INF5490 RF MEMS

L11: RF MEMS kapasitanser

Dagens forelesning

- Tunbare og programmerbare passive komponenter i RF kretser
- Tunbare **RF MEMS kapasitanser**
    - **Vertikalt** tunbare kapasitanser
        - 2-plate kapasitans
        - 3-plate kapasitans
        - Dobbelt luft-gap kapasitans
        - Andre eksempler
    - **Lateralt** tunbare kapasitanser
    - **Termisk** tunbare MEMS kapasitans
    - **Piezoelektrisk** aktuator tunbare kapasitanser
    - Tuning ved endring av **dielektrisk** materiale
- RF MEMS kapasitans banker

Passive komponenter i RF-kretser

- → **MEMS kondensatorer og spoler**
- Aktuelle som **erstatninger** for ”off-chip” passive komponenter
- Tunbarhet og programmerbarhet er ønskelig
  - Tunbare/programmerbare **MEMS kapasitanser**
    - **= varactor** (”variable reactor”)
    - Enkle kapasitanser
    - Programmerbare kapasitans-banker
  - Enkle/programmerbare **MEMS induktanser** (L12)
    - Enkle faste induktanser
    - Programmerbare induktans-banker

Bruksområde for tunbare kapasitanser

- Eks. for frekvenskontroll i VCO
  - = ”Voltage controlled oscillator”
  - Høye krav til
    - Stabilitet
    - Lav fase-støy
    - Bredt frekvensområde

MEMS konkurrerer med dagens halvleder-løsninger

- ÷ MEMS varaktorer har ikke hatt en like stor utvikling som MEMS svitsjer
- ÷ Mange diskrete Si og GaAs varaktorer eksisterer
  - → 30 GHz
  - Eks. Q= 30-60 for 0.5-5 GHz (SiGe)
- ÷ Tunbarhetsområdet for MEMS varaktorer er lite
  - 1.2 – 2.5
  - Tilsvarende for halvleder-varaktorer 4 – 6
- ÷ MEMS er følsom for ulike støyeffekter som gjør seg gjeldende ved lav fjærkonstant, k
  - Men lav k er ønskelig for 3 – 5 V anvendelser

Hvorfor da MEMS varaktorer?

- + Har potensial for **høye Q-verdier**
  - Q = 100 – 400 for mm-frekvenser
- + Kan tåle store RF spennings-sving
- + Kan produseres billig på glass, keramikk, høy-resistivitets Si-substrat
  - For eksempel for "lav-kost" 3 – 60 GHz tunbare nettverk og filtre
- ÷ → Ennå en tid før MEMS varaktorer kan erstatte GaAs varaktorer, spesielt i området under 5 GHz
- + Likevel: er den RF MEMS komponent som er nærmest anvendelser i markedet
  - Forholdsvis moden teknologi
  - Det finnes allerede mange demonstrasjoner av MEMS erstatnings-komponenter, DC → 100 GHz

Særtrekk og utfordringer for RF MEMS kapasitanser

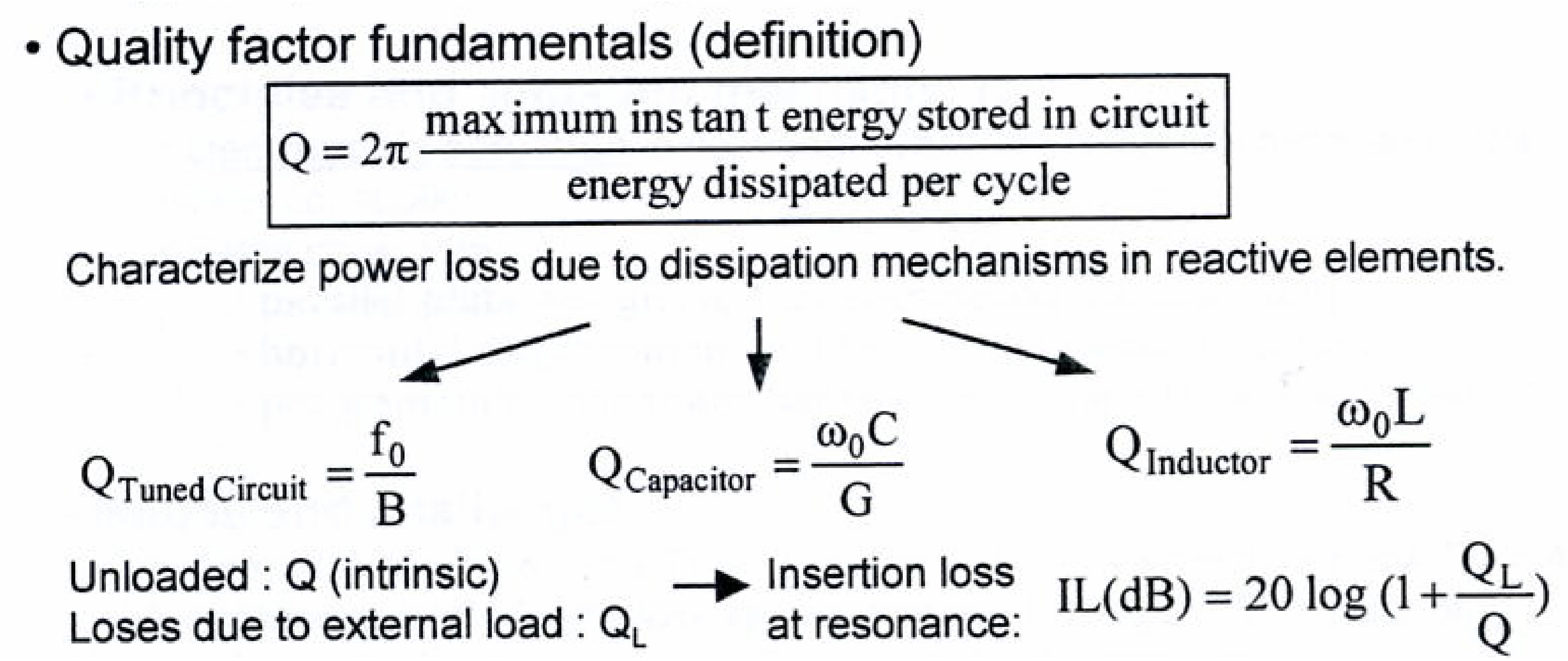
- Problem med høy nok TR
  - → Oppnå tilstrekkelig **Tuning Range (TR)**
    - Definisjon TR: $C_{\max}/C_{\min}$
    - (>2), siden halvleder varaktorer har TR > 4
- Problem forbundet med å ha lav fjær-stivhet
  - Er ønskelig pga.
    - <5V operasjon
  - Er problematisk pga.
    - Aksellerasjon, RF power selv-aktivering, støy-effekter

Særtrekk og utfordringer, forts.

- Design-mål for RF MEMS kapasitanser
  - Høy Q-verdi (>100) over et bredt frekvensbånd (wideband)
  - Enkelhet, sammenlignet med konkurrerende teknologier
  - Billigere
  - Mer pålitelig
  - Enkel og billig pakking

Hvorfor etterstrebes høy Q-verdi?

- Q-faktor karakteriserer tap pga. effekt-dissipering i elementene
- Q bør være størst mulig for å redusere Insertion loss



- Quality factor fundamentals (definition)

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

Characterize power loss due to dissipation mechanisms in reactive elements.

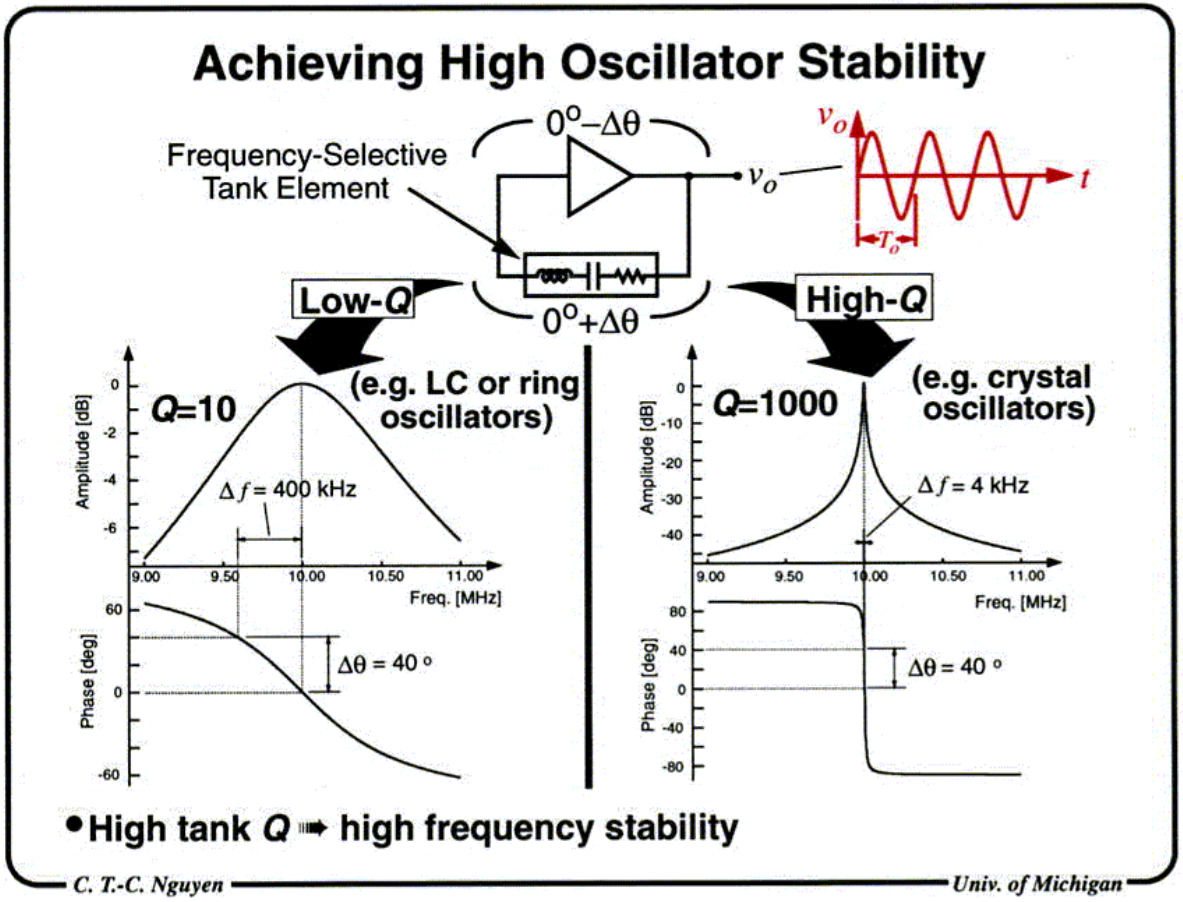
$$Q_{\text{Tuned Circuit}} = \frac{f_0}{B} \qquad Q_{\text{Capacitor}} = \frac{\omega_0 C}{G} \qquad Q_{\text{Inductor}} = \frac{\omega_0 L}{R}$$

Unloaded : Q (intrinsic)
Loses due to external load : Q_L

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

Korrelasjon mellom Q-faktor og oscillator-stabilitet

- **Q-faktoren er helt sentral når det gjelder RF krets-ytelse!**



Achieving High Oscillator Stability

- **High tank Q ➡ high frequency stability**

C. T.-C. Nguyen — Univ. of Michigan

Parallell plate kondensator

- Grunnleggende ligninger
  - $Q = V\,C$, $I = C\,dV/dt$
  - $C = \varepsilon A / g$
- NB! C kan generelt tunes ved hjelp av 3 parametre
  - g, gap
  - A, areal
  - ε, dielektrisitetskonstant

Tunbare RF MEMS kapasitanser

- Elektrostatisk aktivering er en dominerende mekanisme for tuning
  - Lavt effektforbruk
- Noen kategorier
  - Vertikal elektrostatisk forskyvning
    - Parallell plate kondensator
    - Tuning av gapet (ikke-lineær endring)
  - Horisontal (lateral) forskyvning
    - Tuning av arealet (lineær endring)
  - Termisk tunbare MEMS kapasitanser
  - Piezoelektrisk aktuator tunbare kapasitanser
  - Tuning ved å endre dielektrisk materiale

Tunbare RF MEMS kapasitanser, forts.

- Bruk av programmerbare kapasitans-banker
  - Innkobling av faste C-verdier
  - Array av faste kapasitanser
  - MEMS svitsjer for innkobling

Ekvivalentkrets for kapasitans

- Ved høye frekvenser → induktans
  - har en karakteristisk selvresonans-frekvens
  - Induktansen bør holdes så lav som mulig slik at selvresonans ligger mye høyere enn bruksområdet

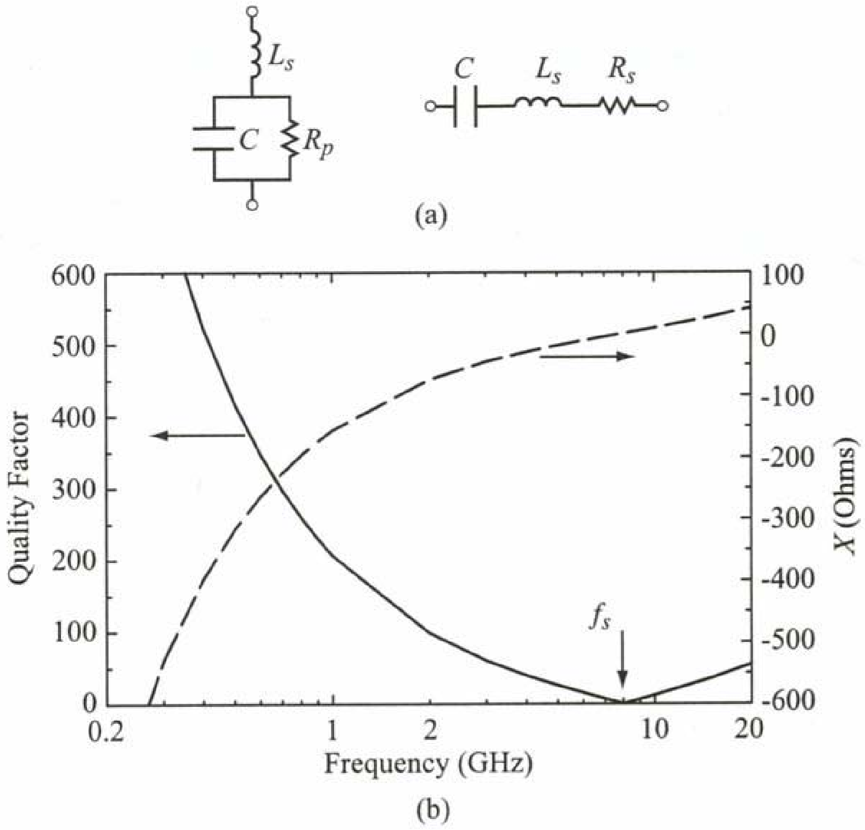
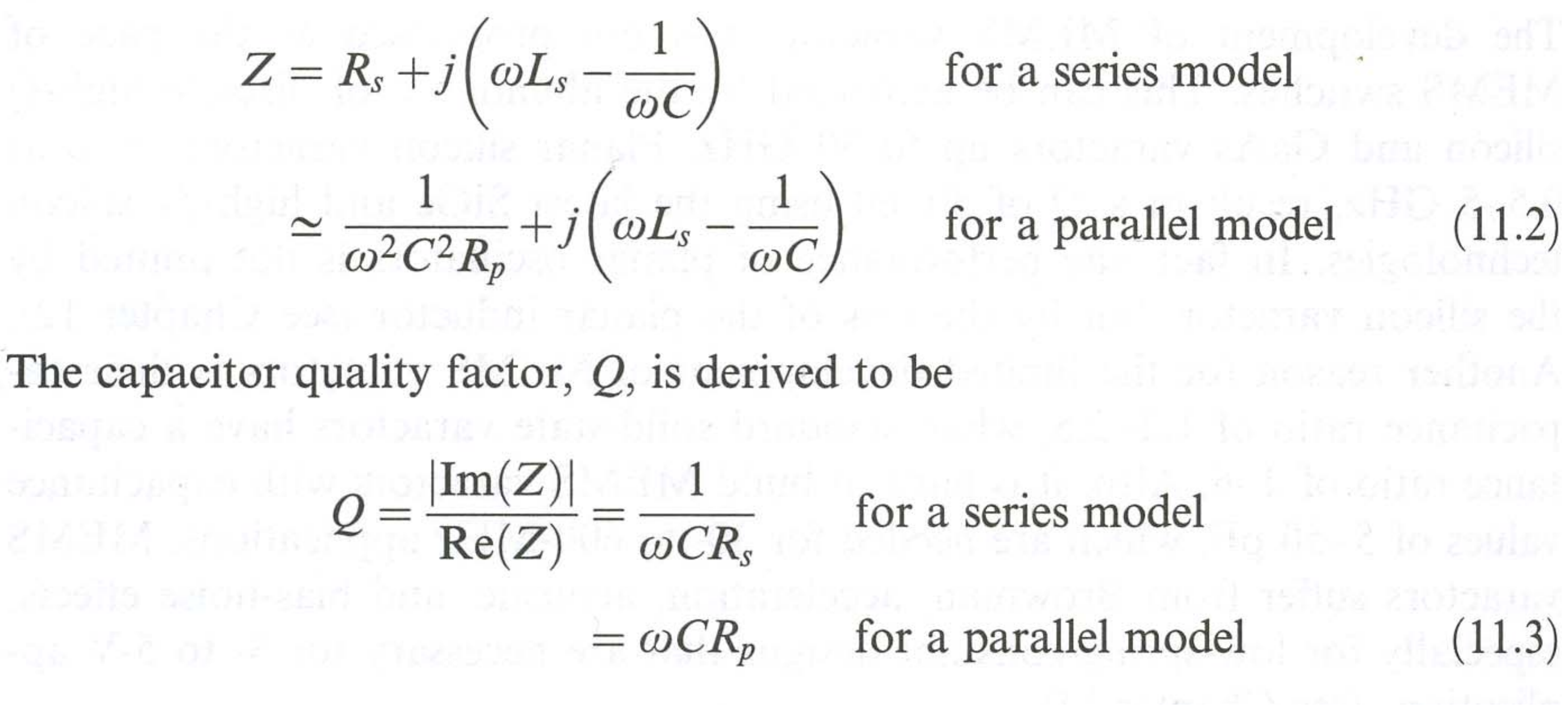


