Hz @ 600kHZ offset



Ex. from MIT

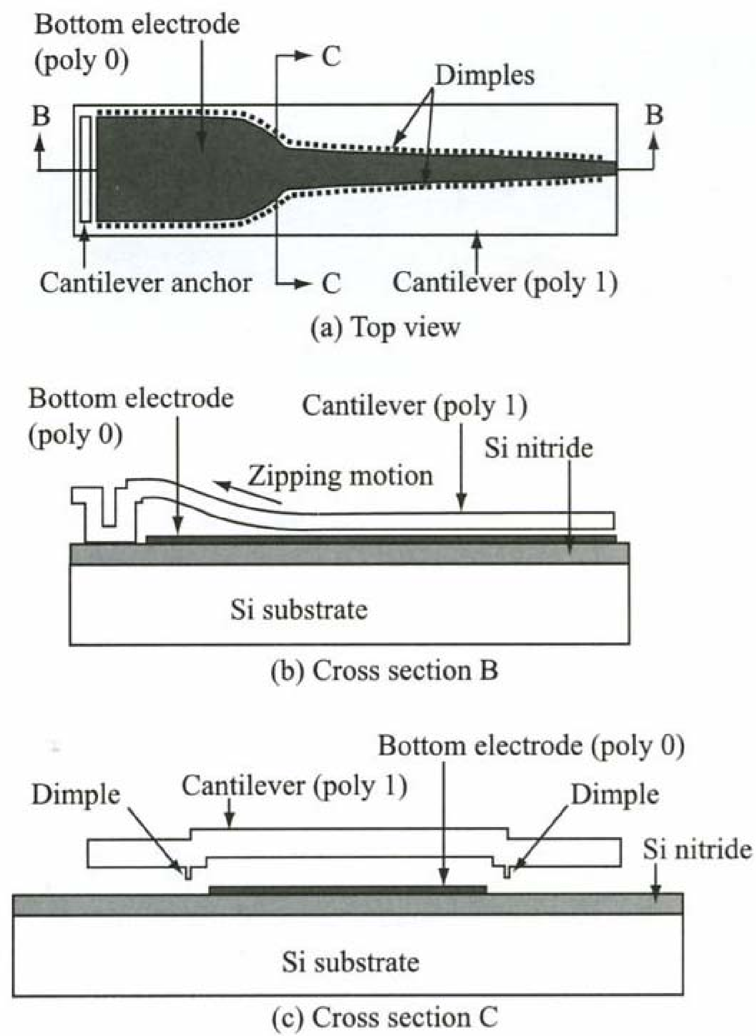


Figure 11.9. Top (a) and cross-sectional (b,c) view of the MIT zipper varactor [8].

Softest near edge

Univ of Colorado, Boulder

- Digitally controlled individual capacitances
- Has individual plates that may be actuated sequentially

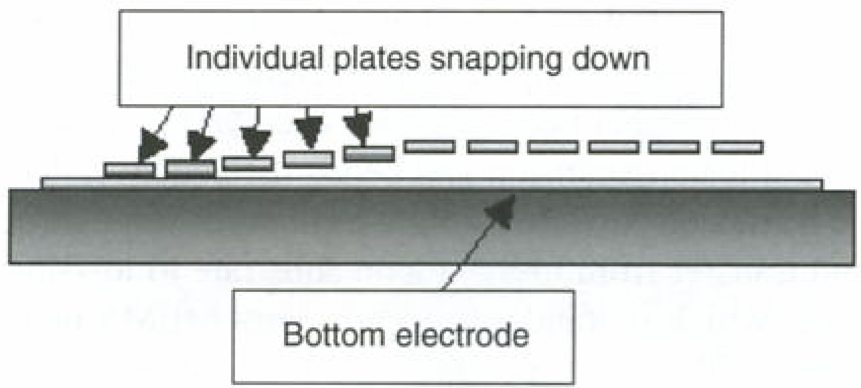
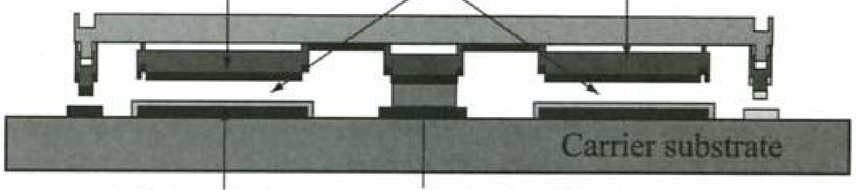
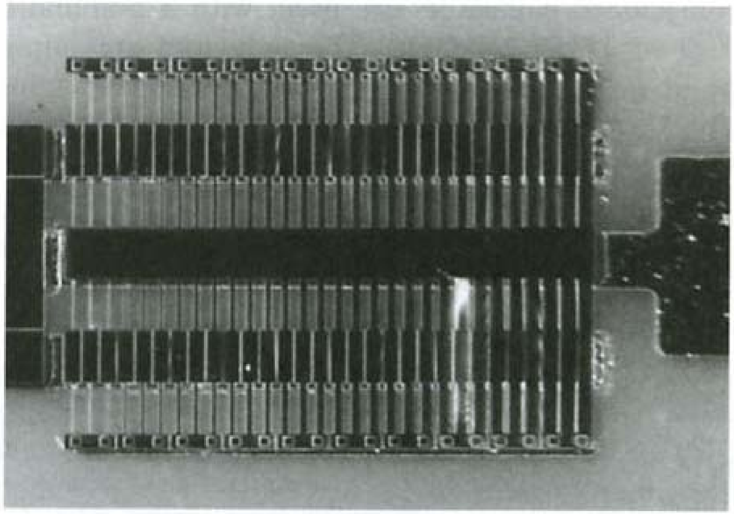


Figure 4.38 Schematic diagram of the capacitor plate arrangement. Reproduced from N. Hoivik, M.A. Michalicek, Y.C. Lee, K.C. Gupta and V.M. Bright, 2001, 'Digitally controllable variable high-Q MEMS capacitor for RF applications', in *Proceedings of IEEE MTT-S Symposium, May 2001, Volume 3*, IEEE, Washington, DC: 2115–2118, by permission of IEEE, © 2001 IEEE

Univ of Colorado, Boulder



(a)



(b)

Figure 11.30. Cross section (a) and top view (b) of the Colorado RF MEMS varactor. The variable capacitors are the dark rectangles on both sides of the center conductor [23] (Copyright IEEE).

Each ”plate” coupled with **different width** of beam, eg. different spring constant for each part

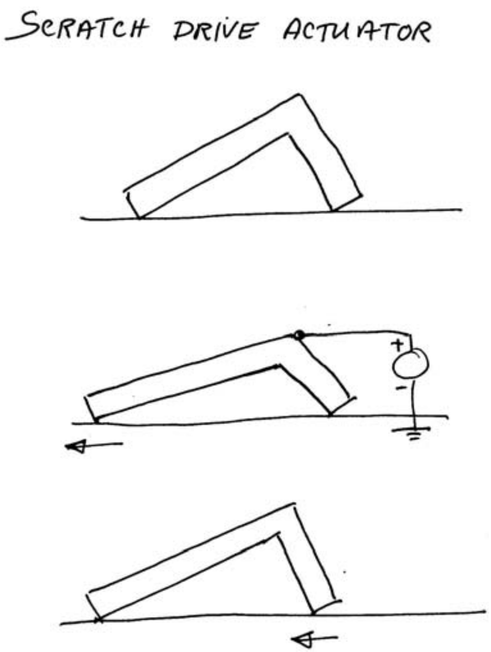
Standard MUMP´s process (poly-Si and gold), alumina-substrate

Electrostatic actuation V= 30 V
TR = 4 : 1
Q = 140 @ 750 MHz

Elevated platform capacitance

- L. Fan et al, 1998
  - One of the electrodes may be elevated to several hundred micrometers above the substrate
    - 250 μm elevation, TR 2400%
    - ÷ Fine tuning difficult

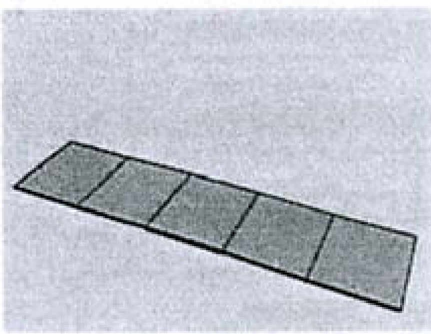
- Uses actuators pushing the structure together
  - ”Scratch drive actuator”
  - Must implement hinges

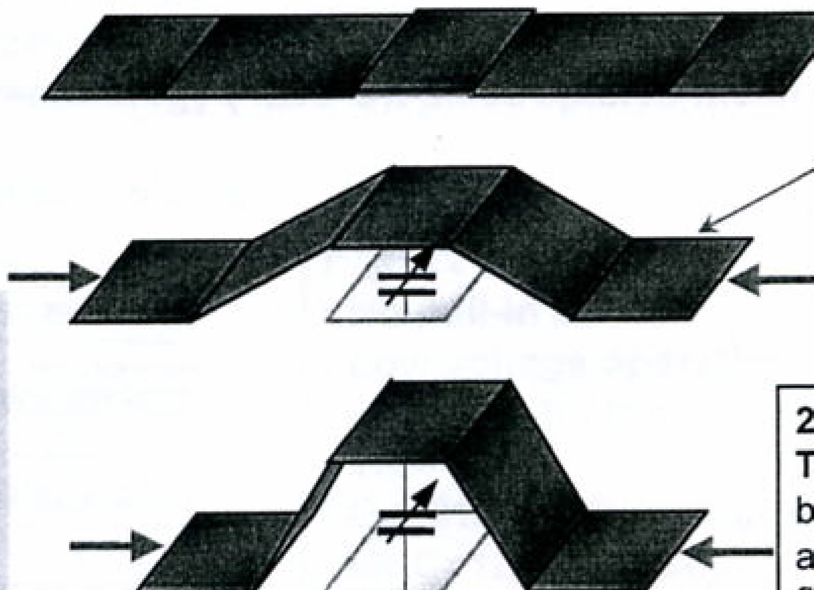


FSRM

Elevated platform MEMS capacitor

Idea: raise a conductive platform (one of the capacitor electrodes) up to several hundred micrometers above substrate (silicon) surface





