INF5490 RF MEMS

F6: RF MEMS svitsjer, II

V2007, Oddvar Søråsen
Institutt for informatikk, UiO

Dagens forelesning

- Design av RF MEMS svitsjer
  - Elektromekanisk design, II
  - RF design
- Eks. på implementasjoner
  - Struktur
  - Ytelse
  - Fremstilling
- Alternative strukturer og aktiveringsmekanismer
- Noen utfordringer

Elektromekanisk design II

- Konstruktør må ta hensyn til
  - **Stress →**
  - Dynamiske forhold
    - Demping
    - Hvordan aktiveringsspenningen påvirker svitsje-hastigheten

Stress

- Stress bygges inn under fremstillingen
  - Ved temperatur-endring
    - ”Residual stress”
  - Pga. ulike egenskaper i nabomaterialer
- Aksialt **tensilt stress** (tøyende spenning)
  - Fjærkonstanten k_z øker (strengen spennes)
  - k_z kan øke 20x når tensilt stress 0 → 300 MPa
  - Vpi kan øke 4.5x når tensilt stress 0 → 300 MPa
- Tensilt stress må inkluderes som designparameter!
  - Kan ikke elimineres, - må tas i betraktning
  - Tensilt stress kan **evalueres** ved å måle ”misalignment” av teststrukturer (forskyvning av mønstre) →

Micro strain gauge with mechanical amplifier

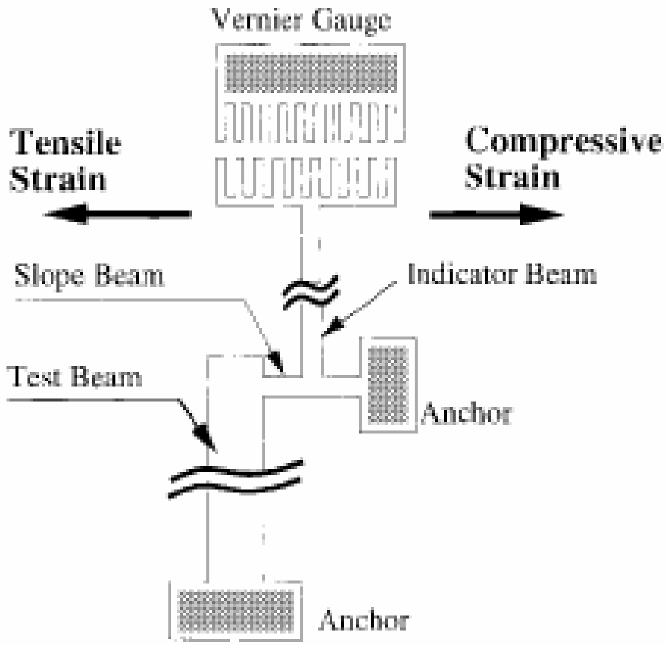


Fig. 1. Schematic diagram of a strain gauge based on the mechanical amplifier.

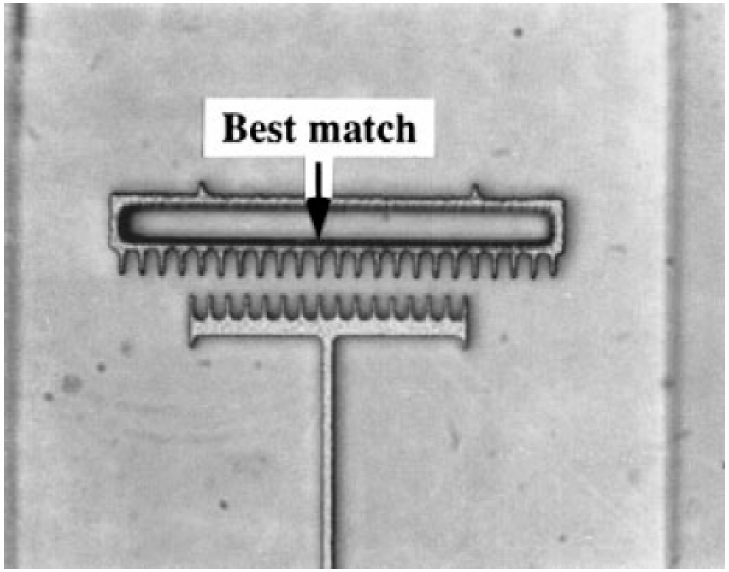


Fig. 4. An example of strain-gauge reading under an optical microscope.

Jmfr. ”skyvelær”

Lin et al, J of MEMS, 1997

Svitsjehastighet og demping

- Svitsjehastigheten er avhengig av **dempingen**
  - Luft, gass må skyves vekk
  - **”squeezed-film damping”**
  - Modelleringsmetoder fra væske-mekanikk
- Hvordan redusere demping?
  - Operere i vakuum
    - Hermetisk kapslede pakker
  - Lage hull i membran
    - Perforert membran

Perforert membran: Raytheon

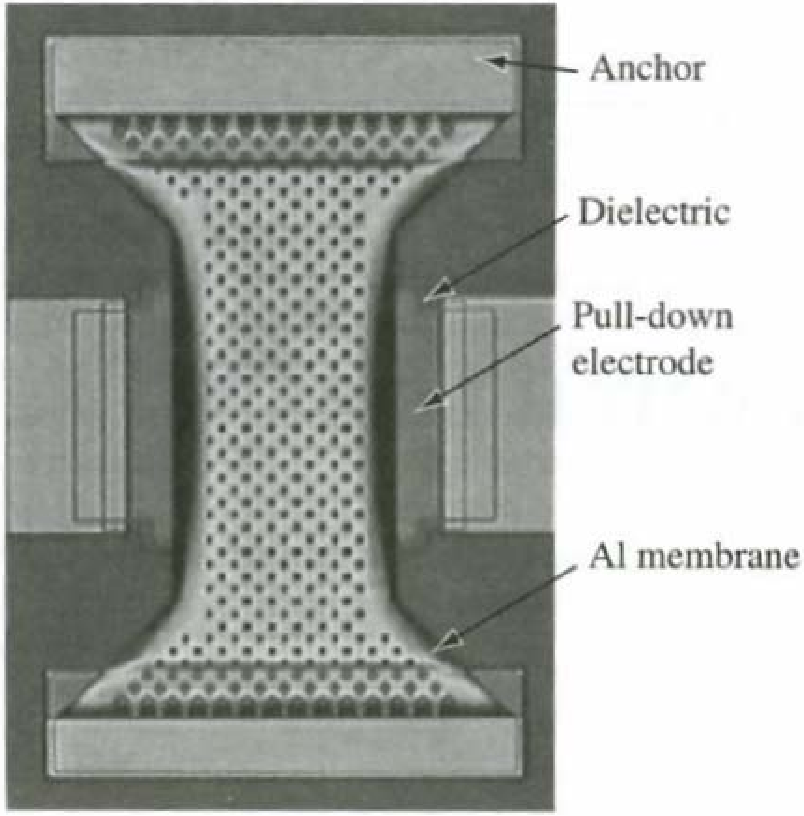
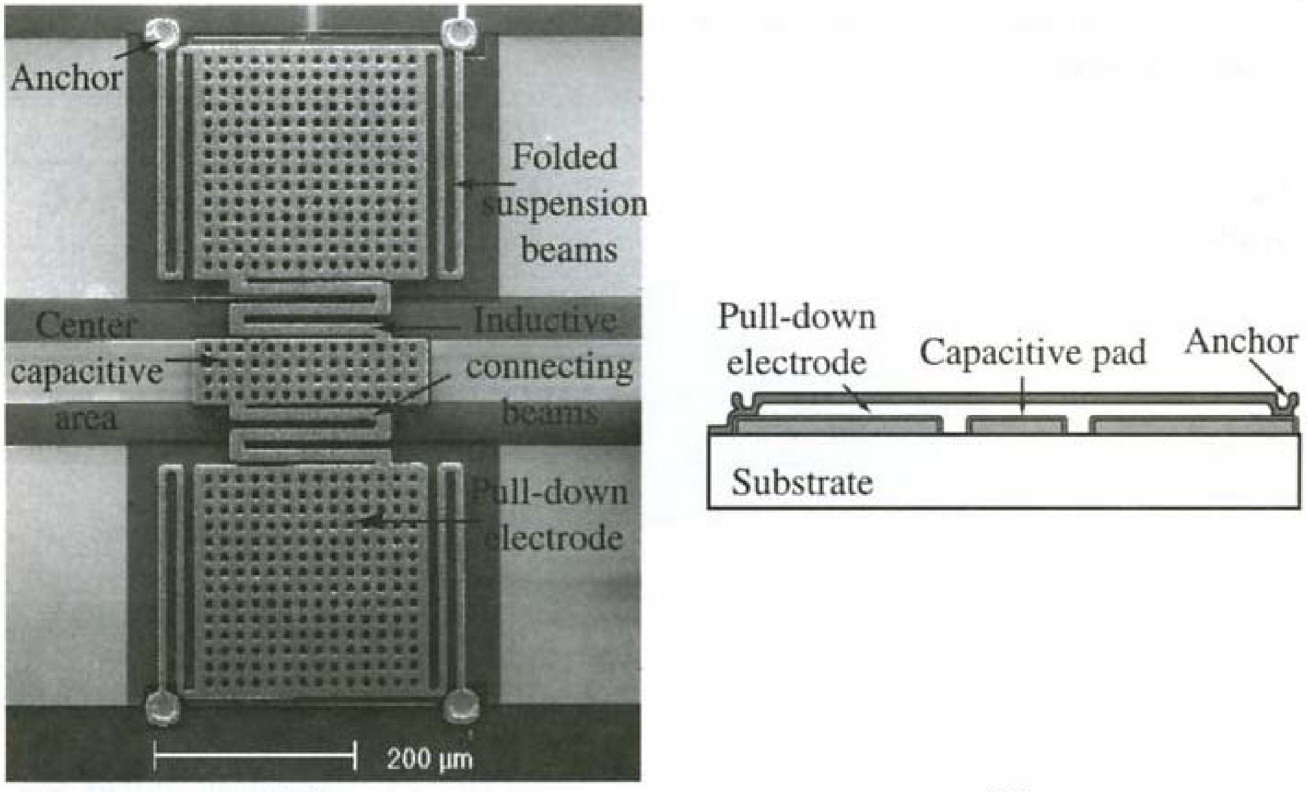


Figure 5.1. Photomicrograph of Raytheon MEMS capacitive shunt switch [2, 3] (Copyright IEEE).

Perforert membran: UMICH



(a) (b)

Figure 5.2. Photomicrograph of the university of Michigan low-voltage MEMS shunt switch. The number of meanders can be varied from 1 to 8 [7] (Copyright IEEE).

Svitsjetider for Raytheon/TI-svitsjen

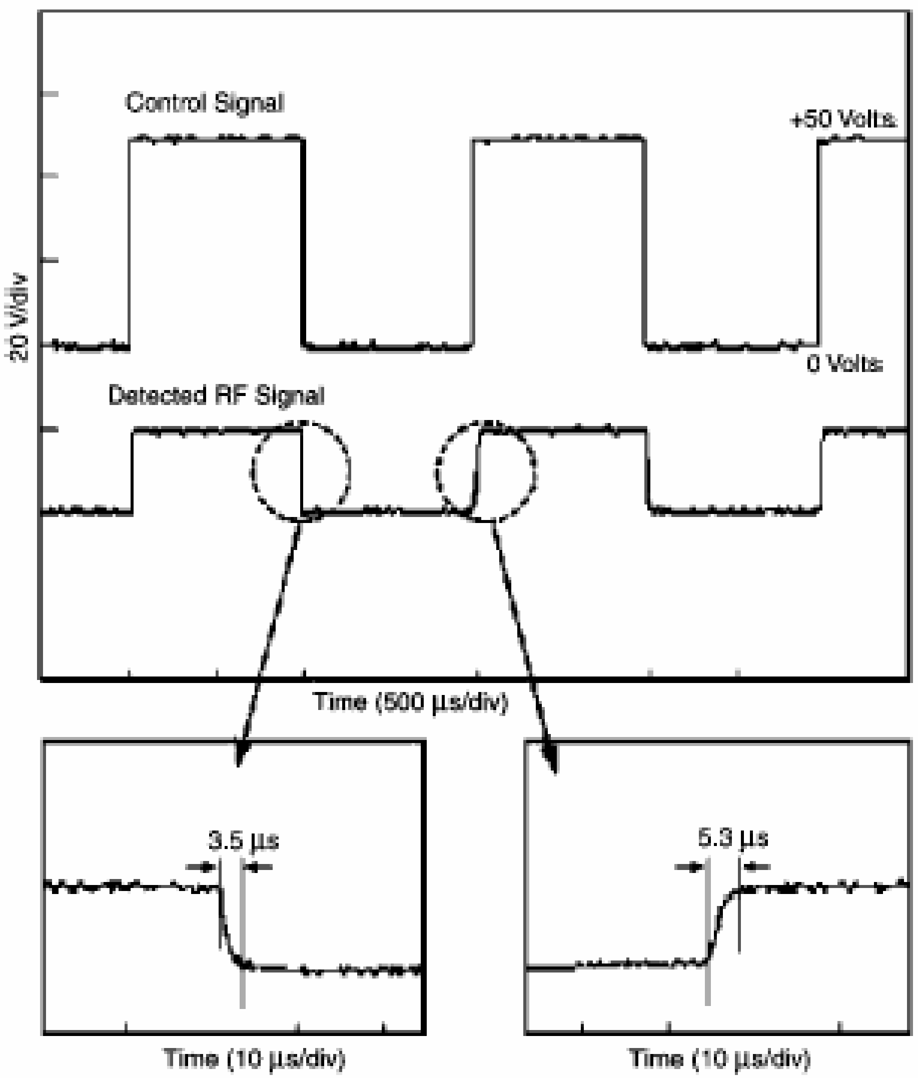
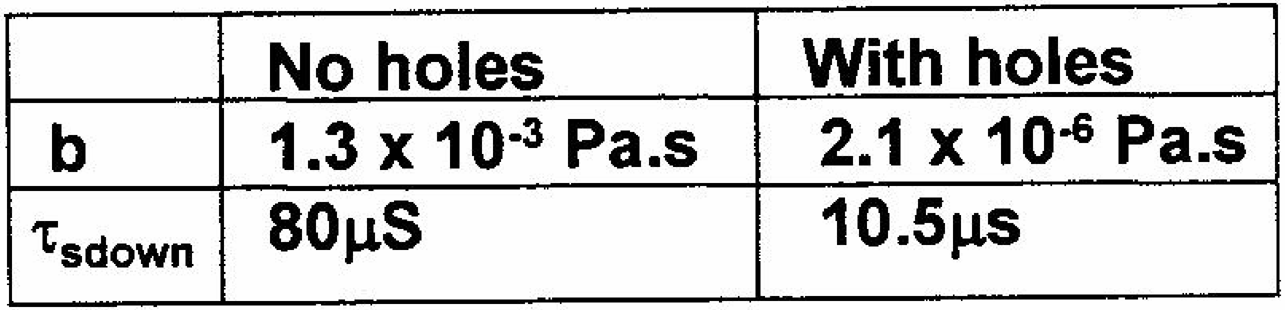


Figure 12. Switching time of the TI capacitive coupling shunt switch is of the order of 3.5–5.3 μs (from [30], Raytheon/TI).

Yao, 2000

Eks. på effekt av perforering

- → Betydelig hastighetsøkning ved å benytte en perforert membran!



	No holes	With holes
b	1.3×10^{-3} Pa.s	2.1×10^{-6} Pa.s
τ_{sdown}	$80\mu S$	$10.5\mu s$

S. Pacheco, L.Katehi, Chapter in 'RF Technologies for Low Power Wireless Communications', Wiley, 2001.

Z.

Svitsje-hastighet

- Svitsje-hastigheten avhenger sterkt av den Q-faktor en kan oppnå
  - Høy Q-faktor betyr liten demping
    - → økt svitsjehastighet
  - Lav Q-faktor betyr stor demping
    - Systemet er **dempings-begrenset** ved $Q \leq 0.5$ [Castaner and Senturia]

Tidsrespons for ulike Q-verdier

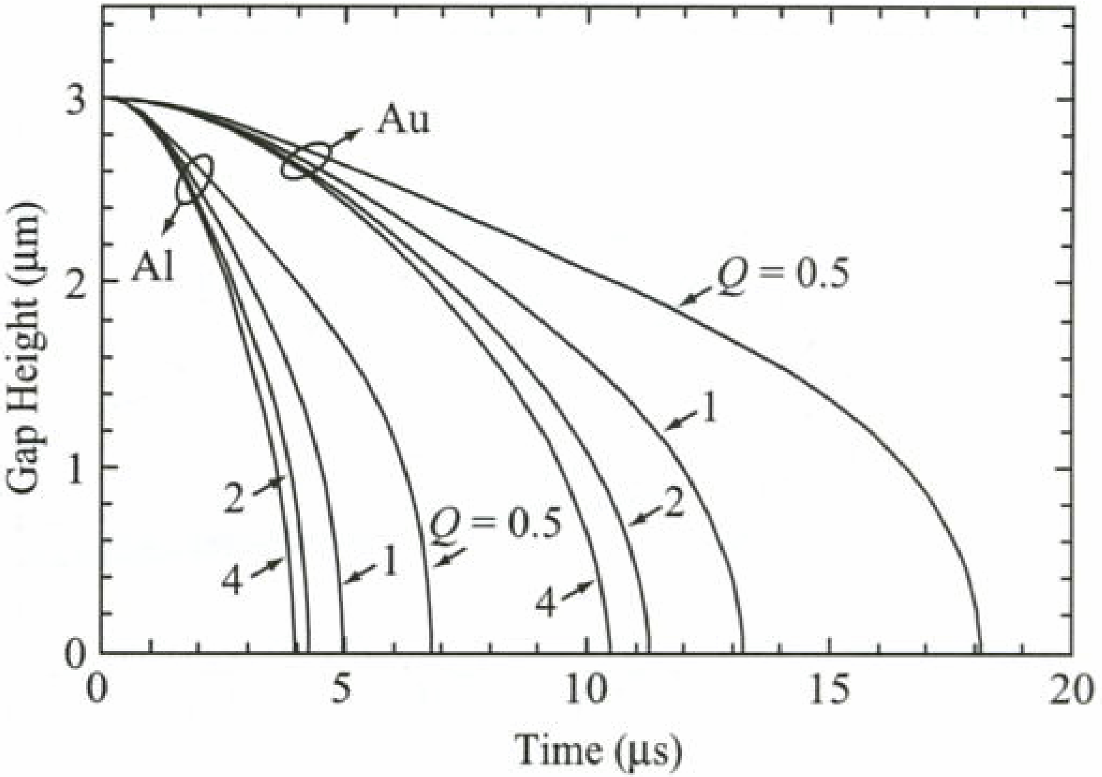


Figure 3.3. Pull-down simulations for the Au and Al beams of Table 3.1 for an applied voltage of 42 V ($V_s = 1.4V_p$).