Figure 11.1. (a) Capacitor models. (b) Calculated reactance and Q of a 1-pF capacitor with $L_s = 0.4$ nH and $R_s = 0.83\ \Omega$ ($f_s = 8$ GHz).

Impedans og Q-faktor til en diskret kondensator

Q-faktor angis 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

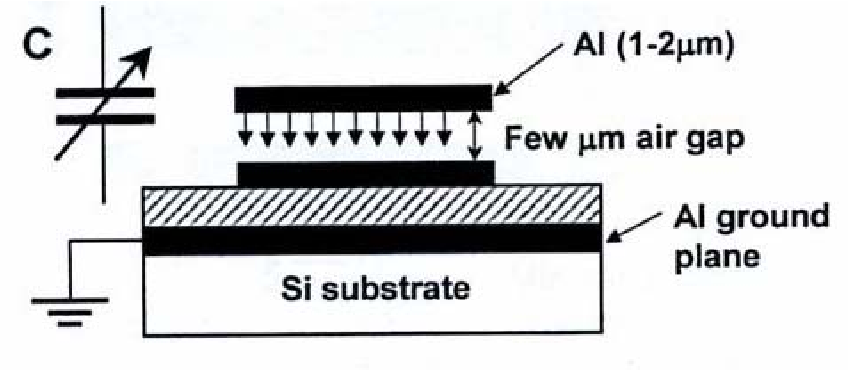
$$Q = \frac{|\mathrm{Im}(Z)|}{\mathrm{Re}(Z)} = \frac{1}{\omega C R_s} \qquad \text{for a series model}$$

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

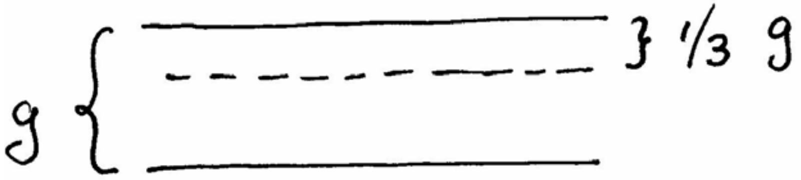
Rebeiz

To-plate tunbar MEMS kapasitans

- Young & Boser, Berkeley
- Gap-tuning
- Den ene platen kan beveges ved elektrostatisk aktivering
- Opererer under likevekt mellom elastiske og elektriske krefter



Beregning av TR for 2-plate kapasitans



$$C_{min} = \varepsilon \frac{A}{g}$$

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

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

Teoretisk tuning-område 50%. Begrenset av pull-in effekten

Young & Boser, Berkeley, forts.

- Etsing av hull i kapasitans-platen
  - For mindre demping (squeezed-film damping)
  - Positivt for ”release”-trinnet i en prosess

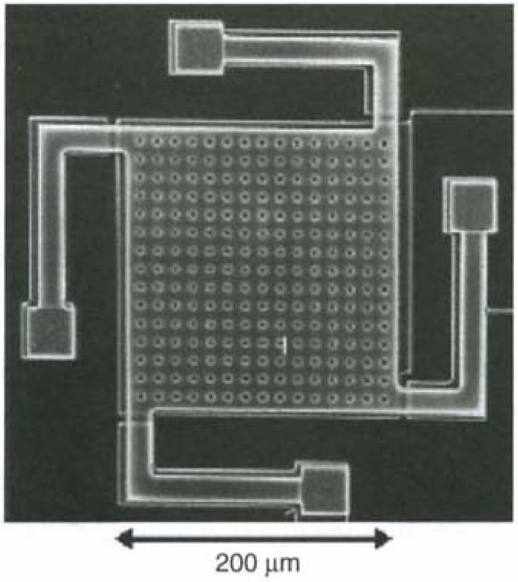
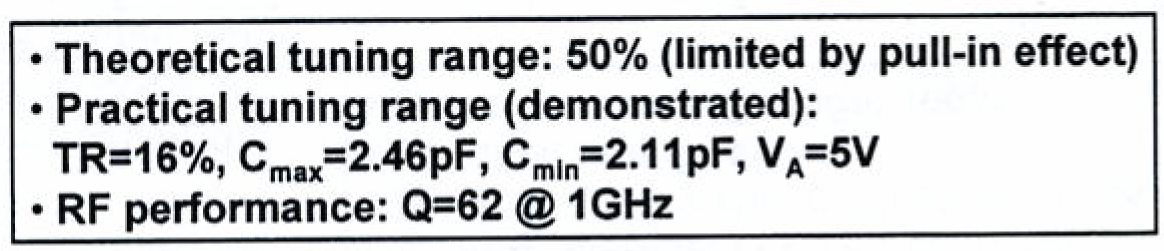


Figure 4.33 Top view of a micromachined variable capacitor. Reproduced from D.J. Young and B.E. Bover, 1996, ‘A micromachined variable capacitor for monolithic low-noise VCOs’, in *Proceedings of the International Conference on Solid-state sensors and Actuators*, IEEE, Washington, DC: 86–89, by permission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

Young & Boser, Berkeley, forts.

Typiske resultater fra implementeringen:

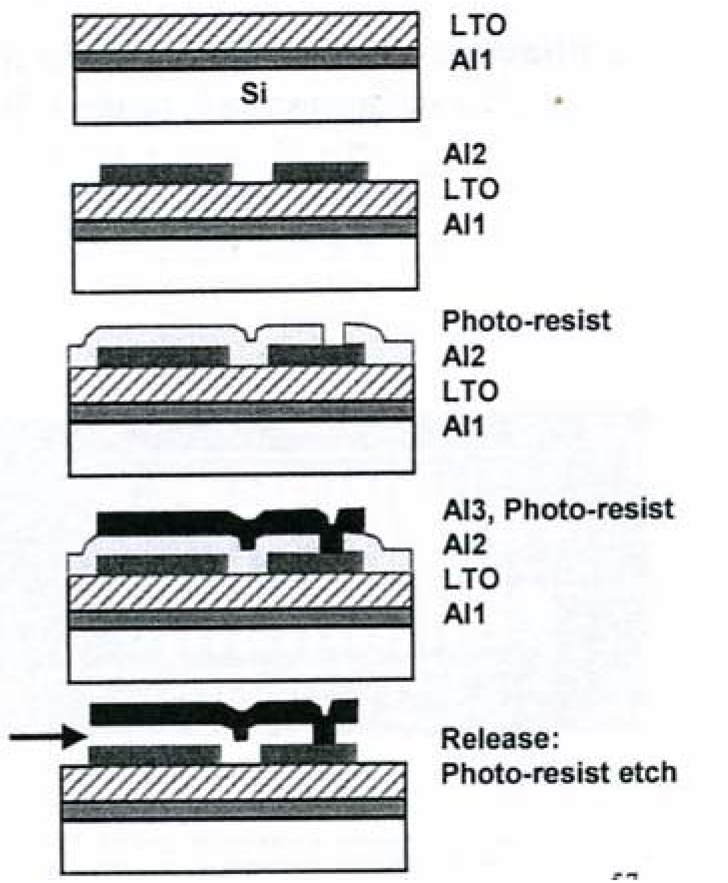


- **Theoretical tuning range: 50% (limited by pull-in effect)**
- **Practical tuning range (demonstrated):**
  TR=16%, C_{max}=2.46pF, C_{min}=2.11pF, V_A=5V
- **RF performance: Q=62 @ 1GHz**

Mai56

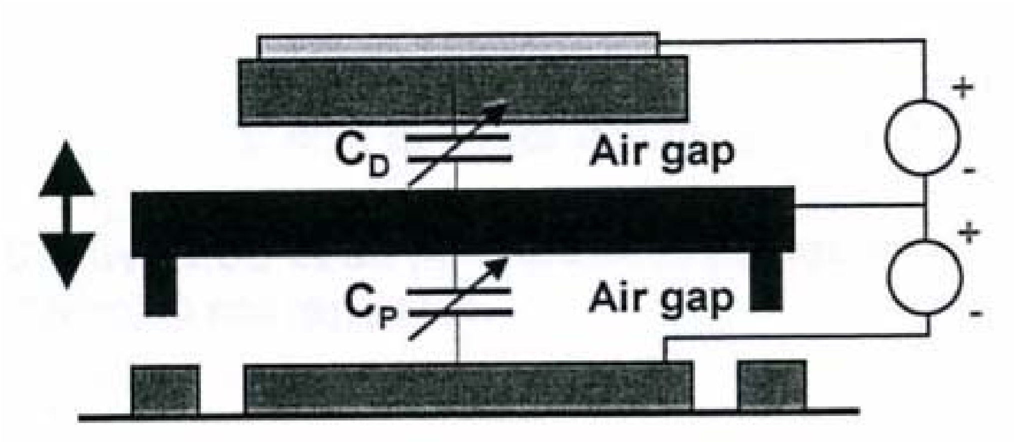
Typiske trekk, Berkeley-eks.

- Overflate mikromaskinering
  - 2 metall-lag + Al jord-plan

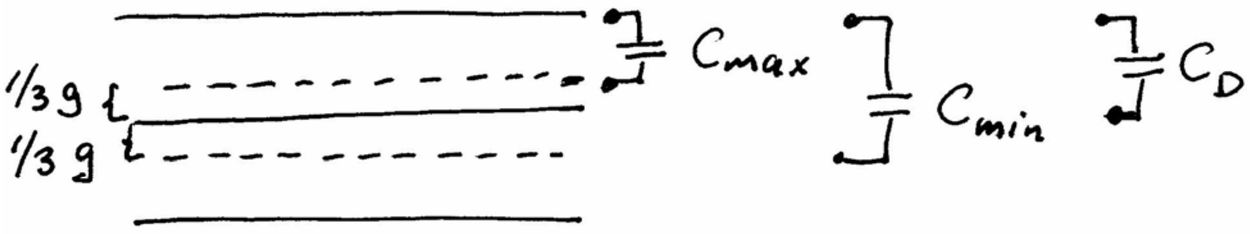


3-plate tunbar MEMS kapasitans

- TR kan utvides ved å introdusere en 3dje plate
  - A. Dec & K. Suyama: ”Micromachined Electro-Mechanically Tunable Capacitors and Their Applications to RF IC´s” 1998. **Columbia University**



Beregning av TR for 3-plate

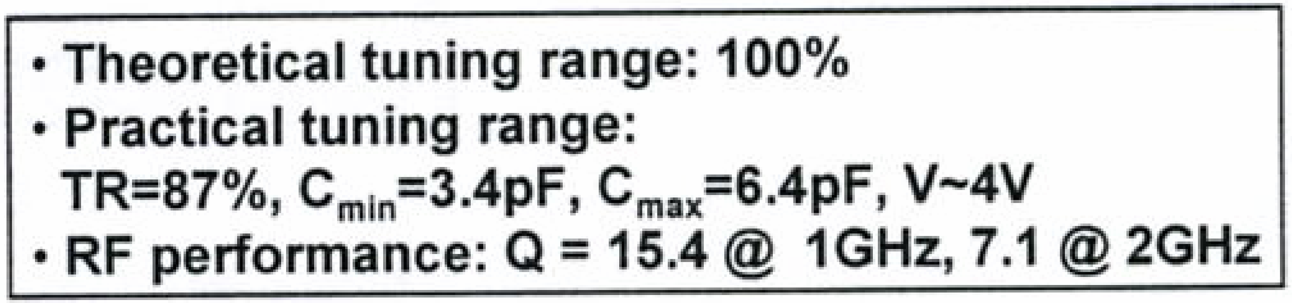


$$C_{max} = \frac{3}{2} C_D \qquad C_{min} = \varepsilon \frac{A}{\frac{4}{3} g} = \frac{3}{4} C_D$$

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

Dvs.: kan tunes 100%

Demonstrerte verdier, 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

Dec & Suyama, forts.