Scratch drive actuator (SDA) arrays

250μm elevation (!!)
TR: 2400%
but very difficult to achieve fine tuning

L. Fan, R. T. Chen, A. Nespola, 11th Annual International Workshop on Micro Electro Mechanical Systems (MEMS '98), 1998.

68

Self actuation

- Design parallel plate capacitances to handle RF power
  - AC applied over the RF MEMS capacitance
    - RF frequency does not modulate C-value
  - BUT, RMS-value of RF-signal will influence C and can induce pull-in by self actuation

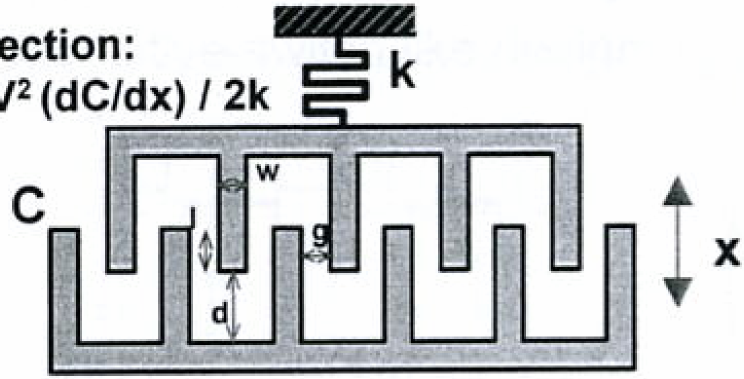
- Capacitances for gap-tuning has limited RF power handling capability due to small electrode gap
  - Decrease distance → RF breakdown

Lateral tunable capacitors

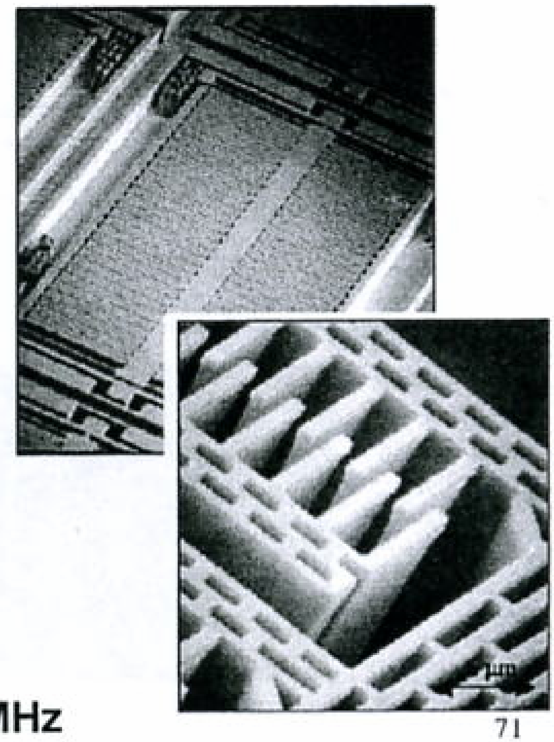
- Horizontal displacement
  - C can be tuned by changing the **area**, $C = \varepsilon A / g$
  - + No theoretical limit for TR
  - + Pull-in effect avoided
  - ÷ Photolithography determines precision of dimensions
  - ÷ More complicated suspension structures?
    - Make sure that the movable structure is suspended!
- Comb structure is common

Comb-like (inter-digital) tunable MEMS capacitors

Deflection:
$x = V^2 (dC/dx) / 2k$



Idea: **area-tuning capacitor**



Design and fabrication

(Rockwell Science Center):

- Comb-like structure using single mask process
- Deep anisotropic silicon etching technique in ICP (inductively coupled plasma) reactor
- **Very flexible design**: **large range of C and TR**

Figures of merit:

- **TR= 200% C_{max}=3.2pF, C_{min}=6.44pF, V=5V**
- **Recent results show: Q > 40-160 @ 400-1600MHz**

J.J. Yao, S. Park and J. DeNatale, Solid-State Sensor and Actuator Workshop, Hilton Head Island, SC, 1998, pp. 124-127.

Ionescu, EPFL: J. J. Yao et al, Rockwell

Simple comb structure

- Ex. from Rockwell Science Center →
  - Inter-digital tunable MEMS capacitance
  - One set of combs is stationary, the other set can be moved
  - Gap is not changing
  - Length of comb and finger length limit tuning range
  - Can be tuned by an electrostatic micro motor or by applying different actuation voltages

Rockwell Science Center, forts.

Ex. of tuning

VS = RF

HS = tuning

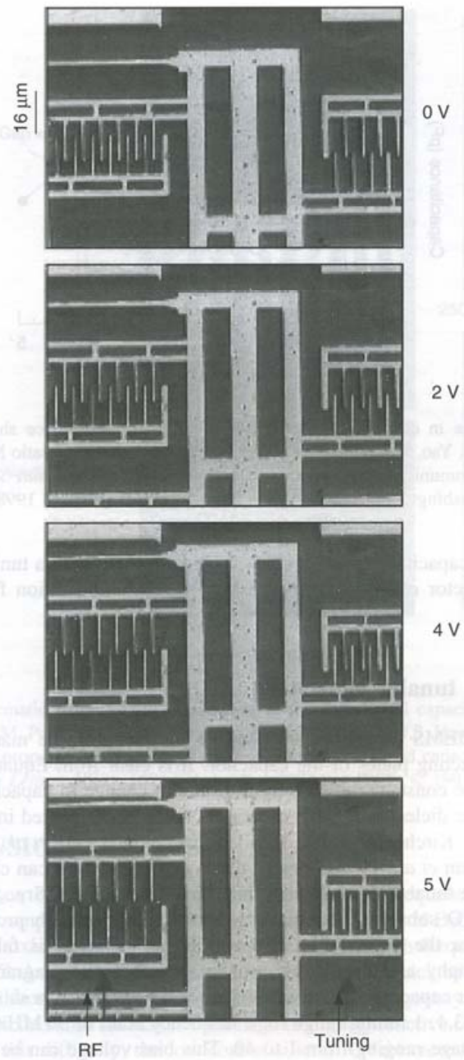


Figure 4.46 Series of images showing a MEMS tunable capacitor with a tuning voltage of 0 to 5-V. Reproduced from J.J. Yao, S. Park and J. DeNatale, 1998, 'High tuning ratio MEMS based tunable capacitors for RF communications applications' in *Proceedings of solid-state sensors and Actuators Workshop*, IEEE, Washington, DC: 124–127, by permission of IEEE, © 1998 IEEE

Rockwell Science Center, contd.

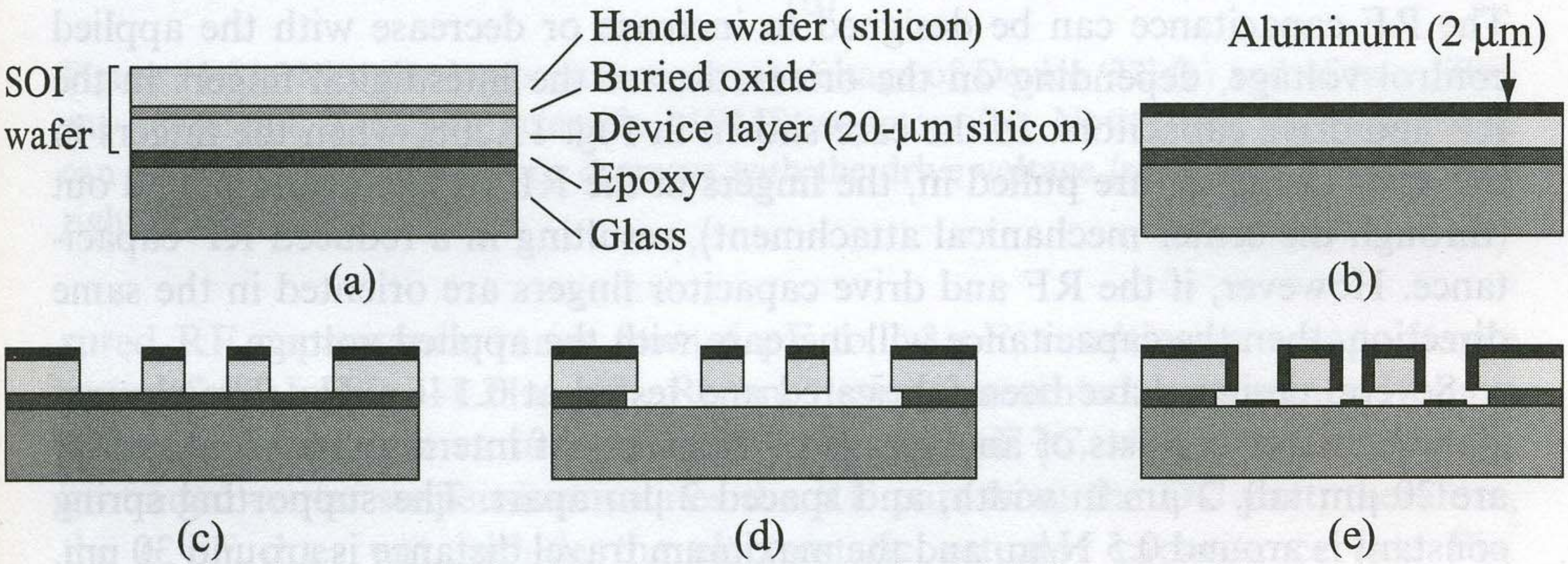


Figure 11.19. Details of the fabrication process of the Rockwell Science Center interdigital capacitor on a glass substrate (see text). Notice that a single mask layer is used [17, 18] (Copyright IEEE).

