INF5490 RF MEMS

L3: Modellering, design og analyse

Oversikt over forelesningen

- Metoder for å modellere RF MEMS
  - **1. Enkle matematiske modeller**
    - Eks. parallell plate kondensator
  - **2. Konvertering til elektriske ekvivalenter**
    - Eks. Mekanisk resonator
    - Samvirke mellom ulike energi-domener
  - **3. Analyse ved Finite Element Methods**
    - Eks. fra CoventorWare
    - Modellering av bulk mikromaskinert prosess

1. Enkle matematiske modeller

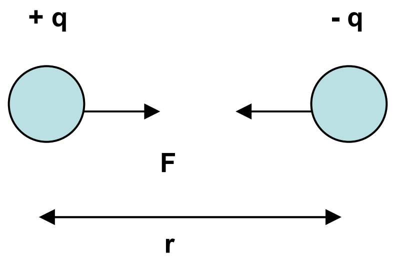
- Ligninger, formler beskriver fysiske fenomener
  - Approksimasjon
  - Eksplisitte løsninger for enkle problemer
    - Linearisering rundt et operasjonspunkt
  - Direkte simulering av ligningssett
    - Typisk differensialligninger
    - Løses ved iterasjoner
- \+ Gir konstruktøren design-innsikt
  - Hvordan endre funksjonalitet ved parametervariasjoner
  - Kan benyttes til innledende ”overslag”

Eks. på matematiske modeller

- Viktige ligninger for RF MEMS komponenter:
  - → Parallell plate kondensator

- **Elektrostatisk** aktivering av kondensator med bevegelig plate opphengt i fjær
- Beregning av **”pull-in”**
  - Formler og figurer →

Elektrostatikk



Elektrisk kraft mellom ladninger: **Coulombs lov**

$$F = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1 q_2}{r^2}$$

Elektrisk felt = kraft pr. enhetsladning

$$\overline{E} = \frac{\overline{F}}{q_0}$$

Arbeid utført av en kraft = endring i potensial-energi

$$W_{a\to b} = \int_a^b \overline{F} \cdot d\bar{l} = U_a - U_b$$

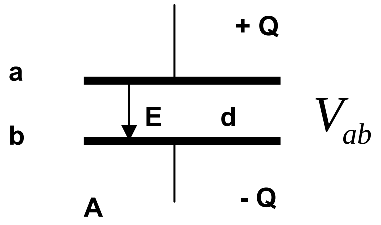
Potensial, V = potensial-energi pr. enhetsladning

$$V = \frac{U}{q_0}$$

Spenning = potensial-differansen

$$V_a - V_b = \int_a^b \overline{E} \cdot d\bar{l}$$

Kapasitans



Definisjon av kapasitans $C = \frac{Q}{V_{ab}}$

Overflate ladningstetthet = σ

$$E = \frac{\sigma}{\varepsilon_0} = \frac{Q}{A} \cdot \frac{1}{\varepsilon_0}$$

Spenning

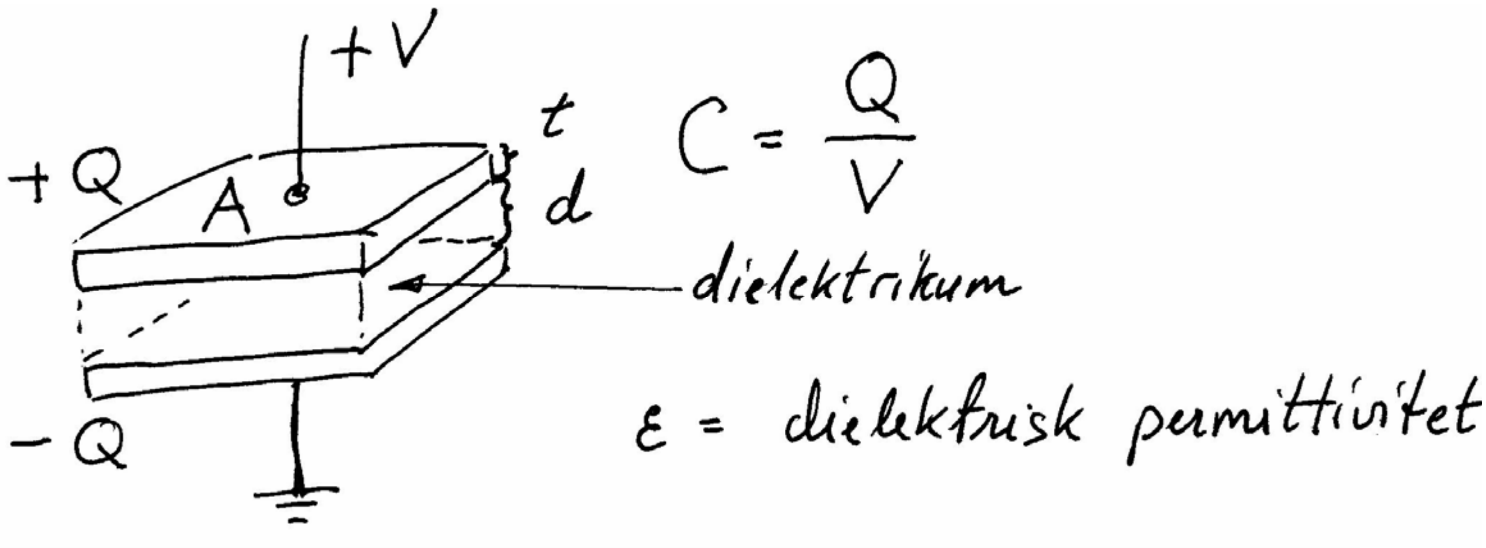
$$V_{ab} = E \cdot d = \frac{Q}{A\varepsilon_0} \cdot d$$

$$C = \frac{Q}{V_{ab}} = \varepsilon_0 \frac{A}{d}$$

Energi lagret i en kondensator, C,
som lades opp til en spenning V_0 ved strøm $i = \dot{Q} = C \frac{dV}{dt}$

$$U = \int v \cdot i \cdot dt = \int v \cdot C \frac{dv}{dt} \cdot dt = C \int_0^{V_0} v \cdot dv = \frac{1}{2} C V_0^{\ 2} = \frac{\varepsilon_0 A}{2d} V_0^{\ 2}$$

Parallell plate kondensator



$$C = \frac{Q}{V}$$

ε = dielektrisk permittivitet

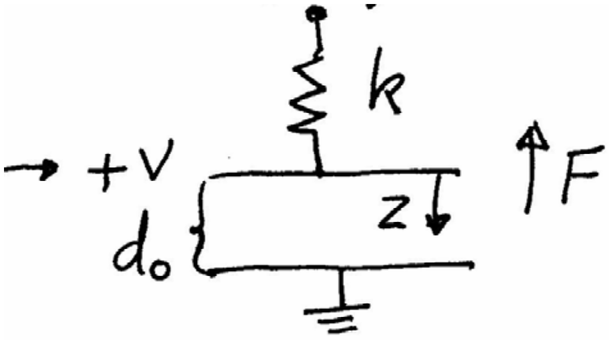
Tiltrekningskraft mellom platene

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

Bevegelig kondensator-plate

- Forutsetninger for beregninger:
  - Anta luft mellom platene
  - Fjær holder øvre plate
    - Fjærkonstant: k
  - Spenning settes på
    - Elektrostatisk tiltrekning
  - Ved likevekt
    - **Kreftene oppover og nedover balanserer →**

Kreftene balanserer



k = fjærkonstant

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

tøyning utfra
likevekt

d0 = gap ved 0V og null fjærutstrekning
d = d0 – z
z=d0 – d

Kraft på øvre plate ved V og d:

$$F_{net} = -\frac{\varepsilon A V^2}{2d^2} + k\left(d_0 - d\right)$$

= 0 ved likevekt

Stabilitet

- Hvordan kreftene utvikler seg når d minker
  - Anta en liten perturbasjon (endring) i gapet ved konstant spenning

$$\delta F_{net} = \left.\frac{\partial F_{net}}{\partial d}\right|_{V} \cdot \delta d$$

$$\delta F_{net} = \left(\frac{\varepsilon A V^2}{d^3} - k\right) \delta d$$

Anta at gapet minker $\delta d < 0$

Hvis kraften oppover også minker, er systemet **USTABILT!** $\delta F_{net} < 0,$

Stabilitet, forts.

Stabilitetsbetingelse:

$$\left.\frac{\partial F_{net}}{\partial d}\right|_{V} < 0$$

$$k > \frac{\varepsilon A V^2}{d^3}$$

Pull-in når:

$$k = \frac{\varepsilon A V_{PI}^2}{d_{PI}^3}$$

Pull-in

$$F_{net} = 0$$

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

$$\uparrow \; = \frac{\varepsilon A V_{PI}^2}{d_{PI}^3}$$

Pull-in oppstår når:

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

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

To likevekts-punkter

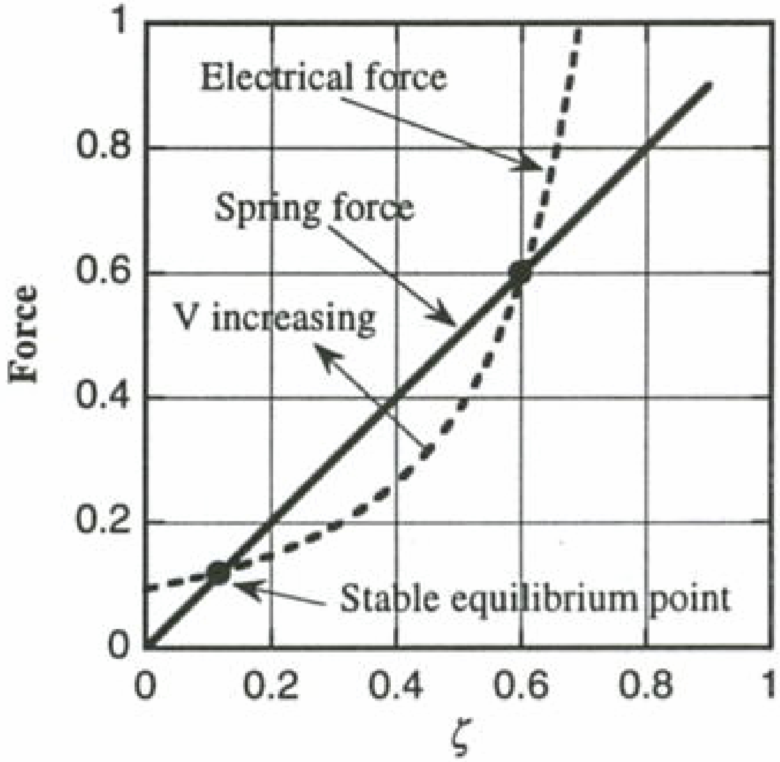


Figure 6.7. Electrical and spring forces for the voltage-controlled parallel-plate electrostatic actuator, plotted for $V/V_{PI} = 0.8$.