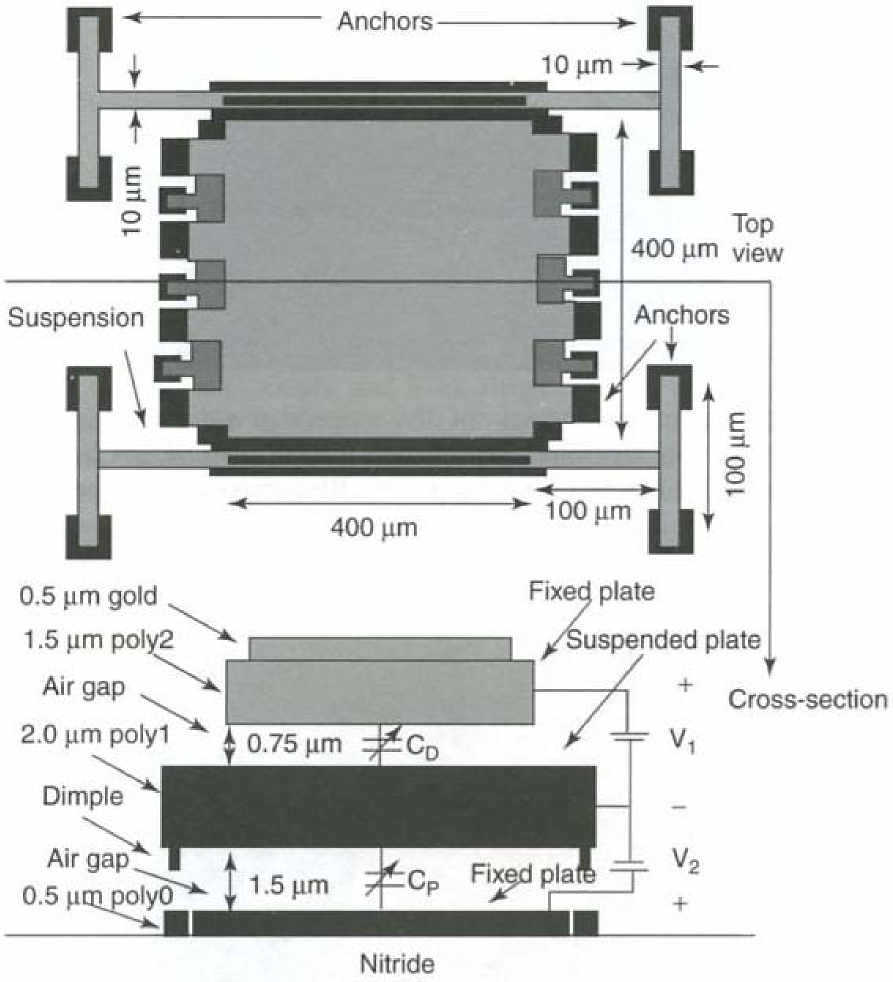


Figure 4.35 Top and cross-sectional views of three-plate varactor. Reproduced from A. Dec and K. Suyama, 1998b, 'Micromachined electromechanically tunable capacitors and their applications to RF IC's', *IEEE Transactions on Microwave Theory and Techniques* **46**(12): 2587–2596, by permission of IEEE,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

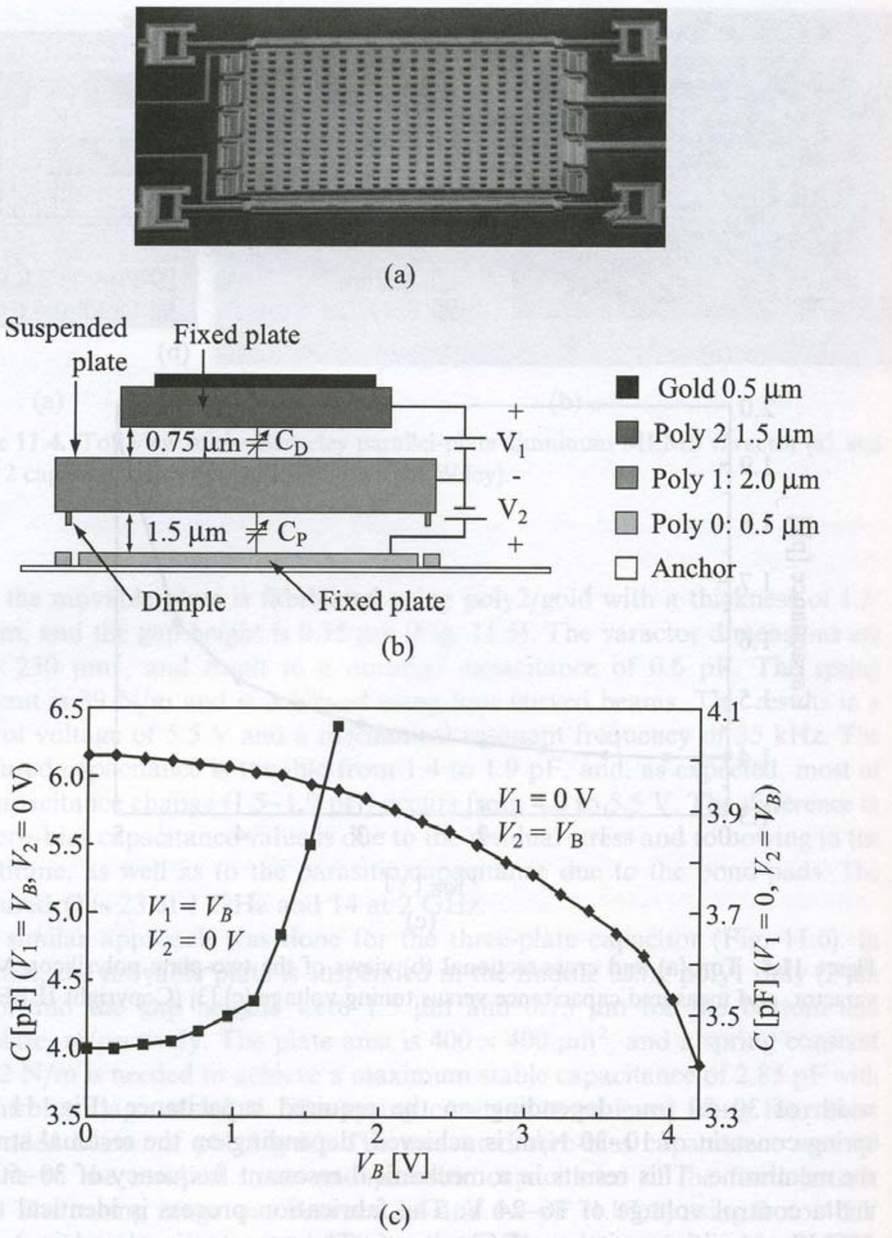


Figure 11.6. Top (a) and cross-sectional (b) view of the three-plate polysilicon MEMS varactor, and measured capacitance versus tuning voltage (c) [2] (Copyright IEEE).

Dec & Suyama, forts.

- Prosess
  - Standard 3-lags poly overflate mikromaskinering (MUMP´s) med HF etsing og ”supercritical drying”
  - Poly brukes ofte som parallell plate selv om den har mindre konduktivitet enn Al pga. overlegne mekaniske egenskaper

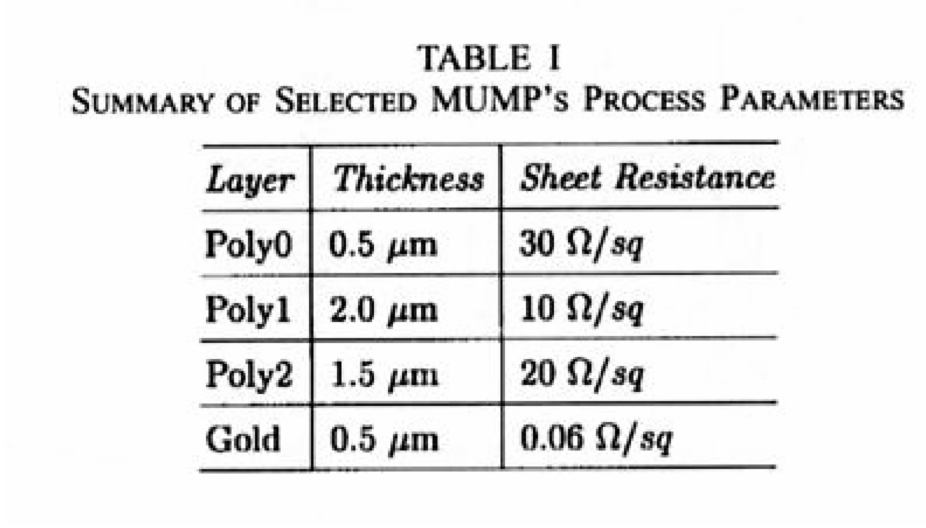
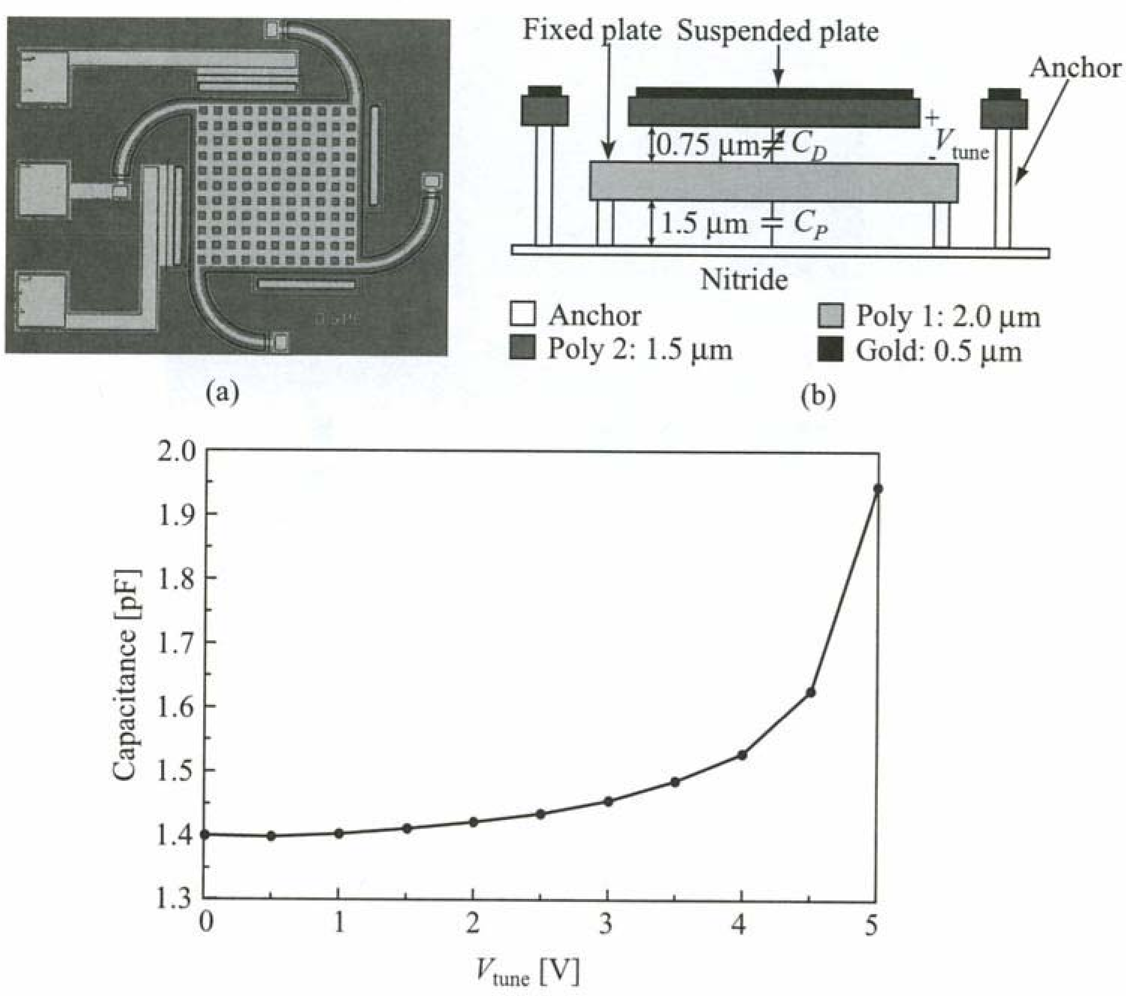


TABLE I

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, eks2



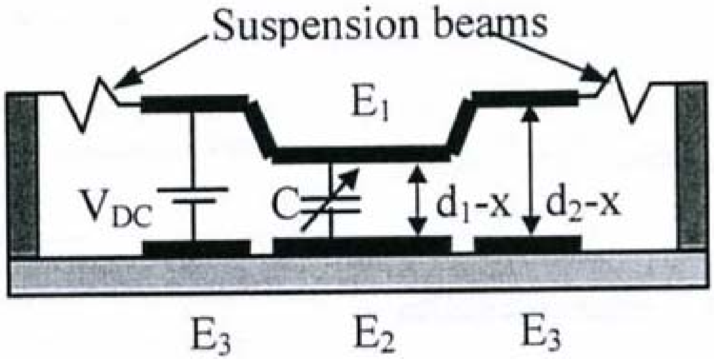
(a) (b)

(c)

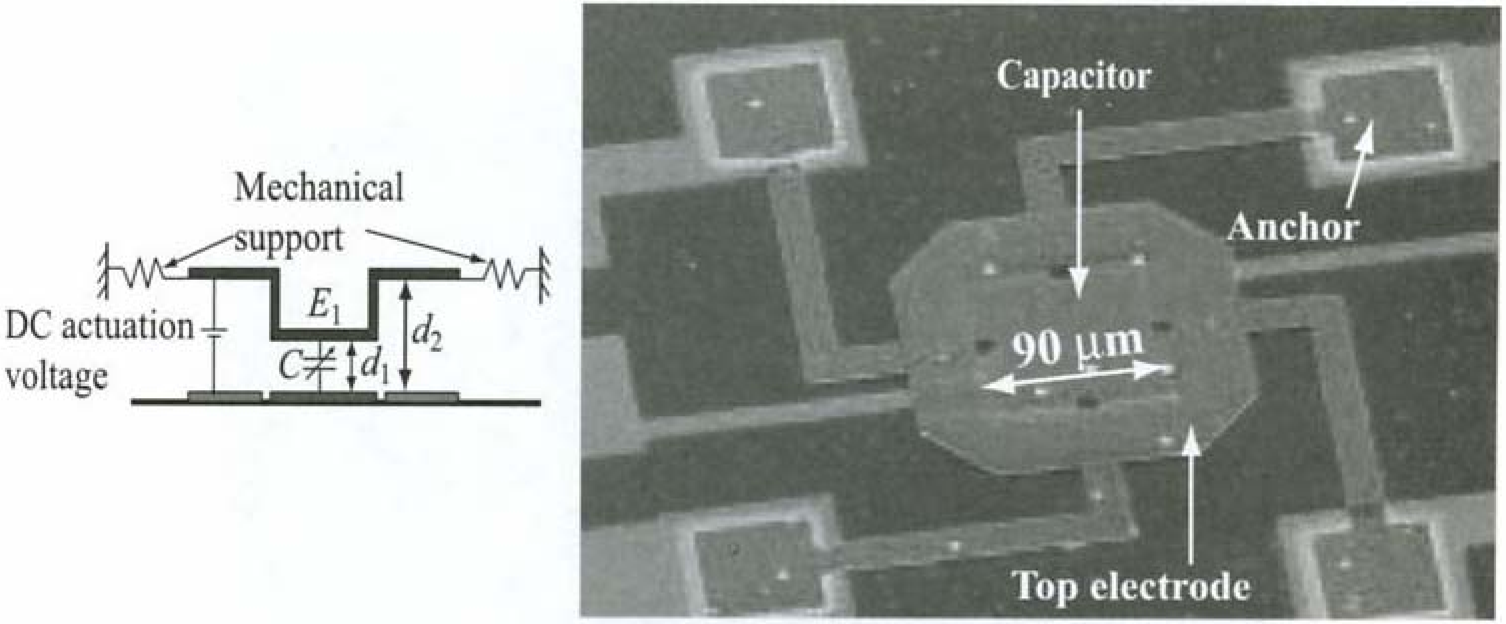
Figure 11.5. Top (a) and cross-sectional (b) views of the two-plate polysilicon MEMS varactor, and measured capacitance versus tuning voltage (c) [3] (Copyright IEEE).

Dobbelt luft-gap kapasitans

- J. Zou et al, 2000, Univ of Illinois
- Hensikt med dobbelt luft-gap
  - Øke TR
    - Eliminere virkningen av pull-in-effekten
  - Kan trekke ned til 1/3 d2 før pull-in inntrer
  - TR kan økes betraktelig hvis 1/3 *d2 > d1
    - Dvs. **midtelektroden kan trekkes helt ned uten å erfare pull-in!**



Univ of Illinois, forts.



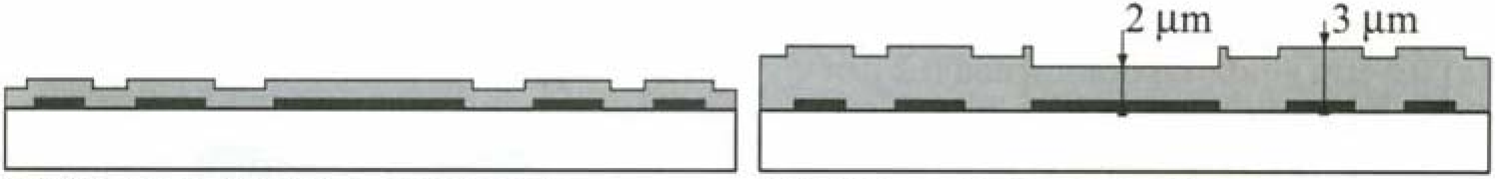
(a) (b)

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, forts.