(Vedr. forskjell på Al og Au, se senere →)

Gass-demping

Dynamisk respons til cantilever beam

$$m \frac{d^2w}{dt^2} + b \frac{dw}{dt} + k \cdot w = F_{ext}$$

w = displacement
m = massen
b = dempekoeffisienten
k = fjærstivheten

$$\frac{W(j\omega)}{F(j\omega)} = \frac{1}{k} \frac{1}{1-\left(\frac{\omega}{\omega_0}\right)^2 + j\omega/(Q\,\omega_0)}$$

$\omega_0 = \sqrt{\frac{k}{m}} =$ resonansfrekvens

$Q = k/(\omega_0 b) =$ kvalitetsfaktor

Gass-demping, forts.

- Q er avhengig av forholdet mellom **m, b, k**
  - m er **”effektiv masse”**
  - Den effektive massen er forskjellig fra total masse siden bare enden (eller den sentrale delen) av bjelken beveger seg
    - m_eff ~ 0.35 – 0.45 *m_total
    - m_eff er avhengig bl.a. av
      - Topologi/ fysisk dimensjoner
      - Fjærkonstanten, materialvalget
      - Bevegelsesmønstret
  - Beregnes mer nøyaktig for ”resonator” i senere forelesning

Gass-demping, forts.

- Q avhenger av b = dempekoeffisienten
- Dempingen, b, avhenger av **viskositeten**
  - Viskositet er motstand gassen yter mot transport
- Eks.: uttrykk for demping av rektangulær parallell plate:

$$b = \frac{3}{2\pi} \cdot \frac{\mu \cdot A^2}{g_0^3}$$

A = arealet

g_0 = gapet

μ = viskositet til gassen

Gass-demping, forts.

Gass-dempingen påvirker Q-faktoren

Kvantitative ligninger:

$$Q = k/(\omega_0 b) \qquad \rho = \text{tetthet}$$

$$Q_{cantilever} = \frac{\sqrt{E\rho}\, H^2}{\mu (WL)^2} g_0^3$$

$$\uparrow \; W \cdot L \rightarrow \frac{W \cdot L}{2}$$

$$Q_{cc} =$$

for clamped-clamped beam

Rebeiz

Svitsje-hastighet, stor demping

Ved et **dempings-begrenset** system

$(Q \le 0.5)$

Bevegelsesligningen $$b \frac{dw}{dt} = F_{ext}$$

Et kvantitativt uttrykk: $$t_s \approx \frac{9 V_{Pi}^2}{4 \omega_0 Q V_s^2} \quad \text{for } V_s \gg V_{Pi}$$

Vs = aktiveringsspenningen

Rebeiz

Tidsrespons for ulike Q-verdier

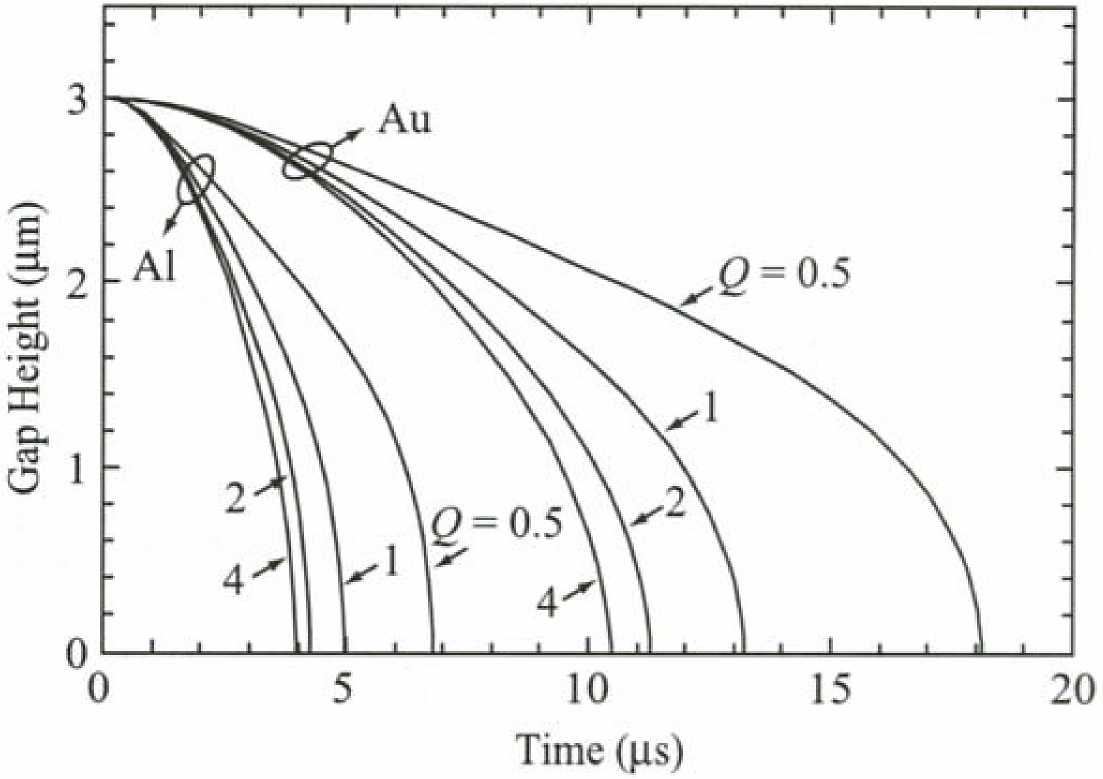


Figure 3.3. Pull-down simulations for the Au and Al beams of Table 3.1 for an applied voltage of 42 V ($V_s = 1.4V_p$).

Merk: Au har størst tetthet → størst masse → lavest ω → høyest svitsjehastighet (t_s)

Svitsje-hastighet

- Svitsje-hastigheten avhenger også sterkt av påtrykt spenning, Vs
  - Vs = konst * Vpi (pull-in) = (aktiverings-spenning)
  - Jo høyere spenning, dess sterkere elektrostatisk kraft
    - → økt svitsjehastighet

Tidsrespons mhp. påtrykt spenning

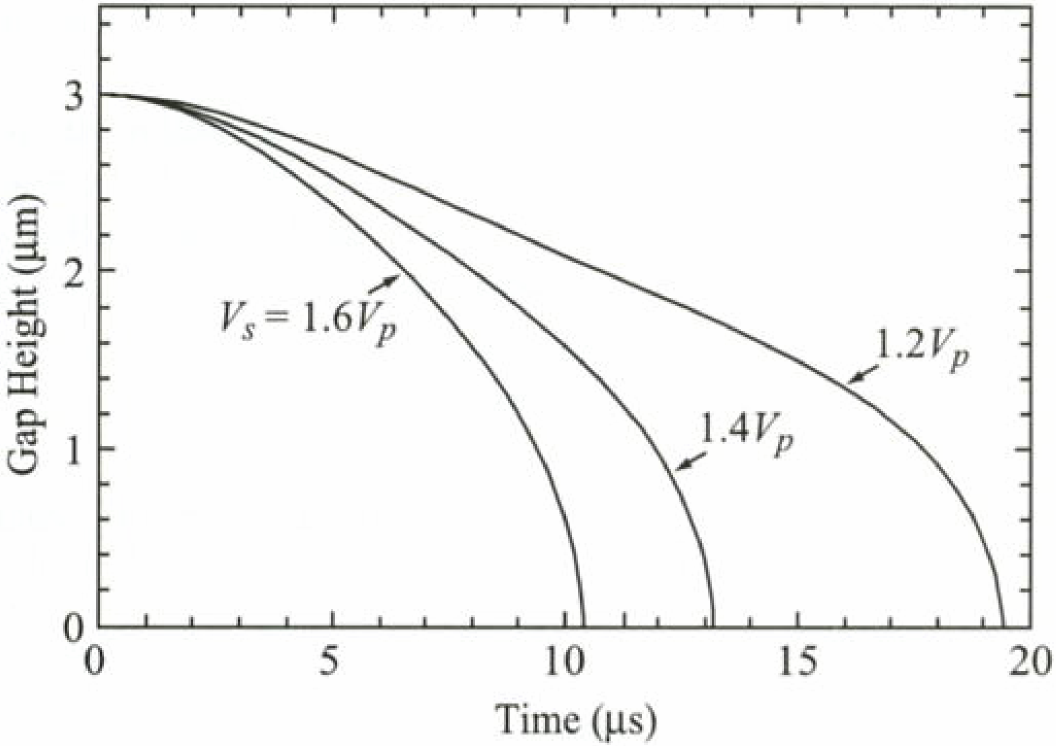


Figure 3.4. Pull-down simulations for the Au beam of Table 3.1 versus the applied voltage, and $Q = 1$.

Svitsje-hastighet, liten demping

Elektrostatisk kraft

$$F = \frac{\varepsilon_0 A V^2}{2 g^2}$$

Aksellerasjonsbegrenset svitsj (b~0)

$$m \frac{d^2 w}{dt^2} + k \cdot w = - \frac{\varepsilon_0 A V^2}{2 g_0^2} \qquad (Q \geq 2)$$

Anvend spenning $V_s = \text{konst} \times V_{pi}$

Svitsje-tid $t_s \approx 3.67 \frac{V_{pi}}{V_s \cdot \omega_0}$

Rebeiz

Aksellerasjonsbegrenset svitsj

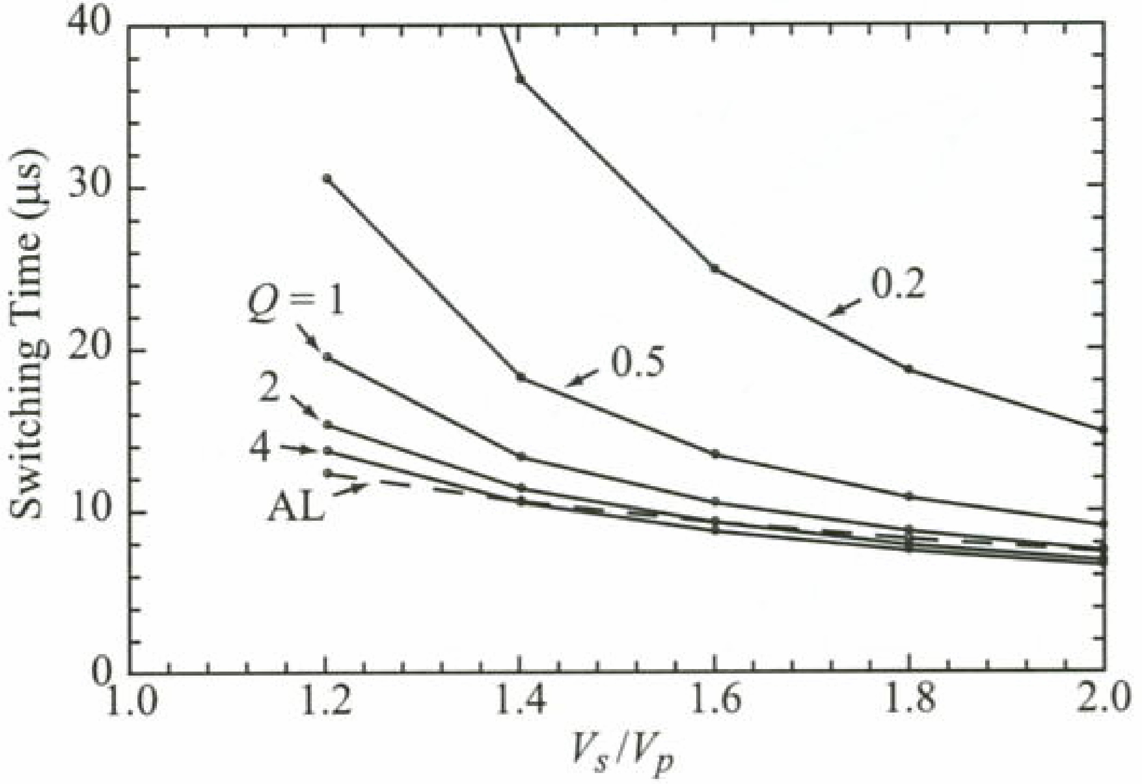


Figure 3.5. Simulated switching times for the Au beam given in Table 3.1. "AL" means acceleration-limited and is given by Eq. (3.23).

Merk: Systemet blir mer og mer aksellerasjonsbegrenset etterhvert som dempingen minker (dvs. Q-faktoren øker). Høy Vs/Vp bedrer forholdet.

RF design av MEMS svitsj

- Kan utføres ved full **elektromagnetisk** modellering
  - 3 dim elektromagnetisk analyse av feltfordelinger
    - Detaljert mekanisk modell
    - Avhengig av materialegenskaper, grensebetingelser etc.
  - Beregning av felt-distribusjoner og S-parametre
- Alternativt: bruk av ekvivalente krets-modeller →
  - Enkle modeller for håndkalkulering
    - Kan brukes til å beregne typiske RF ytelsesparametre

Ekvivalent-krets for kapasitiv svitsj

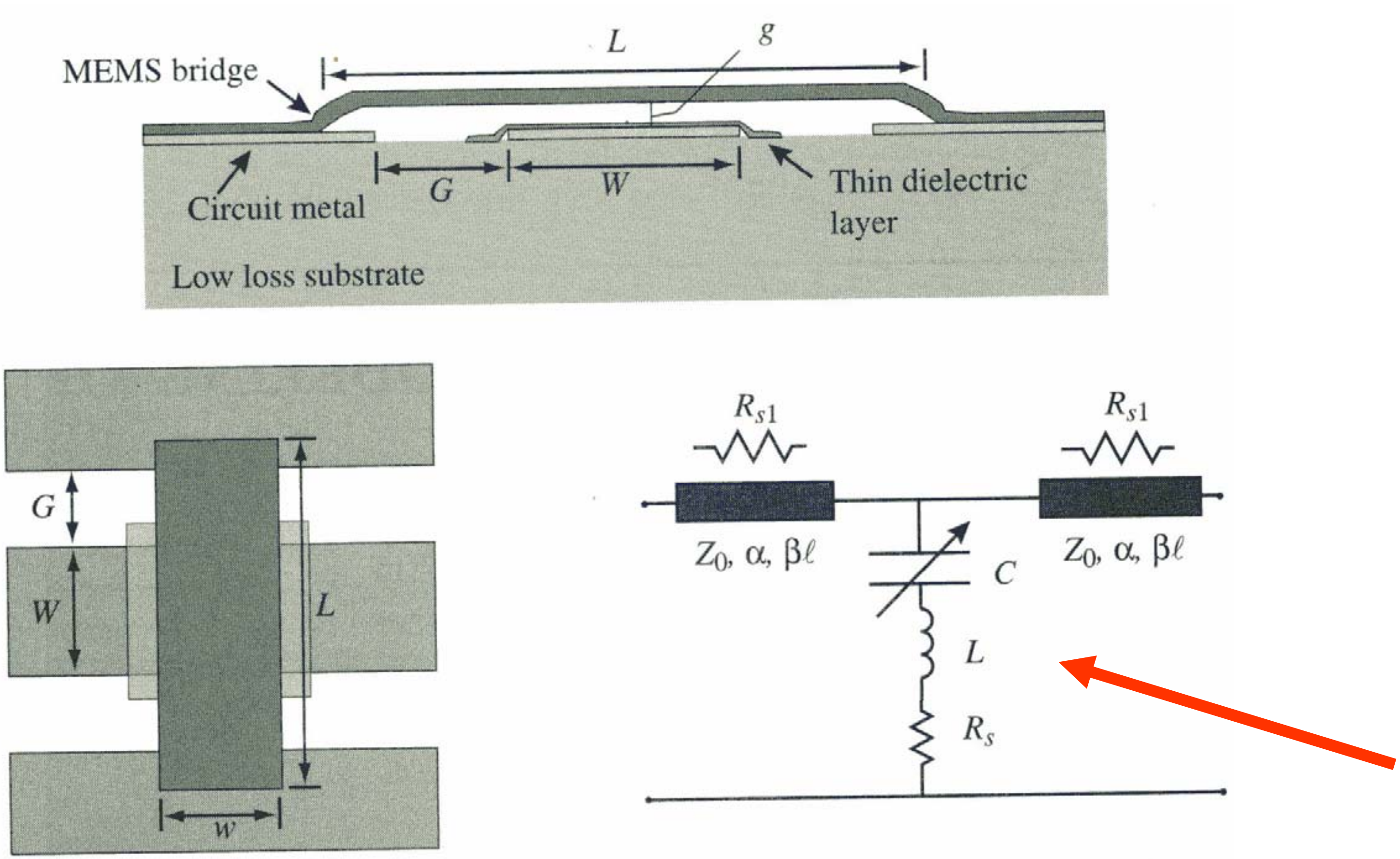


Figure 4.1. Illustration of a typical MEMS shunt switch shown in cross section and plan view. The equivalent circuit is also shown [6] (Copyright IEEE).