$\varsigma = 1 - d/d0$

Senturia

Pull-in

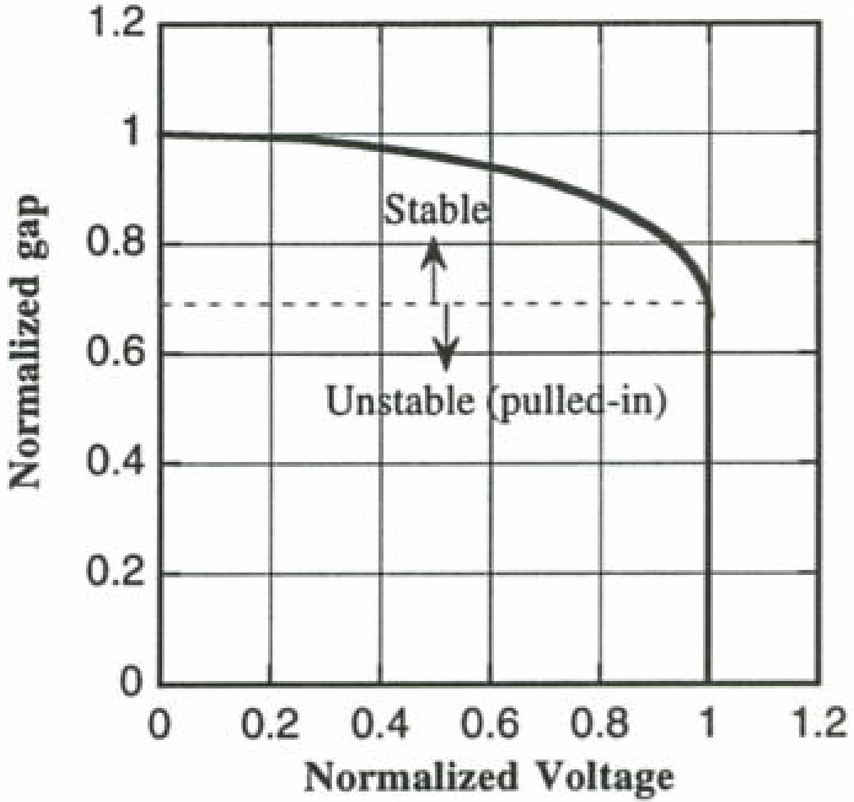


Figure 6.8. Normalized gap as a function of normalized voltage for the electrostatic actuator.

Senturia

2. Konvertering til elektriske ekvivalenter

- Mekanisk oppførsel kan modelleres ved **elektriske kretselementer**
  - Mekanisk struktur → forenklinger → ekvivalent elektrisk krets
  - Mulighet for å binde sammen elektrisk og mekanisk domene
- Motivasjon for konvertering
  - Et rikt utvalg av analyse-verktøy finnes
    - Eks. SPICE
  - Modellering og sam-simulering av elektroniske og mekaniske systemer forenkles

Konvertering til elektriske ekvivalenter, forts.

- I det følgende gjennomgås:
  - – Litt bakgrunn fra kretsteori
  - – Konverteringsprinsipper
    - Ulike analogier eksisterer
  - – Eksempel på en konvertering
    - Mekanisk resonator
  - – Kobling og samvirke mellom ulike energidomener

Kretsteori

- Grunnleggende kretselementer: R, C, L
- Strøm og spennings-ligninger for grunnelementene (ved lave frekvenser)
  - Ohms lov, C og L-ligninger
    - $V = RI$, $I = C\,dV/dt$, $V = L\,dI/dt$
  - **Laplace** transformasjon
    - Fra differensial-ligninger til algebraiske (s-polynomer)
    - → Komplekse impedanser: R, 1/sC, sL
- Kirchhoffs ligninger
  - **Σ strøm** inn i noder = 0, Σ **spenning** rundt løkker = 0

Effort - flow

- Elektriske kretser beskrives av et **variabelsett:**
  - Spenning V: **across** eller **effort**-variabel
  - Strøm I: **through** eller **flow**-variabel
- En effort (”innsats”) -variabel driver en flow-variabel gjennom en impedans, Z
- Eks. på e,f-par i andre energi-domener:
  - Kraft og hastighet
  - Kraftmoment (torque) og angulær hastighet

Through- og across-variable

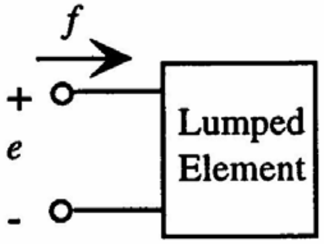


Figure 5.2. Sign conventions for one-port elements in the $e \rightarrow V$ convention.

Kretselement modelleres som 1-port med terminaler

Samme strøm (f = flow) inn og ut og gjennom (through) elementet

f = flow = through-variabel
e= effort= across-variabel
Positiv flow *inn i terminal der samme terminal definerer* ***positiv effort***

Konjugerte power-variable: e,f

- Anta konverteringer mellom energidomener der energien bevares!
- Egenskaper
  - e * f = effekt (power)
  - e / f = impedans
- Generalisert **displacement** representerer tilstanden (state), f. eks. posisjon eller ladning

$$f(t) = \dot{q}(t) \qquad q(t) = \int_{t_0}^{t} f(t)dt + q(t_0)$$

  - e * q = energi

Generalisert momentum

$$p(t) = \int_{t_0}^{t} e(t)dt + p(t_0)$$

– p * f = energi

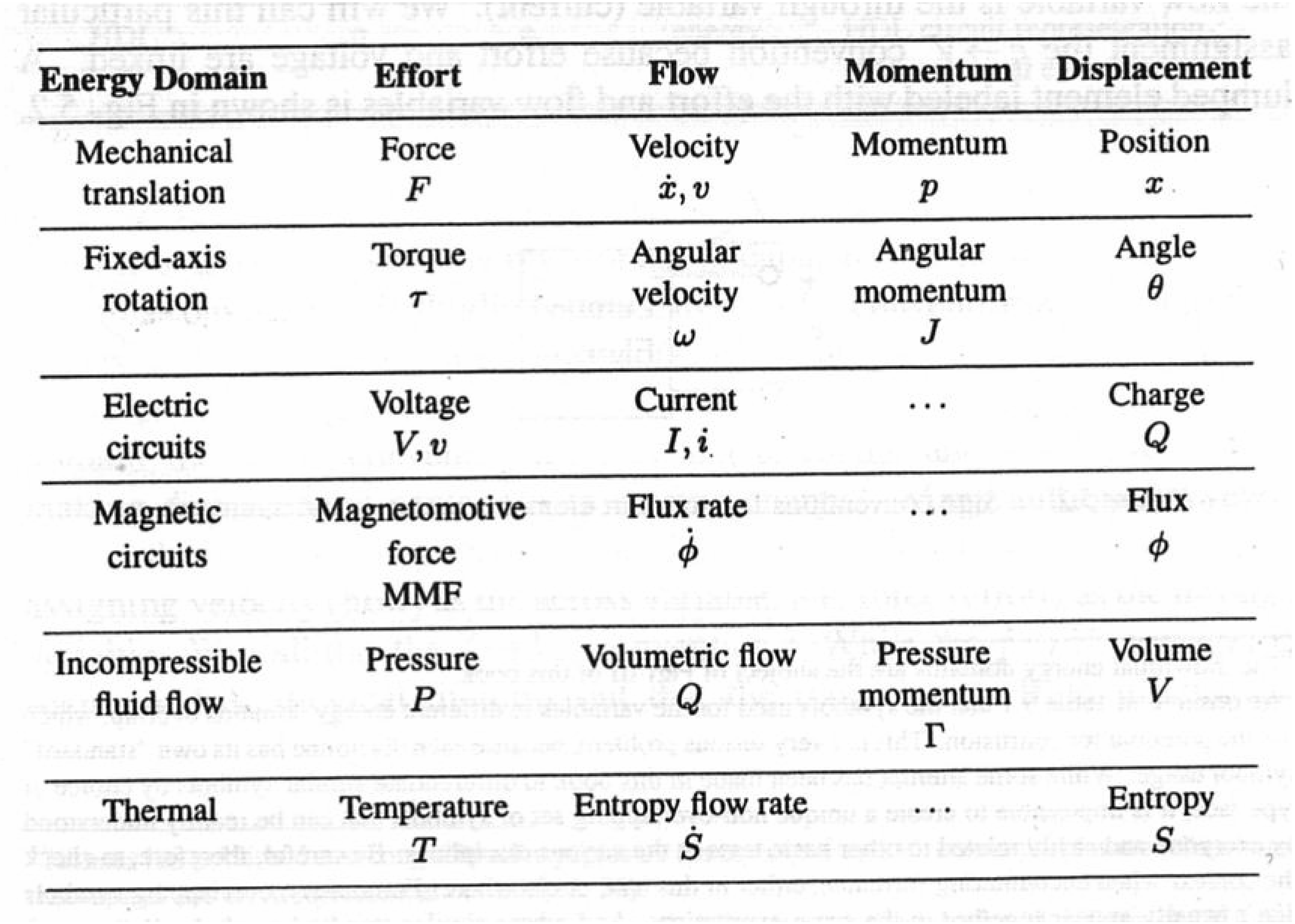
Energi-domener, analogier

- Det eksisterer ulike energi-domener
  - Elektrisk, elastisk, termisk, for væsker etc.

- ***For hvert energidomene er det mulig å definere et sett konjugerte power-variable som kan brukes som basis for en diskret-komponent modellering (lumped modelling) med krets-elementer som er ekvivalente***

- Tabell 5.1 Senturia ->

Eks. på konjugerte power variable



Energy Domain	Effort	Flow	Momentum	Displacement
Mechanical translation	Force F	Velocity $\dot{x}, v$	Momentum p	Position x
Fixed-axis rotation	Torque τ	Angular velocity ω	Angular momentum J	Angle θ
Electric circuits	Voltage V, v	Current I, i	…	Charge Q
Magnetic circuits	Magnetomotive force MMF	Flux rate $\dot{\phi}$	…	Flux ϕ
Incompressible fluid flow	Pressure P	Volumetric flow Q	Pressure momentum Γ	Volume V
Thermal	Temperature T	Entropy flow rate $\dot{S}$	…	Entropy S

Mekanisk energidomene

$e = F$ (kraft)

$f = v, \dot{x}$ (hastighet)

$q = x$ (posisjon) $= \int \dot{x}\, dt$

$p = p$ (momentum) $= \int F\, dt$

(kraft x tid)

$$e \cdot f \rightarrow F \cdot \dot{x} = \frac{F \Delta x}{\Delta t} = \frac{\text{arbeid}}{\text{tid}} = \text{effekt}$$

$$e \cdot q \rightarrow F \cdot x = \text{kraft} \times \text{vei} = \text{arbeid} = \text{energi}$$

$$p \cdot f \rightarrow p \cdot \dot{x} = mv \cdot v = mv^2 = \text{energi}$$

Elektrisk energidomene

$e = V$ (spenning)

$f = I$ (strøm)

$q = \int I\,dt = Q$ (ladning)

$p =$ n.a.