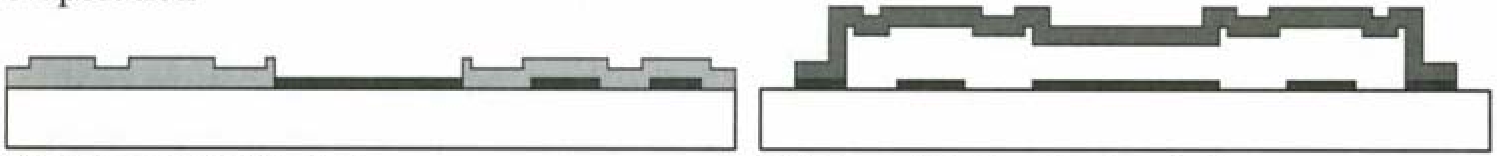
Forenklet fabrikasjonsprosess

- Kobber som offer-lag
- Metaller: gull & permaloy (Ni-Fe)
- Luft-gap: d1 = 2 µm, d3 = 3 µm



(a) 0.5-µm gold and 1-µm copper evaporation

(c) 2-µm copper evaporation



(b) Copper patterning

(d) 2-µm Ni–Fe electroplating, copper sacrificial layer etching, and device releasing

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

Eks fra Univ of Michigan

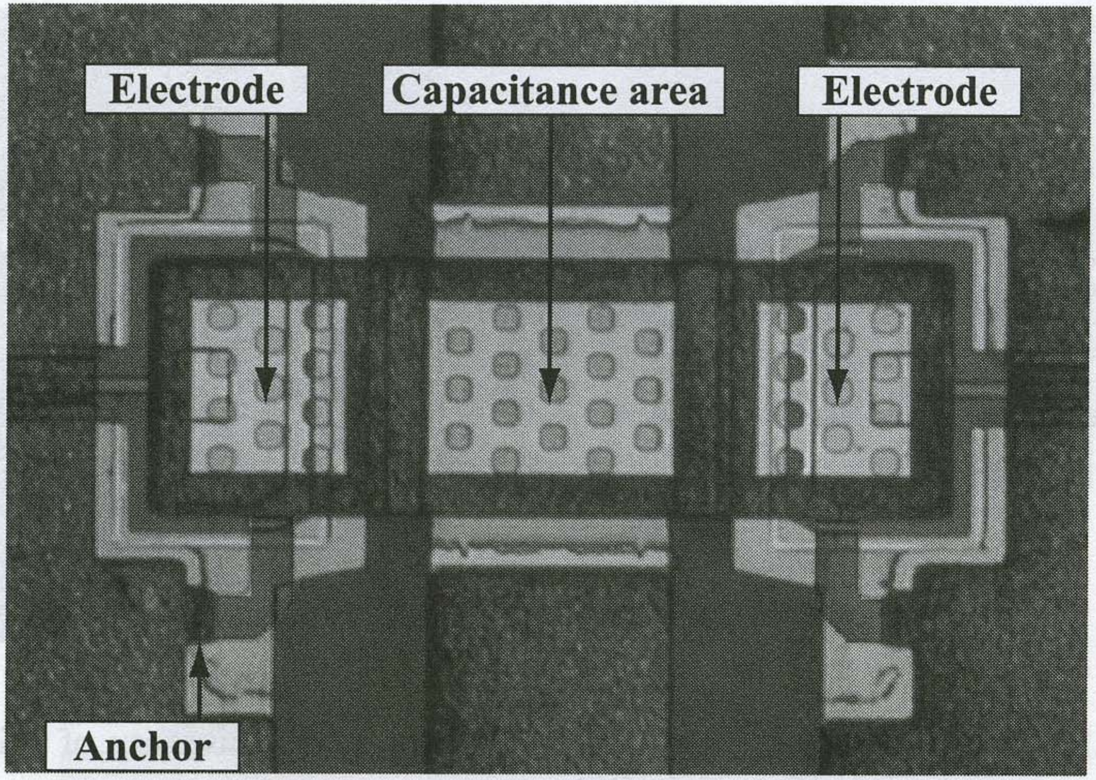
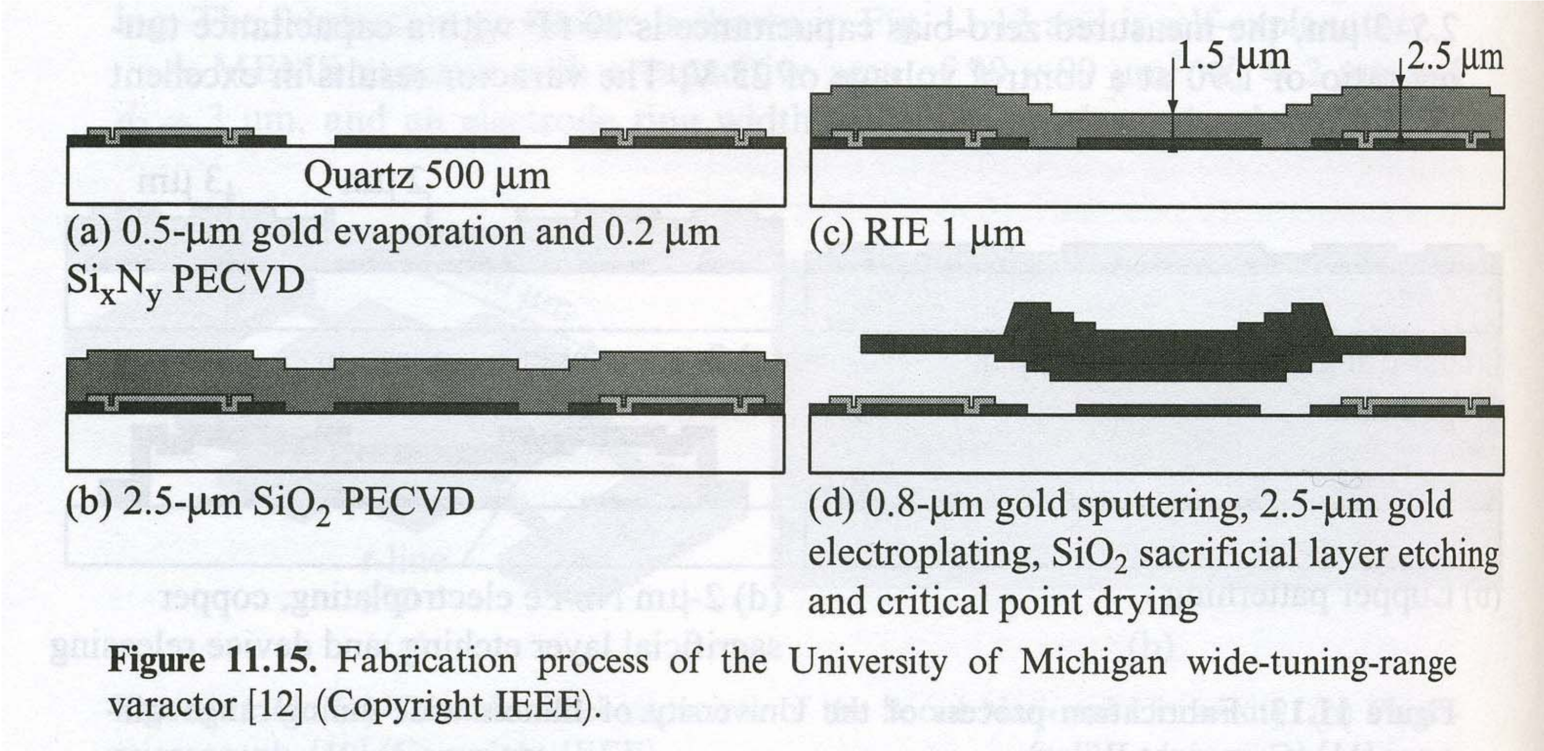


Figure 11.14. Top view of the University of Michigan wide-tuning-range varactor [12] (Copyright IEEE).

Eks fra Univ of Michigan, forts.

- Realisert på kvarts-substrat
- SiO2 offerlag etses delvis → 2-trinns Au membran
- 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, diskret 2-verdi

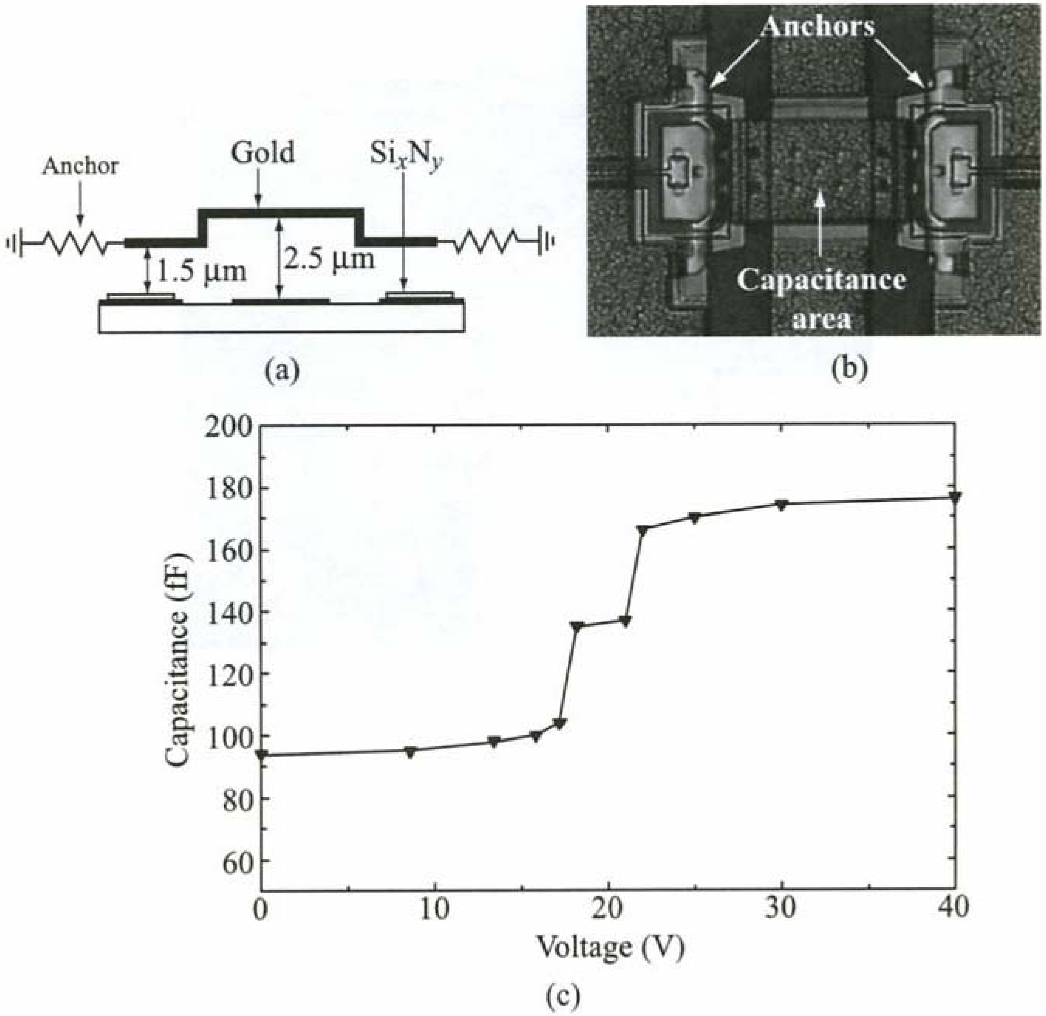
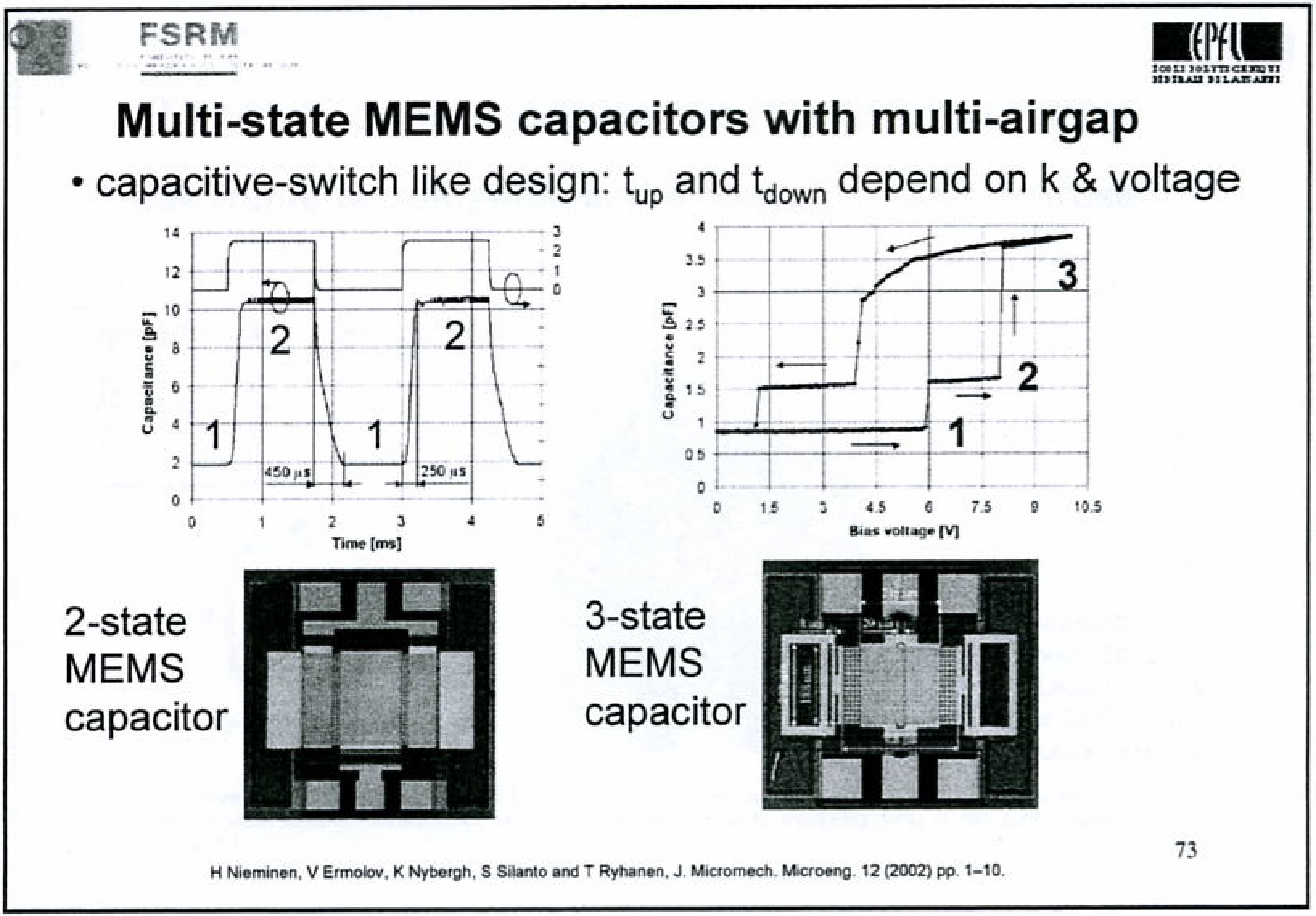


Figure 11.29. Cross section (a), top view (b), and measured capacitance (c) of the Michigan discrete two-value MEMS varactor [12] (Copyright IEEE).