Rebeiz

Ekvivalent-krets, forts.

Svitsj shunt impedans

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

$C = C_u$ eller C_d

Ved resonans

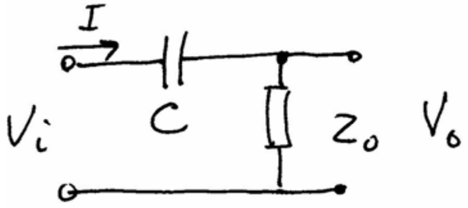
$$\omega_0 L = \frac{1}{\omega_0 C}$$

$$\omega_0 = \sqrt{\frac{1}{LC}}$$

$$Z_s = \begin{cases} \dfrac{1}{j\omega C} & \text{for } f \ll f_0 \\ R_s & \text{''} \quad f = f_0 \\ j\omega L & \text{''} \quad f \gg f_0 \end{cases}$$

Forenklet beregning av ”transmission”

- Modell av kontakt seriesvitsj (for ”lave” frekvenser)



Serie svitsj i ”off”-tilstand

$$V_i = I \cdot \left(\frac{1}{sC} + Z_0 \right) \qquad V_0 = I \cdot Z_0$$

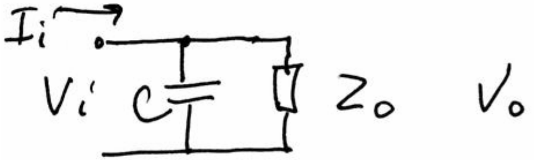
$$\frac{V_0}{V_i} = \frac{Z_0}{Z_0 + \frac{1}{sC}} = \frac{sCZ_0}{1 + sCZ_0} \rightarrow \frac{j\omega C Z_0}{1 + j\omega C Z_0}$$

Transmisjon

$$\left| \frac{V_0}{V_i} \right|^2 = \frac{\omega^2 C^2 Z_0^2}{1 + \omega^2 C^2 Z_0^2} \begin{cases} \rightarrow 0 & \text{når } \omega \rightarrow 0 \\ \rightarrow 1 & \text{når } \omega \rightarrow \infty \end{cases}$$

Forenklet beregning av ”transmission”, forts.

- Modell av kontakt shunt svitsj (for ”lave” frekvenser)



Shunt svitsj i ”off”-tilstand

$$I_i = \frac{V_o}{C \,//\, Z_o} \qquad I_o = \frac{V_o}{Z_o}$$

$$\frac{I_o}{I_i} = \frac{V_o / Z_o}{V_o \Big/ \left(\frac{\frac{1}{sC} \cdot Z_o}{\frac{1}{sC} + Z_o} \right)} = \frac{1}{1 + sCZ_o}$$

$$\frac{I_o}{I_i} \rightarrow \frac{1}{1 + j\omega C Z_o}$$

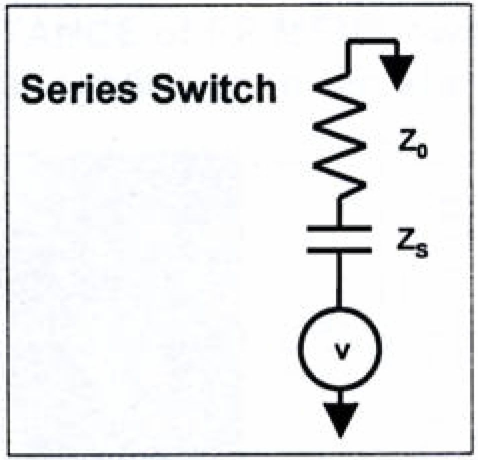
Shunt svitsj, forts.

$$\frac{I_o}{I_i} \rightarrow \frac{1}{1+j\omega C Z_o}$$

Transmisjon

$$\left|\frac{I_o}{I_i}\right|^2 = \frac{1}{1+\omega^2 C^2 Z_o^2} \begin{cases} \rightarrow 1 \text{ når } \omega \rightarrow 0 \\ \rightarrow 0 \text{ når } \omega \rightarrow \infty \end{cases}$$

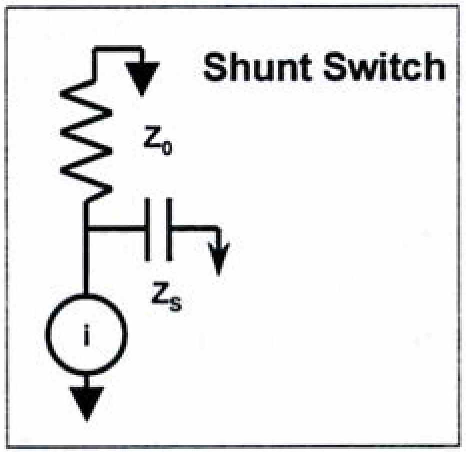
Sammenligning



Transmission ~ $(\omega Z_0 C_S)^2 / [1 + (\omega Z_0 C_S)^2]$

$\rightarrow 0$ as $\omega \rightarrow 0$

$\rightarrow 1$ as $\omega \rightarrow \infty$



Transmission ~ $1 / [1 + (\omega Z_0 C_S)^2]$

$\rightarrow 1$ as $\omega \rightarrow 0$

$\rightarrow 0$ as $\omega \rightarrow \infty$

Elektrisk karakterisering av RF MEMS svitsjer

- Ved ”lave” frekvenser
  - – Bruk impedans – admittans parametre
    - To-port med spenning og strøm (Kirchhoff)
- Ved høye frekvenser
  - – Bruk S-parametre
  - – S-parametrene måles/beregnes når linjene er terminert med sin karakteristiske impedans
  - – S-parametrene er småsignal-parametre
    - RF effekt < DC effekt

S-parametre: repetisjon

- 2-port for definisjon av S-parametre
- ”Power waves”

$$a_n = \frac{1}{2\sqrt{Z_0}}(V_n + Z_0 I_n) \tag{4.36a}$$

$$b_n = \frac{1}{2\sqrt{Z_0}}(V_n - Z_0 I_n) \tag{4.36b}$$

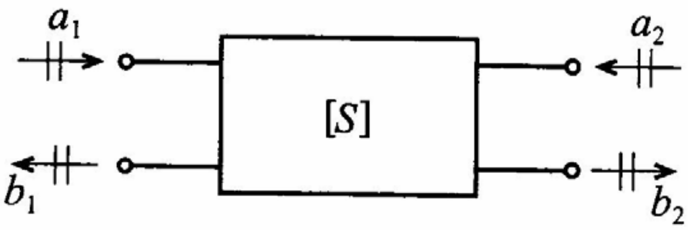


Figure 4-14 Convention used to define *S*-parameters for a two-port network.

Definisjon av S-parametrene

- Beregninger viser at effekten (power):

$$P_n = \tfrac{1}{2}\,\mathrm{Re}\{V_n I_n^*\} = \tfrac{1}{2}\left(\left|a_n\right|^2 - \left|b_n\right|^2\right)$$

S-parametre

$$\begin{Bmatrix} b_1 \\ b_2 \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{Bmatrix} a_1 \\ a_2 \end{Bmatrix} \qquad (4.41)$$

Hva hver enkelt parameter betyr

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

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

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

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

Måling av S-parametre

- S-parametrene måles når linjene er **terminert** med sin karakteristiske impedans

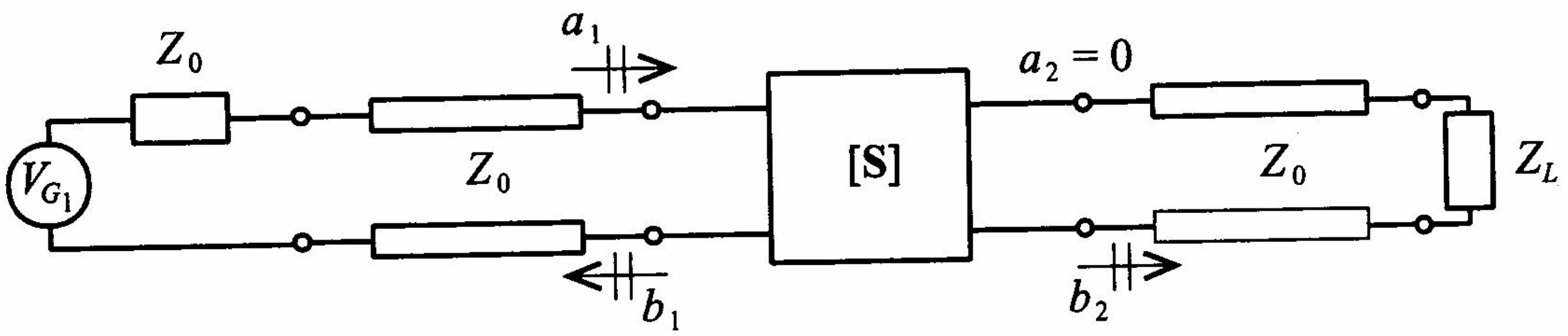


Figure 4-15 Measurement of S_{11} and S_{21} by matching the line impedance Z_0 at port 2 through a corresponding load impedance $Z_L = Z_0$.

RF karakterisering

- Reflekterte og transmitterte signaler må tas i betraktning
- Sentrale parametre beregnes
  - Insertion loss i ON-state =
  - Isolation i OFF-state =
  - Return loss (begge tilstander) =

RF karakterisering, forts.

”IL = Insertion loss” i ”on-state”

$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0} = \frac{transmitted, port2}{incident, port1}$$

Den **inverse** verdien benyttes for å angi IL

Spesifiseres i dB

Degraderes med økende frekvens

RF karakterisering, forts.

”Isolation” i ”off-state”

$$\frac{1}{S_{21}} = \left.\frac{a_1}{b_2}\right|_{a_2=0} = \frac{incident, port1}{transmitted, port2}$$

(Varadan)

$$\frac{1}{S_{12}} = \left.\frac{a_2}{b_1}\right|_{a_1=0} = \frac{incident, port2}{transmitted, port1}$$

(mest vanlig def)

→Stor isolasjon når utgang er liten i forhold til inngangen (eller når inngangen påvirkes lite av utgangen)

”Return loss” i begge tilstander

$$S_{11} = \frac{b_1}{a_1}$$

dvs. stort tap når mye reflekteres

Typiske parameter-målinger

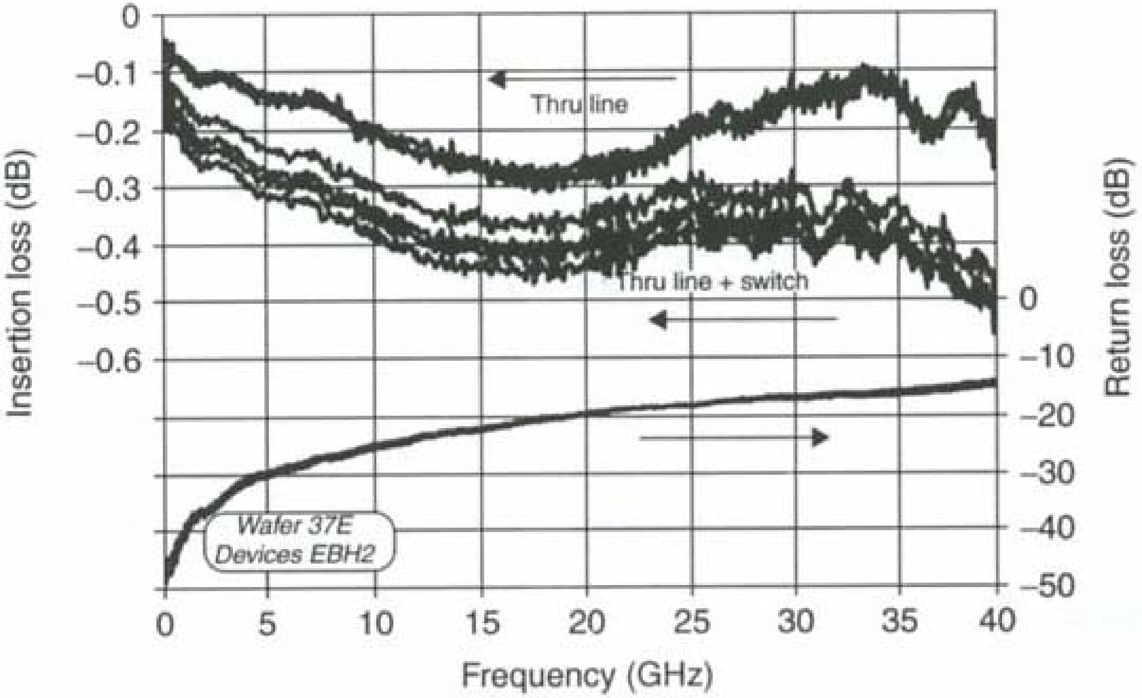


Figure 3.25 Measured insertion loss and return loss RF MEMS switch. Reproduced from C.L. Goldsmith, Z. Yao, S. Eshelman and D. Denniston, 1998, 'Performance of low-loss MEMS capacitive switches', *IEEE MW and Guided wave Letters* **8**(8): 269–271, by permission of IEEE, © 1998 IEEE

Varadan

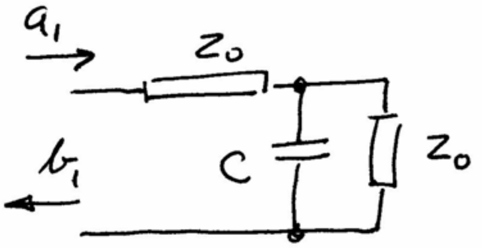
RF modellering

Shunt svitsj
Modelleres med kapasitans i ”up-state”

$$b_1 = S_{11} \cdot a_1 \Big|_{a_2=0}$$

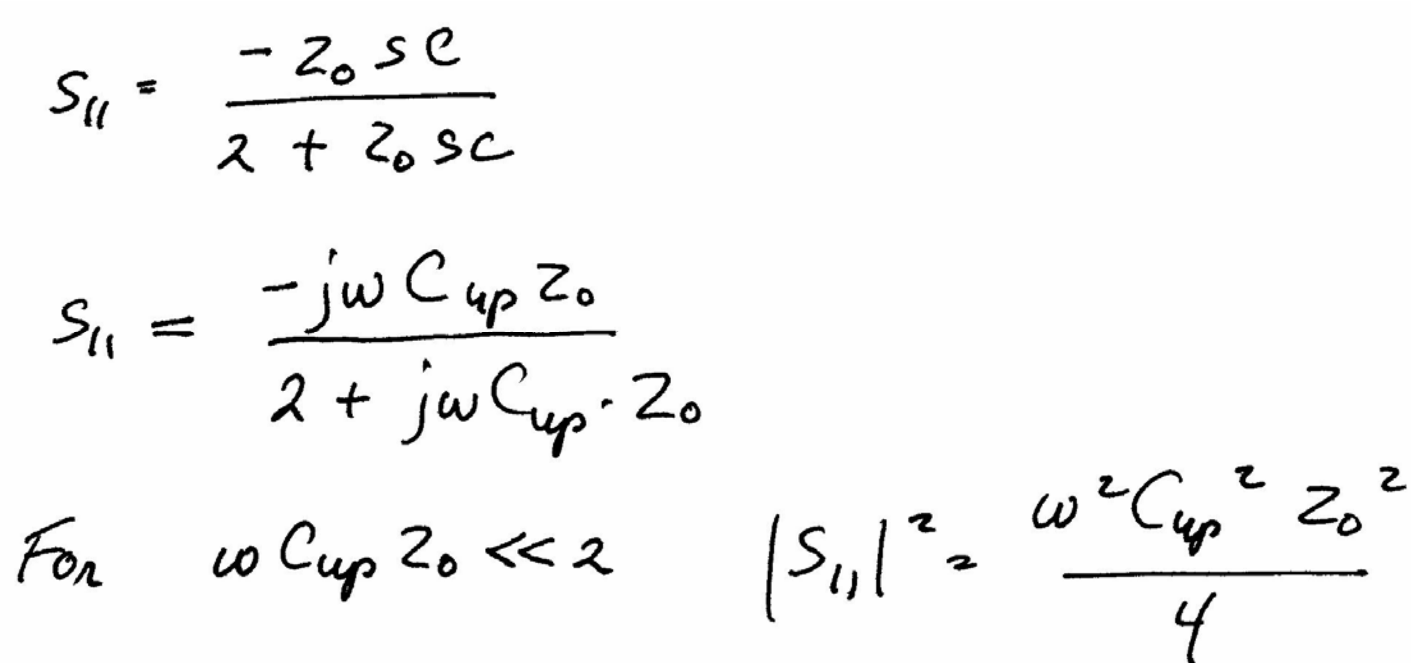
Refleksjon

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



$$S_{11} = \Gamma_0 = \frac{C /\!/ Z_0 - Z_0}{C /\!/ Z_0 + Z_0} = \frac{\dfrac{\frac{1}{sC} \cdot Z_0}{\frac{1}{sC} + Z_0} - Z_0}{\dfrac{\frac{1}{sC} \cdot Z_0}{\frac{1}{sC} + Z_0} + Z_0}$$

RF modellering, forts.



$$S_{11} = \frac{-Z_0 sC}{2 + Z_0 sC}$$

$$S_{11} = \frac{-j\omega C_{up} Z_0}{2 + j\omega C_{up} \cdot Z_0}$$

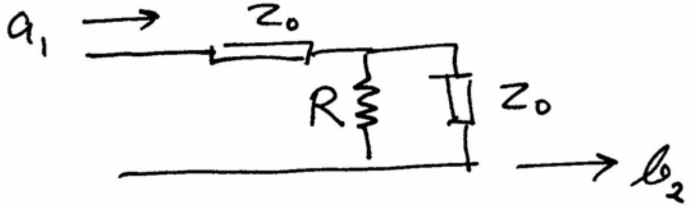
For $\omega C_{up} Z_0 \ll 2$ $\quad |S_{11}|^2 = \dfrac{\omega^2 C_{up}^2 Z_0^2}{4}$

RF modellering, forts.