Rebeiz

Rockwell Science Center, contd.

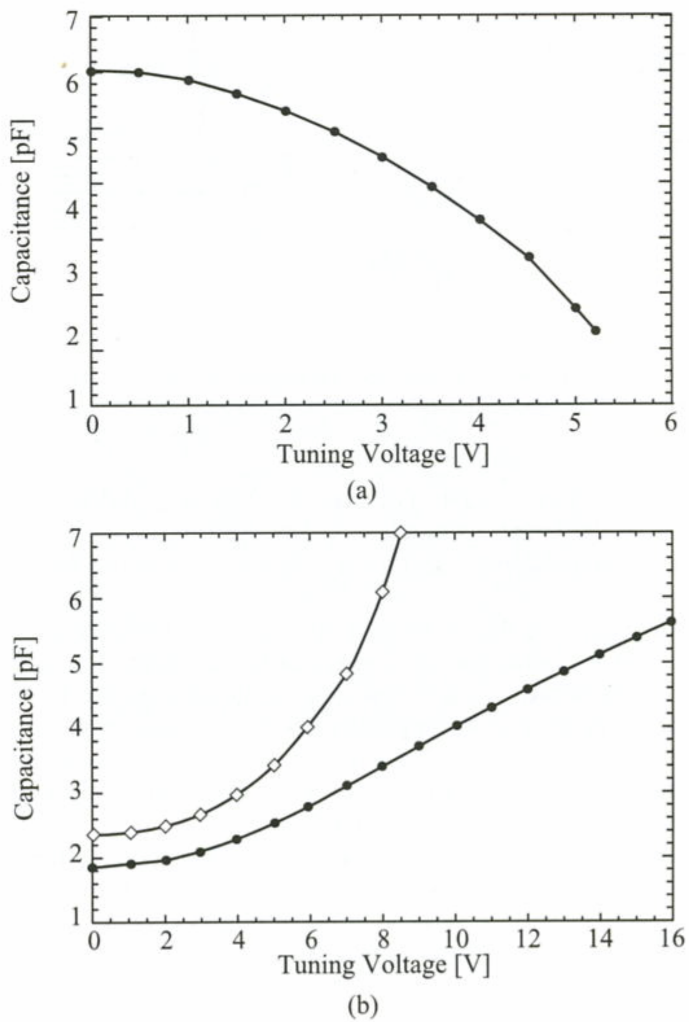


Figure 11.21. Measured capacitance versus voltage of Device '33' (a) and of two different interdigital Rockwell Scientific MEMS varactors (b). Notice that the capacitance can be designed to increase or decrease with the drive voltage (see text) [17, 18] (Copyright IEEE).

Thermal tunable parallel-plate MEMS capacitance

- Use hot and cold arms
  - A high resistivity arm will be hotter and deform more
    - Differential thermal expansion

- Challenges with this technology
  - **Power dissipation**
  - **Low speed**
  - But removes the pull-in limitation!

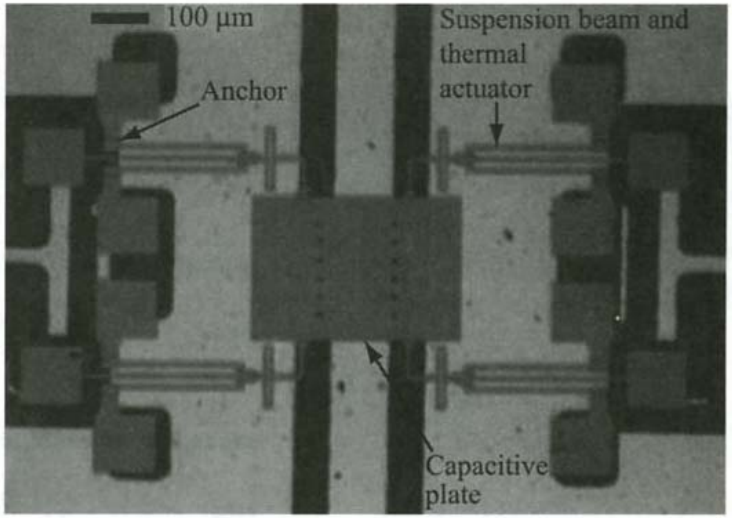


Figure 11.16. Top view of the University of Colorado thermally actuated MEMS varactor in a CPW circuit [13] (Copyright IEEE).

Univ of Colorado

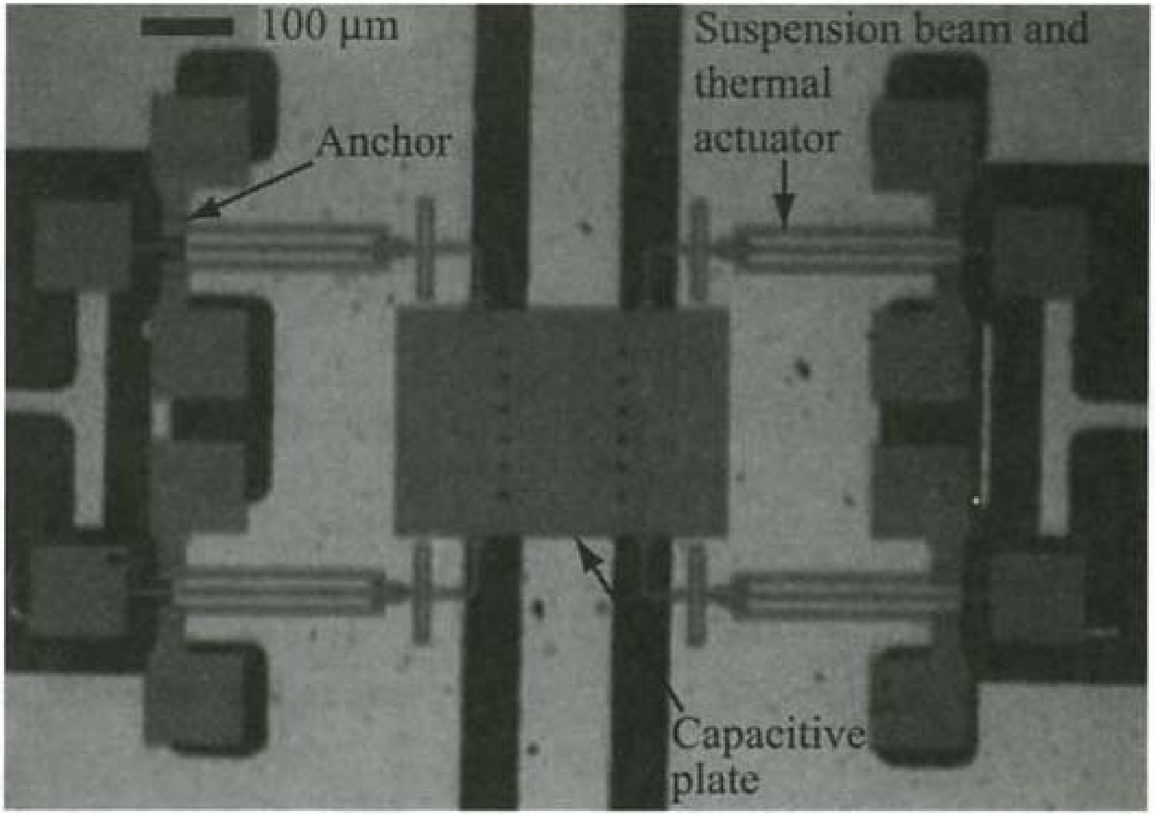
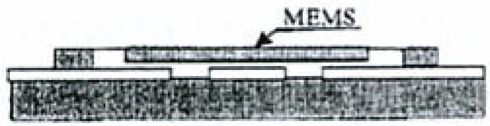
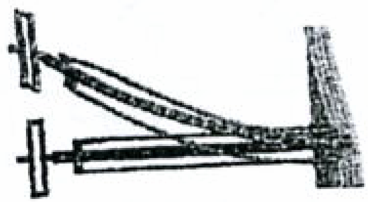


Figure 11.16. Top view of the University of Colorado thermally actuated MEMS varactor in a CPW circuit [13] (Copyright IEEE).