Multi-state MEMS kapasitanser med multi luft-gap

- Eks fra Nokia → Nieminen
  - Ulike segmenter med multi-gap
- Kan tunes i trinn
  - 2 eller 3 trinns
- Kretsen oppviser hysterese-egenskaper



FSRM

Multi-state MEMS capacitors with multi-airgap

- capacitive-switch like design: t_{up} and t_{down} depend on k & voltage

2-state MEMS capacitor

3-state MEMS capacitor

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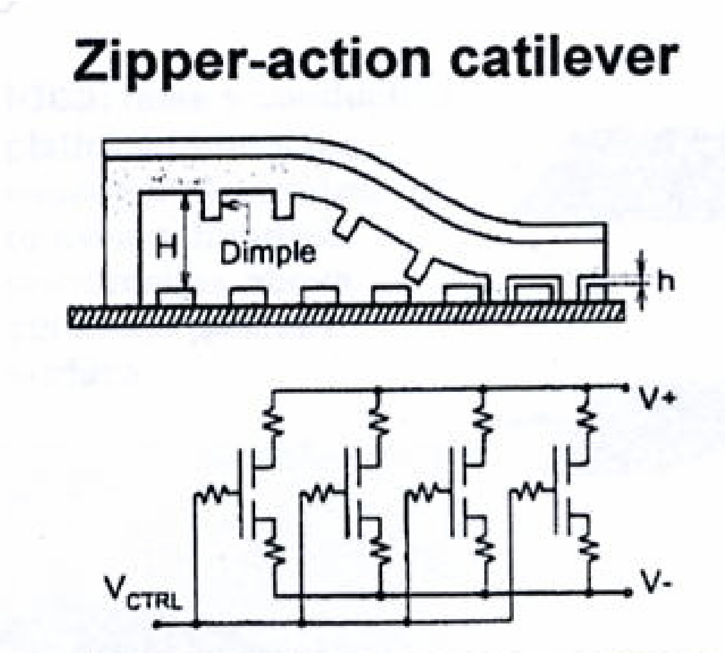
H Nieminen, V Ermolov, K Nybergh, S Silanto and T Ryhanen, J. Micromech. Microeng. 12 (2002) pp. 1–10.

Ionescu, EPFL: H. Nieminen et al

”Glidelås”-kapasitans

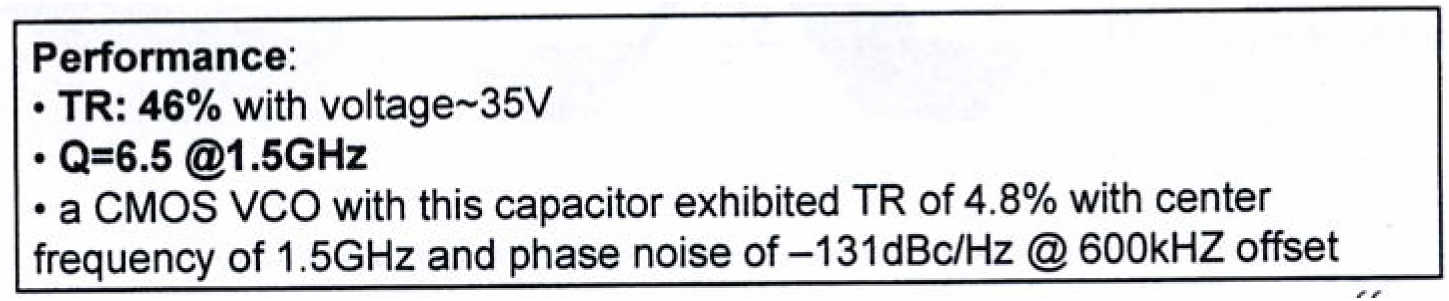
- Eks. på glidelås cantilever kapasitans
- Design og fabrikasjon ved Columbia University
  - Lang, tynn bjelke legger seg ned fra enden
  - Små kapasitans-bidrag legges til i parallell



Zipper-action catilever

Colombia University, forts.

- Ytelse:



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

Eks fra MIT

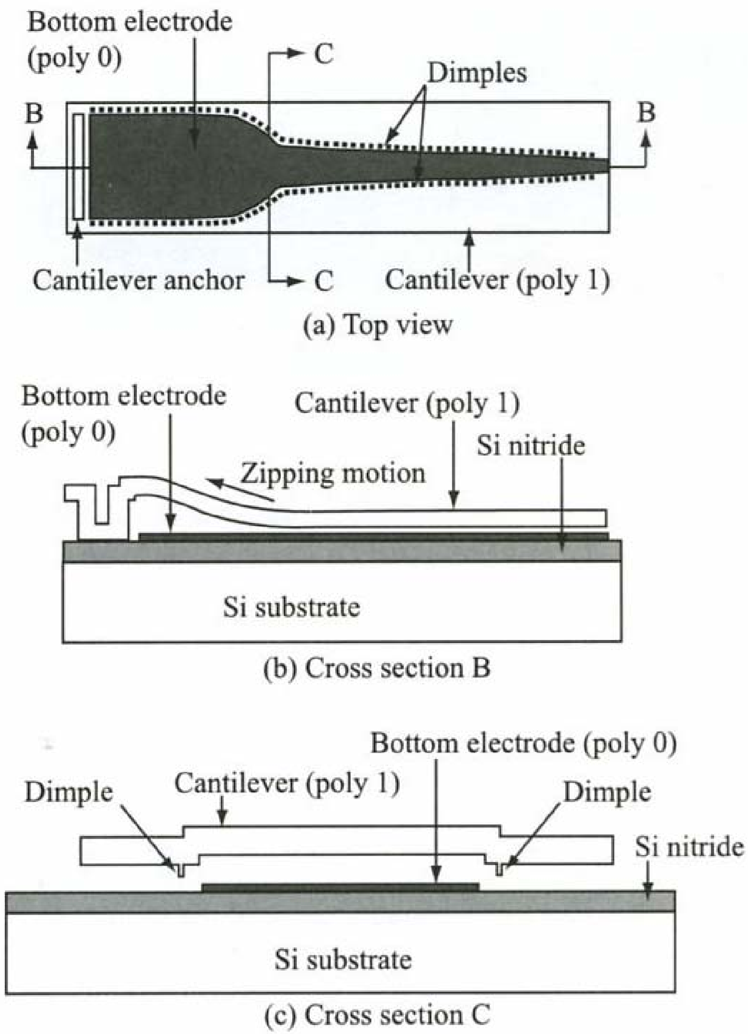


Figure 11.9. Top (a) and cross-sectional (b,c) view of the MIT zipper varactor [8].

Mykest nær endepunktet

Rebeiz

Univ of Colorado, Boulder

- Digitalt kontrollerte enkelt-kapasitanser
- Har individuelle plater som kan trekkes ned etterhvert

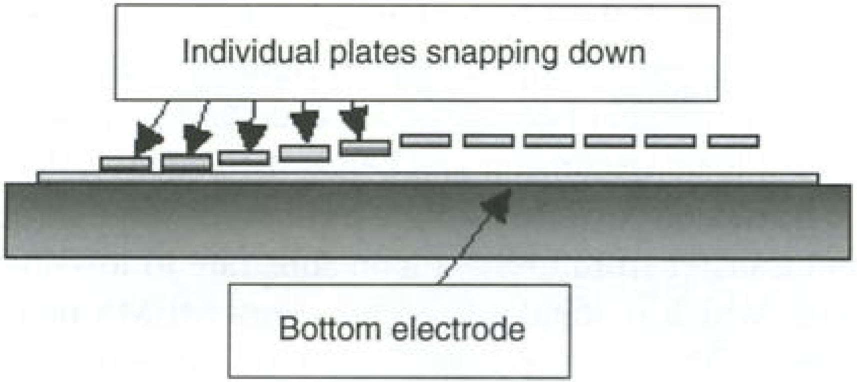
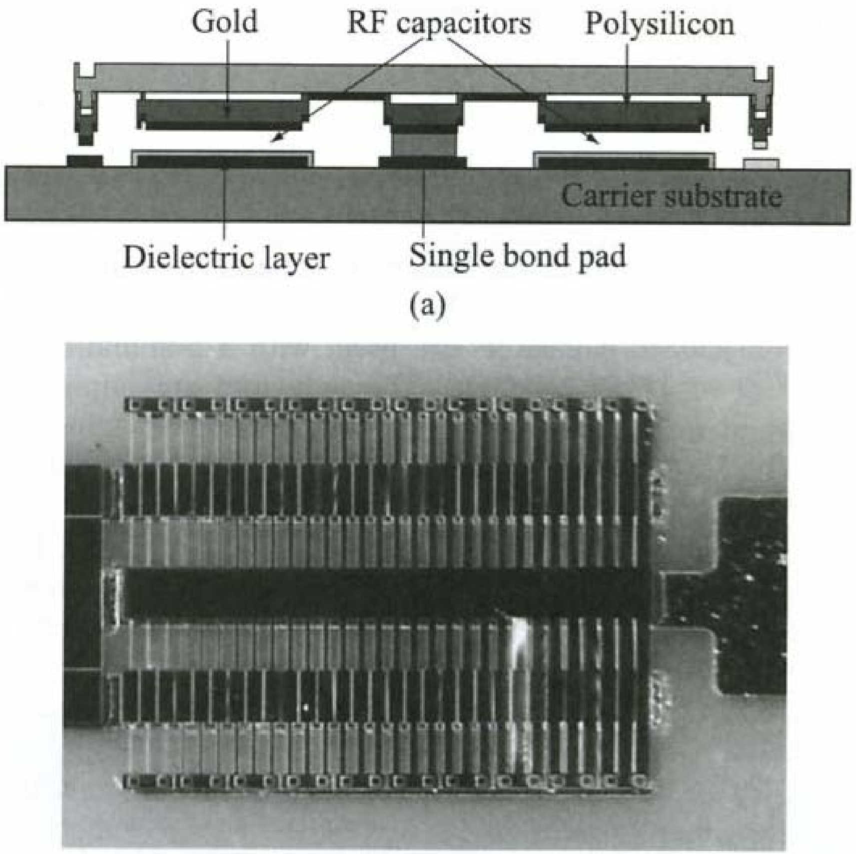


Figure 4.38 Schematic diagram of the capacitor plate arrangement. Reproduced from N, Hoivik, M.A. Michalicek, Y.C. Lee, K.C. Gupta and V.M. Bright, 2001, 'Digitally controllable variable high-Q MEMS capacitor for RF applications', in *Proceedings of IEEE MTT-S Symposium, May 2001, Volume 3*, IEEE, Washington,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

Varadan

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).

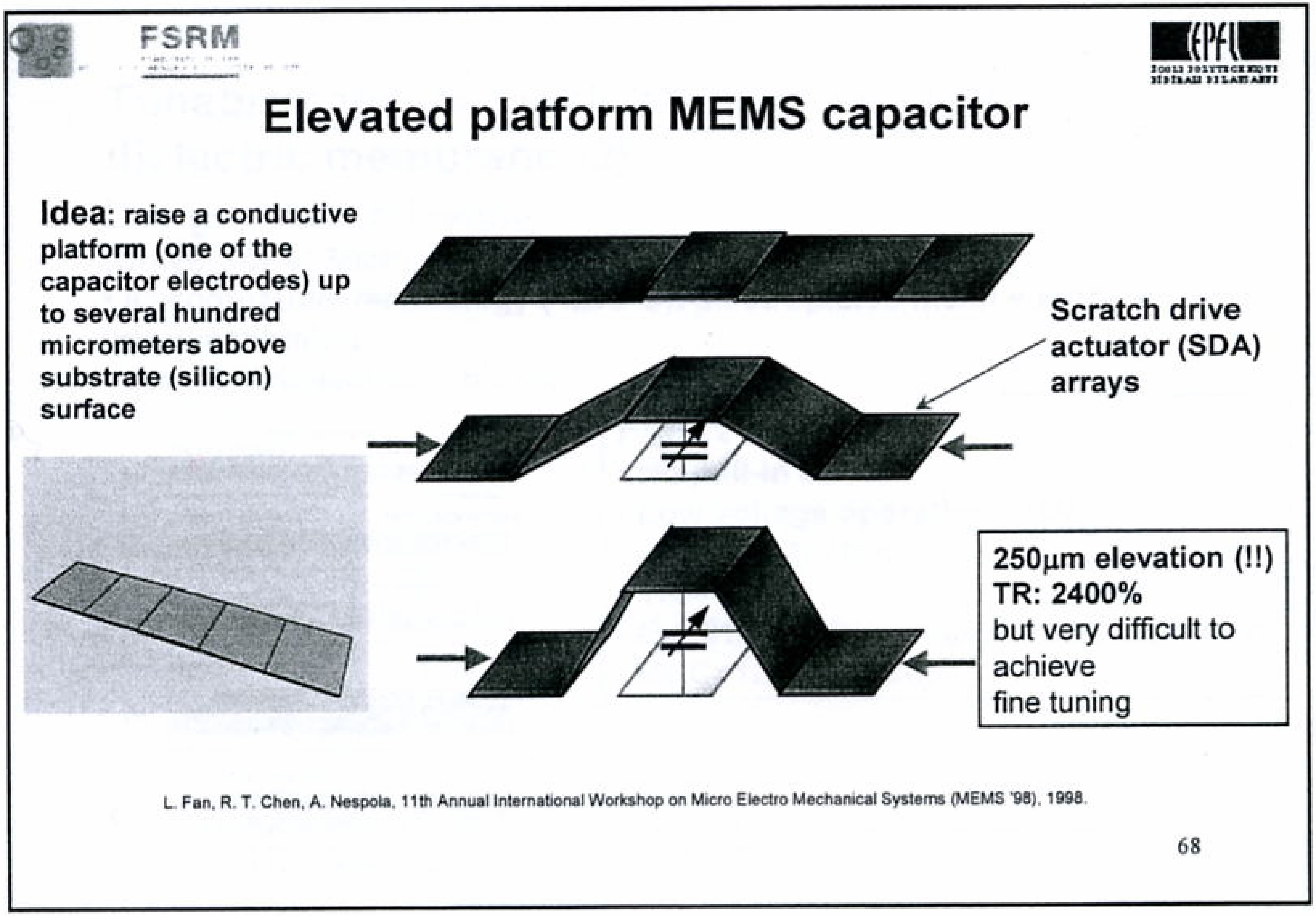
Hver plate koblet med forskjellig bredde på bjelken, dvs.ulik fjærkonstant for hver del

Univ of Colorado, Boulder, forts.

- Standard MUMP´s prosess (poly-SI og gull), alumina-substrat
- Elektrostatisk aktivering V= 30 V
- TR = 4 : 1
- Q = 140 @ 750 MHz

Elevert plattform kapasitans

- L. Fan et al, 1998
  - – En av elektrodene kan heves opp til flere hundre mikrometer over substratet
    - 250 µm elevasjon, TR 2400%
    - ÷ Vanskelig å oppnå fin-tuning
- Benytter aktuator som skyver strukturen sammen
  - – ”Scratch drive actuator”
  - – Må realisere hengsler



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.