Shunt svitsj
Serie-resistans i ”down-state”

Transmisjon

$$b_2 = S_{21} \cdot a_1 \Big|_{a_2=0}$$



Transmittert effekt = 1 + reflektert

negativt

$$S_{21} = 1 + \frac{Z_L - Z_0}{Z_L + Z_0}$$

$$= \frac{2\, Z_L}{Z_0 + Z_L} = \frac{2\, R // Z_0}{Z_0 + R // Z_0}$$

RF parasitter

- Meandere bidrar til parasitter
  - – Meandere gjør fjæropphenget mykere
    - Flere ”grener” gir lavere Vpi
  - – → fører til **parasitt induktans**
    - → påvirker RF-ytelsen

- Nøyaktig modellering må ta hensyn til parasitt induktans og parasitt resistans

Parasitt induktans

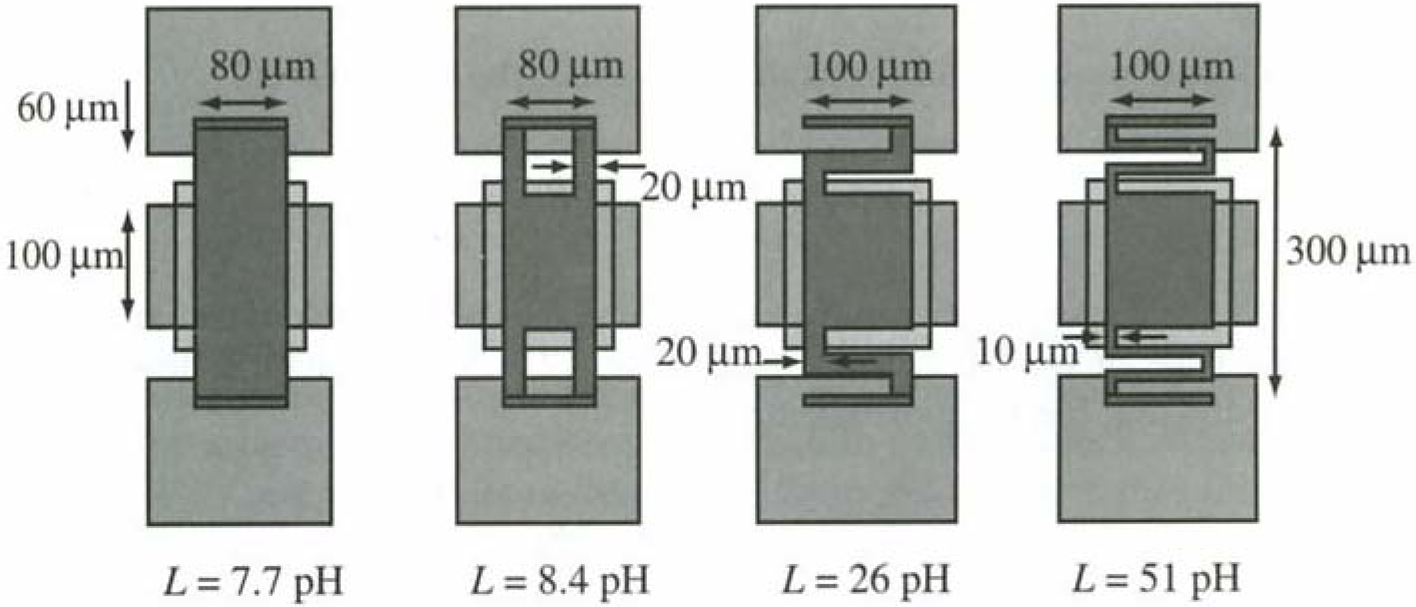


Figure 4.4. Simulated inductance for low-spring-constant MEMS bridges.

Meander-opphenget gir "spole"-virkning

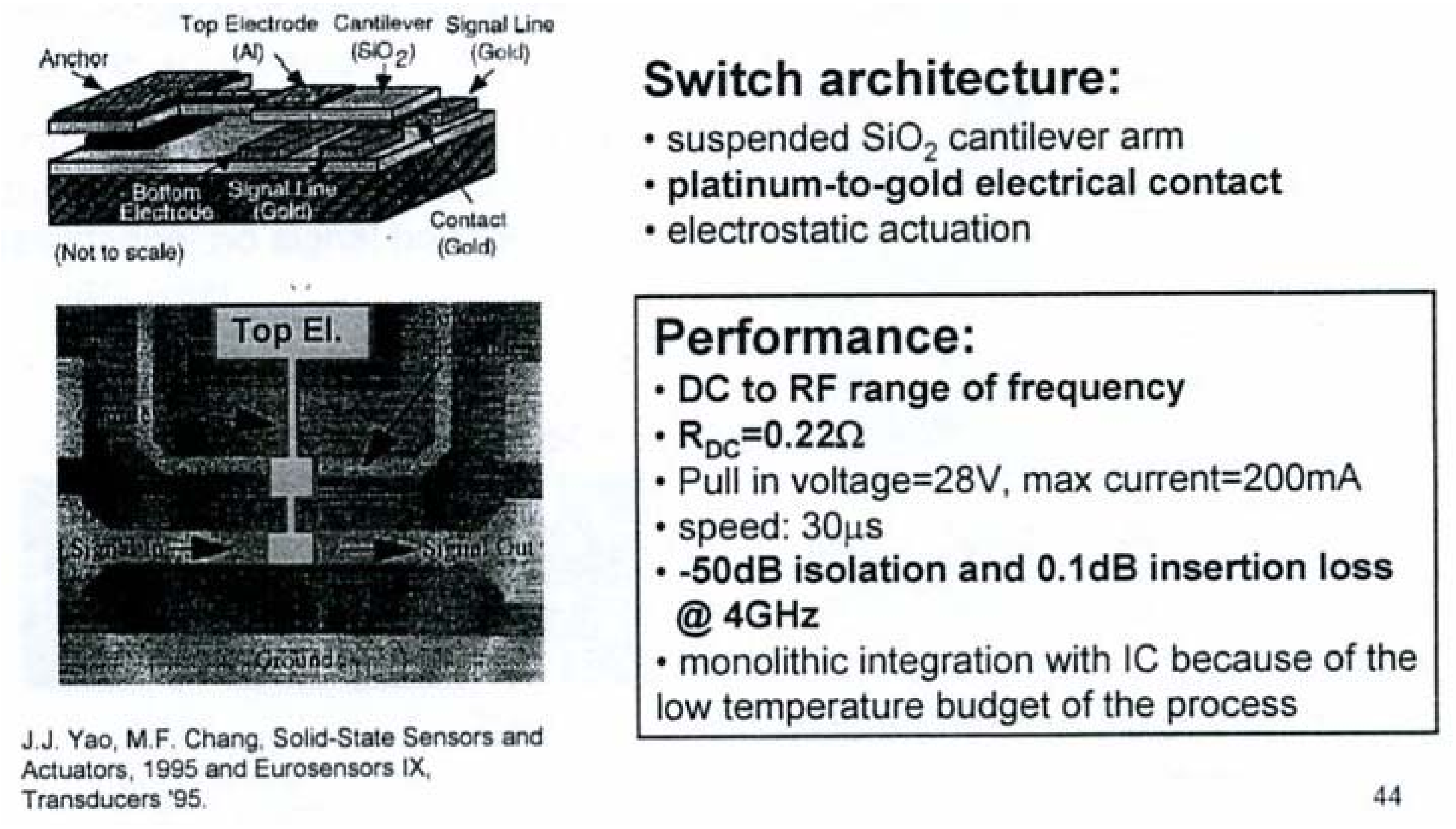
Rebeiz

Eksempler på implementasjoner

- **Serie-svitsjer**
  - Struktur og ytelse
  - Fremstilling

  - Eks. på **kontakt-svitsjer** →

Cantilever beam med elektrostatisk aktivering



J.J. Yao, M.F. Chang, Solid-State Sensors and Actuators, 1995 and Eurosensors IX, Transducers '95.

Switch architecture:

- suspended SiO_2 cantilever arm
- **platinum-to-gold electrical contact**
- electrostatic actuation

Performance:

- **DC to RF range of frequency**
- **$R_{DC}=0.22\Omega$**
- Pull in voltage=28V, max current=200mA
- speed: 30μs
- **-50dB isolation and 0.1dB insertion loss @ 4GHz**
- monolithic integration with IC because of the low temperature budget of the process

44

Rockwell serie-svitsj

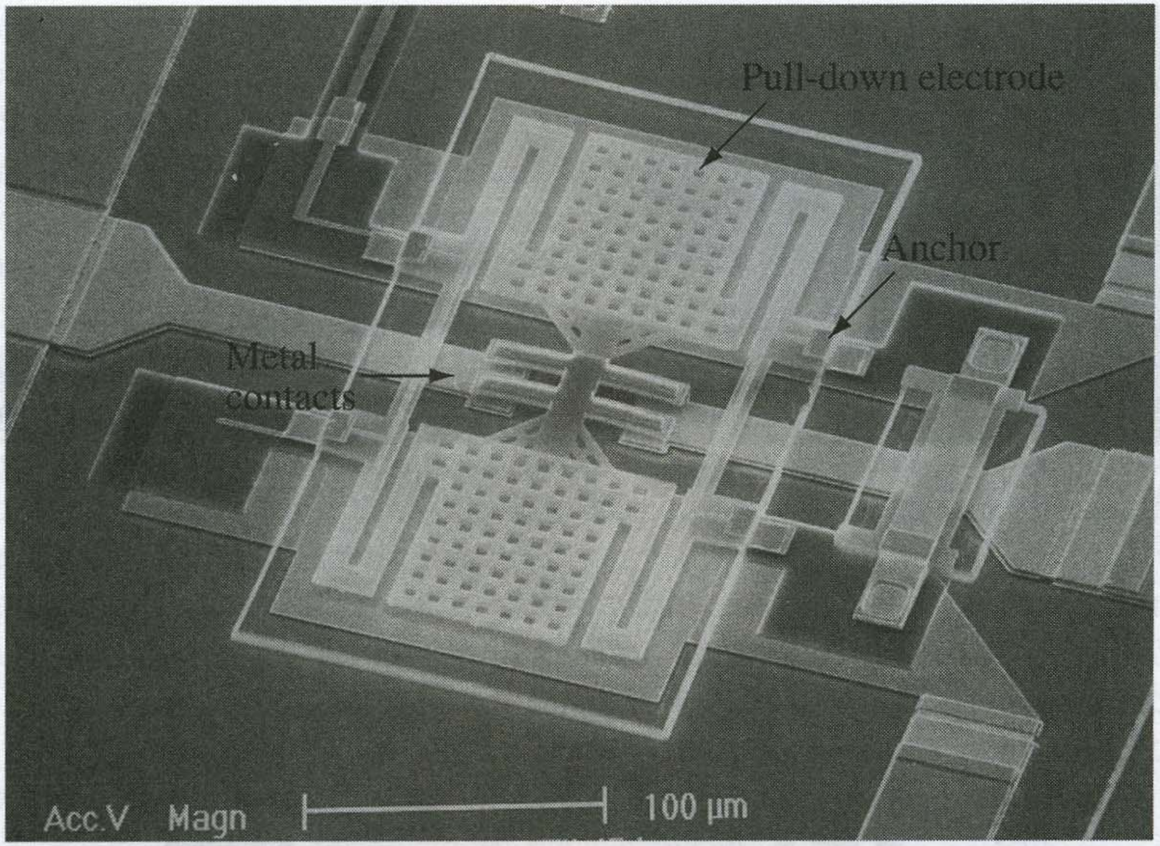


Figure 5.8. SEM of the Rockwell Scientific MEMS series switch [24] (Copyright IEEE).

Rebeiz

Fremstilling, ”Rockwell switch”

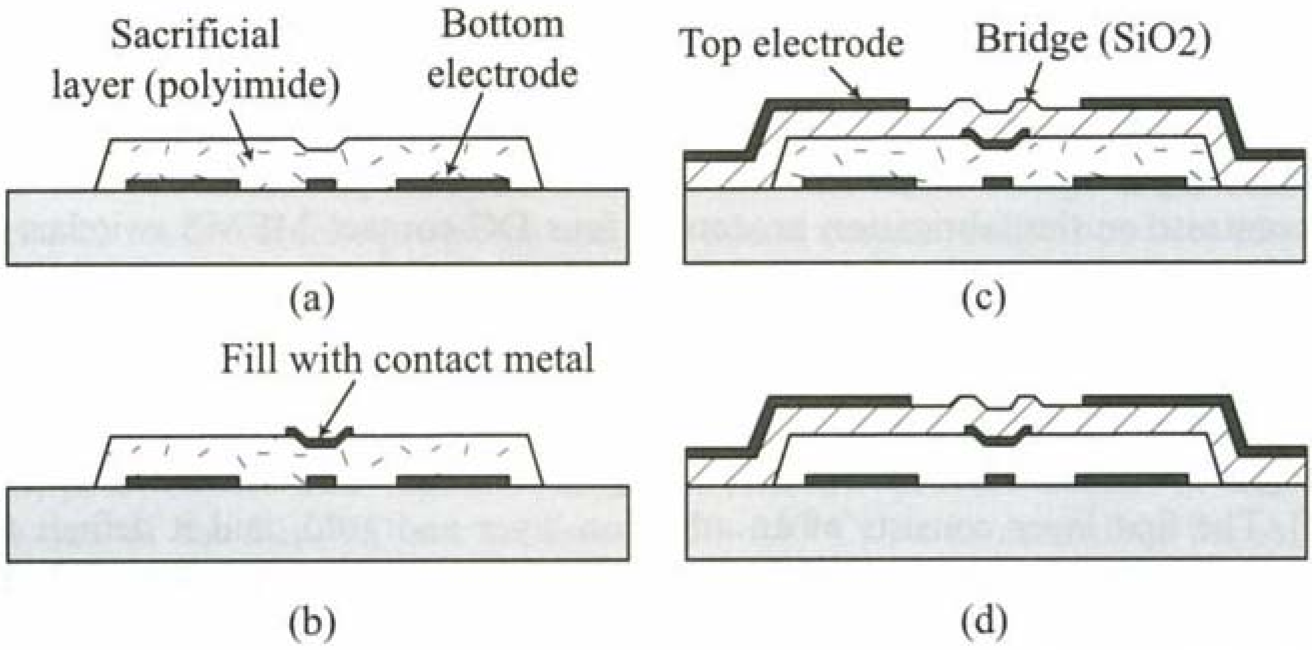


Figure 6.6. The fabrication process of the Rockwell Scientific series switch [8, 9].

Prinsipiell skisse

Rebeiz

Rockwell serie-svitsj, forts.