$e \cdot f \rightarrow V \cdot I =$ effekt

$e \cdot q \rightarrow V \cdot Q = V \int I\,dt =$ energi

e → V - konvensjonen

- **Senturia** og **Tilmans** holder seg til e→V – konvensjonen
- Eks. elektriske og mekaniske kretser
  - e → V (spenning) tilsvarer F (kraft)
  - f → I (strøm) tilsvarer v (hastighet)
  - q→ Q (posisjon) tilsvarer x (posisjon)
  - e * f = ”power” som tilføres elementet

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

Andre konvensjoner

- Det finnes ulike konvensjoner for å definere **through-** eller **across-variable**

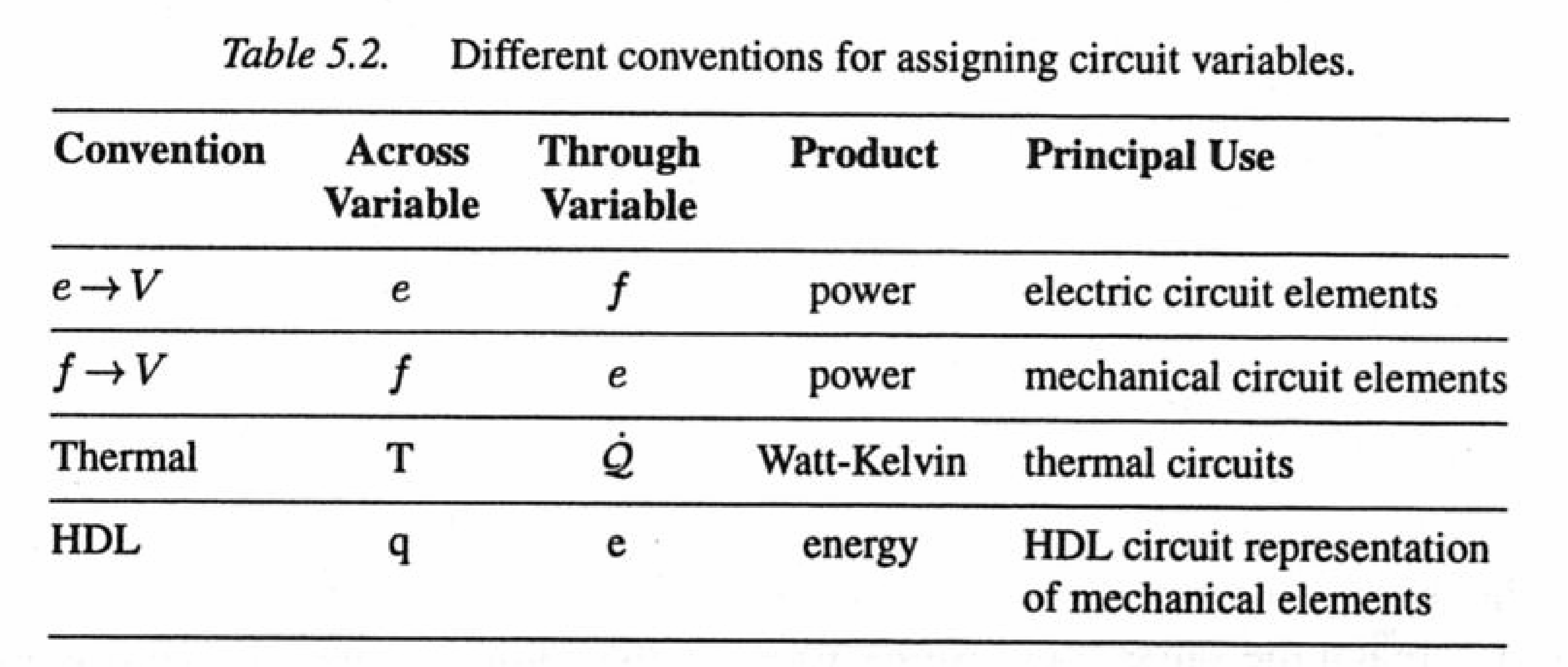
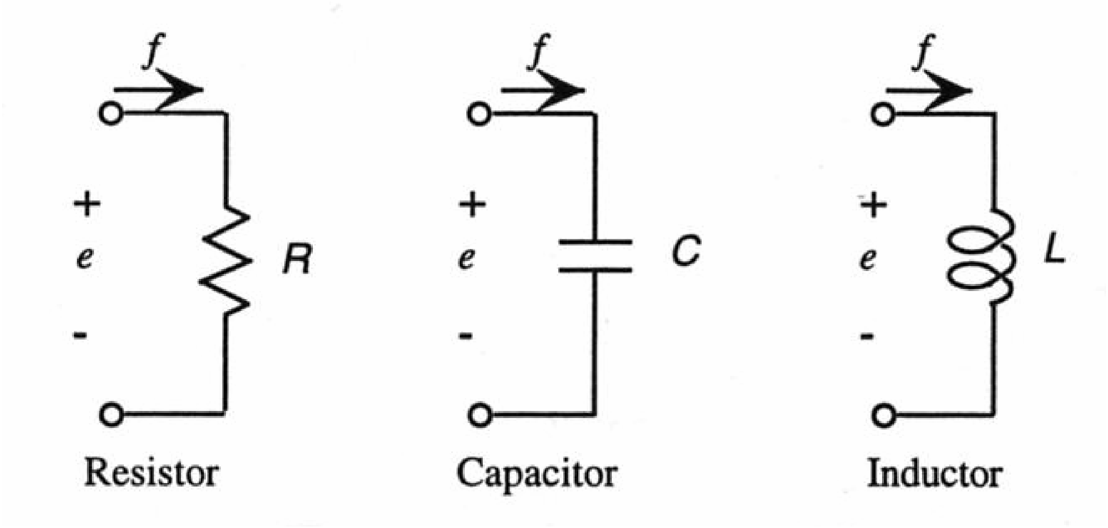


Table 5.2. Different conventions for assigning circuit variables.

Convention	Across Variable	Through Variable	Product	Principal Use
$e \rightarrow V$	e	f	power	electric circuit elements
$f \rightarrow V$	f	e	power	mechanical circuit elements
Thermal	T	$\dot{Q}$	Watt-Kelvin	thermal circuits
HDL	q	e	energy	HDL circuit representation of mechanical elements

Generaliserte krets-elementer

- **En-port** krets-elementer
  - – R dissiperende element
  - – C, L energi-lagrings elementer
  - – Elementene kan ha en **generell funksjon!**
    - **Kan brukes i forskjellige energi-domener**



Generalisert kapasitans

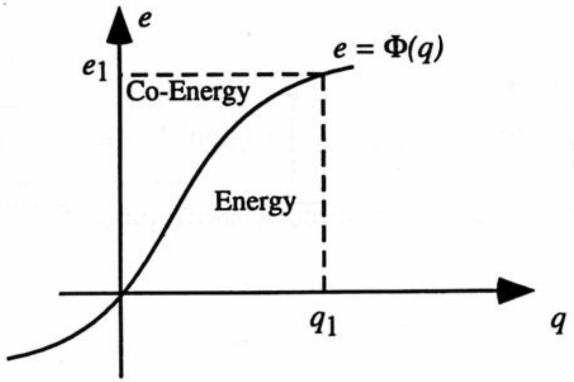


Figure 5.5. Illustrating energy and co-energy for a generalized capacitor.

Sammenlign med et forenklet tilfelle:
- en **lineær** kondensator

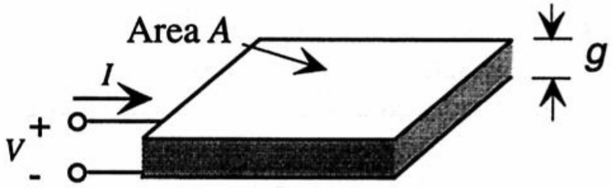
$$Q = V \cdot C$$

definisjon av C

$$V = \frac{1}{C} \cdot Q$$

$$\Downarrow$$

$$e = \frac{1}{C} \cdot q$$



$$C = \frac{\varepsilon A}{g}$$

Generalisert kapasitans, forts.

Kapasitans assosieres med lagret **potensiell energi**

$$\mathcal{W}(q_1) = \int_0^{q_1} e\,dq = \int_0^{q_1} \Phi(q)\,dq \qquad (5.10)$$

Co-energy:

$$\mathcal{W}^*(e) = eq - \mathcal{W}(q) \qquad (5.11)$$

$$\mathcal{W}^*(e_1) = \int_0^{e_1} q\,de = \int_0^{e_1} \Phi^{-1}(e)\,de \qquad (5.12)$$

Energi lagret i parallell-plate kondensator

Energy:

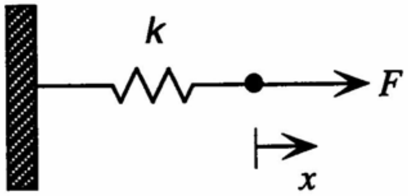
$$W(Q) = \int_0^Q e \cdot dq = \int_0^Q \frac{q}{C} \cdot dq = \frac{Q^2}{2C}$$

Co-energy:

$$W^*(V) = \int_0^V q \cdot de = \int_0^V C \cdot v \cdot dv = \frac{CV^2}{2}$$

$W^*(V) = W(Q)$ for lineær kapasitans

Mekanisk fjær



Hook´s lov: $F = k \cdot x$

Lagret energi: $$W(x_1) = \int_0^{x_1} F(x)dx = \frac{1}{2}kx_1^2 \qquad (5.18)$$

Sammenlign med kondensator $W(Q) = \frac{1}{2} \cdot \frac{1}{C} \cdot Q^2$

Q displacement

x1 displacement

→ **1/C tilsvarer k**

”Compliance”

- ”Compliance” = ”ettergivenhet”

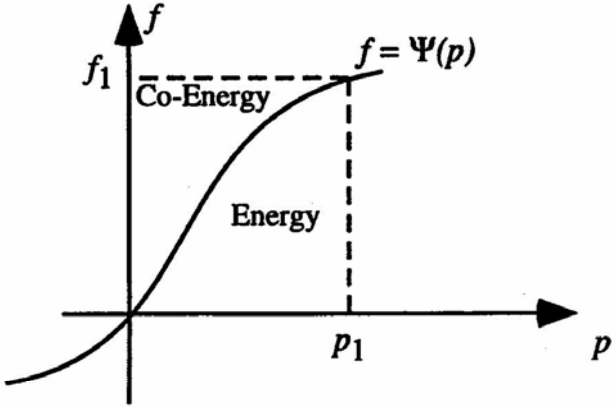
$$C_{spring} = \frac{1}{k}$$

- Stiv fjær → liten kondensator
- Myk fjær → stor kondensator

Generalisert induktans

Energi er også definert som:

$$\underset{\underset{\int e\,dt}{\uparrow}}{f \cdot p} = \underset{\underset{v}{\uparrow}}{\text{flow}} \times \underset{\underset{m \cdot v}{\uparrow}}{\text{momentum}}$$

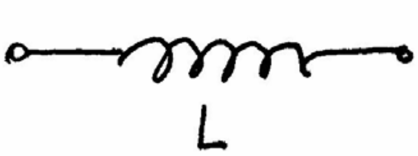


Energi = lagret kinetisk energi

$$W(p_1) = \int_0^{p_1} f(p)\,dp$$

Eks.: Elektrisk spole

Co-energy: $$W^*(f) = \int_0^{f_1} p(f)\,df$$



$$V = L\,\frac{dI}{dt}$$

$$p = \int e\,dt = \int V\,dt = \int L\,\frac{dI}{dt}\,dt = \int L\,dI$$

$$p(f) = p(I) = L\,I$$

$$W^*(f_1) = W^*(I_1) = \int_0^{I_1} L\cdot I\cdot dI = \frac{1}{2}\,L\,I_1^{\,2}$$

Analogien mellom masse (mekanisk ”inertance”) og induktans L

Et mekanisk system har **lineært momentum**: $p = mv$

Flow: $f = v = \frac{p}{m}$

$$W(p_1) = \int_0^{p_1} f(p)\,dp = \int_0^{p_1} \frac{p}{m}\,dp = \frac{p_1^2}{2m}$$

Co-energy:

$$W^*(v_1) = \int_0^{v_1} p(v)\,dv = \int_0^{v_1} (mv)\,dv = \frac{1}{2} m v_1^2$$

Analogi mellom m og L

$$W^*(f_1) = W^*(I_1) = \int_0^{I_1} L \cdot I \cdot dI = \frac{1}{2} L I_1^2$$

Sammenlign med: $W^*(v_1) = \qquad = \frac{1}{2} m v_1^2$

I_1 = flow

v_1 = —"—

L tilsvarer **m**

m = L ”inertance”