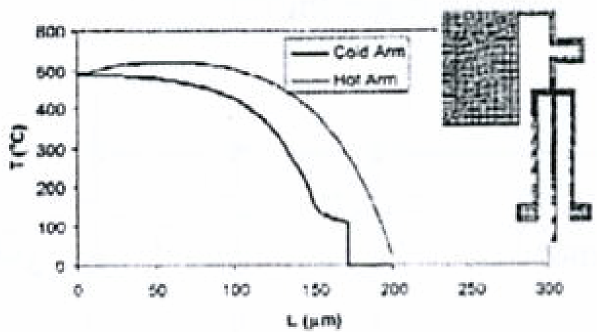
Z. Feng et al, Univ of Colorado: **Design and Modeling of RF MEMS Tunable Capacitors Using Electro-thermal Actuators**

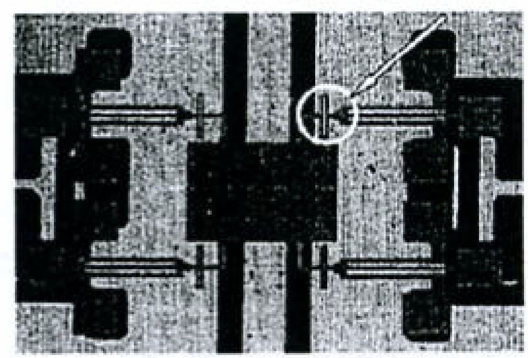
Thermally tunable parallel-plate MEMS capacitor





- capacitor designed for milimeter-wave (up to 40GHz) applications using standard MUMP's process (poly-Si and gold) and transfer of the device on ceramics substrate
- **actuation is electro-thermal by 4 vertical electrothermal actuators** (hot & cold arms)





Performance:
TR=2.7:1
Q=300 @
C=0.1pF, 10GHz

Z. Feng, W. Zhang, B. Su, K.F. Harsh, K.C. Gupta, V. Bright, Y.C. Lee, Microwave Symposium Digest, 1999 IEEE MTT-S International , Volume: 4 , June 1999, pp. 1507 –1510.

Temperature gradient causes a vertical displacement

Electro-thermal tuning

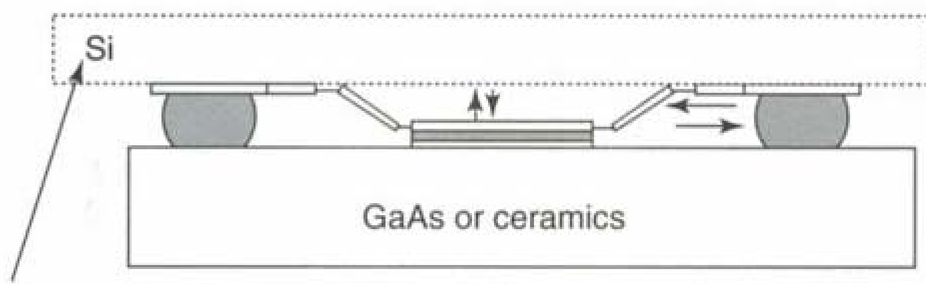


Figure 4.39 Flip-chip assembly of silicon-based MEMS. Reproduced from K.F. Harsh, B. Su, W. Zhang, V.M. Bright and Y.C. Lee, 2000, 'The realization and design considerations of flip-chip integrated MEMS tunable capacitor', *Sensors and Actuators A: Physical* **80**: 108–118, with permission from Elsevier Science, © 2000 Elsevier Science

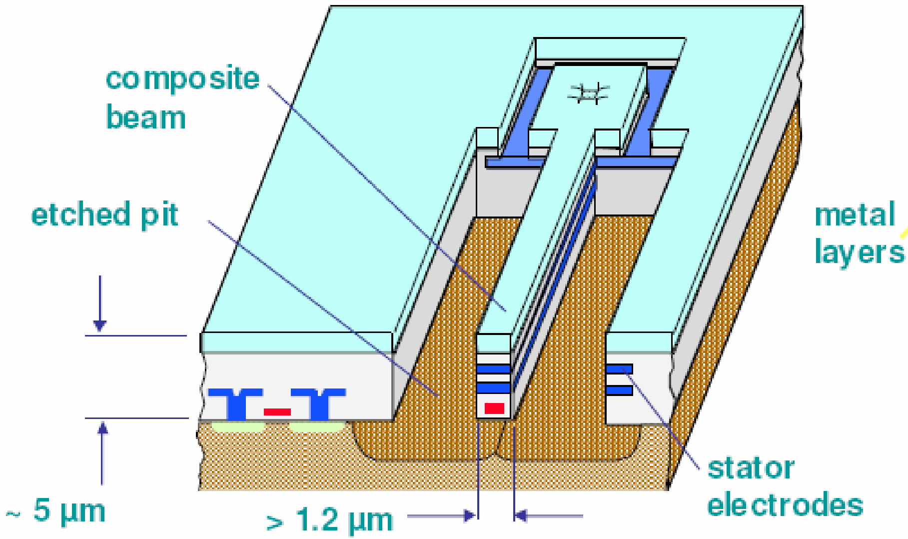
Varadan

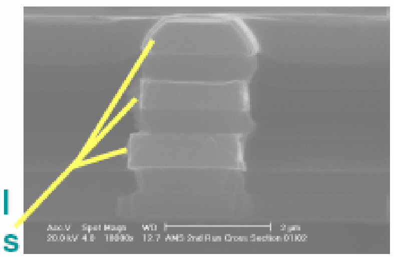
Variable capacitors in CMOS-MEMS

ASIMPS: CMOS-MEMS Process

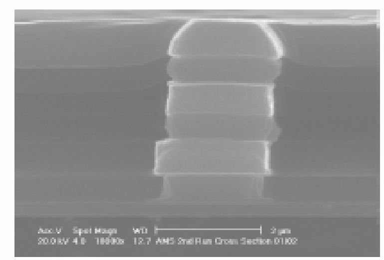
CNRS – INPG – UJF

- Microstructures made from conventional CMOS followed by two maskless post-CMOS process steps





M1-2-3 with field oxide



M1-2-3 w/o field oxide

- **Potential Applications**
  - **Inertial sensors, RF MEMS, infrared sensors, flow and force sensors, ... with on-chip detection and conditioning**

G. Fedder *et al.*, Sensors & Actuators A, v.57, no.2, 1996

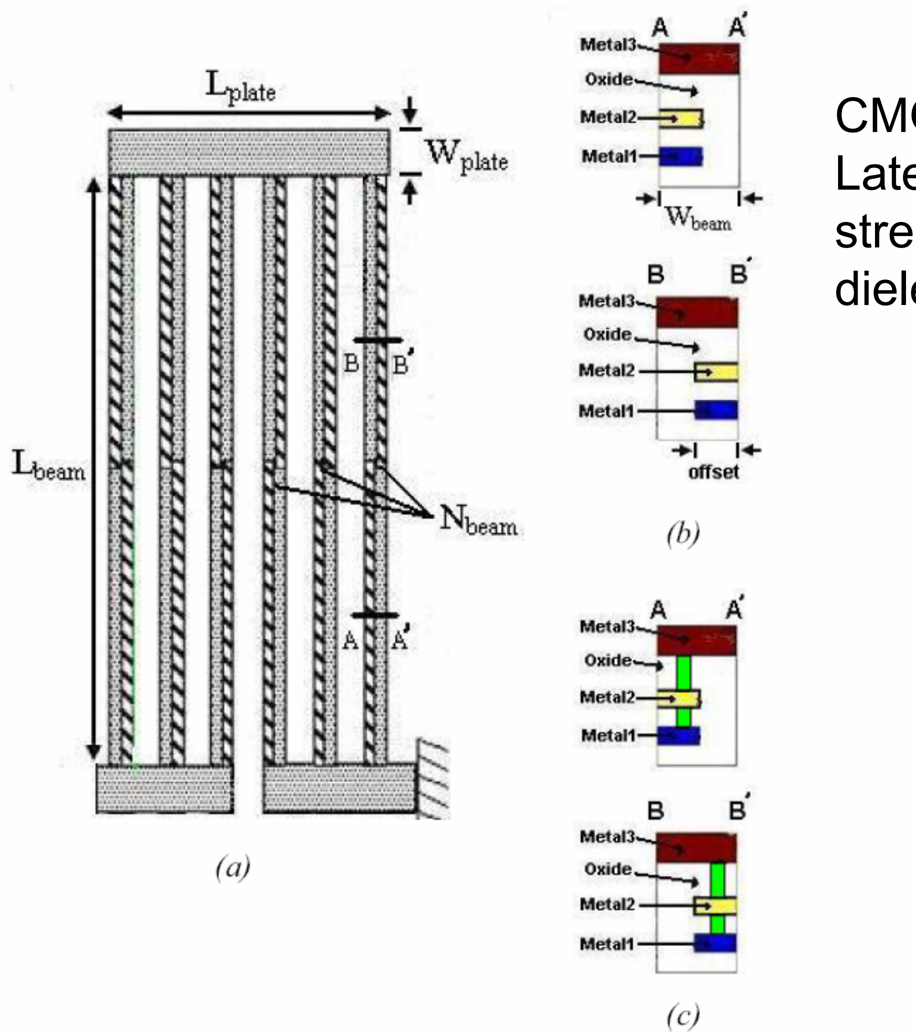


Figure 1. *(a) Layout and design parameters for a folded-flexure micromover, (b) Cross section of the micromover beams at two positions, showing the embedded metal offset, (c) Cross section of the micromover beams with vias between metal layers.*

CMOS-MEMS:
Lateral displacement due to different stress gradients in metal and dielectrics