Gap-tuning, selvaktivering

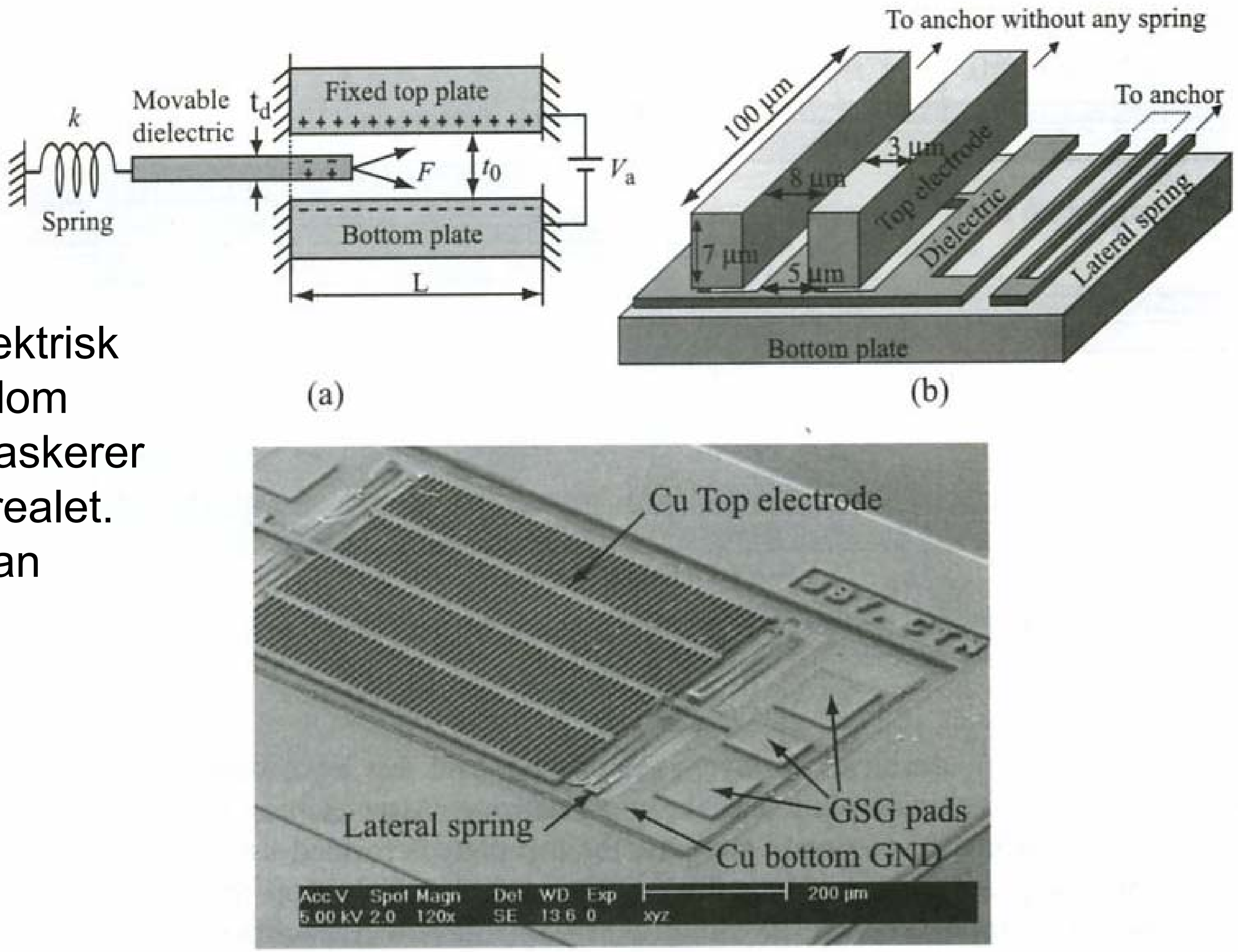
- Må konstruere slik at parallell plate kapasitansene kan behandle RF power
  - AC spenning påtrykkes RF MEMS kapasitansen
  - RF frekvensen modulerer ikke C-verdien
  - MEN, rms-verdien av RF-signalet vil influere C og kan indusere pull-in ved selvaktivering

- Kapasitanser for gap-tuning har begrenset RF power handlings-mulighet pga. lite elektrodegap
  - Reduksjon av avstand → RF breakdown

Lateralt tunbare kapasitanser

- Horisontal bevegelse
  - Kan tunes ved å variere arealet, $C = \varepsilon A / g$
  - + Ingen teoretisk grense for TR
  - + Unngår pull-in-effekten
  - ÷ Fotolitografi bestemmer presisjon av avstander
  - ÷ Mer kompliserte opphengs-strukturer?
    - Må sikre at den bevegelige strukturen henger oppe
- Kamstruktur er vanlig

Bevegelig dielektrisk membran mellom faste plater, maskerer det effektive arealet. Univ of Michigan



(a) (b)

(c)

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).

Rebeiz

Univ of Micigan, forts.

- Prinsipp: både topp og bunn er rigide
- Tuning oppnås ved en bevegelig dielektrisk membran (høy-k = ε) som er elektrostatisk drevet
- Ytelsesparametre
  - IC kompatibel teknologi (<200 ° C), post CMOS
  - Elektroplettert metall + overflate mikromaskinering
  - Bevegelig dielektrisk membran av Nitrid
  - Ingen pull-in effekt
  - Lav aktiveringsspenning < 10 V med k= 0.187 N/m
  - TR = 40%
  - Q = 218 @ 1 GHz for C = 1.14 pF design (noe av det høyeste som er rapportert!)

Univ of Micigan, forts.

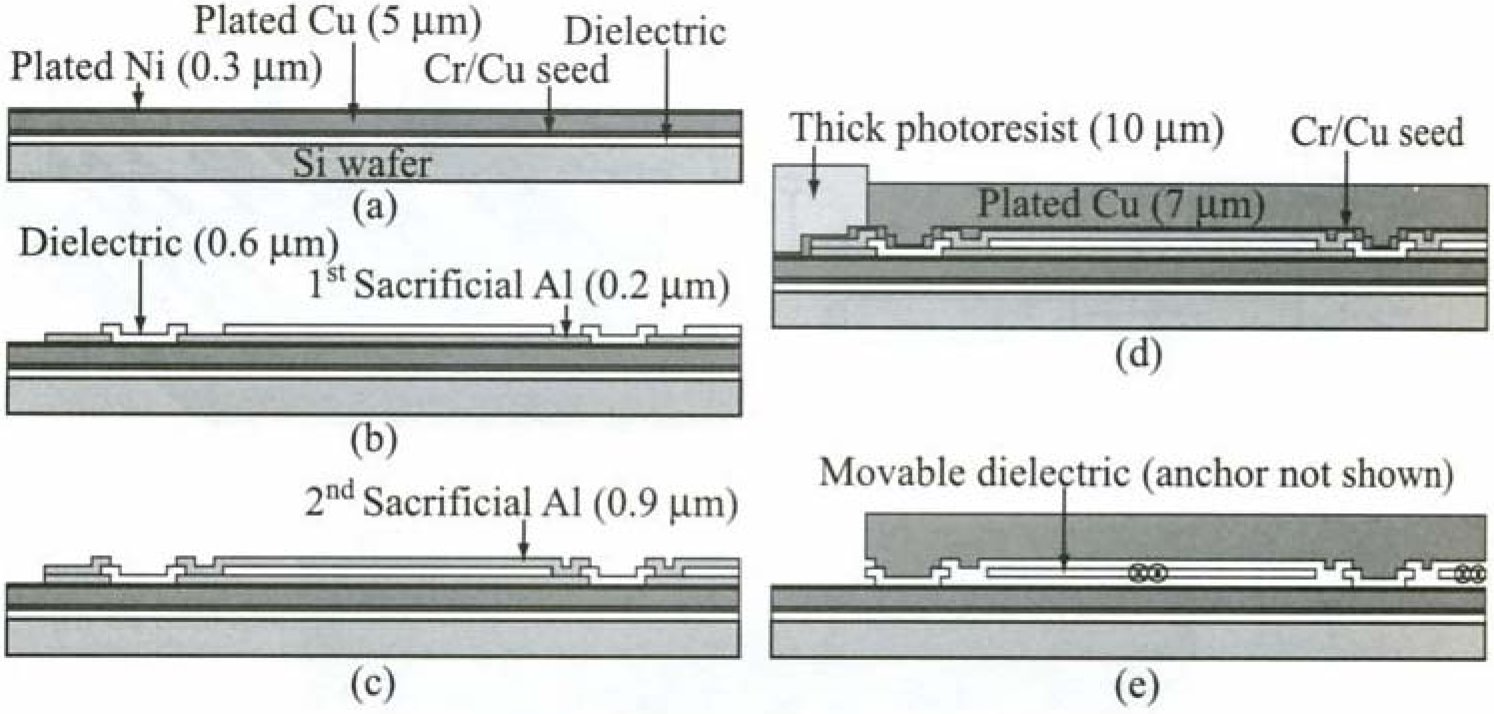


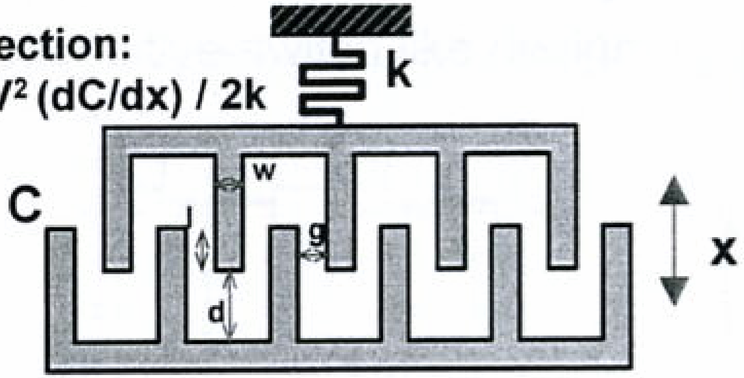
Figure 11.24. Fabrication process of the UoM interdigital capacitor [19] (Copyright IEEE).

Enkel kam-struktur

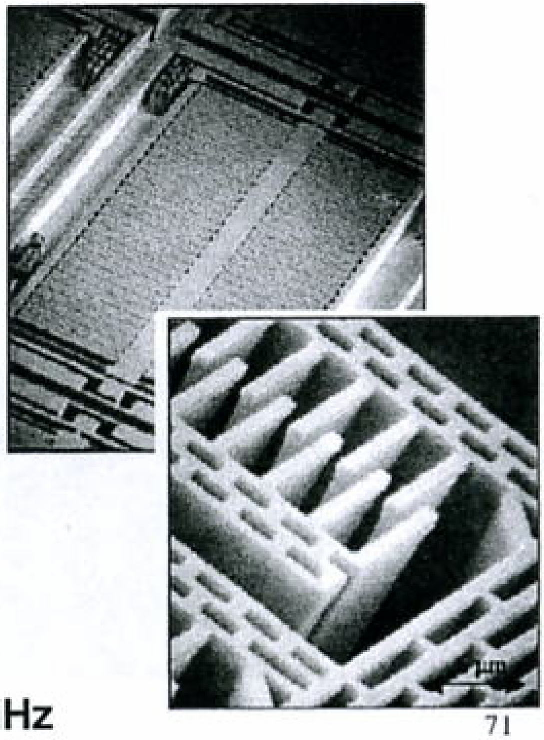
- Eks fra Rockwell Science Center →
  - Inter-digital tunbar MEMS kapasitans
  - Et sett kammer er stasjonære, det andre settet kan beveges
  - Gapet forblir uendret
  - Lengden av kammen begrenser tuning range
  - Tuning ved elektrostatisk mikromotor eller ulike akviverings-spenninger

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

Rockwell Science Center, forts.

Eks fra tuning

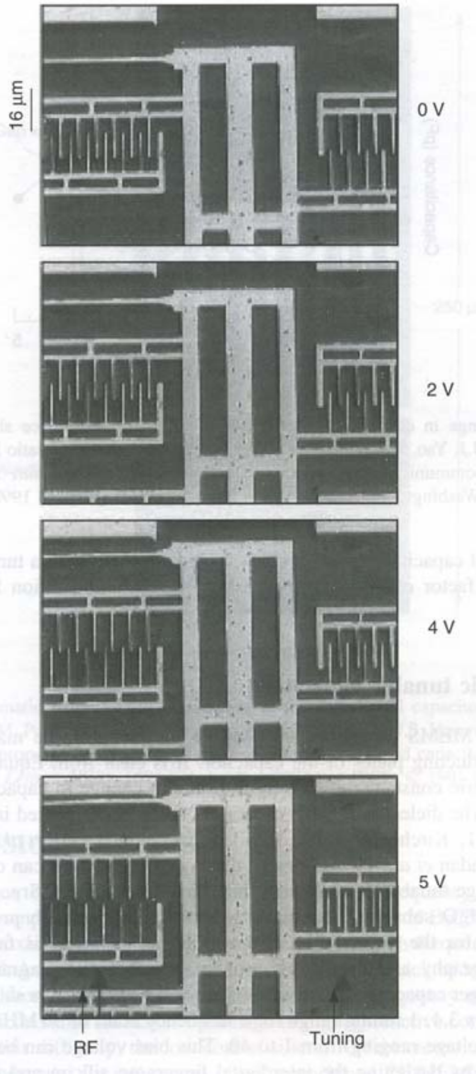


Figure 4.46 Series of images showing a MEMS tunable capacitor with a tuning voltage of 0 to 5-V. Reproduced from J.J. Yao, S. Park and J. DeNatale, 1998, 'High tuning ratio MEMS based tunable capacitors for RF communications applications' in *Proceedings of solid-state sensors and Actuators Workshop*,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

Varadan

Rockwell Science Center, forts.

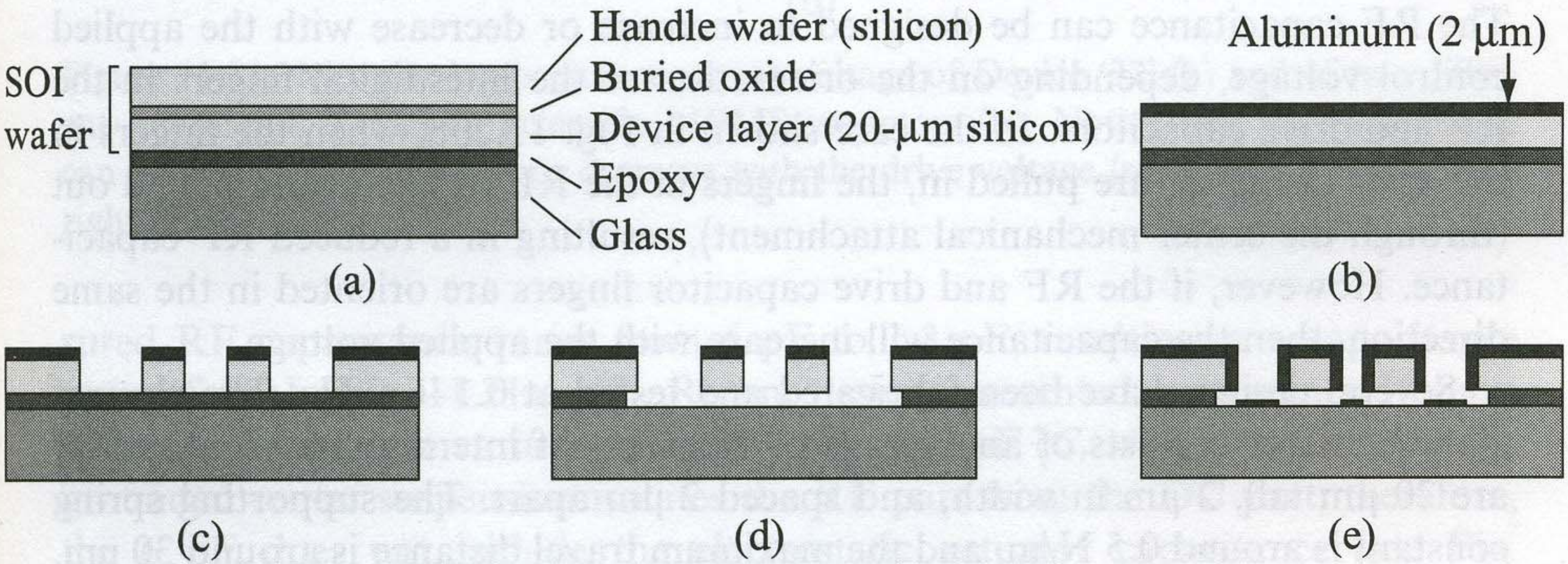


Figure 11.19. Details of the fabrication process of the Rockwell Science Center interdigital capacitor on a glass substrate (see text). Notice that a single mask layer is used [17, 18] (Copyright IEEE).

Rebeiz

Rockwell Science Center, forts.

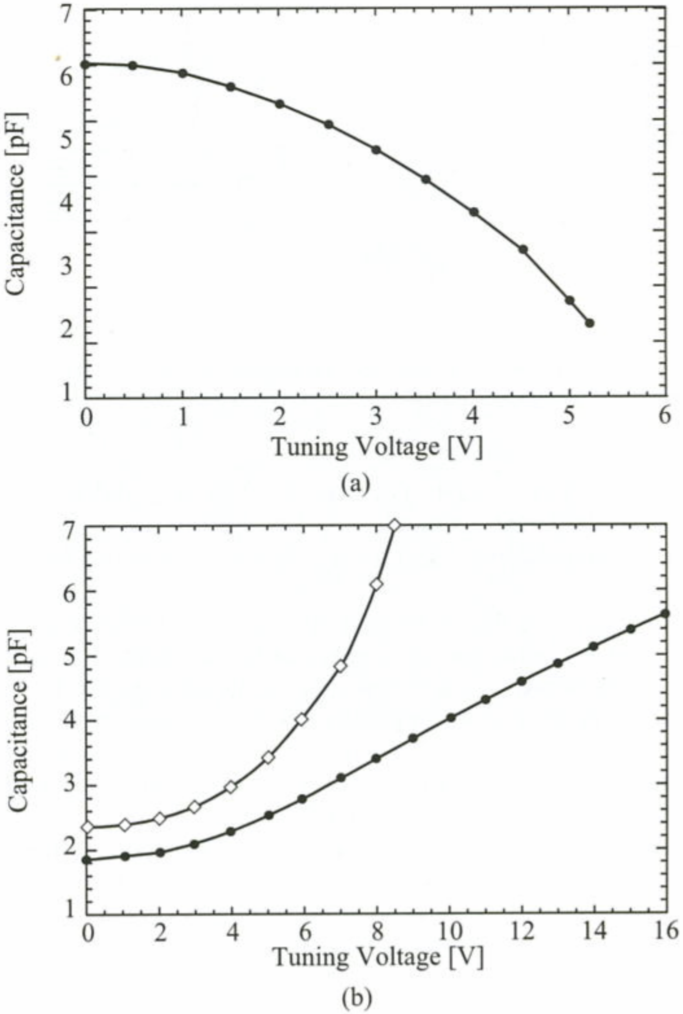


Figure 11.21. Measured capacitance versus voltage of Device '33' (a) and of two different interdigital Rockwell Scientific MEMS varactors (b). Notice that the capacitance can be designed to increase or decrease with the drive voltage (see text) [17, 18] (Copyright IEEE).