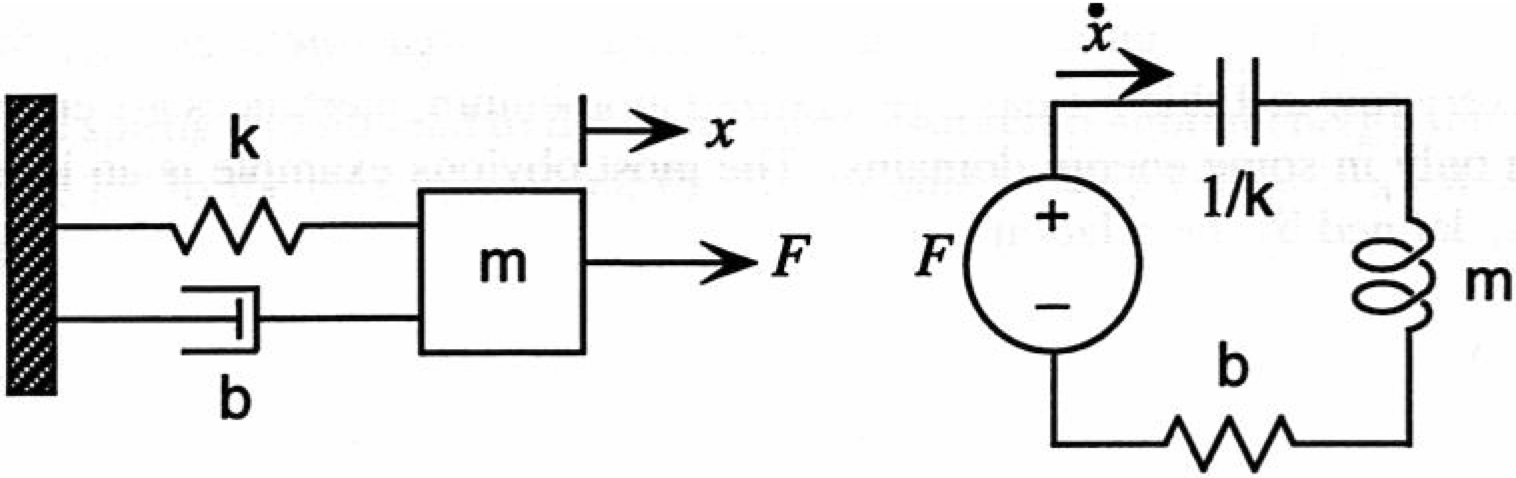
Mekanisk ”inertance” (treghet) = masse m
har analogi til induktans L

Sammenkobling av elementer

- e → V har to grunnleggende prinsipper
  - Elementer som deler en felles *flow* og derved en felles variasjon i *displacement* er koblet i **serie**
  - Elementer som deler en felles *effort* er koblet i **parallell**

Eks. på sammenkobling:

”Direkte omforming”

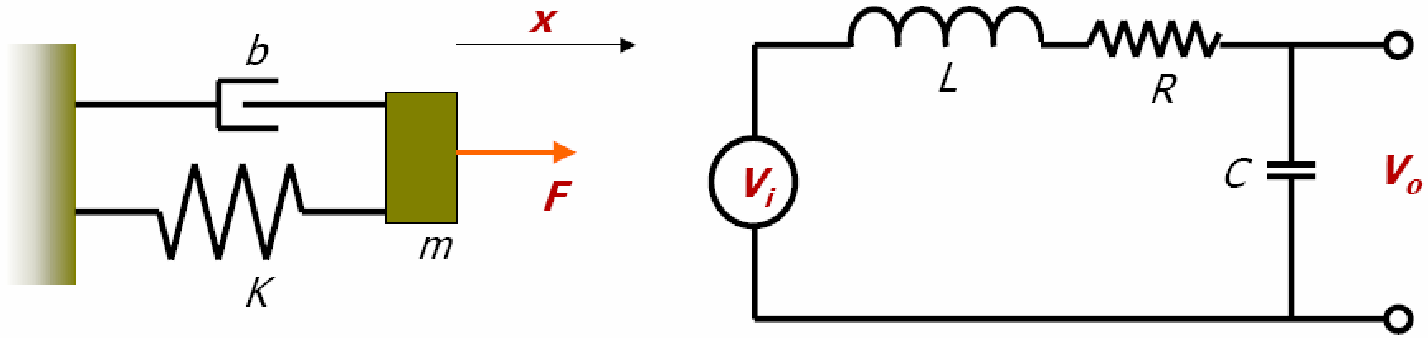


Spring-mass-dashpot system

Equivalent circuit

Figure 5.9. Translating mechanical to electrical representations.

Mechanical / Electrical Systems



Input : external force F

Output : displacement x

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

m mass, b damping, K stiffness

Transfer function :

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

Input : voltage V_i

Output : voltage V_o

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

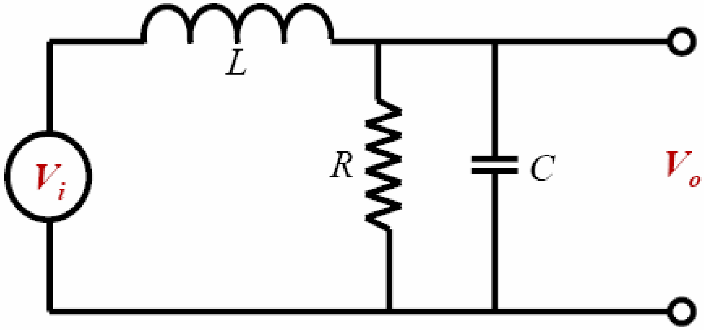
L induct., R resist., C capacit.

Transfer function :

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

Mechanical / Electrical Systems

Alternative circuit:



Input : voltage V_i

Output : voltage V_o

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

L inductance , R resistance , C capacitance

Transfer function :

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

Resonators

- Analogy between mechanical and electrical system:
  - Mass *m* - inductivity *L*
  - Spring *K* - capacitance *C*
  - Damping *b* - resistance *R* (depending where *R* is placed in circuit)

- Solution to 2nd order differential equation:

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

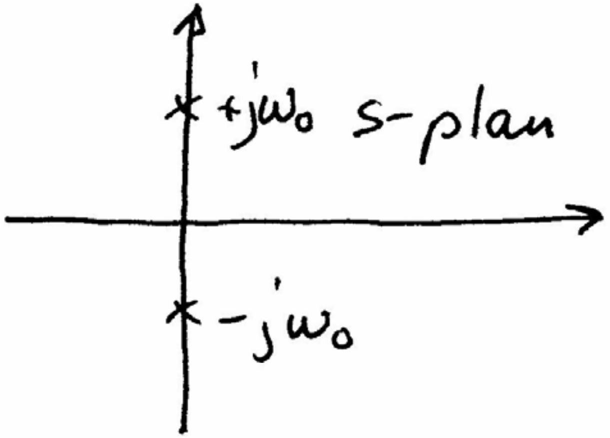
$\omega_0 = 2\pi f_0$ natural frequency

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

Q quality factor

Udempet system

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



$$|H(j\omega_0)| = \infty$$

$$H(j\omega) = \frac{1}{1 - \left(\frac{\omega}{\omega_0}\right)^2}$$

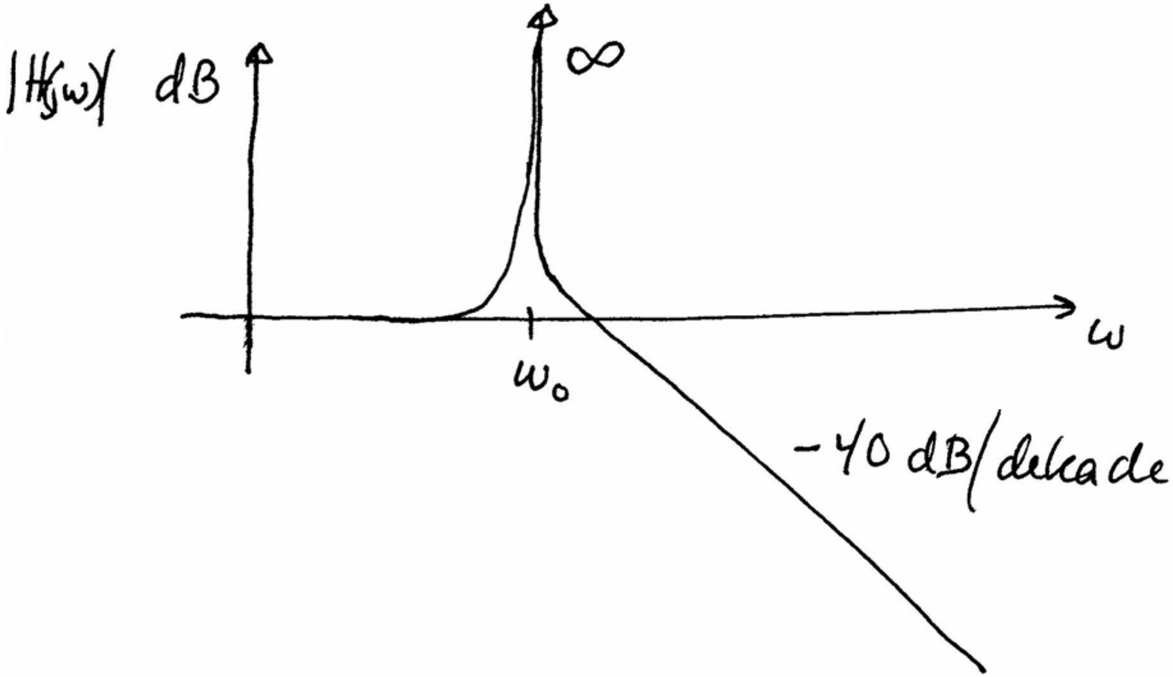
$$\omega_0 = \sqrt{\frac{1}{LC}}, \omega_0 = \sqrt{\frac{k}{m}}$$

Udempet system, forts.

$$H(j\omega) = \frac{1}{1 - \left(\frac{\omega}{\omega_0}\right)^2}$$

$|H(j\omega)| = 1$ når $\omega \ll \omega_0$ 0 dB

$|H(j\omega)| = -\left(\frac{\omega_0}{\omega}\right)^2$ når $\omega \gg \omega_0$ −40 dB/dekade

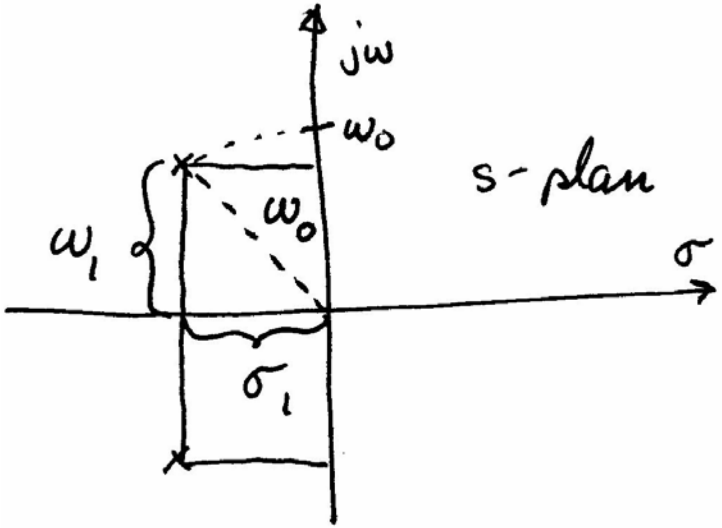


Ved demping

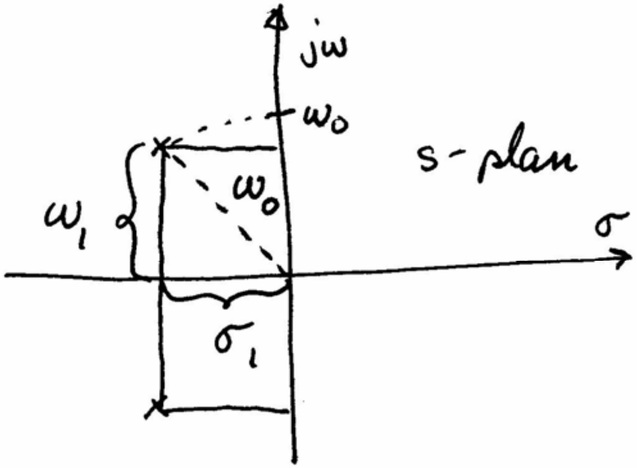
$$s^2 + \frac{\omega_0}{Q} s + \omega_0^2 = 0$$

$$s = -\frac{\omega_0}{2Q} \pm j\,\omega_0 \sqrt{1 - \frac{1}{4Q^2}}$$

$$= -\sigma_1 \pm j\,\omega_1$$



Dempet system, forts.