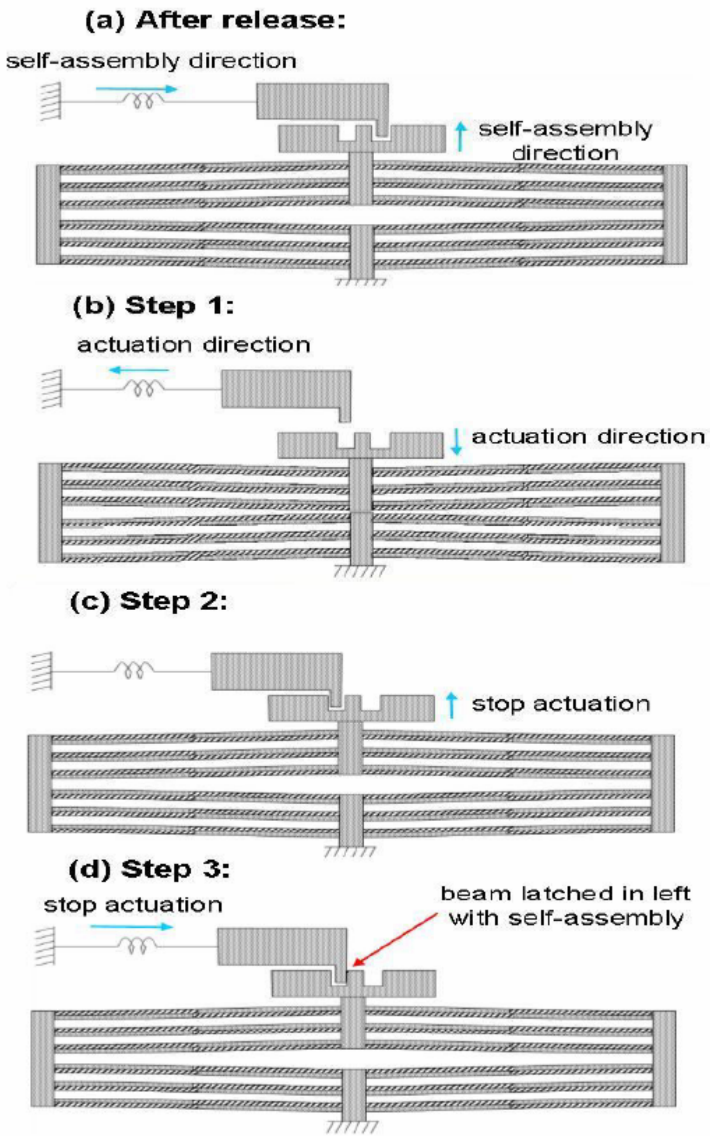


Figure 5. Sequential steps for lateral latch mechanism.

Different thermal expansion coefficients (TCEs) for Al and dielectrics causes movement upon heating

(Master thesis NANO 09)

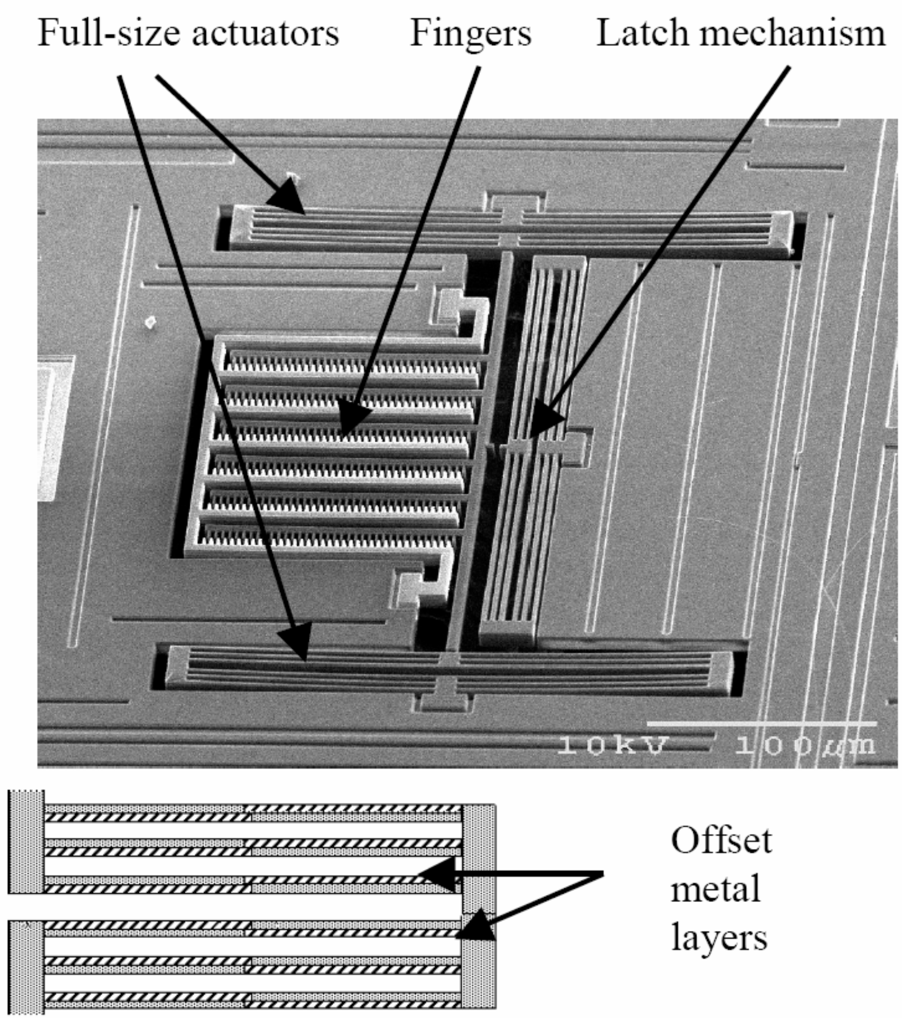


Figure 2. (a) SEM of a released capacitor in the TSMC 0.35 µm CMOS process with full-size actuators. (b) half-size actuator layout.

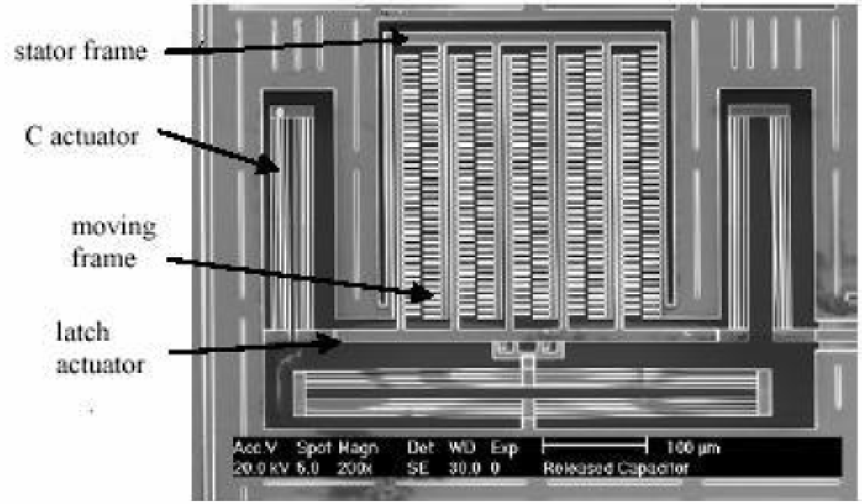
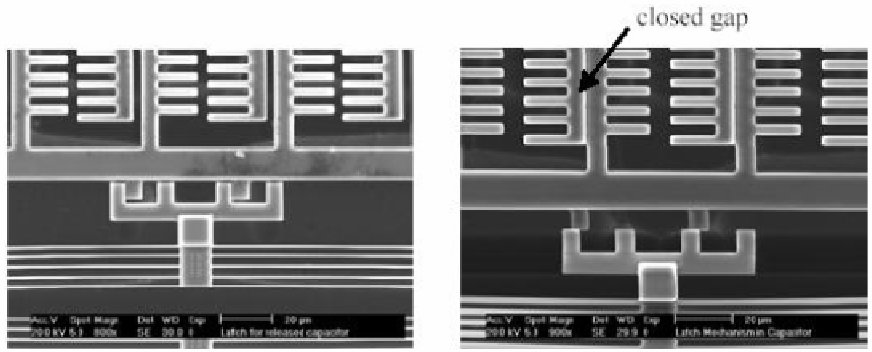


Figure 6. An unengaged comb-finger tunable capacitor.



(a) (b)

Figure 7. *Capacitor latching. (a) A disengaged comb finger latch state, (b) A different latch state, where the comb truss beams contact mechanically.*

Vertical curling upon post-CMOS release

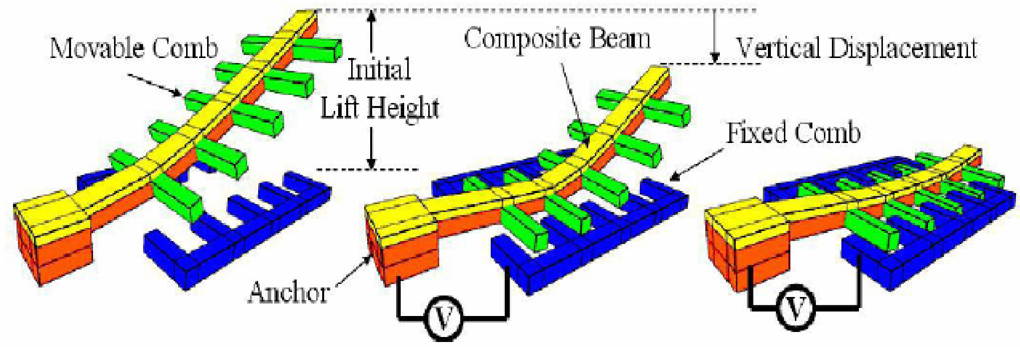


Figure 1. The resonator at different driving states. (a) Initial state. (b) Bias voltage state. (c) Critical bias voltage state.

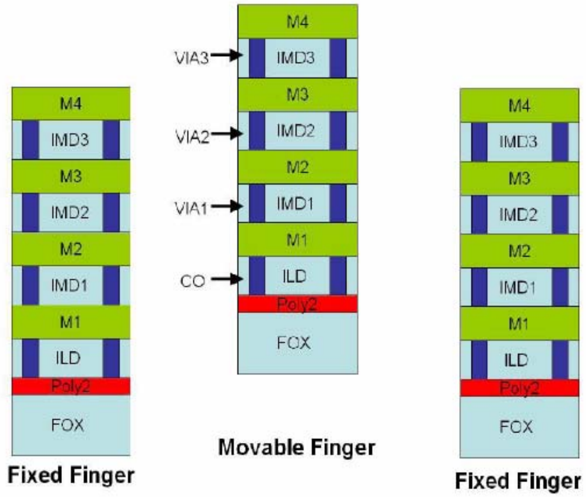


Figure 3. Cross-section of the movable and fixed comb.