Rebeiz

Termisk tunbar parallell-plate MEMS kapasitans

- Benytter varme og kalde armer
  - – En høy-resistivitets-arm vil bli varmere og vil deformeres mer
    - Differensiell termisk ekspansjon
- Ulempen med teknikken
  - – **Effekt-dissipasjon**
  - – **Lav hastighet**
  - – Men fjerner pull-in-begrensningen

Z. Feng et al, Univ of Colorado

Design and Modeling of RF MEMS Tunable Capacitors Using Electro-thermal Actuators

Zhiping Feng, Wenge Zhang, Bingzhi Su, Kevin F. Harsh, K. C. Gupta, V. Bright, and Y. C. Lee
C AMPmode
University of Colorado at Boulder
Boulder, CO 80309-0425

Univ of Colorado, forts.

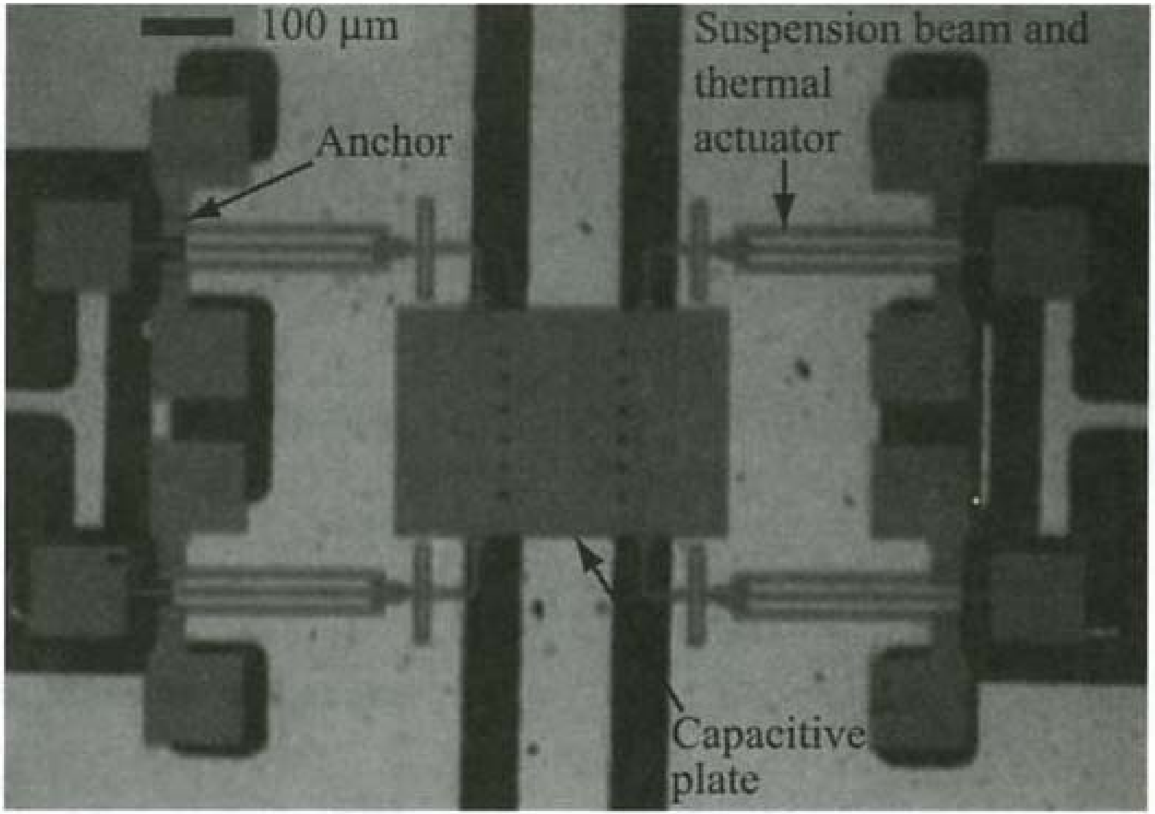
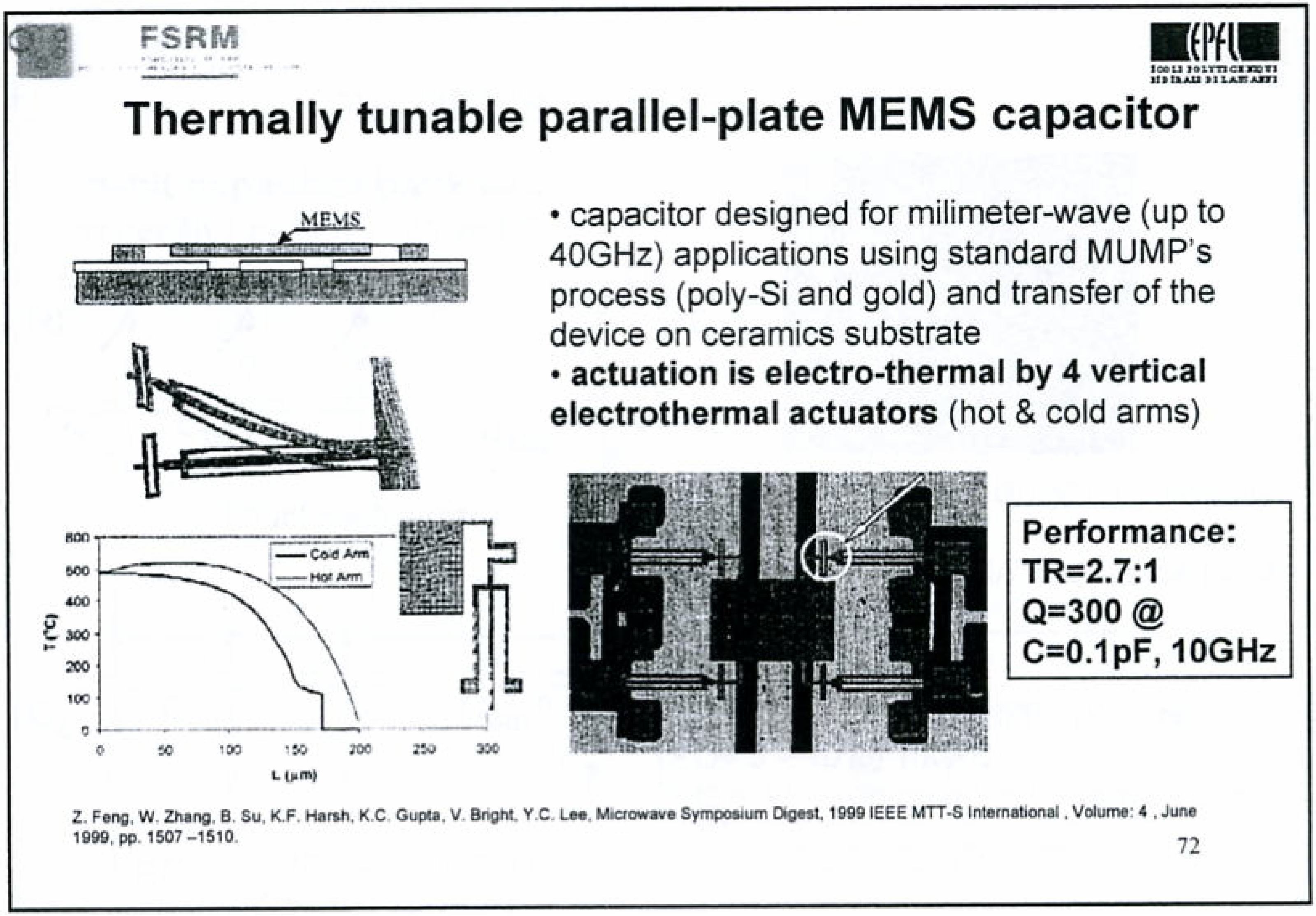


Figure 11.16. Top view of the University of Colorado thermally actuated MEMS varactor in a CPW circuit [13] (Copyright IEEE).



FSRM

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.

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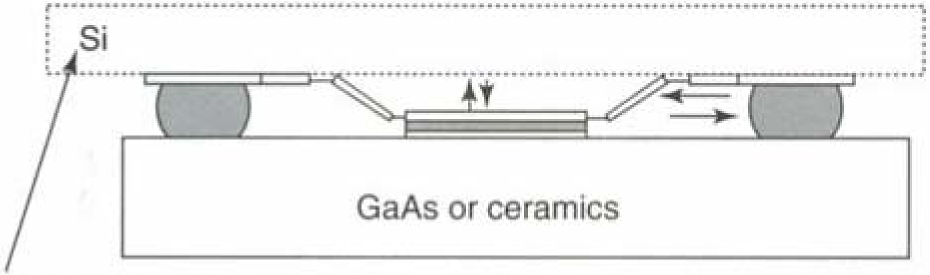
Temperaturdifferansen forårsaker en vertikal bevegelse

Elektro-termisk tuning



Silicon is conductive and should be removed after flip-chip assembly to enhance *Q*

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

Piezoelektrisk tuning

- En bias spenning forårsaker vertikal bevegelse av kondensator-platen
- + Lav drive-spenning
- + Lineær tuning av kapasitans

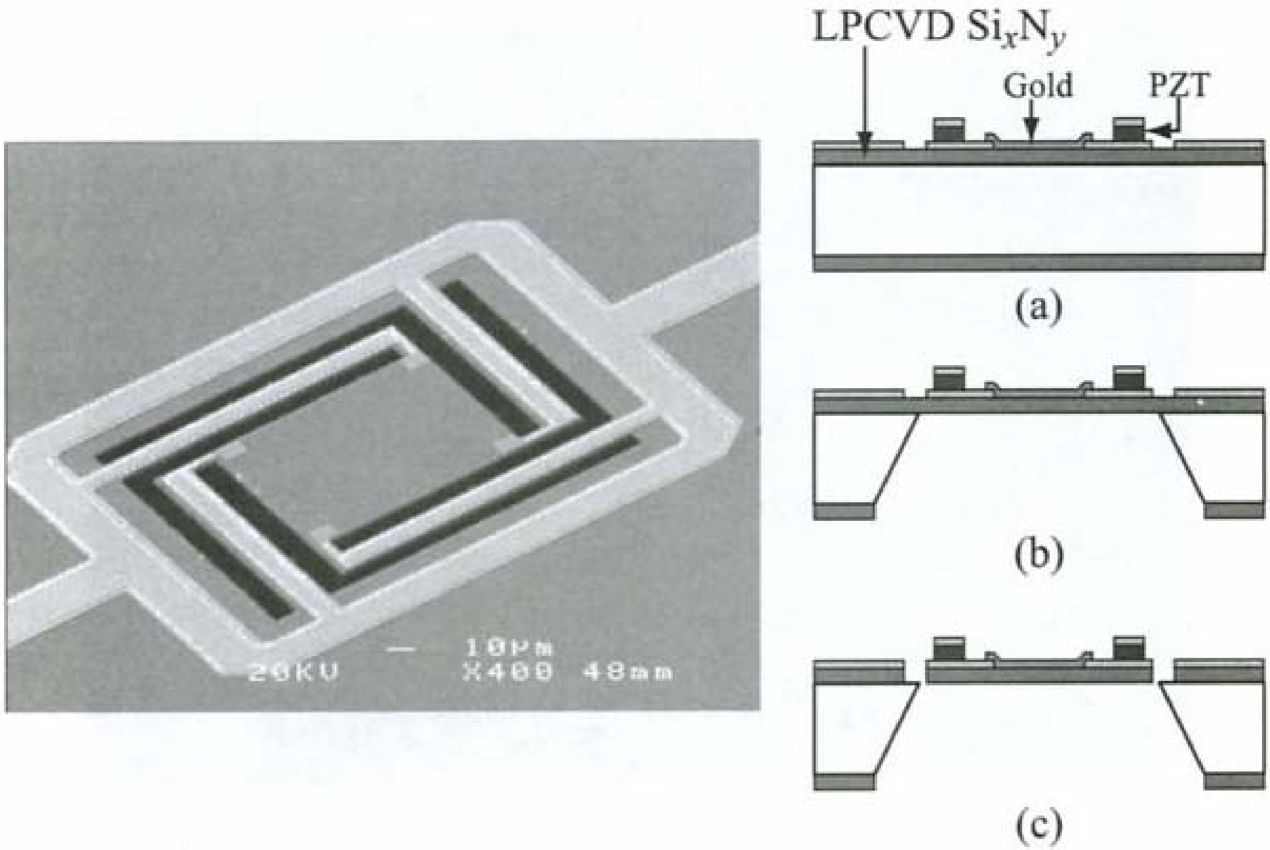


Figure 11.17. Top view and fabrication process of the LG-Electronics piezoelectric varactor [15] (Copyright IEEE).

To av bjelkene forlenges

Rebeiz

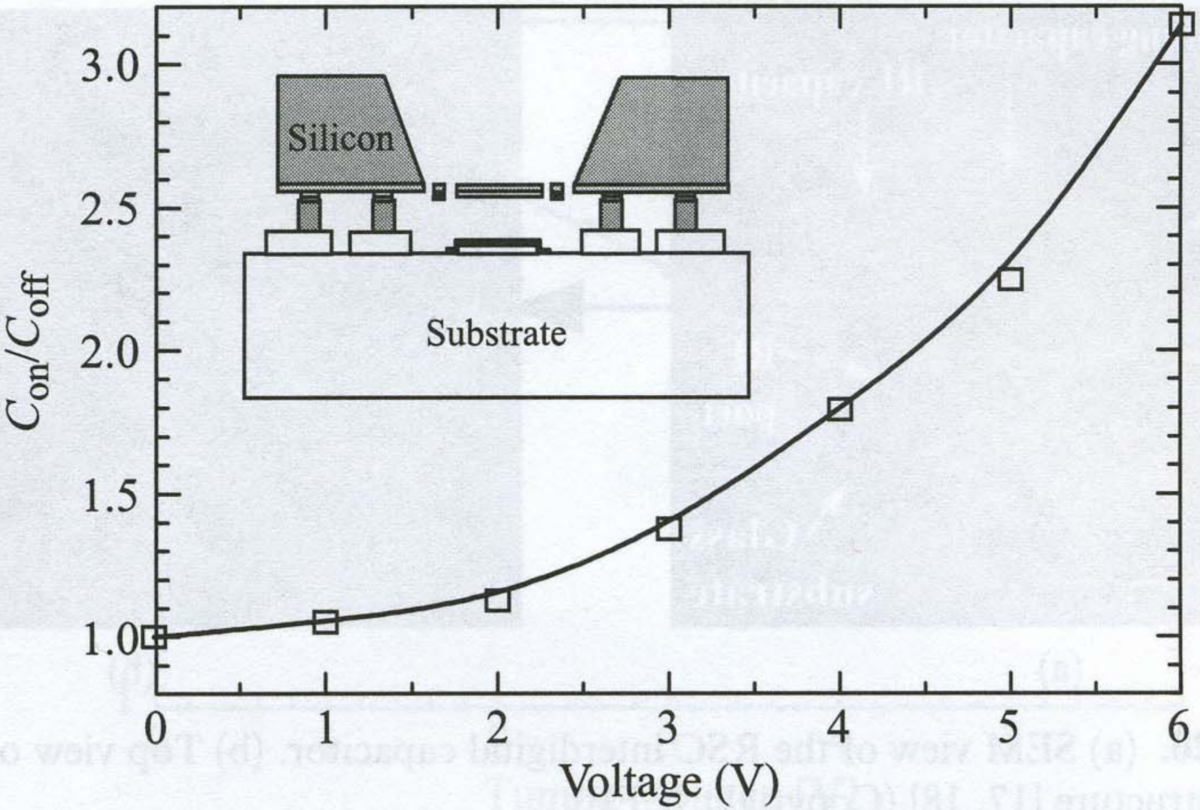


Figure 11.18. Measured capacitance ratio of the LG-Electronics piezoelectric varactor [15] (Copyright IEEE).