$$\frac{\omega_0}{Q} = \frac{b}{m} = \frac{1}{\tau} \qquad \omega_0 = \sqrt{\frac{k}{m}}$$

$$\sigma_1 = \frac{1}{2\tau} = \frac{b}{2m}$$

$$\omega_1 = \omega_0\sqrt{1 - \frac{1}{4\omega_0^2\tau^2}} = \omega_0\sqrt{1 - \frac{b^2}{4km}}$$

$$\omega_1^2 + \sigma_1^2 = \omega_0^2$$

Mechanical Resonator

- Frequency and phase shift under damping:

$$x(t) = Ae^{-t/2\tau}\cos(\omega_1 t + \varphi)$$

$$\tau = m/b \quad \text{damping time}$$

$$\omega_1 = \omega_0\sqrt{1 - \frac{1}{4\omega_0^2\tau^2}} = \omega_0\sqrt{1 - \frac{b^2}{4Km}}$$

$$\varphi \quad \text{phase shift}$$

- Energy dissipation:

$$E(t) = E_0 e^{-t/\tau}$$

Hva betyr ”damping time”?

τ = damping time

$$e^{-t/2\tau}\Big|_{t=\tau} = e^{-1/2} = \frac{1}{\sqrt{e}}$$

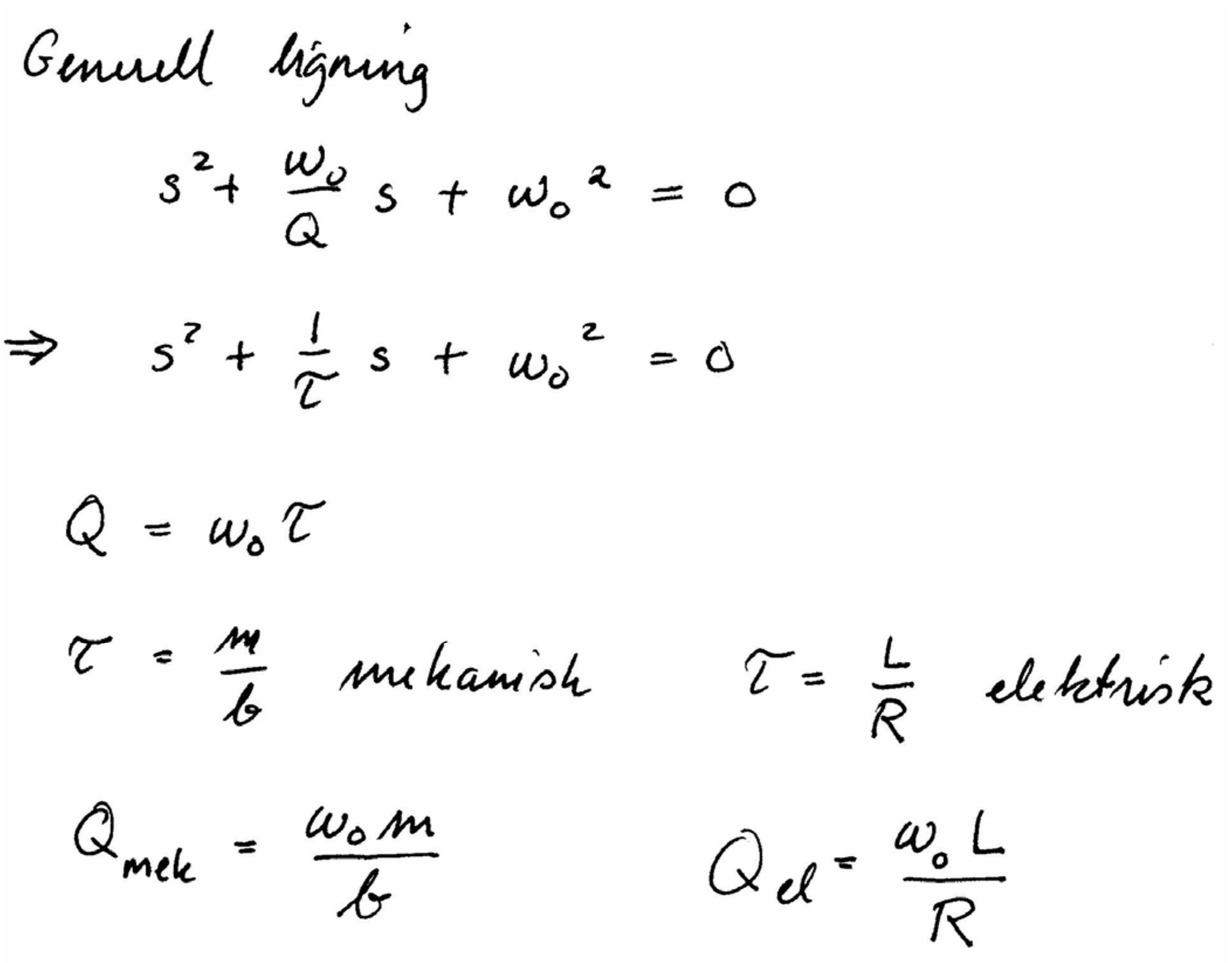
Effekten

$$|x(t)|^2\Big|_{t=\tau} = \frac{1}{e}$$

$$x(t) = Ae^{-t/2\tau}\cos(\omega_1 t + \varphi)$$

$$x(0) = A\cdot\cos\varphi$$ initialbetingelser

Q-faktor og dempetid



Generell ligning

$$s^2 + \frac{\omega_0}{Q} s + \omega_0^2 = 0$$

$$\Rightarrow \quad s^2 + \frac{1}{\tau} s + \omega_0^2 = 0$$

$$Q = \omega_0 \tau$$

$\tau = \frac{m}{b}$ mekanisk $\qquad \tau = \frac{L}{R}$ elektrisk

$$Q_{mek} = \frac{\omega_0 m}{b} \qquad Q_{el} = \frac{\omega_0 L}{R}$$

Quality Factor

- How fast does energy dissipate?
- What is the maximum amplitude for a given frequency?

Definition: Quality factor (Q factor)

Ratio of stored energy and lost energy:

$$Q = 2\pi \frac{E}{|\Delta E|} = 2\pi \frac{\tau}{T} = \omega_0 \tau$$

Mechanical system:

$$Q = \omega_0 \frac{m}{b} = \frac{\sqrt{Km}}{b}$$

Similar for electric systems: (a)

$$Q = \omega_0 \frac{L}{R} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

(b)

$$Q = \omega_0 RC = R\sqrt{\frac{C}{L}}$$

Q-faktor, forts.

Impedans i seriegren $\underbrace{R}_{re} + \underbrace{j\omega L}_{imag}$

$$Q_{el} = \frac{Z_{imag}}{Z_{re}} = \frac{\omega_0 L}{R}$$

$$Q = 2\pi \frac{\text{energy stored}}{\text{energy lost}} = \omega_0 \tau = 2\pi f_0 \cdot \tau$$

$$= 2\pi \frac{\tau}{T_0}$$

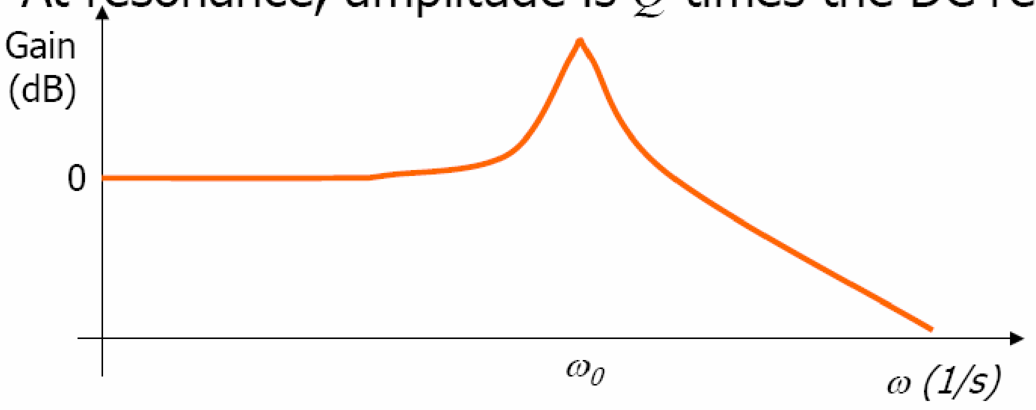
T_0 = perioden

Quality Factor

- How fast does energy dissipate?

$$\tau = \frac{Q}{\omega_0} \qquad \tau = \frac{m}{b}\,(\text{mechanical})$$

- What is the maximum amplitude for a given frequency?
  At resonance, amplitude is Q times the DC response



Amplituden ved resonans

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

$$H(j\omega) = \frac{\omega_0^2}{(\omega_0^2 - \omega^2) + j \frac{\omega \omega_0}{Q}}$$

$$|H(j\omega_0)| = \left| \frac{\omega_0^2}{0 + j \frac{\omega_0^2}{Q}} \right| = Q$$

Interaksjon mellom energidomener

- **Sammenkobling** av forskjellige energidomener hvor det ikke er energitap
  - – 1. Hver av energidomenene omformes til sin elektriske ekvivalent
  - – 2. Transformator og gyrator benyttes til sammenkobling
  - – 3. Transformator kan ”fjernes”
    - komponentverdiene må regnes om til nye verdier
    - vindingstall (”turn ratio”) er en sentral parameter

Interaksjon mellom energidomener

- Lineære 2-port elementer er
  - Transformator og gyrator

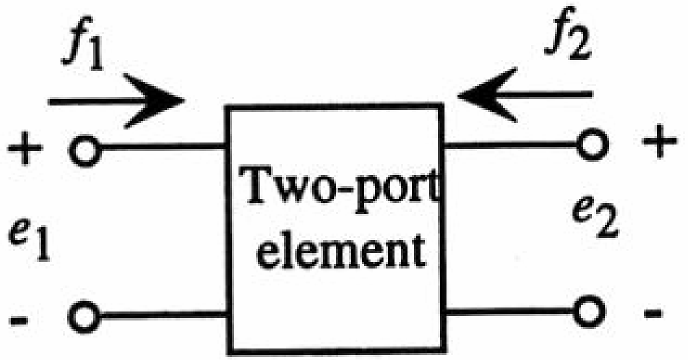


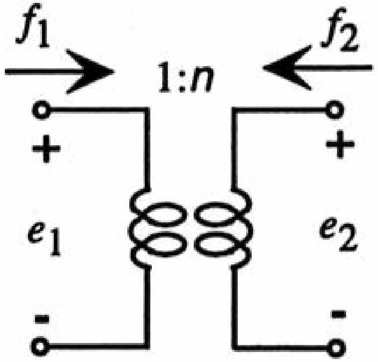
Figure 5.11. General two-port element.