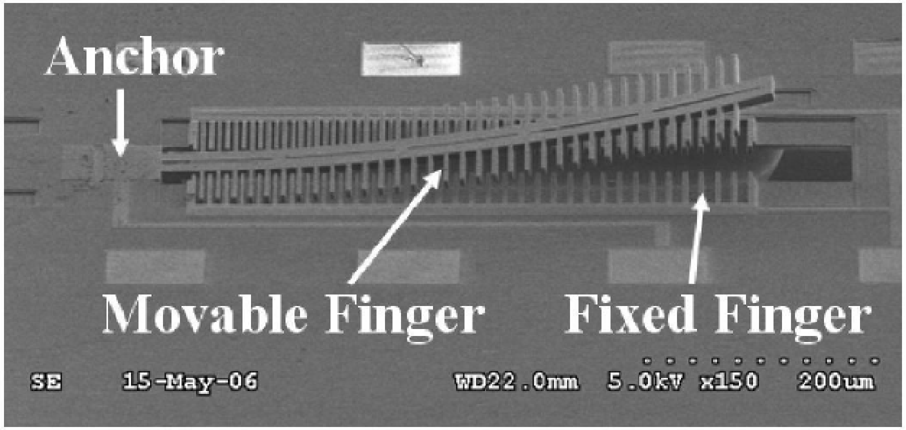


Figure 4. Fabricated resonator device.

The effect can be used for making variable C!
(Master thesis NANO 09)

National Chung Hsing Univ, Taiwan, Dai et al

Piezoelectric tuning

A bias voltage causes the capacitor plate to move vertically

+ Low drive-voltage
+ Linear tuning of capacitance

Two of the beam lengths increase

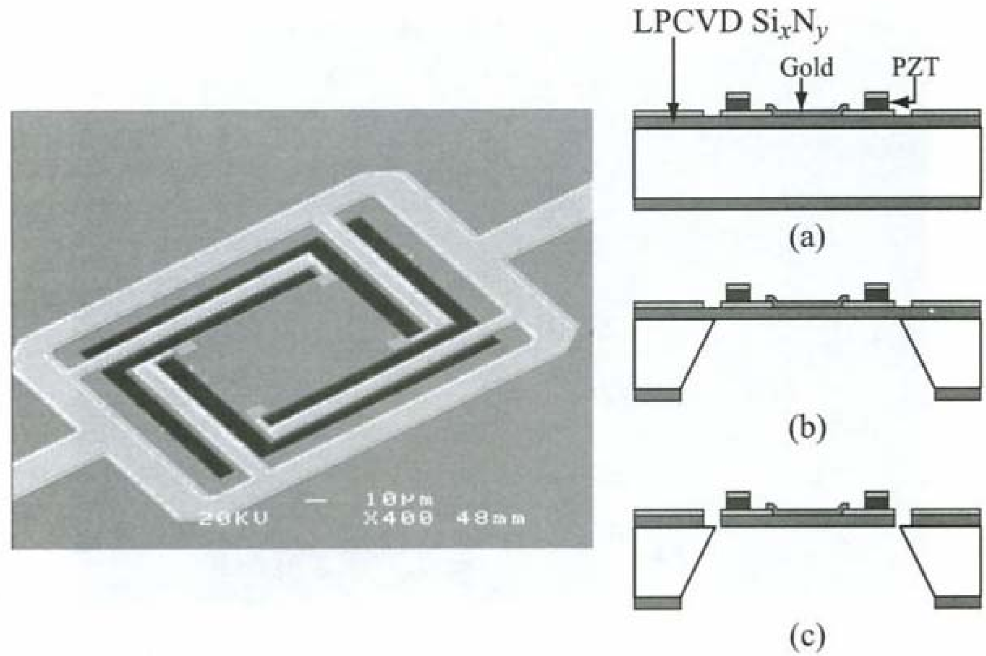


Figure 11.17. Top view and fabrication process of the LG-Electronics piezoelectric varactor [15] (Copyright IEEE).

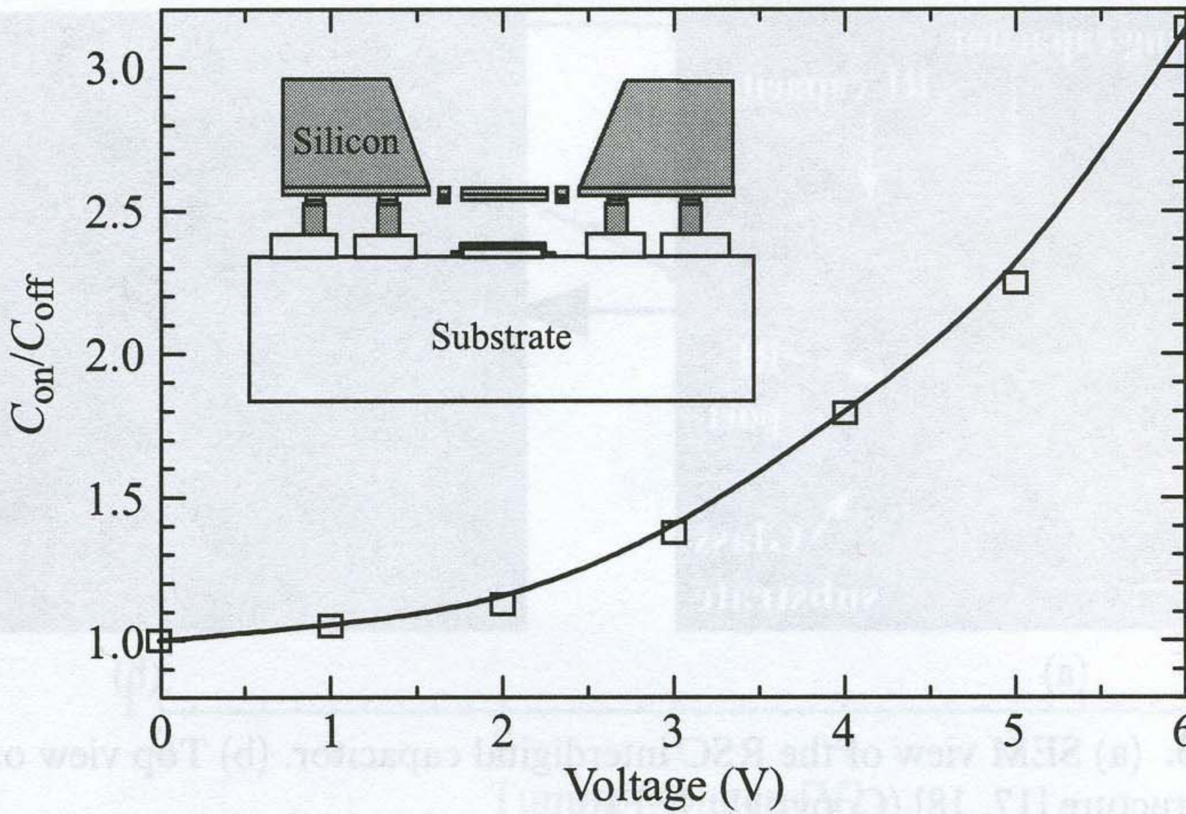


Figure 11.18. Measured capacitance ratio of the LG-Electronics piezoelectric varactor [15] (Copyright IEEE).

Dielectric tunable capacitances

- Change the material properties between plates
  - DC bias voltage can change electrical properties
    - Dielectric layer
    - Dielectric constant, ε
  - Ferro-electric thin-films, Var fig. 4.48 →

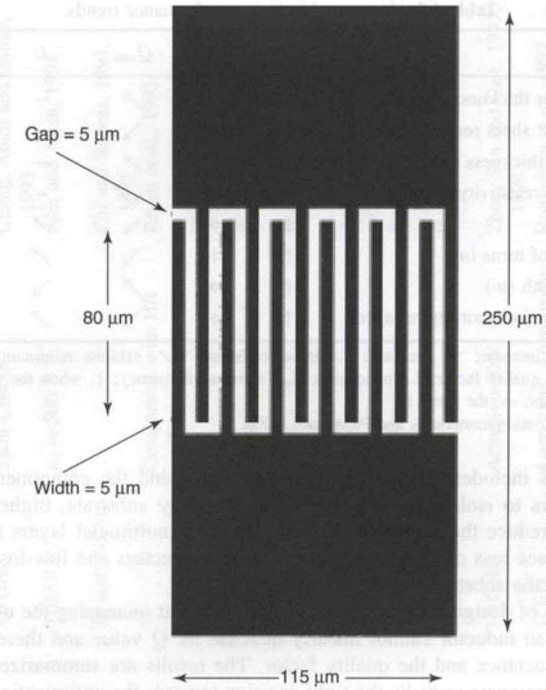


Figure 4.48 Schematic diagram and dimensions of the interdigital capacitor. Reproduced from S.W. Kirchoefer, J.M. Pond, A.C. Carter, W. Change, K.K. Agarwal, J.S. Horwitz and D.B. Chrisey, 1998, 'Microwave properties of $Sr_{0.5}Ba_{0.5}TiO_3$ thin film interdigitated capacitors', *Microwave and Optical Technology Letters* **18**(3): 168–171, by permission of IEEE, © 1998 IEEE