Dielektrisk tunbare kapasitanser

- Endring av materialegenskapene mellom platene
  - DC bias spenning kan endre de elektriske egenskapene
    - Dielektrisitets-laget
    - Dielektrisitetskonstanten, ε
  - Ferro-elektriske tynn-filmer, Var fig. 4.48 →

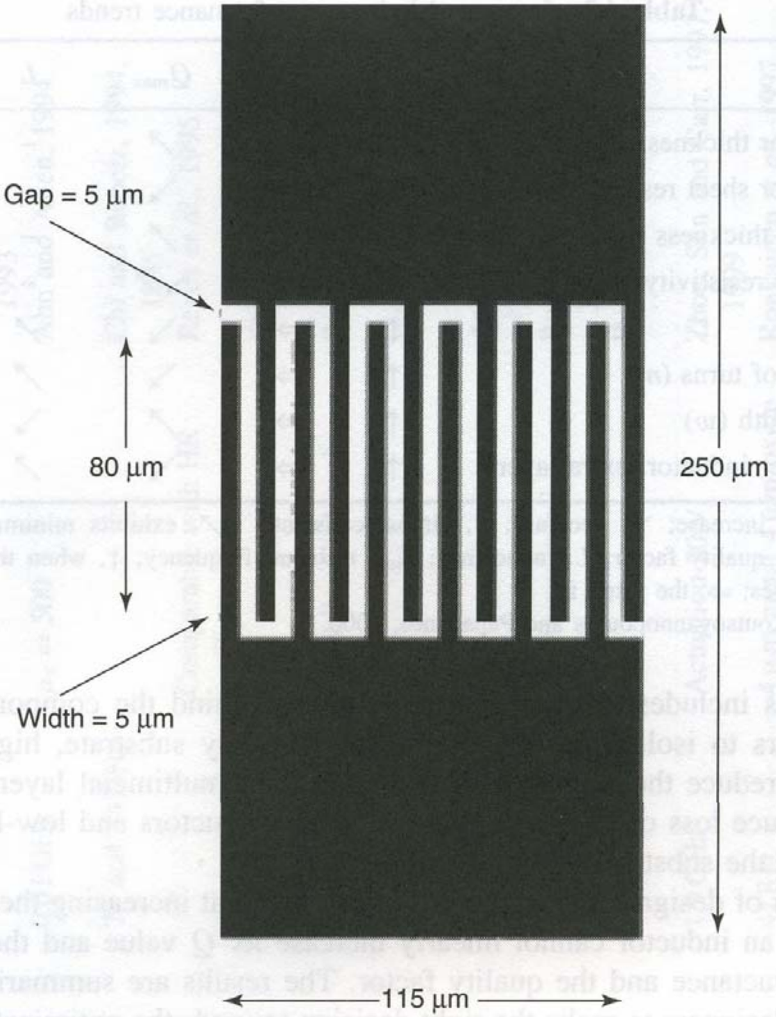
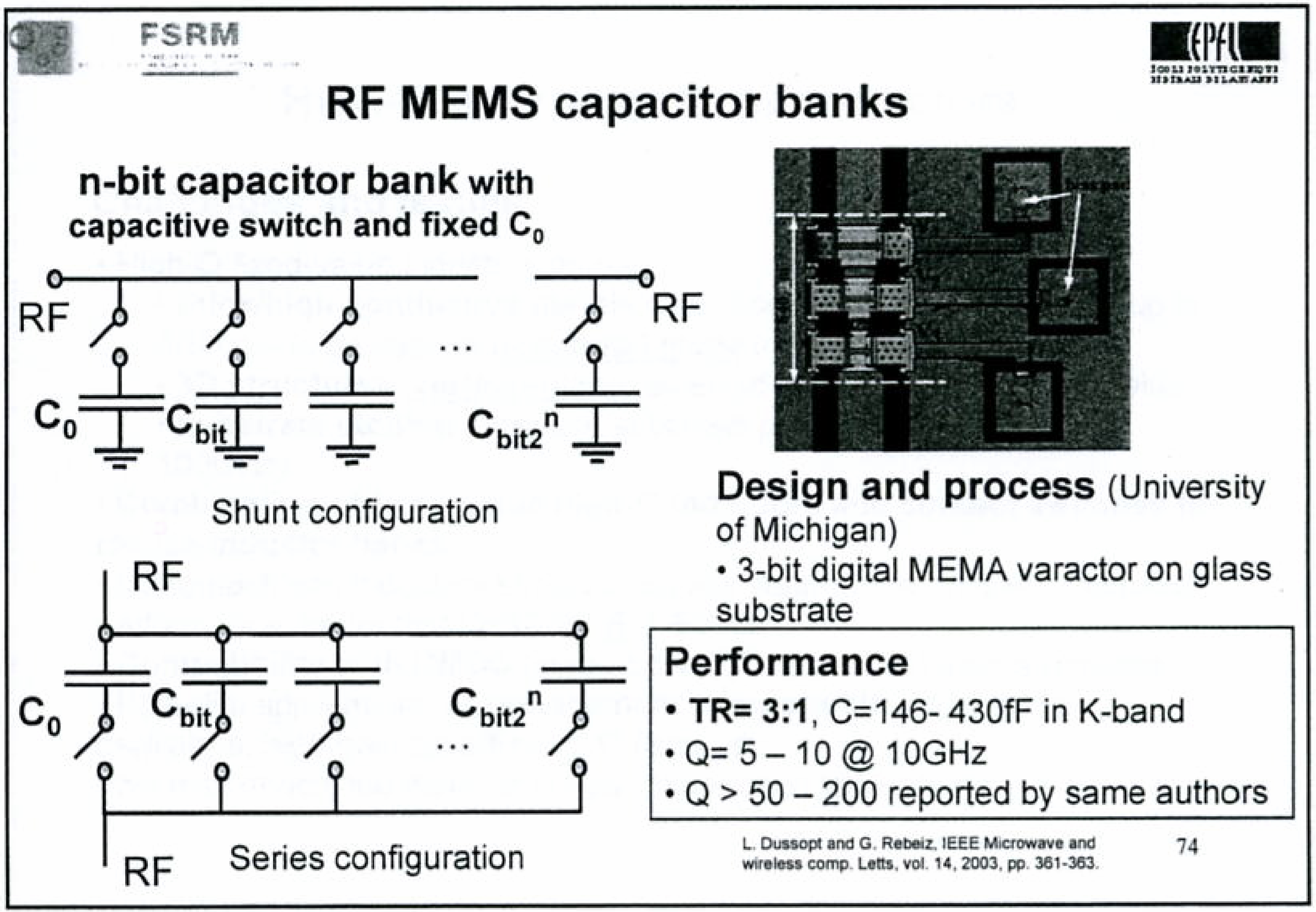


Figure 4.48 Schematic diagram and dimensions of the interdigital capacitor. Reproduced from S.W. Kirchoefer, J.M. Pond, A.C. Carter, W. Change, K.K. Agarwal, J.S. Horwitz and D.B. Chrisey, 1998, 'Microwave properties of $Sr_{0.5}Ba_{0.5}TiO_3$ thin film interdigitated capacitors', *Microwave and Optical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

RF MEMS kapasitans banker

- Kan programmeres ved en digital verdi
  - Kobler inn faste C-verdier
  - Både serie- og shunt-konfigurasjon er mulig



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.

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Termiske forhold, stress

- Termisk design av MEMS kapasitanser?
  - Et eksempel
    - H. Nieminen et al: ”Design of a Temperature-Stable RF MEMS Capacitor, J MMSyst, vol 13, no 5, 2004:
    - Legge kapasitansen inn i en ramme-struktur →
    - Bruke rammen for å kompensere for det termisk induserte stresset
    - Feste kapasitansen slik at når rammen blir deformert, så får en minimale stress-effekter på kapasitansen (f.eks. hjørnene beveger seg lite)

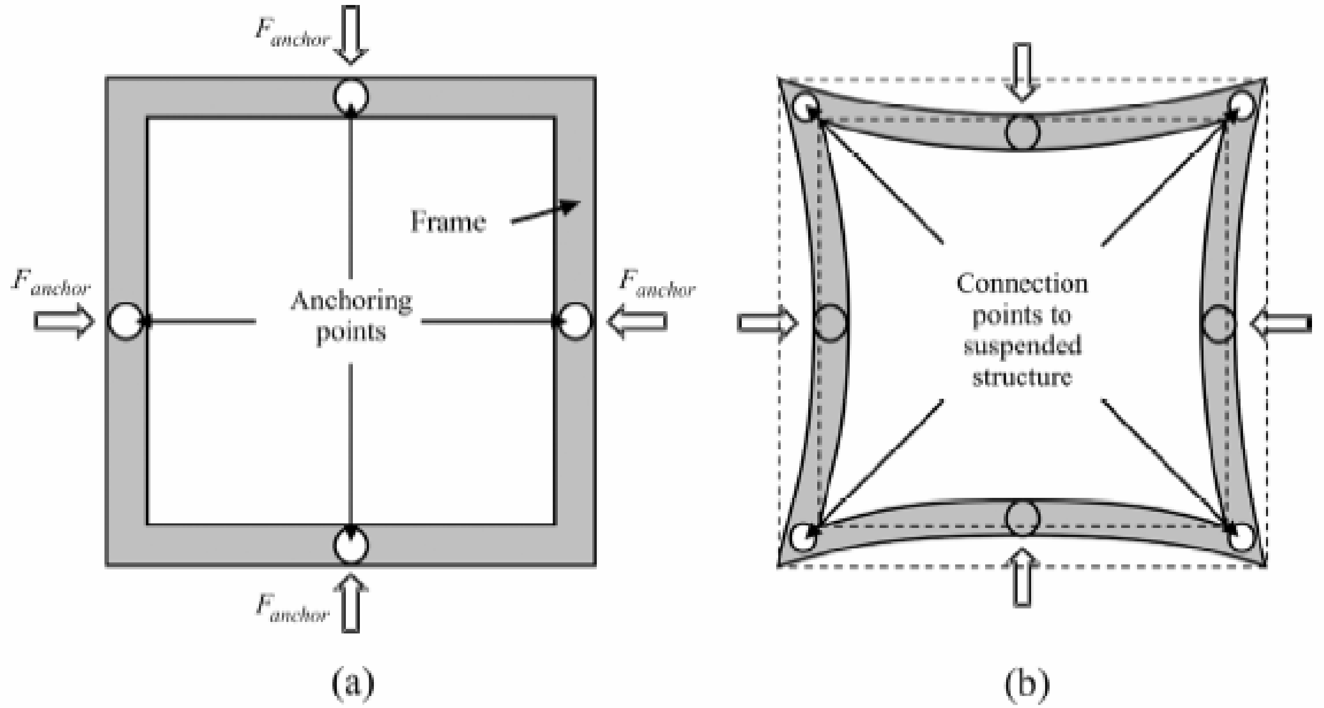

Fig. 2. The steps to create geometrical compensation of a suspended structure against external stress for arbitrary geometry are as follows. (a) Create frame geometry. Designate anchoring points. The force (F_{anchor}) that simulates the effect of external stress is exerted on these anchoring points. 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.

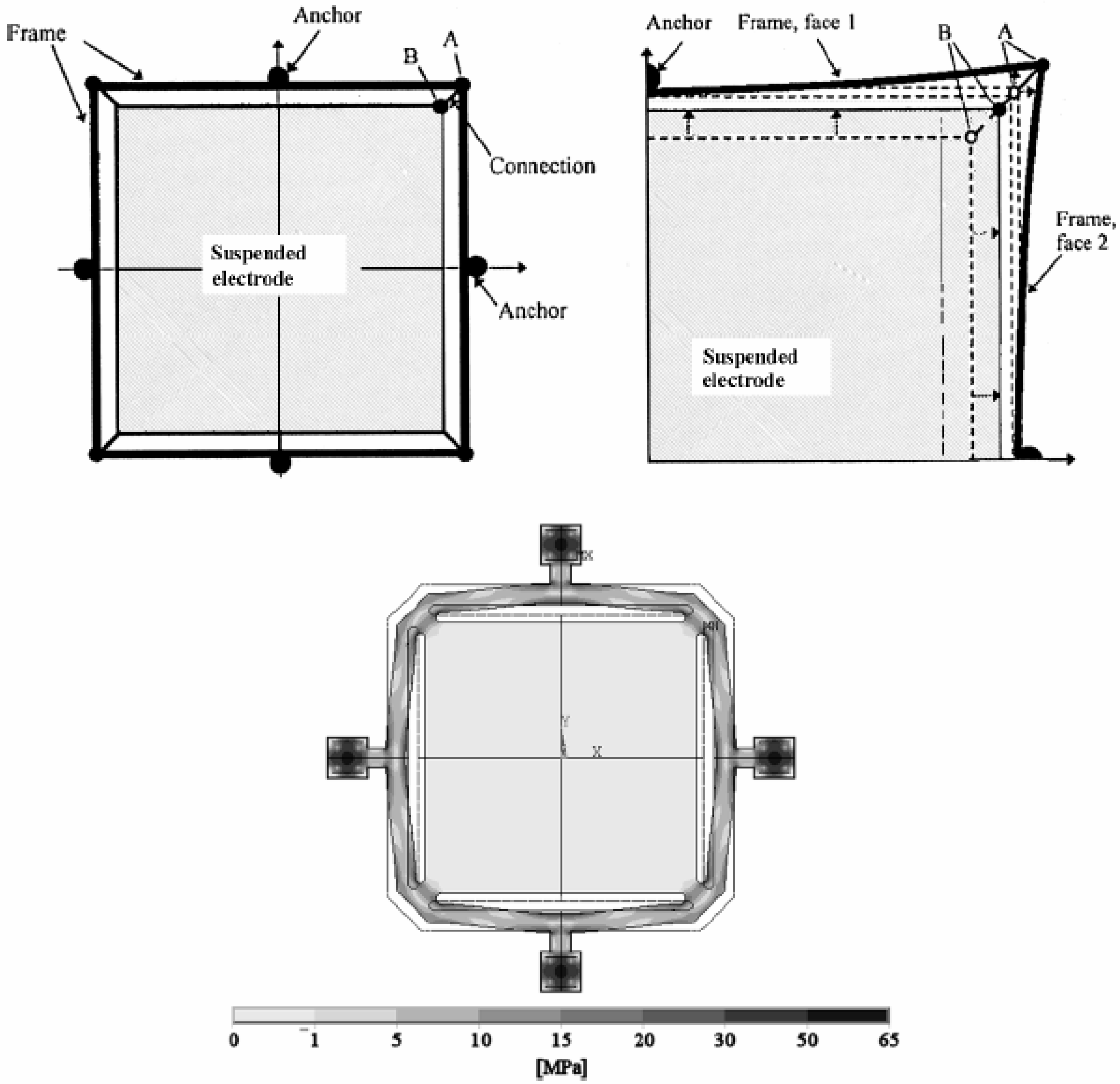

Fig. 3. FEM analysis of the temperature-compensated capacitor. Simulation is done with ANSYS. The temperature change is -50 °C. The substrate is silicon. The suspended electrode, the frame and the anchors are 4-μm-thick gold. The scale at the bottom of the figure shows stress. Displacements in the figure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