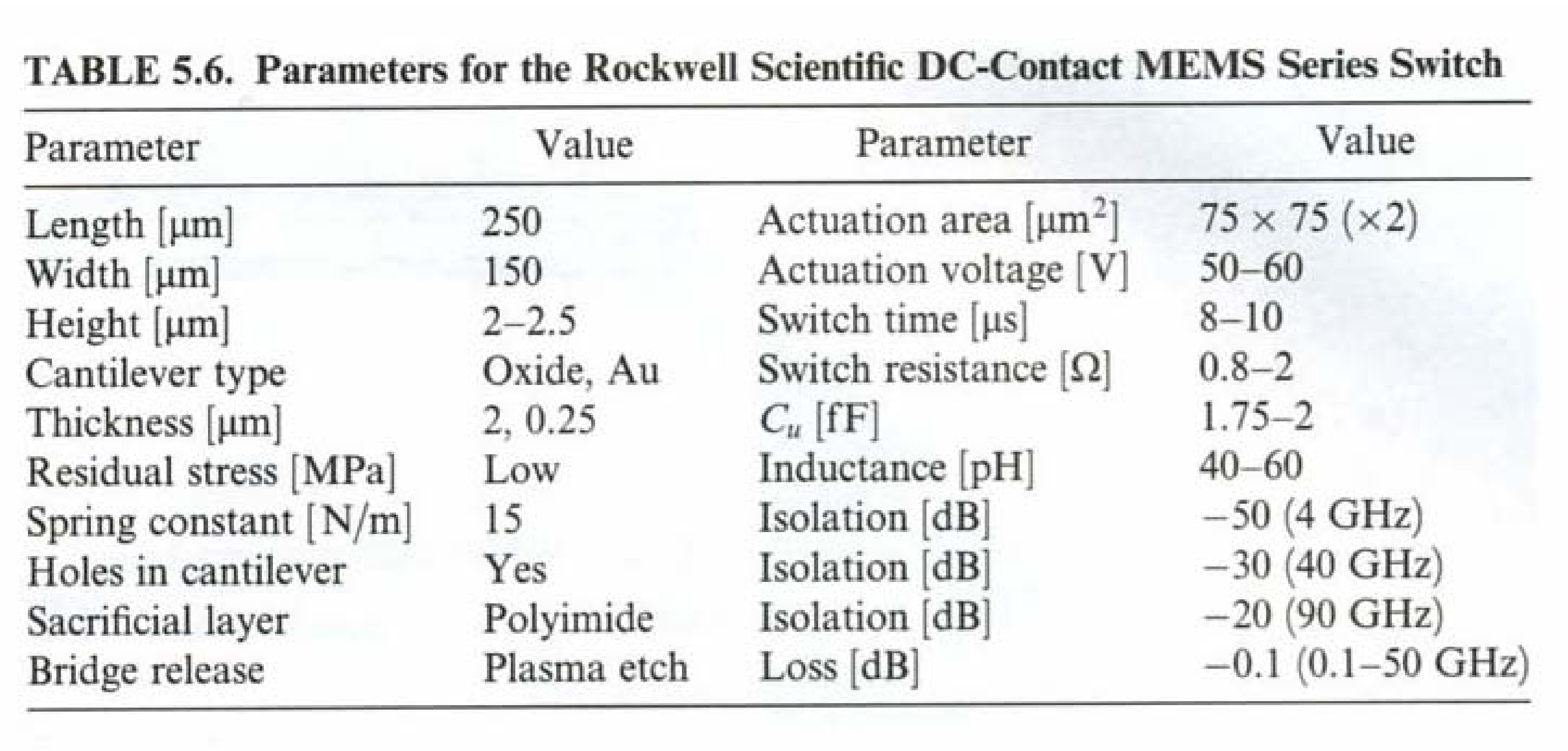


TABLE 5.6. Parameters for the Rockwell Scientific DC-Contact MEMS Series Switch

Parameter	Value	Parameter	Value
Length [μm]	250	Actuation area [μm^2]	75 × 75 (×2)
Width [μm]	150	Actuation voltage [V]	50–60
Height [μm]	2–2.5	Switch time [μs]	8–10
Cantilever type	Oxide, Au	Switch resistance [Ω]	0.8–2
Thickness [μm]	2, 0.25	C_u [fF]	1.75–2
Residual stress [MPa]	Low	Inductance [pH]	40–60
Spring constant [N/m]	15	Isolation [dB]	−50 (4 GHz)
Holes in cantilever	Yes	Isolation [dB]	−30 (40 GHz)
Sacrificial layer	Polyimide	Isolation [dB]	−20 (90 GHz)
Bridge release	Plasma etch	Loss [dB]	−0.1 (0.1–50 GHz)

Motorola

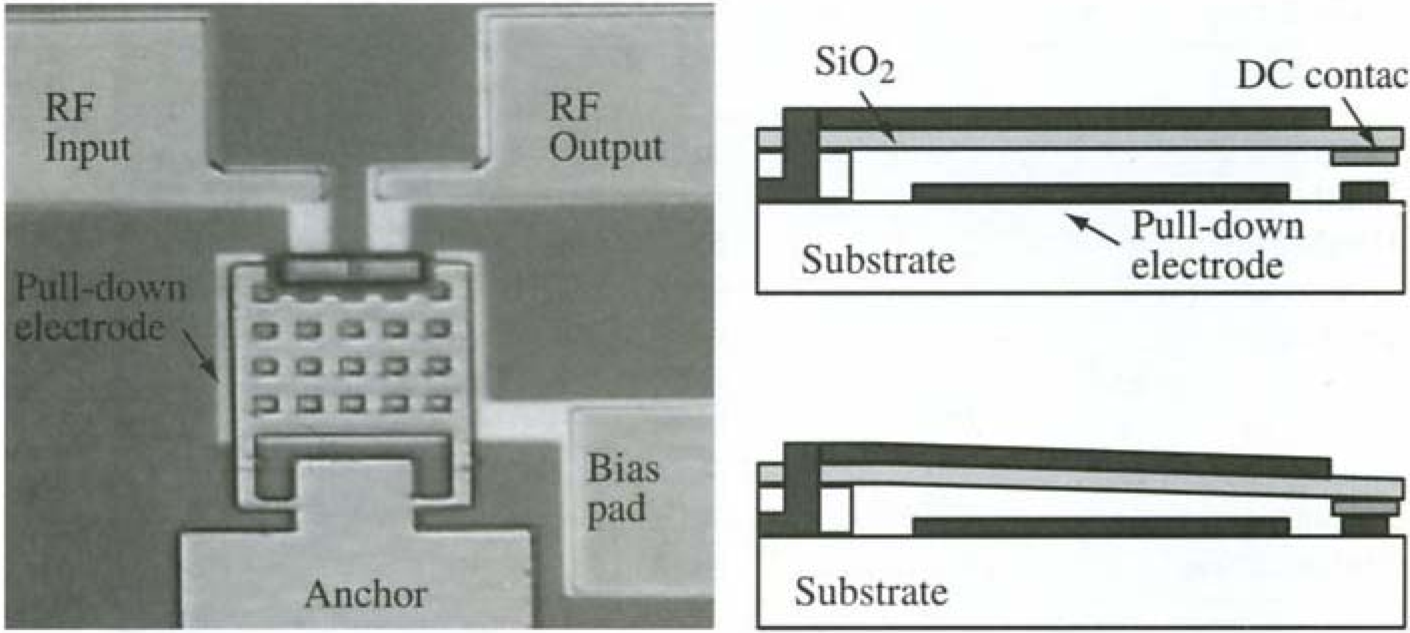


Figure 5.9. Photomicrograph of the Motorola DC-contact MEMS series switch and cross sections in the up- and down-state positions (Copyright IEEE).

Motorola, forts.

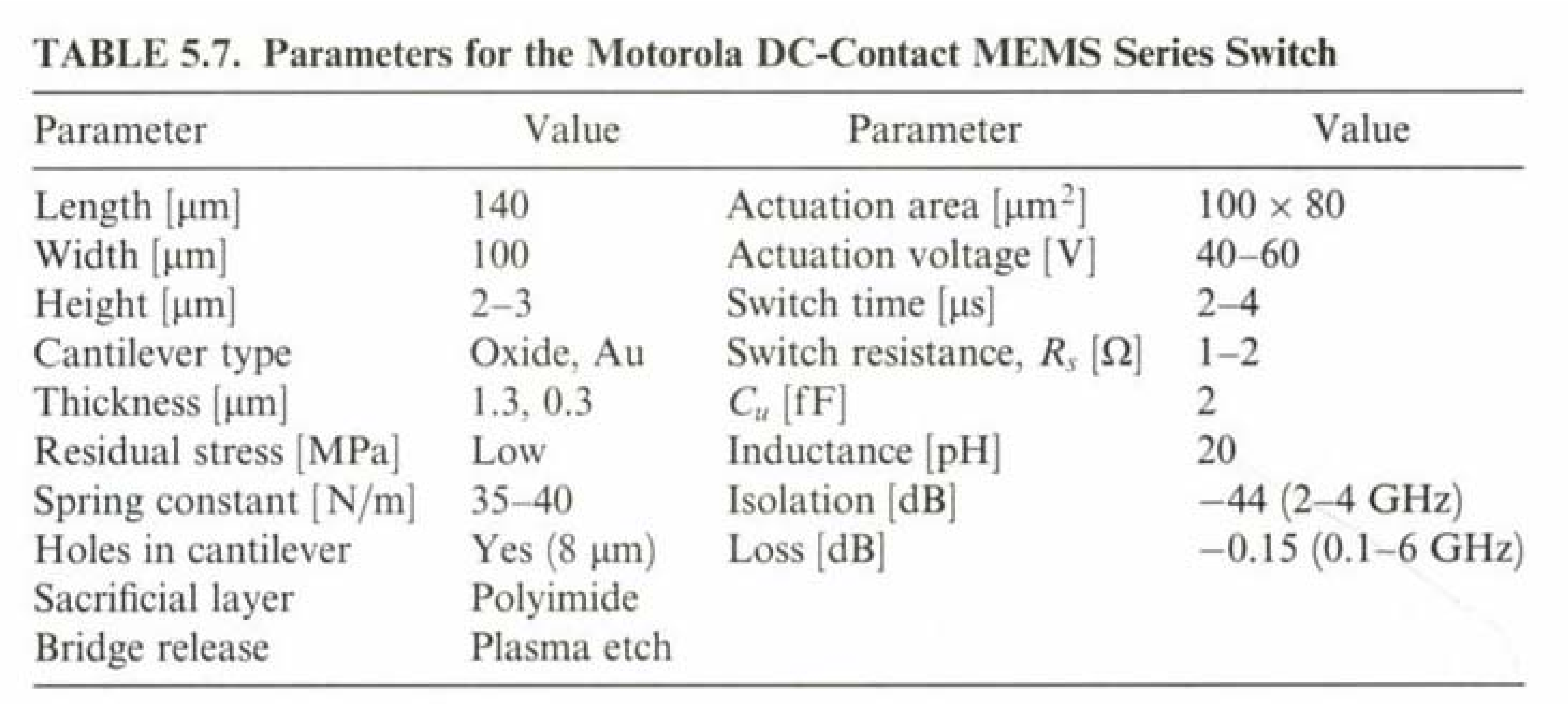


TABLE 5.7. Parameters for the Motorola DC-Contact MEMS Series Switch

Parameter	Value	Parameter	Value
Length [μm]	140	Actuation area [μm^2]	100 × 80
Width [μm]	100	Actuation voltage [V]	40–60
Height [μm]	2–3	Switch time [μs]	2–4
Cantilever type	Oxide, Au	Switch resistance, R_s [Ω]	1–2
Thickness [μm]	1.3, 0.3	C_u [fF]	2
Residual stress [MPa]	Low	Inductance [pH]	20
Spring constant [N/m]	35–40	Isolation [dB]	−44 (2–4 GHz)
Holes in cantilever	Yes (8 μm)	Loss [dB]	−0.15 (0.1–6 GHz)
Sacrificial layer	Polyimide		
Bridge release	Plasma etch		

Rebeiz

Lincoln

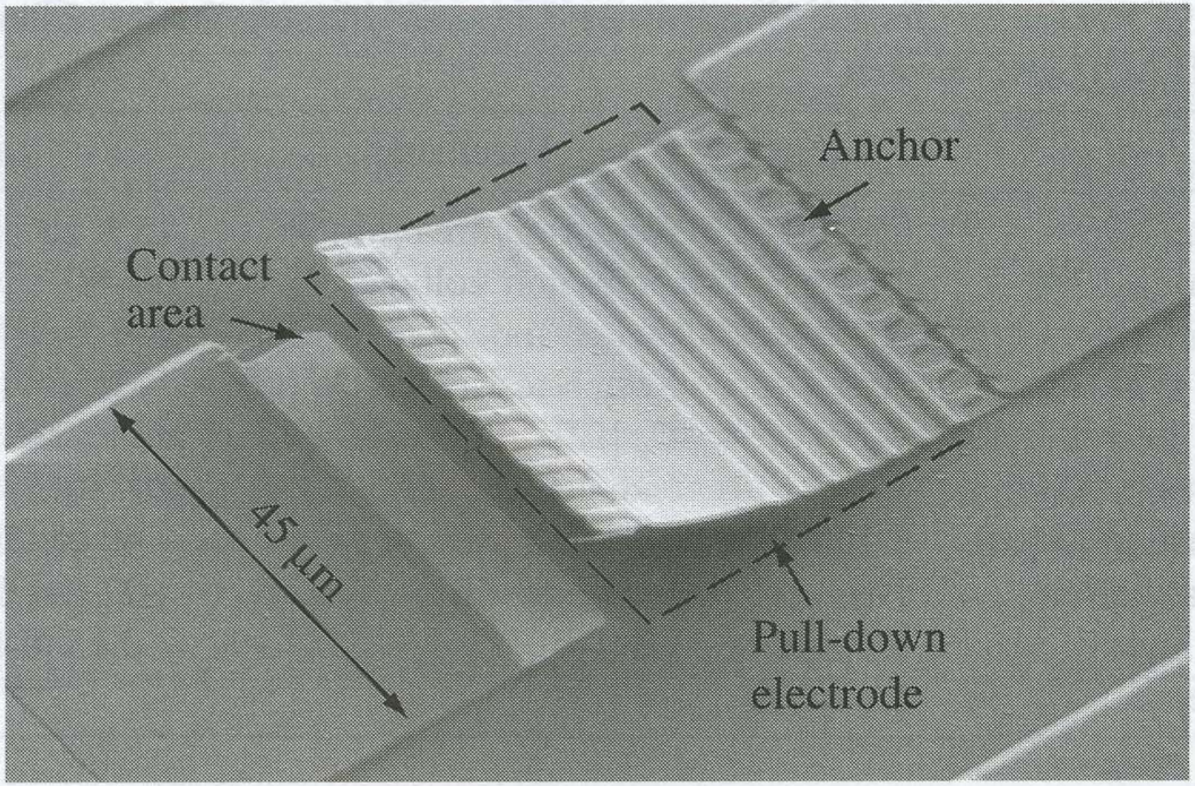


Figure 5.12. SEM of the Lincoln Laboratory in-line DC-contact MEMS series switch [31] (Copyright IEEE).

Lincoln, forts.

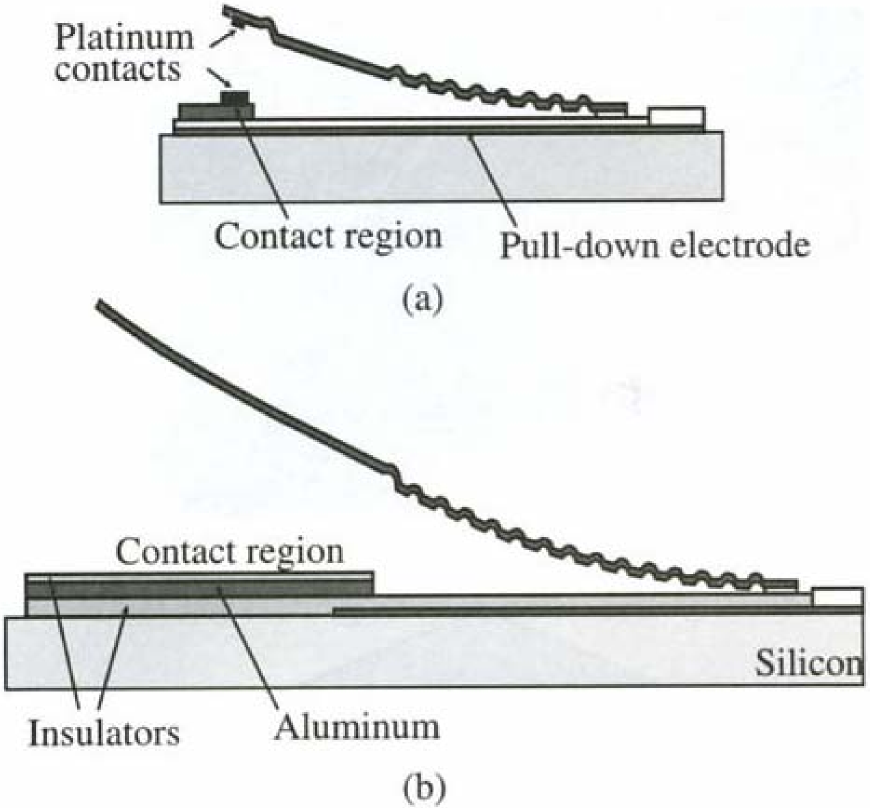


Figure 5.13. Cross section of the DC-contact (a) and capacitive-contact (b) Lincoln Laboratory inline switch (Copyright IEEE).

Lincoln, forts.