University of Michigan

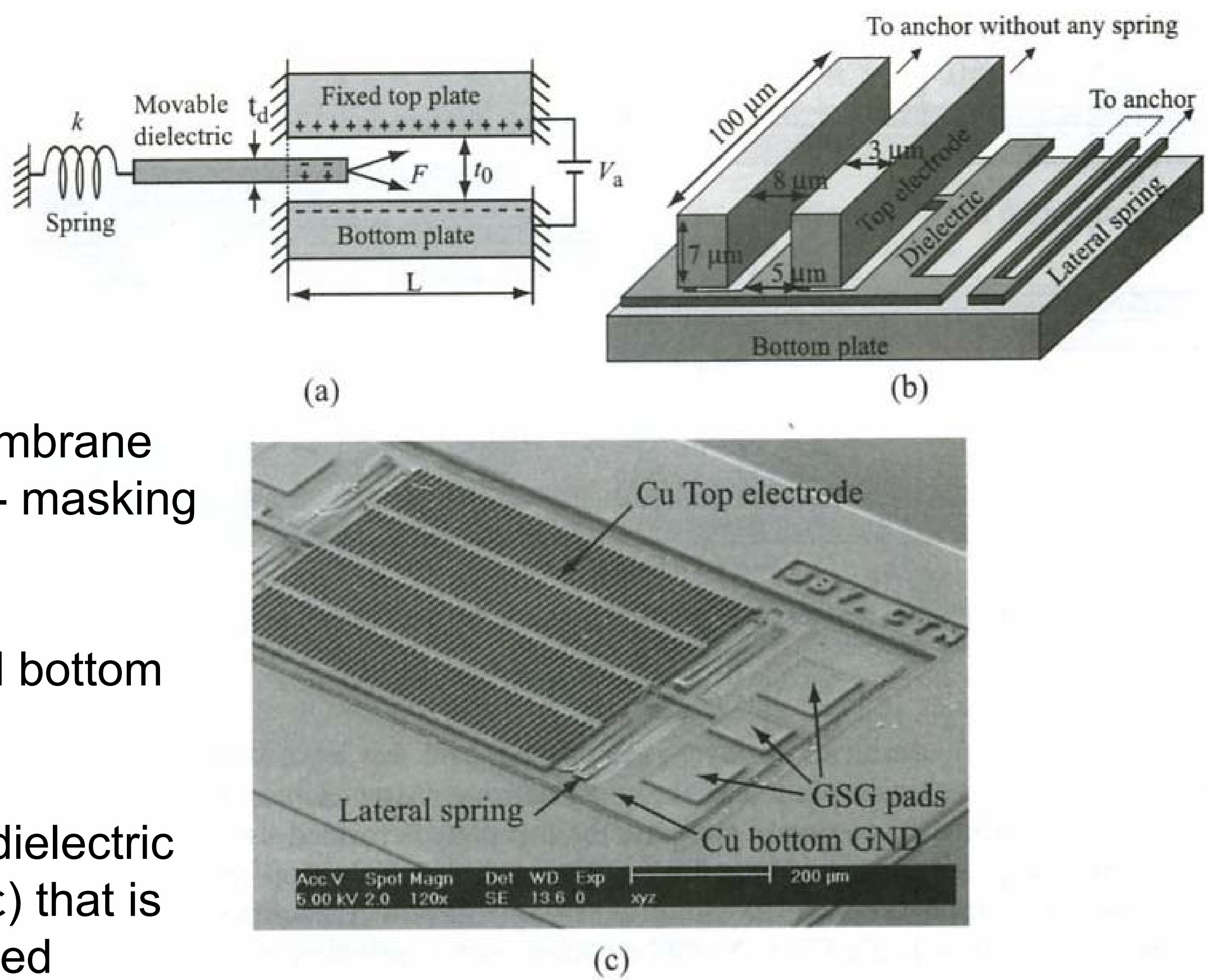


Figure 11.23. The UoM interdigital capacitor with a movable dielectric layer (a,b), and SEM picture of the fabricated device (c) [19] (Copyright IEEE).

Movable dielectric membrane between fixed plates, - masking the effective area

Principle: both top and bottom are rigid

Tuning by a movable dielectric membrane (high-k = ε) that is electrostatically actuated

Univ of Micigan, contd.

- Performance parameters
  - IC compatible technology (<200 ° C), post CMOS
  - Electroplated metal + surface micromachining
  - Movable dielectric Nitride membrane
  - No pull-in effect
  - Low actuation voltage < 10 V with k = 0.187 N/m
  - TR = 40%
  - Q = 218 @ 1 GHz for C = 1.14 pF design (maybe the highest Q published!)

Univ of Micigan, contd.

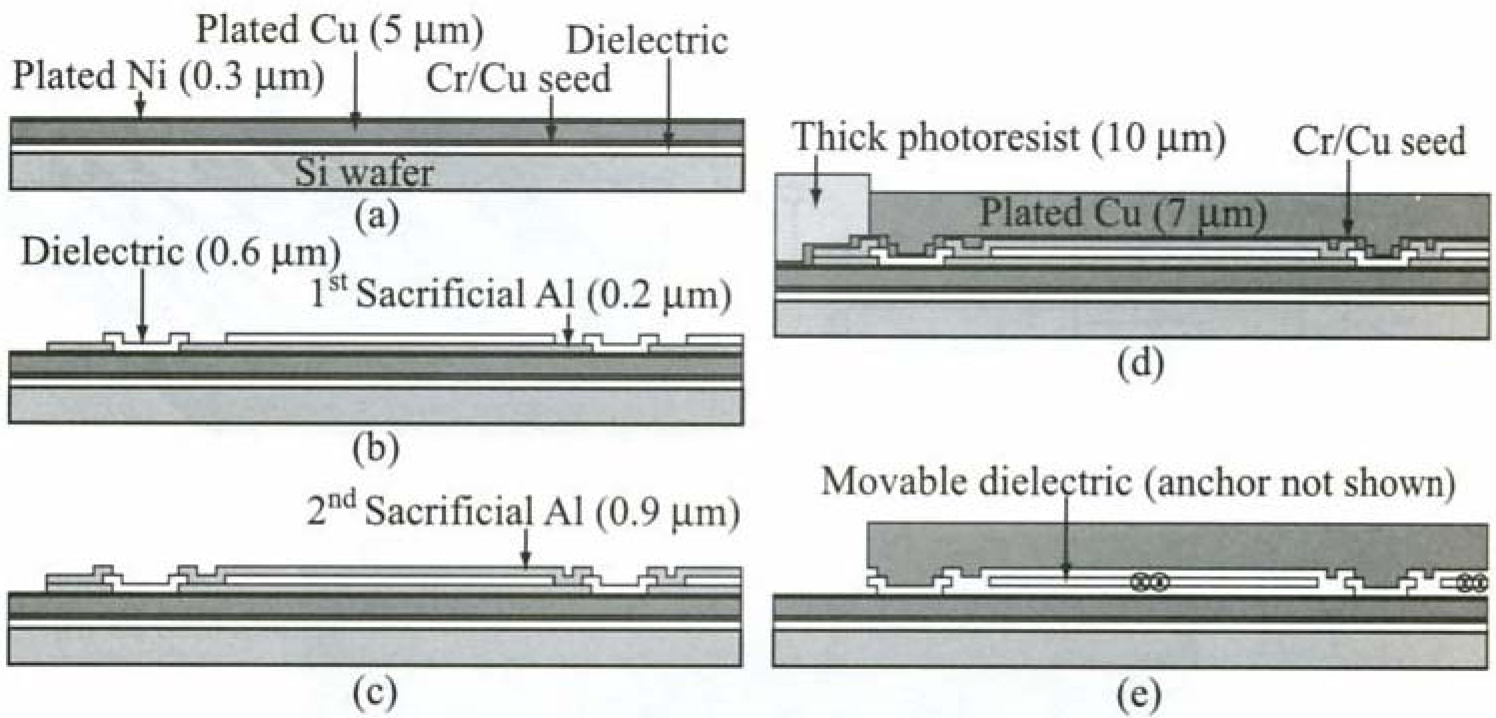


Figure 11.24. Fabrication process of the UoM interdigital capacitor [19] (Copyright IEEE).

Rebeiz

RF MEMS capacitance banks

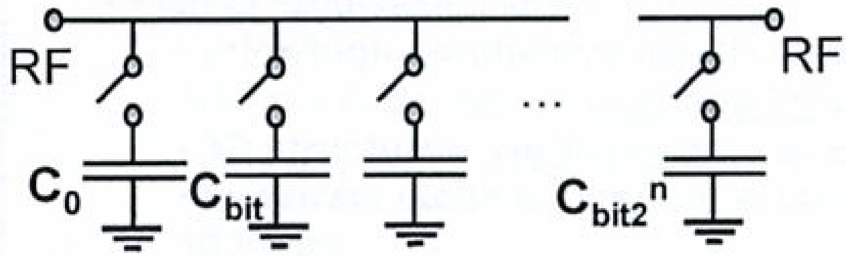
- Use of programmable capacitance banks
  - Use an ”array” of fixed capacitances
  - Connect to the desired C-value
  - MEMS switches used for connecting
  - Can be programmed using a digital signal