$$e_1 f_1 + e_2 f_2 = 0 \qquad (5.41)$$

Transformator

TRANSFORMER:

$$\begin{pmatrix} e_2 \\ f_2 \end{pmatrix} = \begin{pmatrix} n & 0 \\ 0 & -\frac{1}{n} \end{pmatrix} \begin{pmatrix} e_1 \\ f_1 \end{pmatrix} \tag{5.42}$$



Transformer

$$e_2 = n \cdot e_1$$

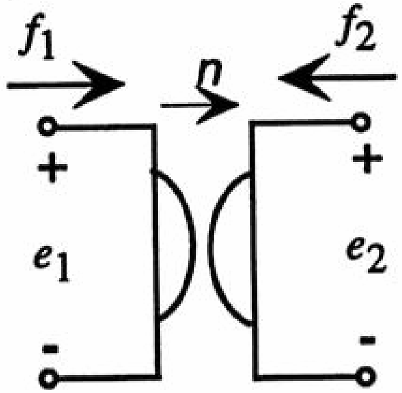
$$f_2 = -\frac{1}{n} f_1$$

n = ”turns ratio”

Gyrator

GYRATOR:

$$\begin{pmatrix} e_2 \\ f_2 \end{pmatrix} = \begin{pmatrix} 0 & n \\ -\frac{1}{n} & 0 \end{pmatrix} \begin{pmatrix} e_1 \\ f_1 \end{pmatrix} \tag{5.43}$$



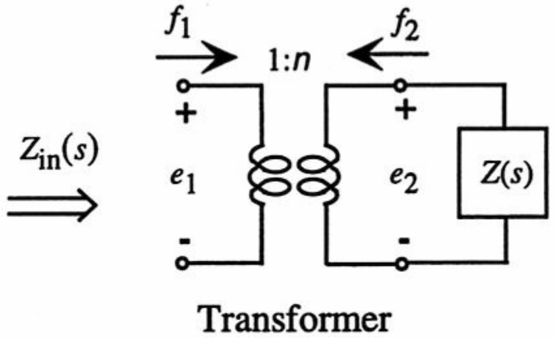
Gyrator

$$e_2 = n \cdot f_1$$

$$f_2 = -\frac{1}{n} e_1$$

Impedanser transformeres

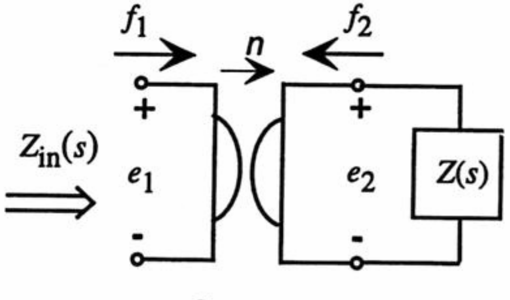
$$Z_{in}(s) = \frac{Z(s)}{n^2}$$



Transformer

n^2 = koblingskoeff mellom energidomenene

$$Z_{in}(s) = \frac{n^2}{Z(s)}$$



Gyrator

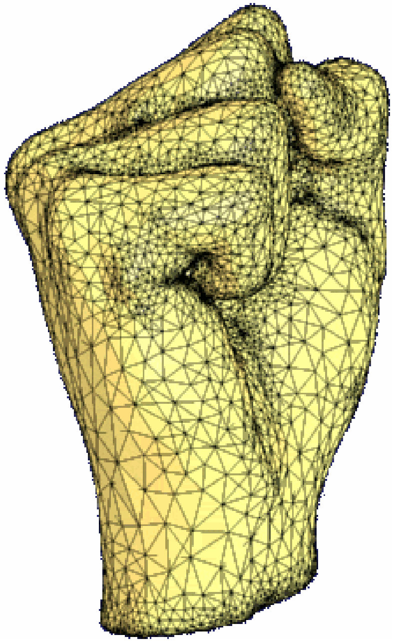
F.eks

$$\frac{1}{sC} \longrightarrow sL$$

3. Analyse ved Finite Element Methods

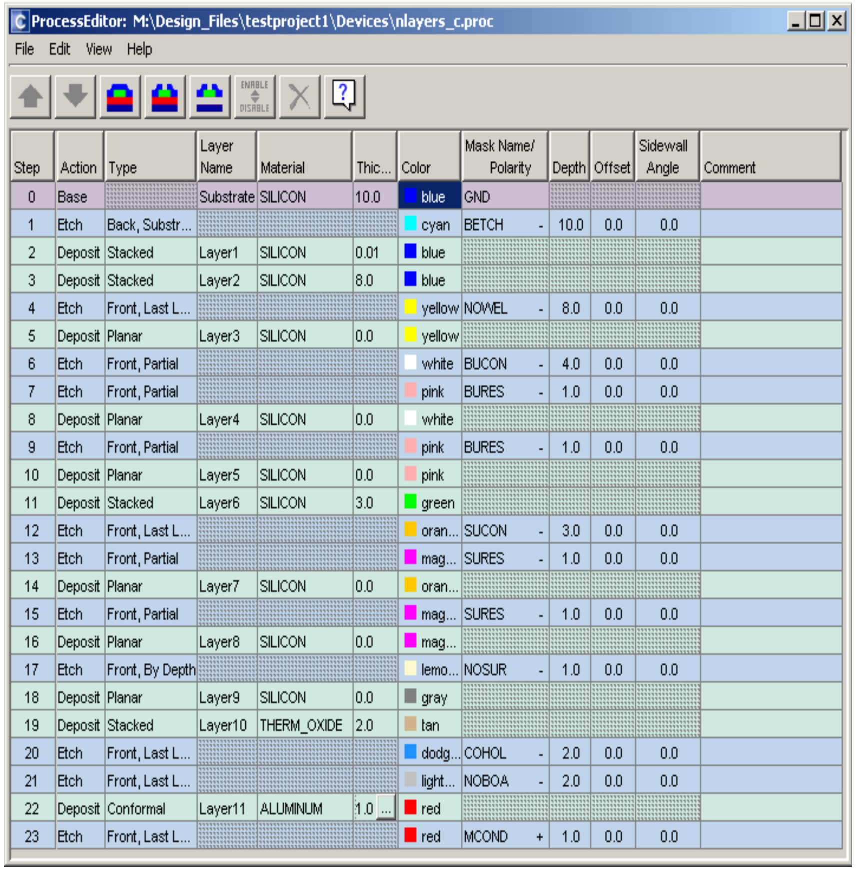
- Typiske trekk
  - Oppdeling i små-elementer: ”meshing”
  - Løse matematiske ligninger for interaksjonen mellom elementene
  - Mange iterasjoner utføres før stabil løsning oppnås
- + Mer realistiske resultater
  - Matematiske modeller er approksimasjoner
    - Utilstrekkelige ved komplekse sammenhenger og strukturer
    - Jmfr. bøyning av bjelke: ladningsfordeling ←→ kraft
- Bruk av FEM-simuleringer
  - CoventorWare
  - Eksempler fra modellering av bulk prosess →

Finite Element Methods



- Features
  - + good precision
  - + coupled electrostatic/ mech interaction
  - + can cope with irregular topologies
  - - insight into parameters influence is lost
  - - only small parts are practical
- Critical issues
  - proper system selection, building the 3D model
  - partitioning (meshing) , simulation parameters

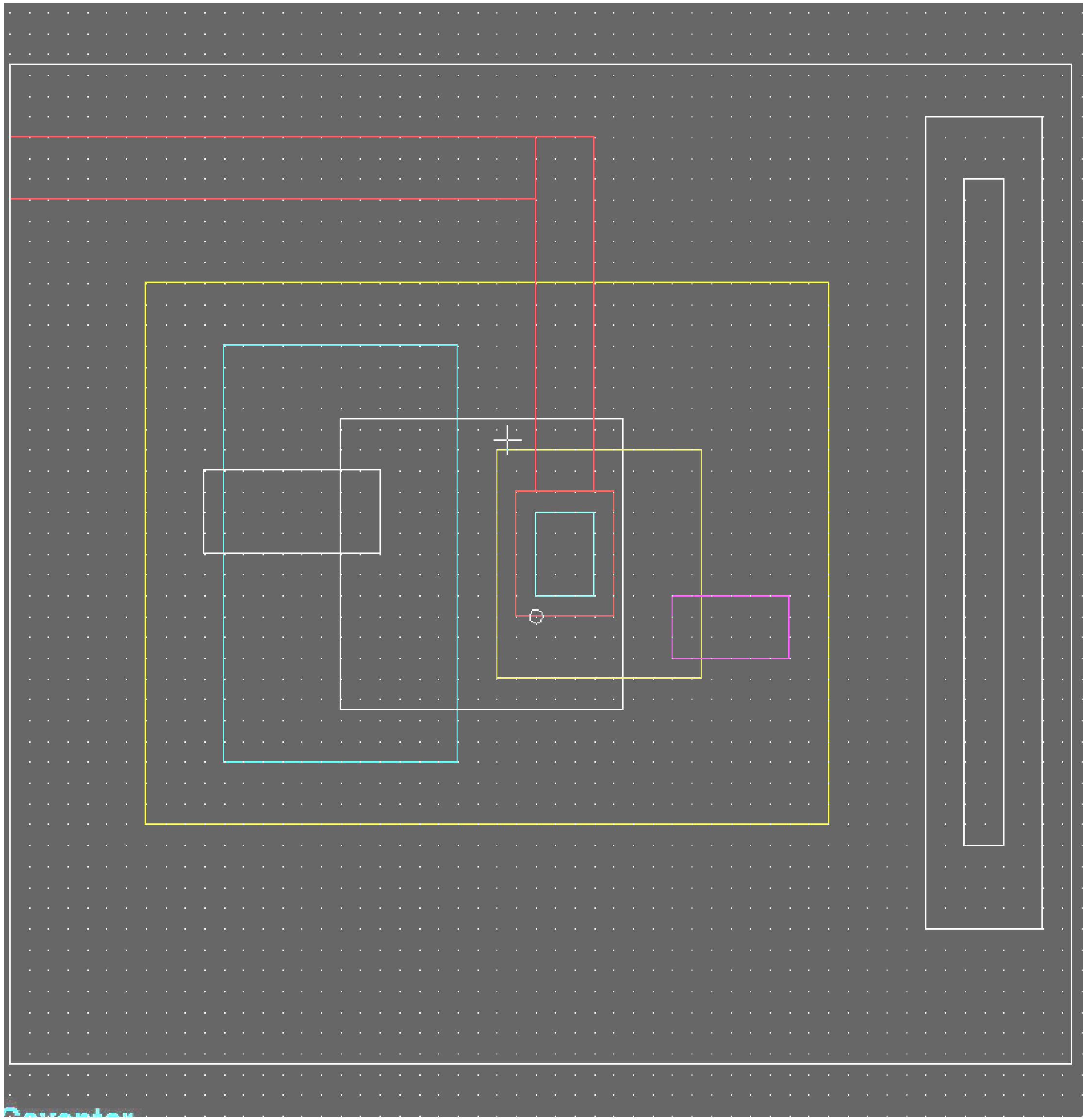
3D model building: process specification