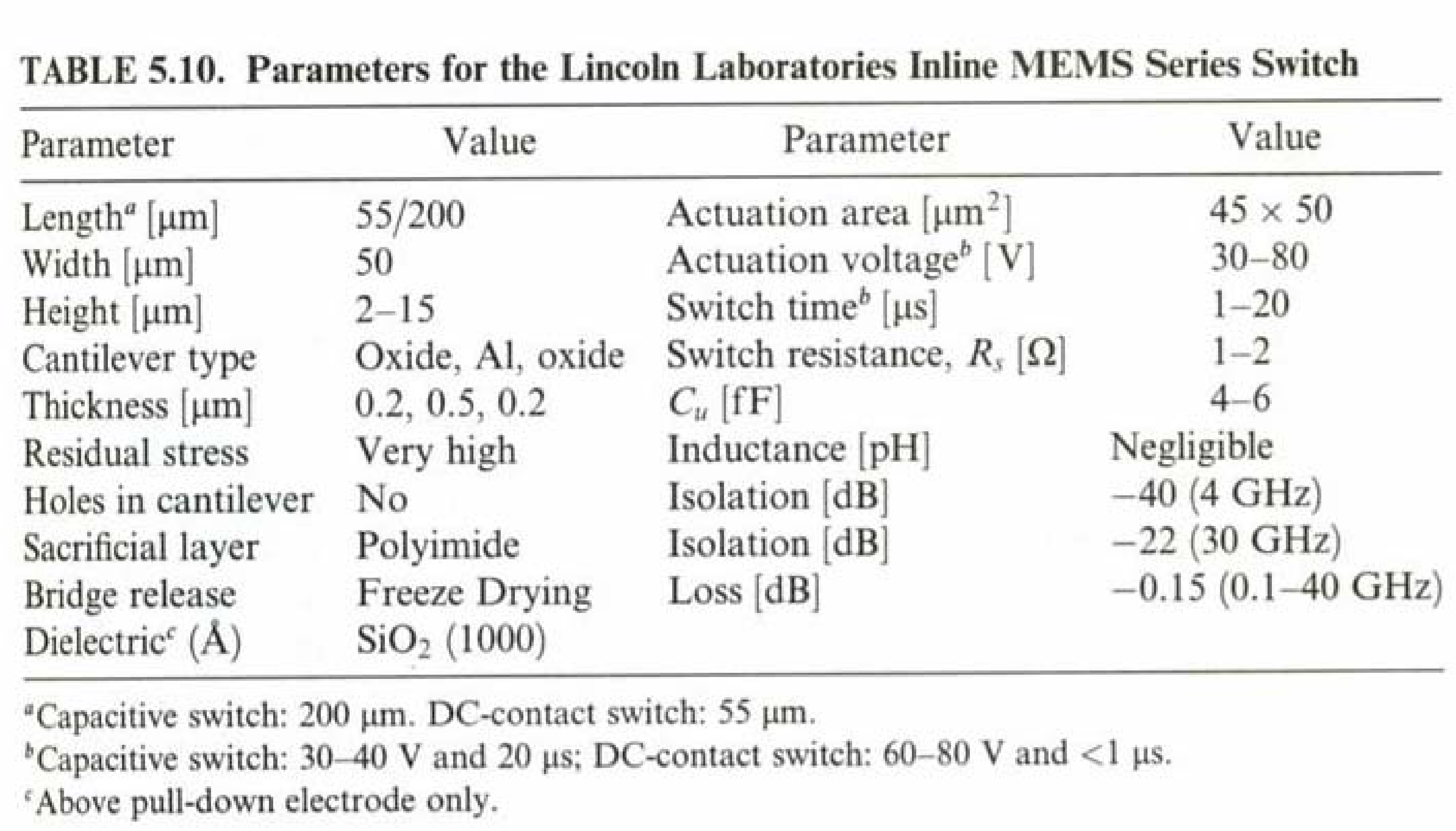


TABLE 5.10. Parameters for the Lincoln Laboratories Inline MEMS Series Switch

Parameter	Value	Parameter	Value
Length[a] [µm]	55/200	Actuation area [µm^2]	45 × 50
Width [µm]	50	Actuation voltage[b] [V]	30–80
Height [µm]	2–15	Switch time[b] [µs]	1–20
Cantilever type	Oxide, Al, oxide	Switch resistance, R_s [Ω]	1–2
Thickness [µm]	0.2, 0.5, 0.2	C_u [fF]	4–6
Residual stress	Very high	Inductance [pH]	Negligible
Holes in cantilever	No	Isolation [dB]	−40 (4 GHz)
Sacrificial layer	Polyimide	Isolation [dB]	−22 (30 GHz)
Bridge release	Freeze Drying	Loss [dB]	−0.15 (0.1–40 GHz)
Dielectric[c] (Å)	SiO$_2$ (1000)		

[a] Capacitive switch: 200 µm. DC-contact switch: 55 µm.

[b] Capacitive switch: 30–40 V and 20 µs; DC-contact switch: 60–80 V and <1 µs.

[c] Above pull-down electrode only.

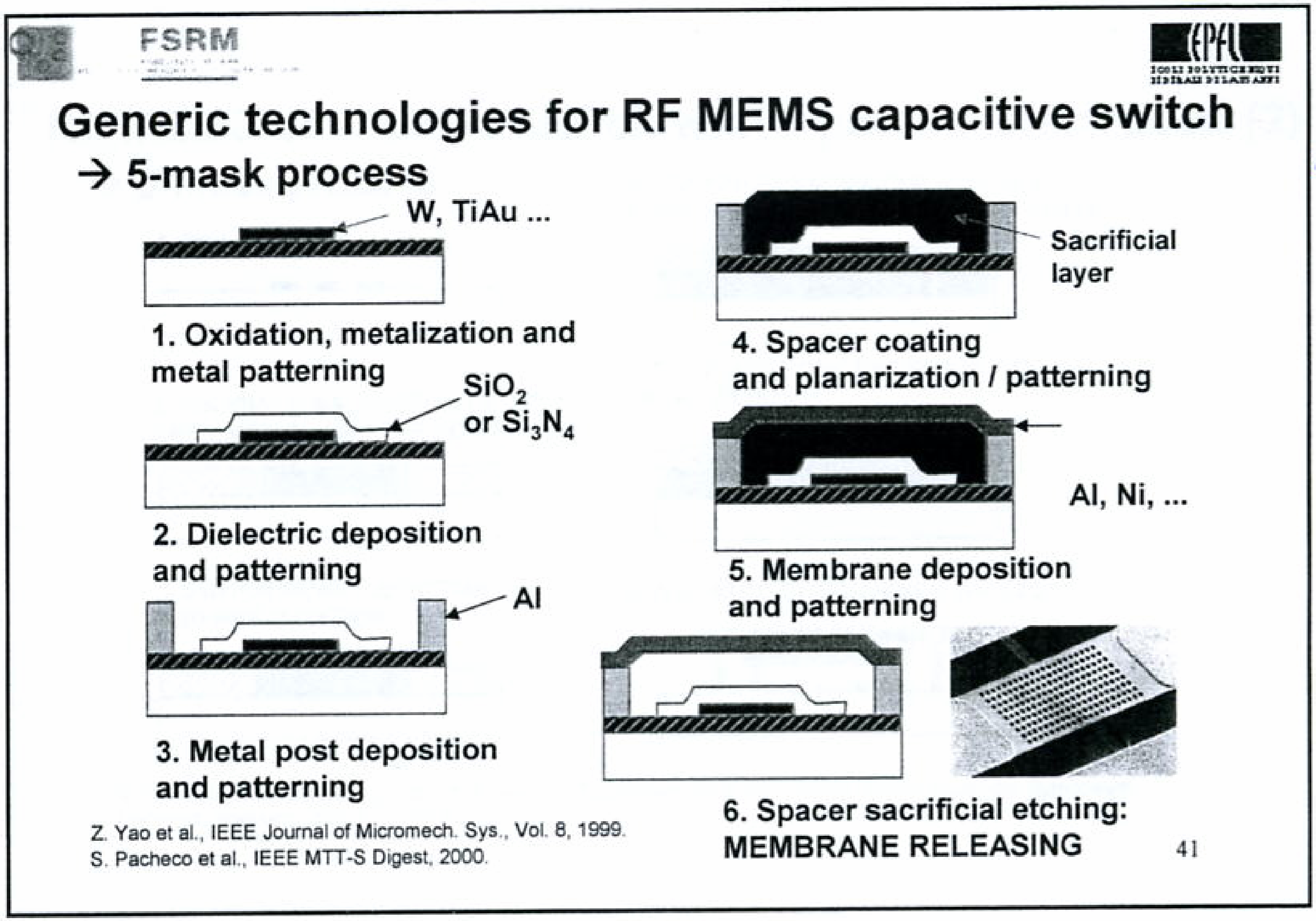
Eksempler på implementasjoner

- **Shunt-svitsjer**

  - Struktur og ytelse
  - Fremstilling

  - Eks. på kapasitive **shunt-svitsjer** →

Fremstilling av kapasitiv svitsj



Generic technologies for RF MEMS capacitive switch

→ 5-mask process

1. Oxidation, metalization and metal patterning
2. Dielectric deposition and patterning
3. Metal post deposition and patterning
4. Spacer coating and planarization / patterning
5. Membrane deposition and patterning
6. Spacer sacrificial etching: MEMBRANE RELEASING

Z. Yao et al., IEEE Journal of Micromech. Sys., Vol. 8, 1999.
S. Pacheco et al., IEEE MTT-S Digest, 2000.

41

Raytheon

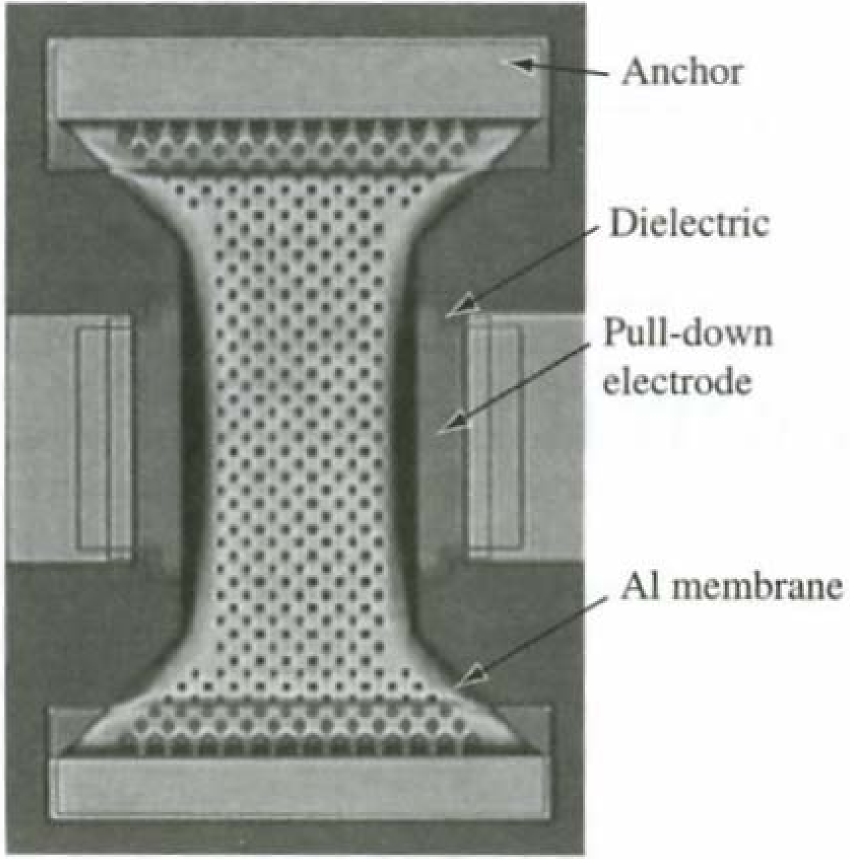


Figure 5.1. Photomicrograph of Raytheon MEMS capacitive shunt switch [2, 3] (Copyright IEEE).

Raytheon, forts.

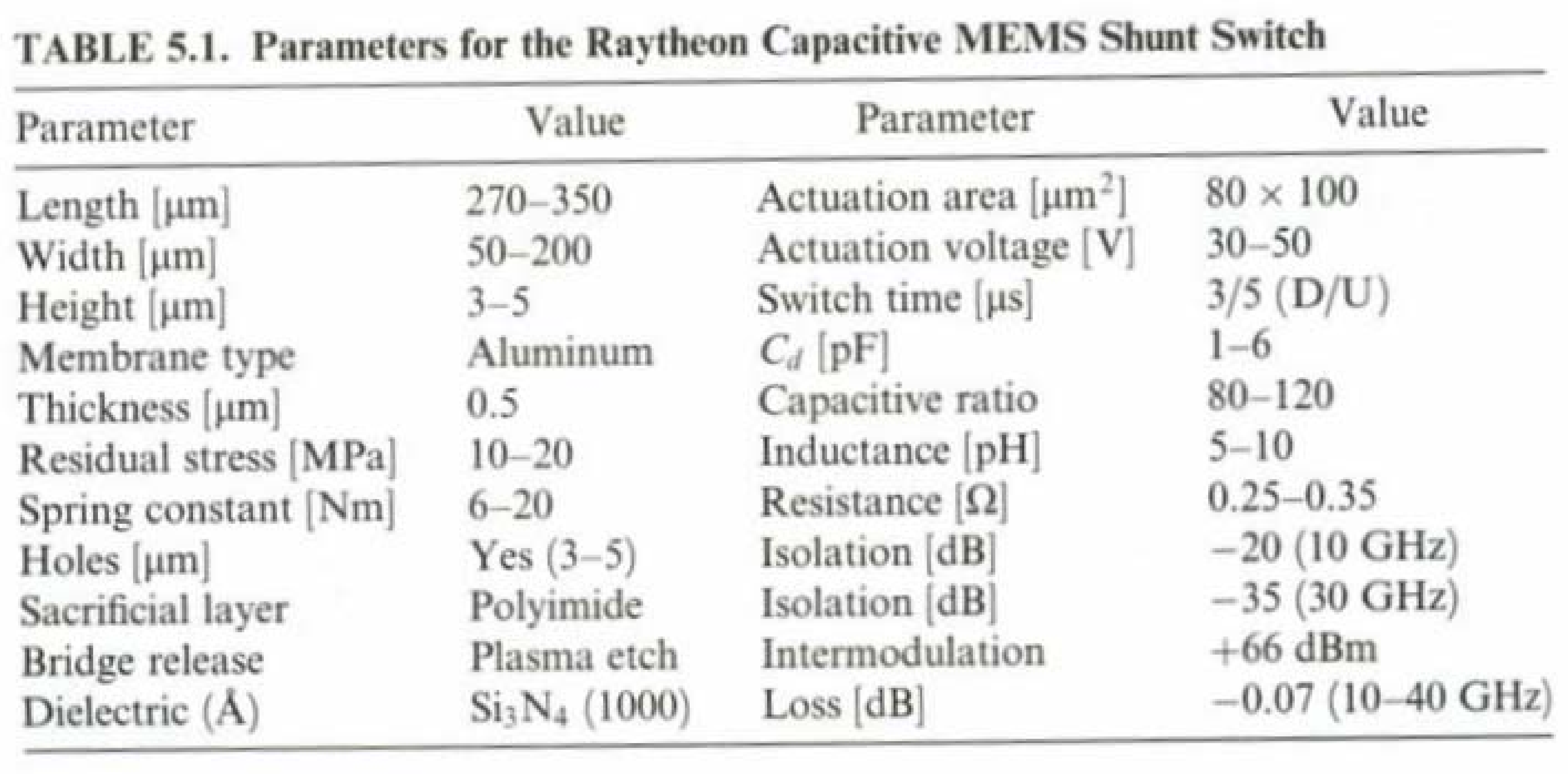
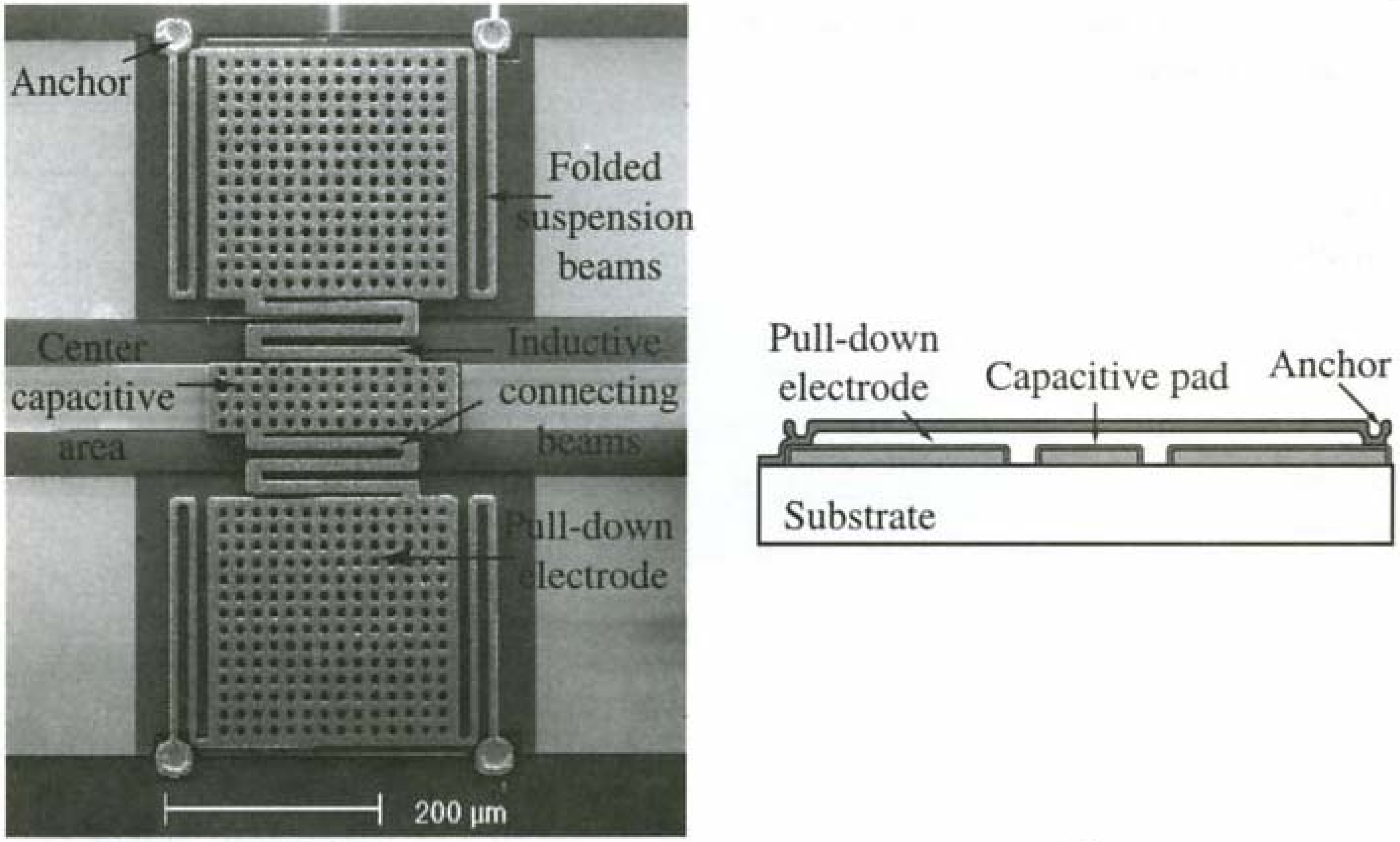