  - Both series and shunt configurations are possible

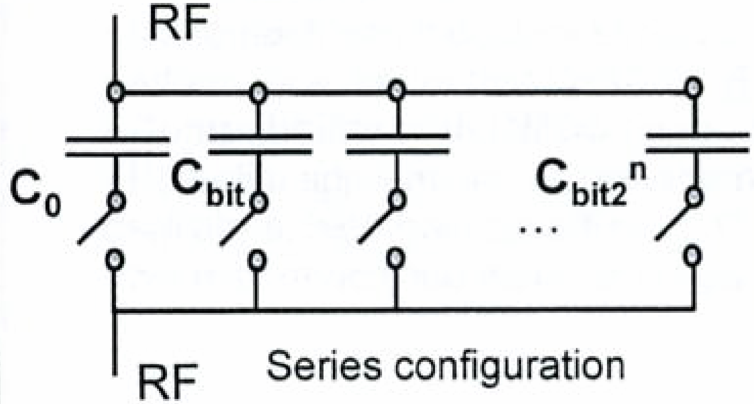
FSRM

RF MEMS capacitor banks

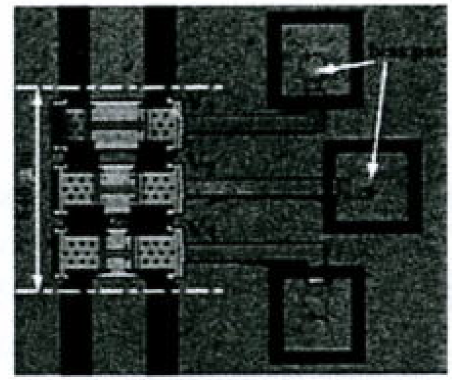
n-bit capacitor bank with capacitive switch and fixed C_0



Shunt configuration



Series configuration



Design and process (University of Michigan)

- 3-bit digital MEMA varactor on glass substrate

Performance

- **TR= 3:1**, C=146- 430fF in K-band
- Q= 5 – 10 @ 10GHz
- Q > 50 – 200 reported by same authors

L. Dussopt and G. Rebeiz, IEEE Microwave and wireless comp. Letts, vol. 14, 2003, pp. 361-363.

74

Eliminate influence of thermal stress

- One example
  - H. Nieminen et al: ”Design of a Temperature-Stable RF MEMS Capacitor, J MMSyst, vol 13, no 5, 2004:
  - Design capacitance into a **frame-structure** →
  - Use frame to compensate the thermal induced stress
  - Anchor the capacitance in such a way that when the frame is deformed, minimal stress is induced on the capacitance itself
    - Ex. corners displace very little
    - Anchor the capacitance in the corners!

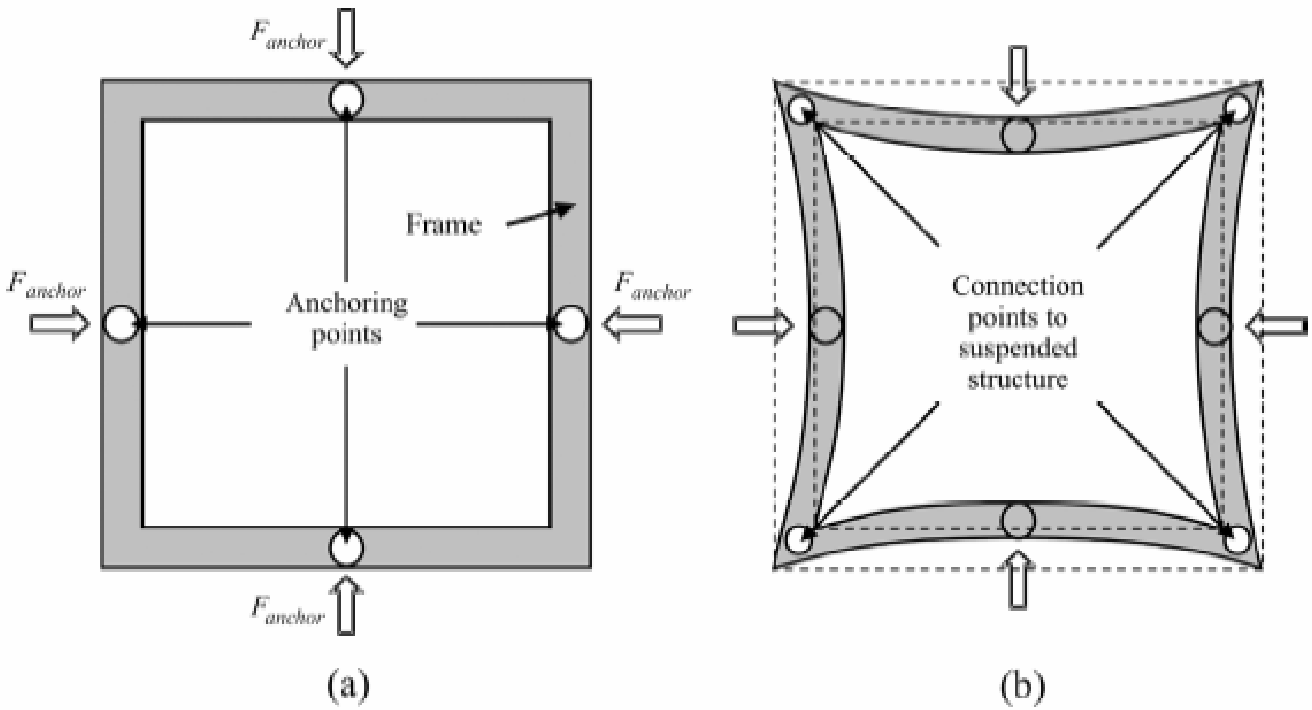


Fig. 2. The steps to create geometrical compensation of a suspended structure against external stress for arbitrary geometry are as follows. (a) Create frame geometry. Designate anchoring points. The force (F_{anchor}) that simulates the effect of external stress is exerted on these anchoring points. The force is directed to the geometrical center of the frame. (b) The frame bends due to the force. However, if the anchoring points and the geometry of the frame are selected properly, there are points in the frame that do not move or move very slightly. These are points where the frame is connected to the suspended structure.

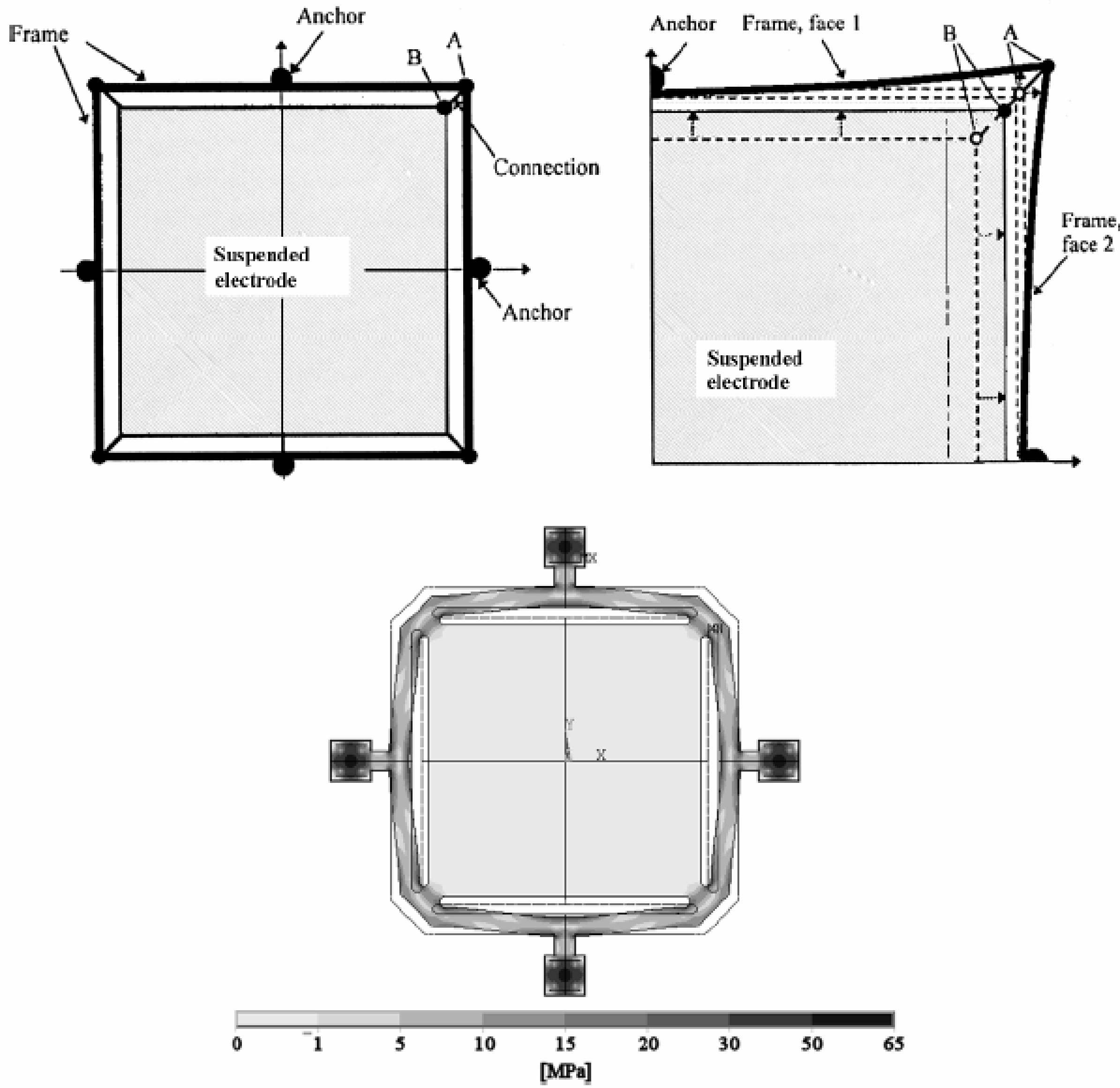


Fig. 3. FEM analysis of the temperature-compensated capacitor. Simulation is done with ANSYS. The temperature change is $-50\ ^\circ\mathrm{C}$. The substrate is silicon. The suspended electrode, the frame and the anchors are 4-μm-thick gold. The scale at the bottom of the figure shows stress. Displacements in the figure are exaggerated.