Step	Action	Type	Layer Name	Material	Thic...	Color	Mask Name/ Polarity	Depth	Offset	Sidewall Angle	Comment
0	Base		Substrate	SILICON	10.0	blue	GND				
1	Etch	Back, Substr...				cyan	BETCH -	10.0	0.0	0.0	
2	Deposit	Stacked	Layer1	SILICON	0.01	blue					
3	Deposit	Stacked	Layer2	SILICON	8.0	blue					
4	Etch	Front, Last L...				yellow	NOWEL -	8.0	0.0	0.0	
5	Deposit	Planar	Layer3	SILICON	0.0	yellow					
6	Etch	Front, Partial				white	BUCON -	4.0	0.0	0.0	
7	Etch	Front, Partial				pink	BURES -	1.0	0.0	0.0	
8	Deposit	Planar	Layer4	SILICON	0.0	white					
9	Etch	Front, Partial				pink	BURES -	1.0	0.0	0.0	
10	Deposit	Planar	Layer5	SILICON	0.0	pink					
11	Deposit	Stacked	Layer6	SILICON	3.0	green					
12	Etch	Front, Last L...				oran...	SUCON -	3.0	0.0	0.0	
13	Etch	Front, Partial				mag...	SURES -	1.0	0.0	0.0	
14	Deposit	Planar	Layer7	SILICON	0.0	oran...					
15	Etch	Front, Partial				mag...	SURES -	1.0	0.0	0.0	
16	Deposit	Planar	Layer8	SILICON	0.0	mag...					
17	Etch	Front, By Depth				lemo...	NOSUR -	1.0	0.0	0.0	
18	Deposit	Planar	Layer9	SILICON	0.0	gray					
19	Deposit	Stacked	Layer10	THERM_OXIDE	2.0	tan					
20	Etch	Front, Last L...				dodg...	COHOL -	2.0	0.0	0.0	
21	Etch	Front, Last L...				light...	NOBOA -	2.0	0.0	0.0	
22	Deposit	Conformal	Layer11	ALUMINUM	1.0 ...	red					
23	Etch	Front, Last L...				red	MCOND +	1.0	0.0	0.0	

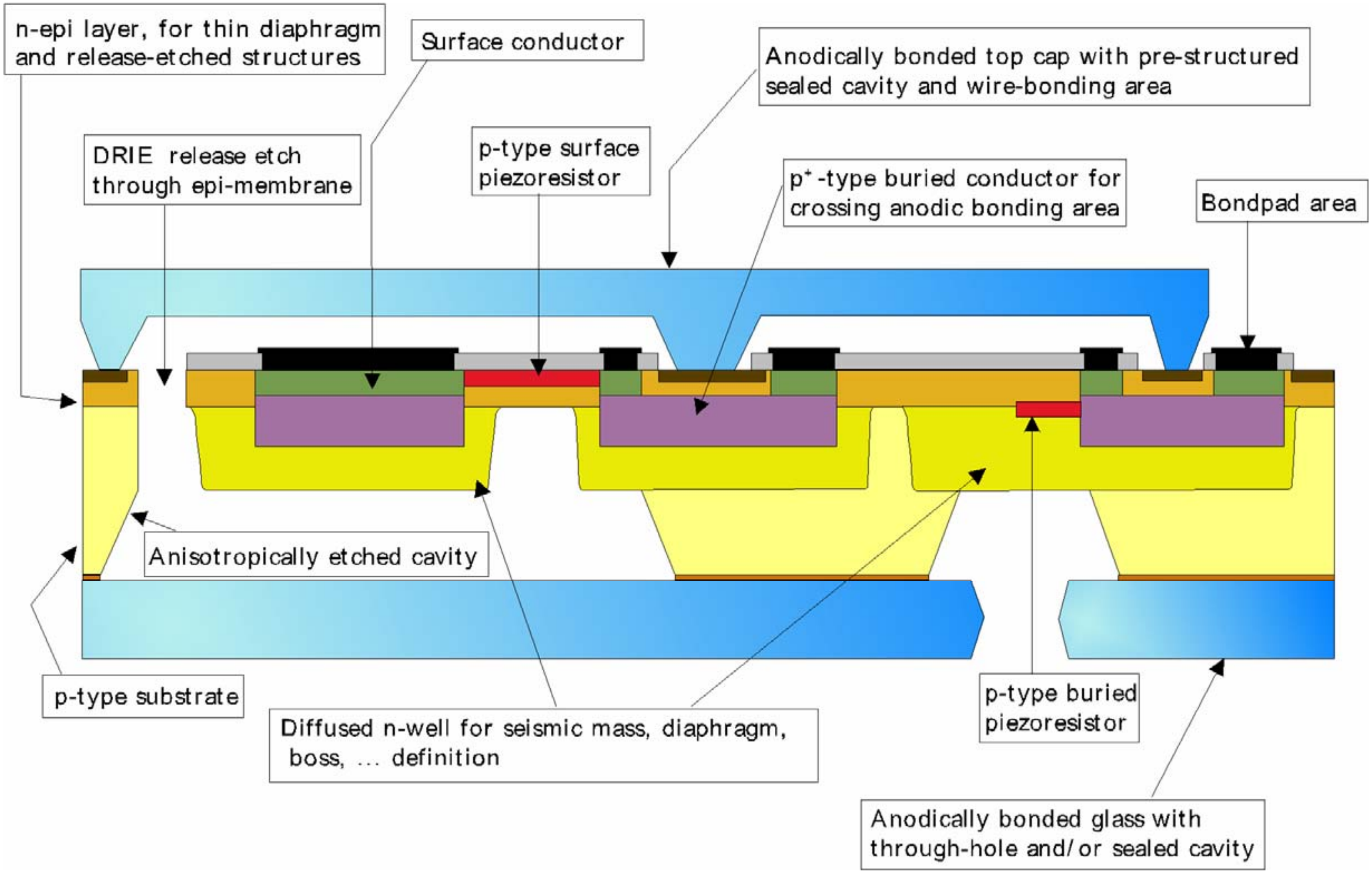
- Specify a **process file** which matches an actual foundry process
  - – simplifications
  - – realistic: essential process features included
- **--> pseudo layers**

3D model building: layout



Make accompanying **layout**

MultiMEMS, typical features



n-epi layer, for thin diaphragm and release-etched structures

Surface conductor

Anodically bonded top cap with pre-structured sealed cavity and wire-bonding area

DRIE release etch through epi-membrane

p-type surface piezoresistor

p^+-type buried conductor for crossing anodic bonding area

Bondpad area

Anisotropically etched cavity

p-type substrate

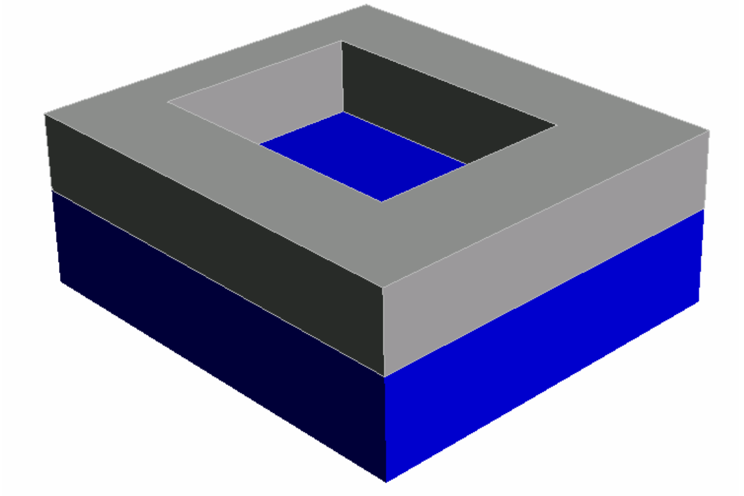
Diffused n-well for seismic mass, diaphragm, boss, … definition

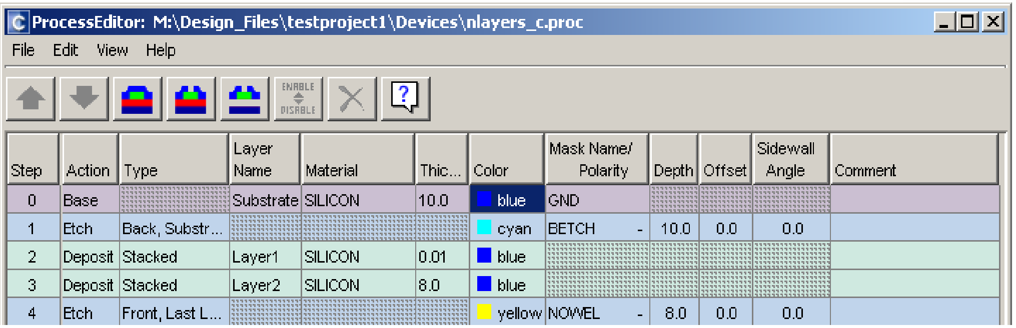
p-type buried piezoresistor

Anodically bonded glass with through-hole and/or sealed cavity

How to model the MultiMEMS bulk process in CoventorWare?

- Problem:
  - – the process is not based on “stacking layers”
- Create a pseudo process!
  - – simplified, but matching
  - – transfer to a procedure of **stacking layers**
    - some layers with zero spacing
    - slicing the bulk material into sub-layers **in contact**
    - make etchings and re-fillings

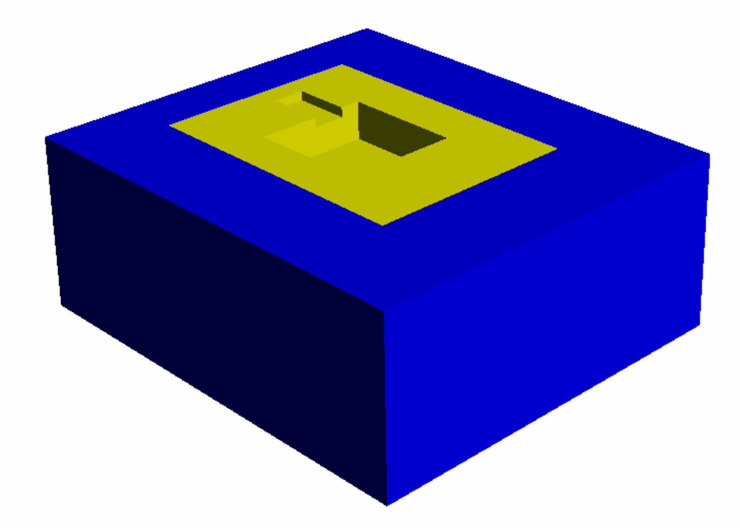


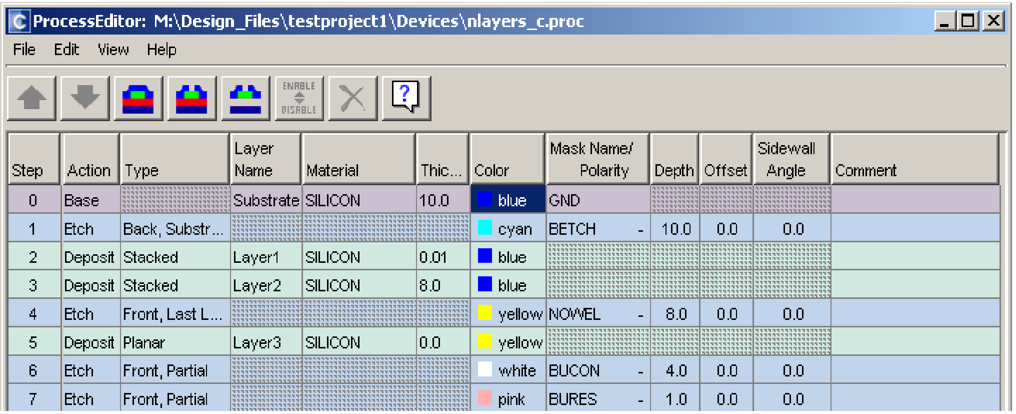


ProcessEditor: M:\Design_Files\testproject1\Devices\nlayers_c.proc

Step	Action	Type	Layer Name	Material	Thic...	Color	Mask Name/ Polarity	Depth	Offset	Sidewall Angle	Comment
0	Base		Substrate	SILICON	10.0	🟦 blue	GND				
1	Etch	Back, Substr...				🟦 cyan	BETCH -	10.0	0.0	0.0	
2	Deposit	Stacked	Layer1	SILICON	0.01	🟦 blue					
3	Deposit	Stacked	Layer2	SILICON	8.0	🟦 blue					
4	Etch	Front, Last L...				🟨 yellow	NOWEL -	8.0	0.0	0.0	