TABLE 5.1. Parameters for the Raytheon Capacitive MEMS Shunt Switch

Parameter	Value	Parameter	Value
Length [μm]	270–350	Actuation area [μm^2]	80 × 100
Width [μm]	50–200	Actuation voltage [V]	30–50
Height [μm]	3–5	Switch time [μs]	3/5 (D/U)
Membrane type	Aluminum	C_d [pF]	1–6
Thickness [μm]	0.5	Capacitive ratio	80–120
Residual stress [MPa]	10–20	Inductance [pH]	5–10
Spring constant [Nm]	6–20	Resistance [Ω]	0.25–0.35
Holes [μm]	Yes (3–5)	Isolation [dB]	−20 (10 GHz)
Sacrificial layer	Polyimide	Isolation [dB]	−35 (30 GHz)
Bridge release	Plasma etch	Intermodulation	+66 dBm
Dielectric (Å)	Si_3N_4 (1000)	Loss [dB]	−0.07 (10–40 GHz)

Rebeiz

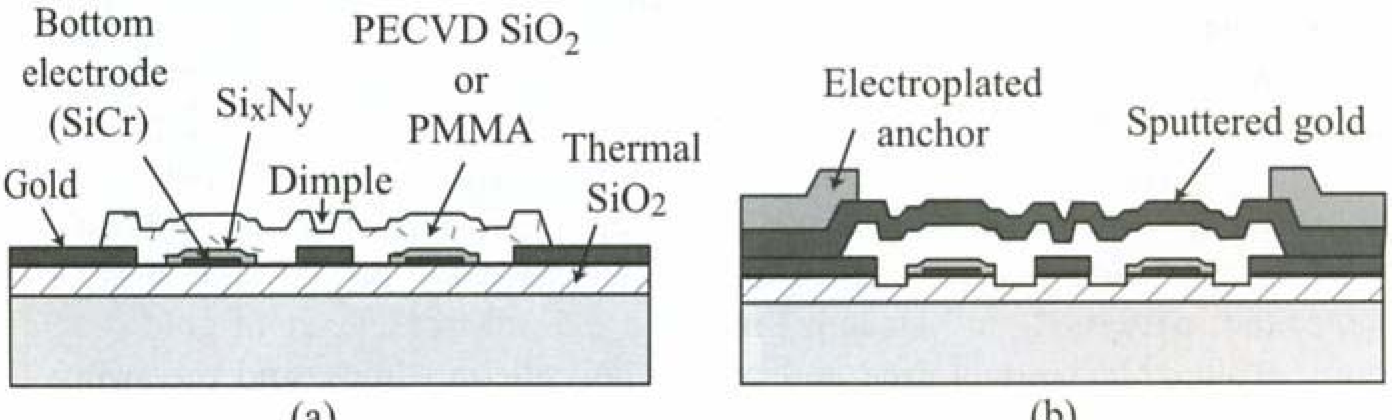
Univ of Michigan



(a) (b)

Figure 5.2. Photomicrograph of the university of Michigan low-voltage MEMS shunt switch. The number of meanders can be varied from 1 to 8 [7] (Copyright IEEE).

Fremstilling, ”Michigan switch”



(a)

(b)

Figure 6.7. The fabrication process of the Michigan all-metal series switch [10, 11] (Copyright IEEE).

Rebeiz

Univ of Michigan

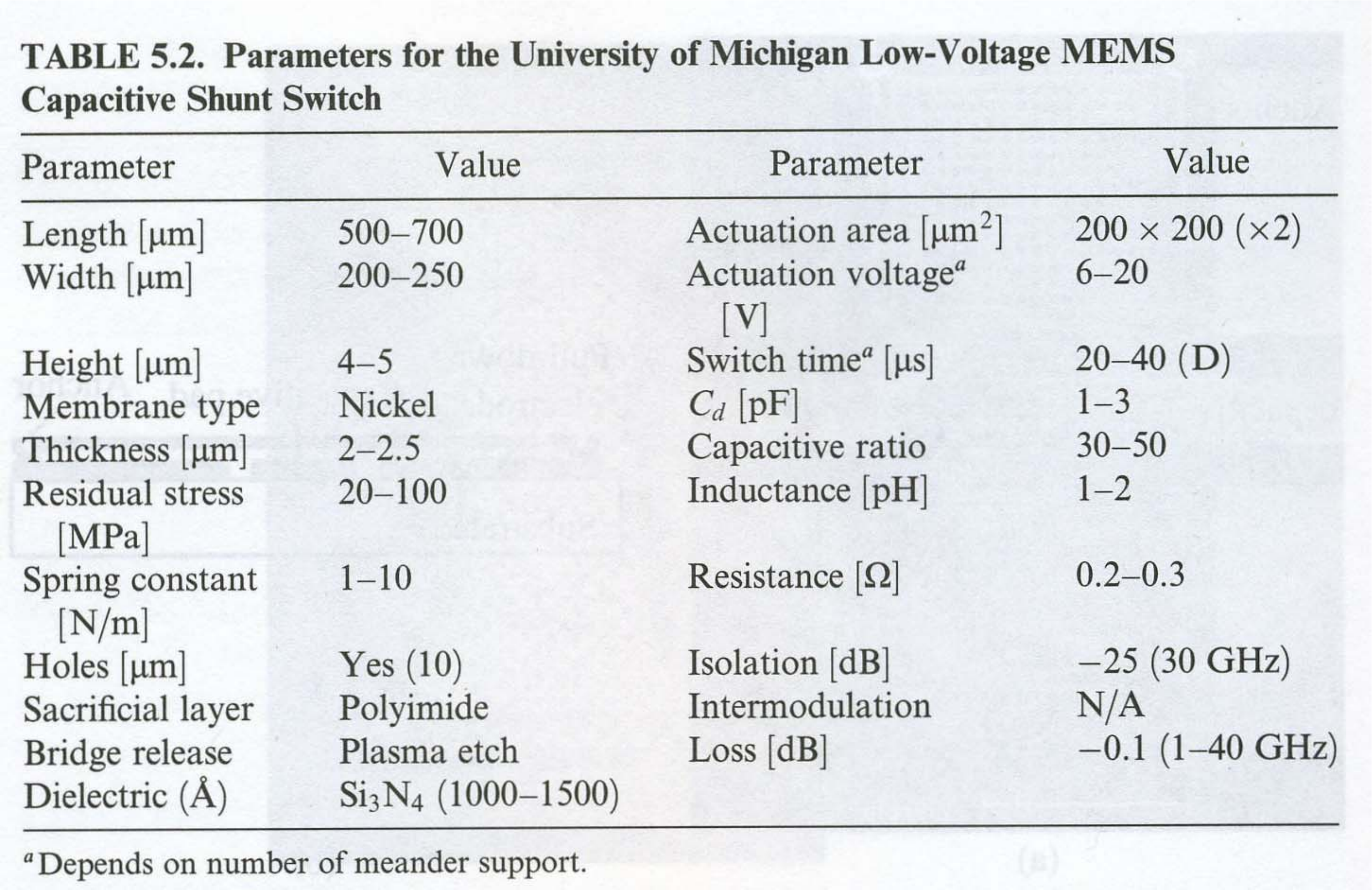


TABLE 5.2. Parameters for the University of Michigan Low-Voltage MEMS Capacitive Shunt Switch

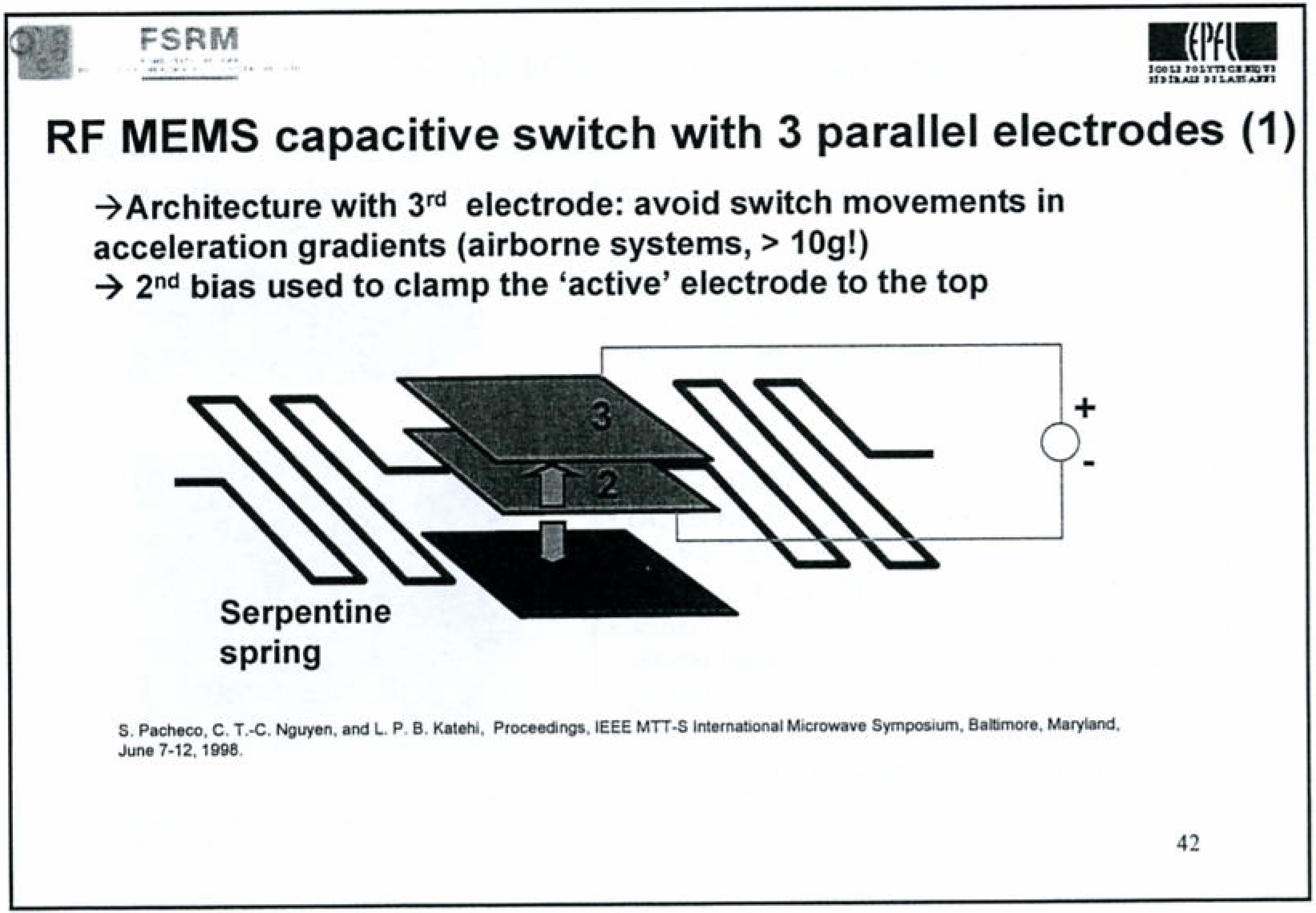
Parameter	Value	Parameter	Value
Length [μm]	500–700	Actuation area [μm^2]	200 × 200 (×2)
Width [μm]	200–250	Actuation voltage^a [V]	6–20
Height [μm]	4–5	Switch time^a [μs]	20–40 (D)
Membrane type	Nickel	C_d [pF]	1–3
Thickness [μm]	2–2.5	Capacitive ratio	30–50
Residual stress [MPa]	20–100	Inductance [pH]	1–2
Spring constant [N/m]	1–10	Resistance [Ω]	0.2–0.3
Holes [μm]	Yes (10)	Isolation [dB]	−25 (30 GHz)
Sacrificial layer	Polyimide	Intermodulation	N/A
Bridge release	Plasma etch	Loss [dB]	−0.1 (1–40 GHz)
Dielectric (Å)	Si_3N_4 (1000–1500)		

[a] Depends on number of meander support.

Rebeiz

Alternative svitsje-strukturer

- 3 elektroder kan også brukes
  - Topp-elektroden brukes for å ”clampe” den aktive elektroden til toppen
  - Spesielt viktig for systemer utsatt for høye aksellerasjoner



RF MEMS capacitive switch with 3 parallel electrodes (1)

→Architecture with 3rd electrode: avoid switch movements in acceleration gradients (airborne systems, > 10g!)

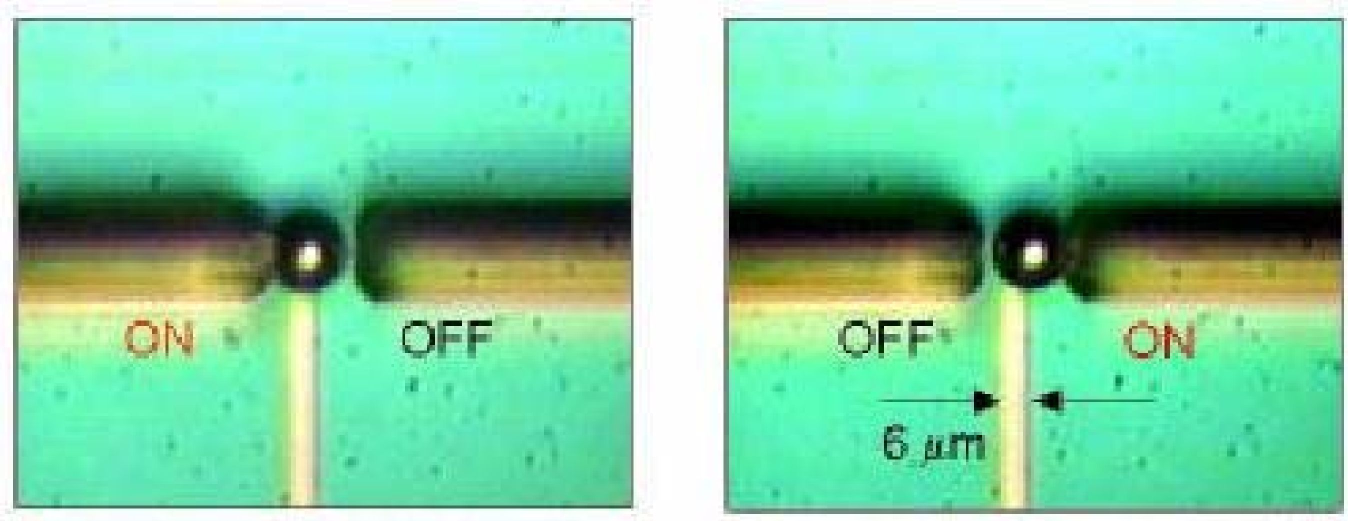
→ 2nd bias used to clamp the 'active' electrode to the top

S. Pacheco, C. T.-C. Nguyen, and L. P. B. Katehi, Proceedings, IEEE MTT-S International Microwave Symposium, Baltimore, Maryland, June 7-12, 1998.

Alternative aktiveringsmekanismer

- Væske/metall kontakt-svitsj
  - Kan løse pålitelighetsproblemet (degradering) en har ved faststoff - til - faststoff
    - → Bruke **væske-til-faststoff**
  - Kvikksølv (Hg) velges pga. dets egenskaper
    - Lav kontakt-resistans
    - Hindrer signal-ringing
    - Ikke kontakt-slitasje
  - Elektrostatisk aktivering
    - Aktiveringsspenning 100 – 150 V
  - Væske ikke akseptert i IC-industrien!

Kvikksølv-svitsj



Kvikksølvkulen flytter seg

Planar prosess, foto, JHU, Appl Physics Lab

Kvikksølv-svitsj

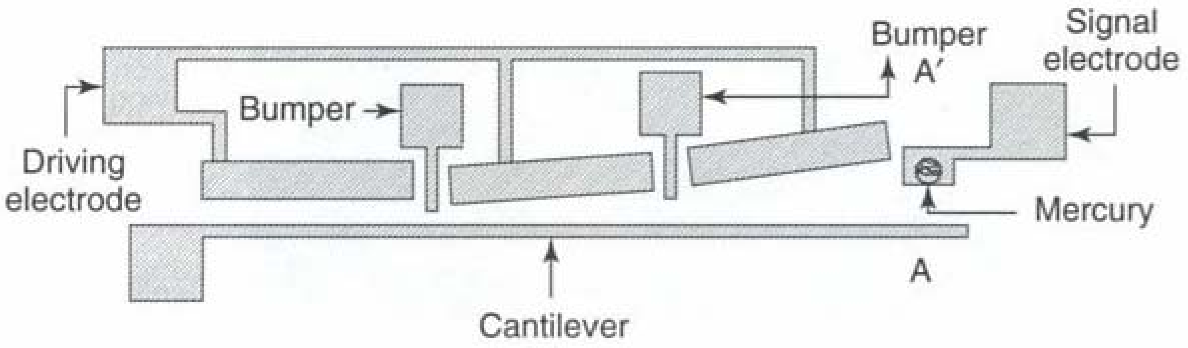


Figure 3.33 Schematic diagram of the mercury contact micro relay. Reproduced from S. Saffer, J. Simon and C.J. Kim, 1996, 'Mercury contact switching with gap-closing microcantilever', *Proceedings of SPIE*, 2882: 204–209, by permission of SPIE

Figuren viser svitsjen sett ovenfra

Kvikksølv-svitsj, forts.

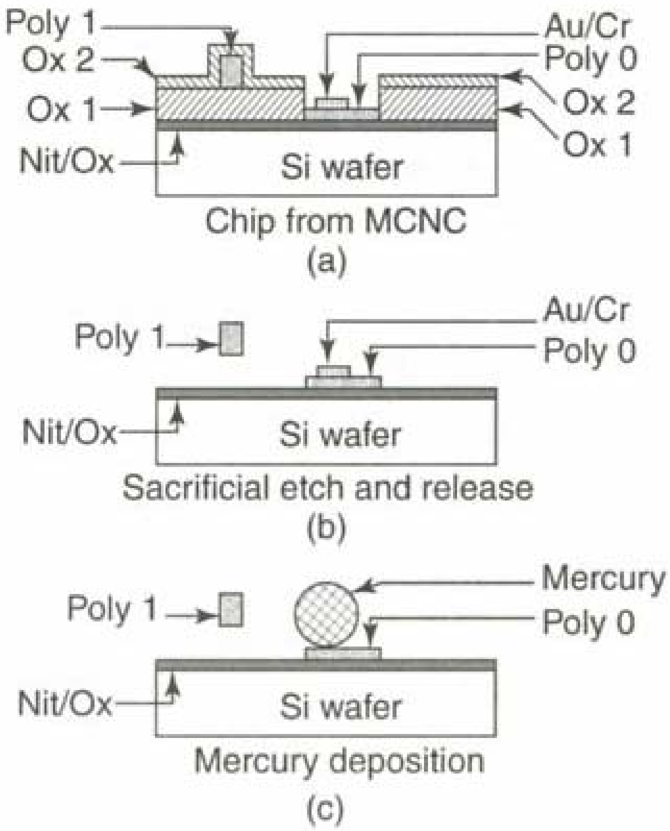


Figure 3.34 Process flow at cross-section AA′ of Figure 3.33. Note: MCNC, Microelectronics Center of North Carolina. Reproduced from S. Saffer, J. Simon and C.J. Kim, 1996, 'Mercury contact switching with gap-closing microcantilever', *Proceedings of SPIE*, 2882: 204–209, by permission of SPIE

Varadan

Termisk svitsjing

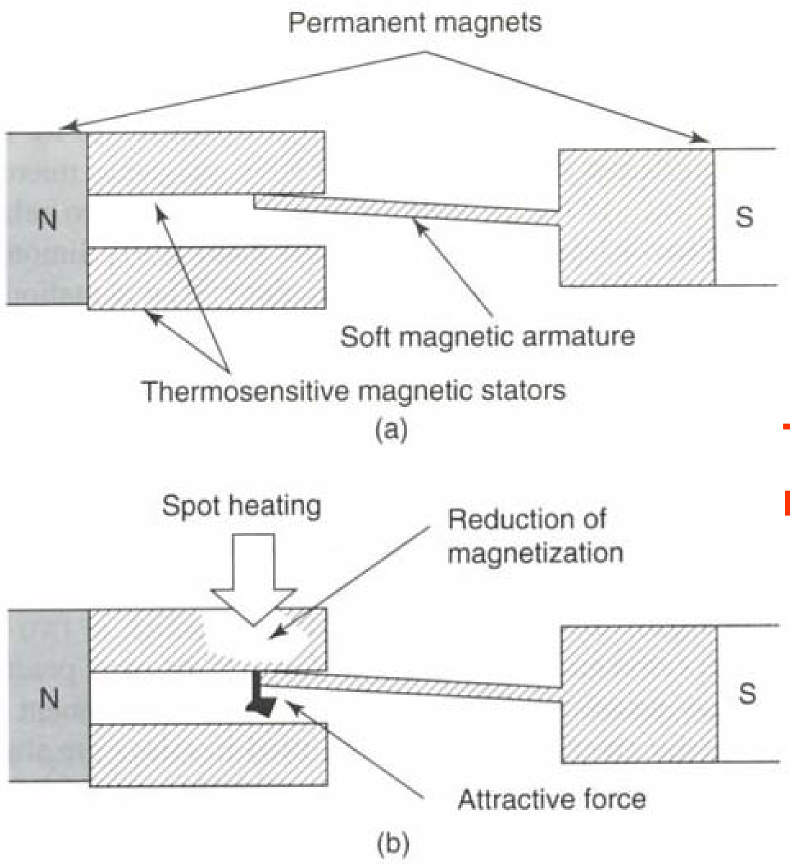
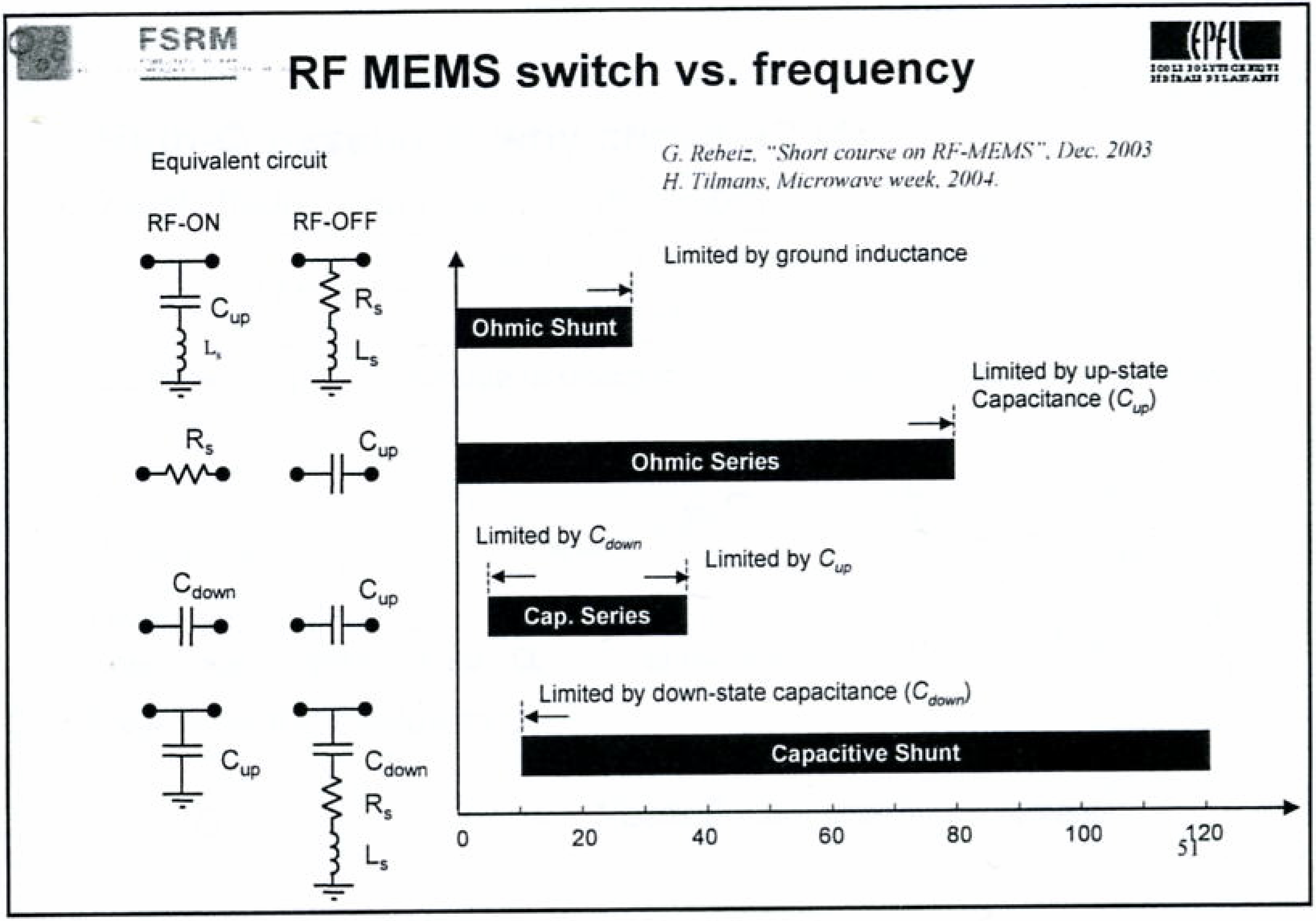


Figure 3.38 Principle of operation of thermally controlled magnetization micro relay. (a) without heat; (b) with heat. Note: N, north; S, south. Reproduced from E. Hashimoto, H. Tanaka, Y. Suzuki, Y. Uensishi and A. Watabe, 1994, 'Thermally controlled magnetic actuator (TCMA) using thermo sensitive magnetic materials', in *Proceedings of IEEE Microelectromechanical Systems Workshop, 1994*, IEEE, Piscataway, NJ, USA: 108–113, by permission of IEEE, © 1994 IEEE

Termofølsomme magneter



RF MEMS switch vs. frequency

Equivalent circuit

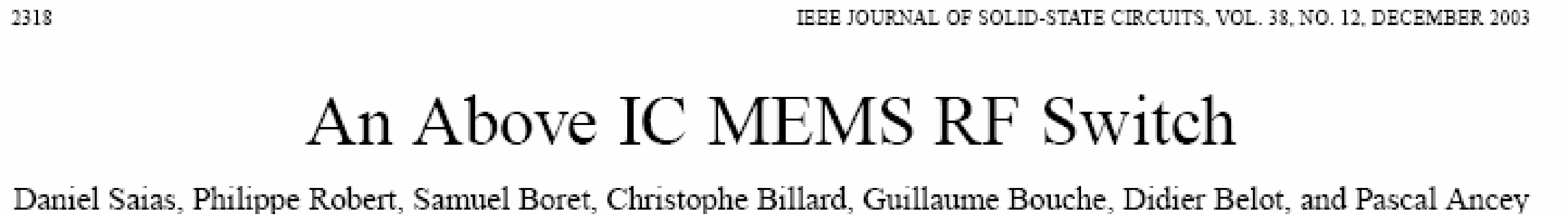
G. Rebeiz, "Short course on RF-MEMS", Dec. 2003
H. Tilmans, Microwave week, 2004.

Noen utfordringer ved svitsj-design

- Høyt elektrisk felt i små dimensjoner
  - Deler av metall-overflaten kan smelte
  - Væske-metall-damp fortsetter ledningen når svitsjen er i av-tilstand
- Selvaktivering
  - Hvis signalet, som kan være lite, overlagres et DC-signal, kan det forekomme **selvaktivering**
  - Det kan derfor være en fordel å dekoble aktiverings- og signal-linjer
    - Separate områder

Utfordring: System-on-Chip (SoC)

Svitsj integrert med IC:



2318 IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 38, NO. 12, DECEMBER 2003

An Above IC MEMS RF Switch

Daniel Saias, Philippe Robert, Samuel Boret, Christophe Billard, Guillaume Bouche, Didier Belot, and Pascal Ancey

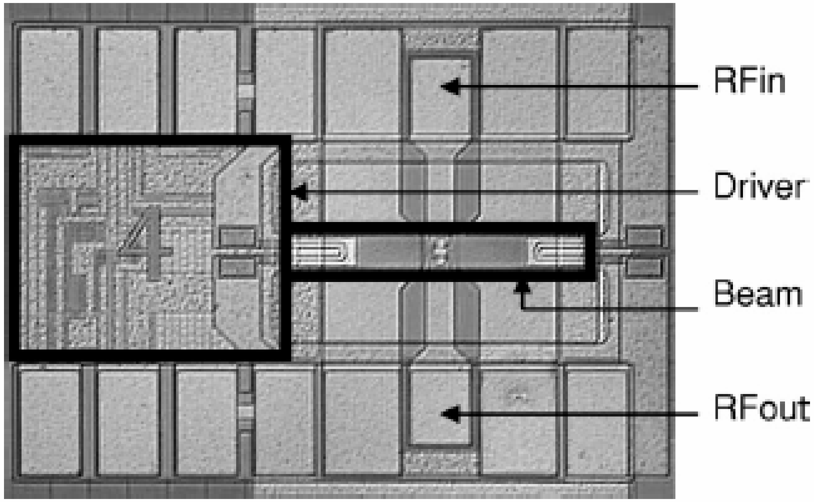


Fig. 9. Switch and driver die Micrograph.

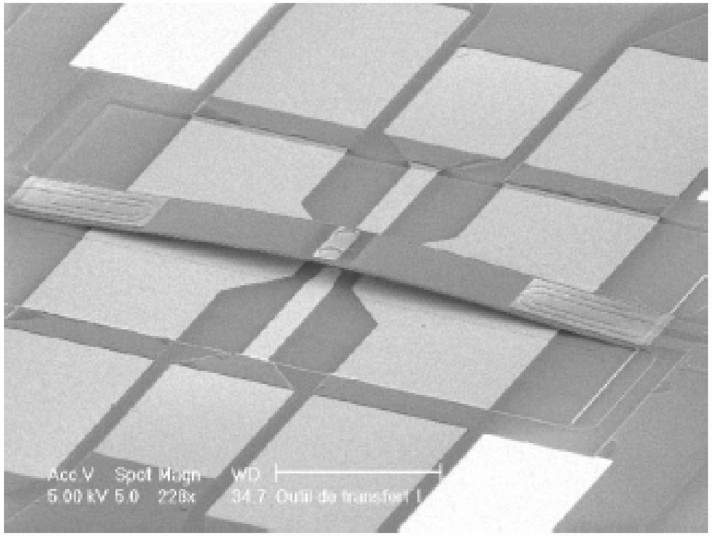


Fig. 1. SEM view of the microswitch.

Saias et al, 2003

Sammenligning av ytelse ved ulike løsninger

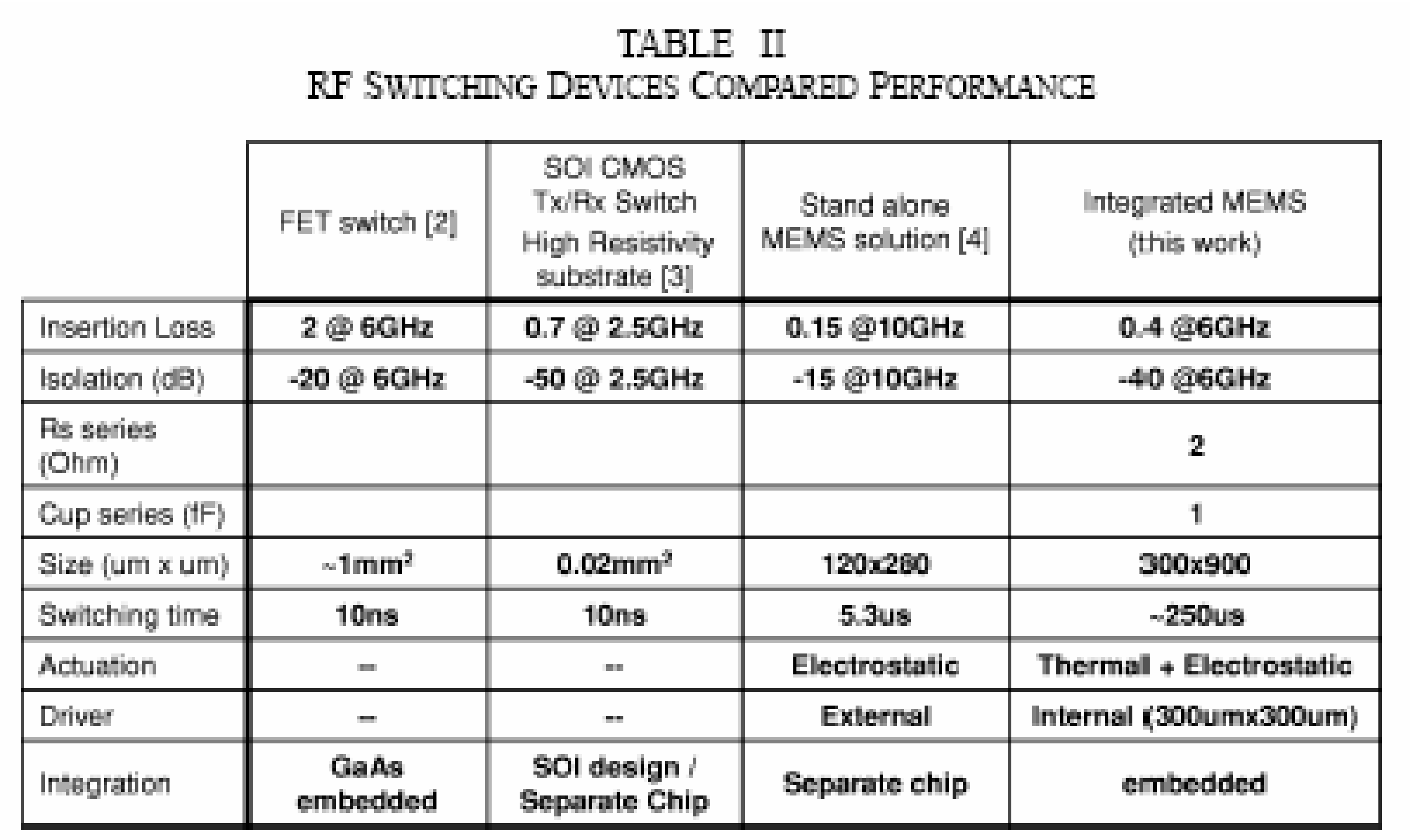


TABLE II

RF SWITCHING DEVICES COMPARED PERFORMANCE

	FET switch [2]	SOI CMOS Tx/Rx Switch High Resistivity substrate [3]	Stand alone MEMS solution [4]	Integrated MEMS (this work)
Insertion Loss	**2 @ 6GHz**	**0.7 @ 2.5GHz**	**0.15 @10GHz**	**0.4 @6GHz**
Isolation (dB)	**-20 @ 6GHz**	**-50 @ 2.5GHz**	**-15 @10GHz**	**-40 @6GHz**
Rs series (Ohm)				**2**
Cup series (fF)				**1**
Size (um x um)	**~1mm^2**	**0.02mm^2**	**120x280**	**300x900**
Switching time	**10ns**	**10ns**	**5.3us**	**~250us**
Actuation	**--**	**--**	**Electrostatic**	**Thermal + Electrostatic**
Driver	**--**	**--**	**External**	**Internal (300umx300um)**
Integration	**GaAs embedded**	**SOI design / Separate Chip**	**Separate chip**	**embedded**

Saias et al, 2003