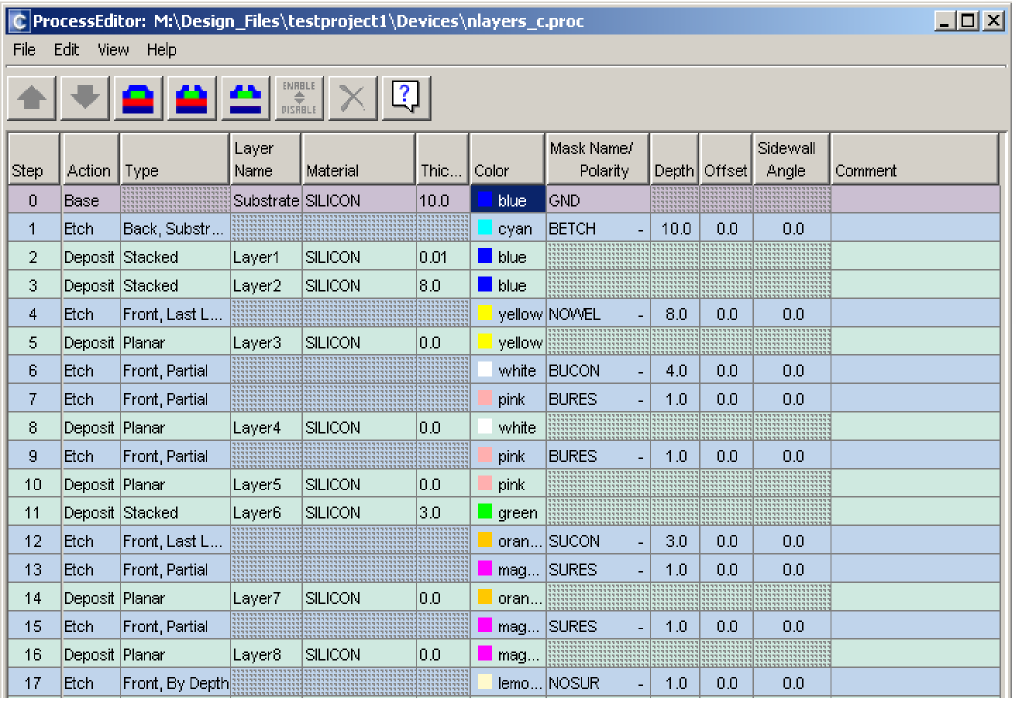
Two slices of the base material stacked. **N-well** opening



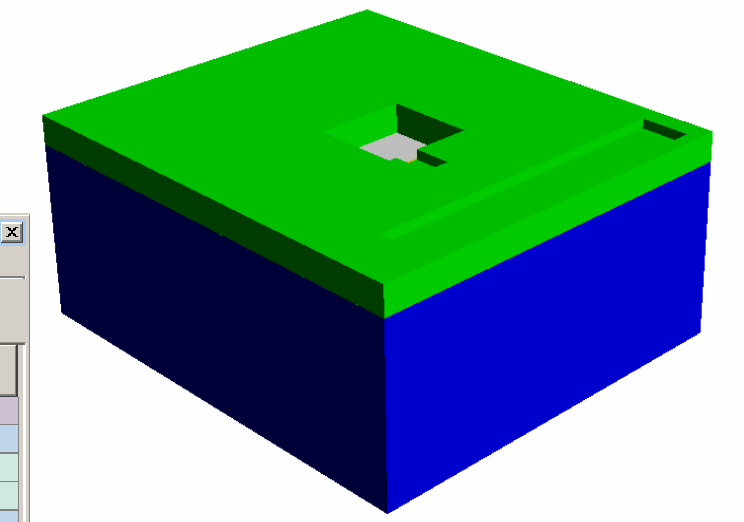


Step	Action	Type	Layer Name	Material	Thic...	Color	Mask Name/ Polarity	Depth	Offset	Sidewall Angle	Comment
0	Base		Substrate	SILICON	10.0	blue	GND				
1	Etch	Back, Substr...				cyan	BETCH -	10.0	0.0	0.0	
2	Deposit	Stacked	Layer1	SILICON	0.01	blue					
3	Deposit	Stacked	Layer2	SILICON	8.0	blue					
4	Etch	Front, Last L...				yellow	NOWEL -	8.0	0.0	0.0	
5	Deposit	Planar	Layer3	SILICON	0.0	yellow					
6	Etch	Front, Partial				white	BUCON -	4.0	0.0	0.0	
7	Etch	Front, Partial				pink	BURES -	1.0	0.0	0.0	

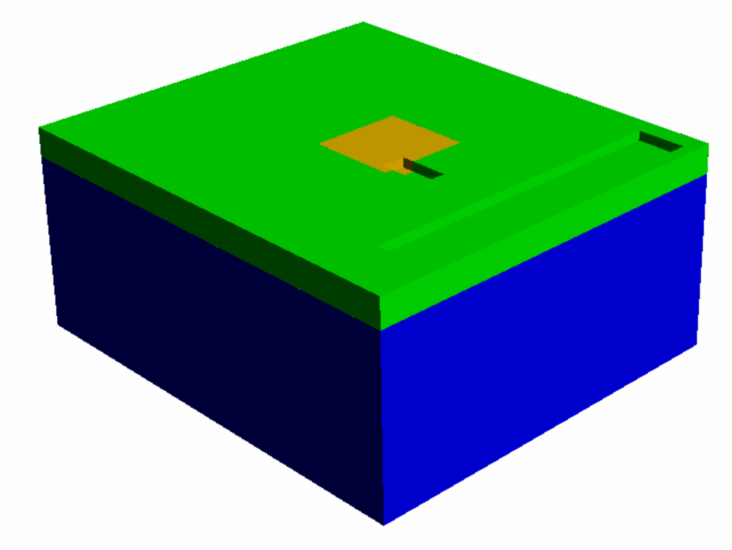
N-well in-filling. Etching holes for **buried conductor** implant and **buried resistor** implant

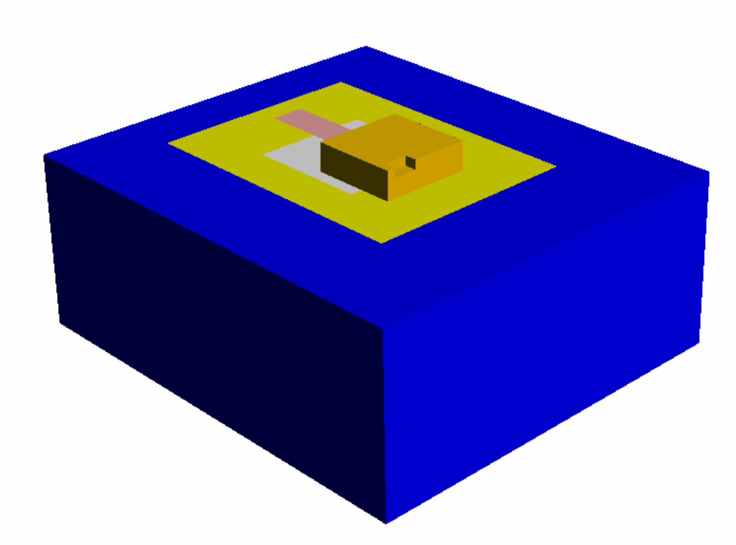


Step	Action	Type	Layer Name	Material	Thic...	Color	Mask Name/ Polarity	Depth	Offset	Sidewall Angle	Comment
0	Base		Substrate	SILICON	10.0	blue	GND				
1	Etch	Back, Substr...				cyan	BETCH -	10.0	0.0	0.0	
2	Deposit	Stacked	Layer1	SILICON	0.01	blue					
3	Deposit	Stacked	Layer2	SILICON	8.0	blue					
4	Etch	Front, Last L...				yellow	NOWEL -	8.0	0.0	0.0	
5	Deposit	Planar	Layer3	SILICON	0.0	yellow					
6	Etch	Front, Partial				white	BUCON -	4.0	0.0	0.0	
7	Etch	Front, Partial				pink	BURES -	1.0	0.0	0.0	
8	Deposit	Planar	Layer4	SILICON	0.0	white					
9	Etch	Front, Partial				pink	BURES -	1.0	0.0	0.0	
10	Deposit	Planar	Layer5	SILICON	0.0	pink					
11	Deposit	Stacked	Layer6	SILICON	3.0	green					
12	Etch	Front, Last L...				oran...	SUCON -	3.0	0.0	0.0	
13	Etch	Front, Partial				mag...	SURES -	1.0	0.0	0.0	
14	Deposit	Planar	Layer7	SILICON	0.0	oran...					
15	Etch	Front, Partial				mag...	SURES -	1.0	0.0	0.0	
16	Deposit	Planar	Layer8	SILICON	0.0	mag...					
17	Etch	Front, By Depth				lemo...	NOSUR -	1.0	0.0	0.0	



Add **epi-layer**. Etch holes for **surface conductor** and **surface resistor**, -fill in. Etch hole for n+ implant. (Implants are invisible)

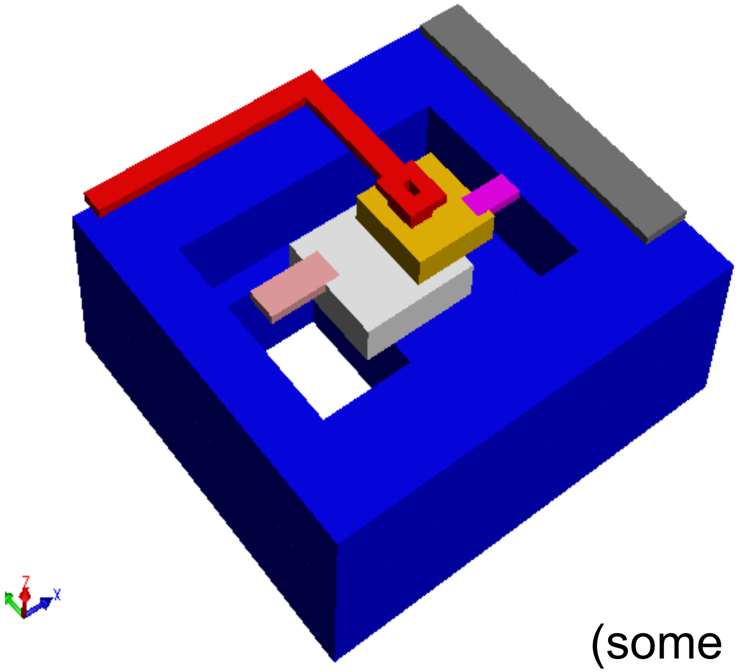




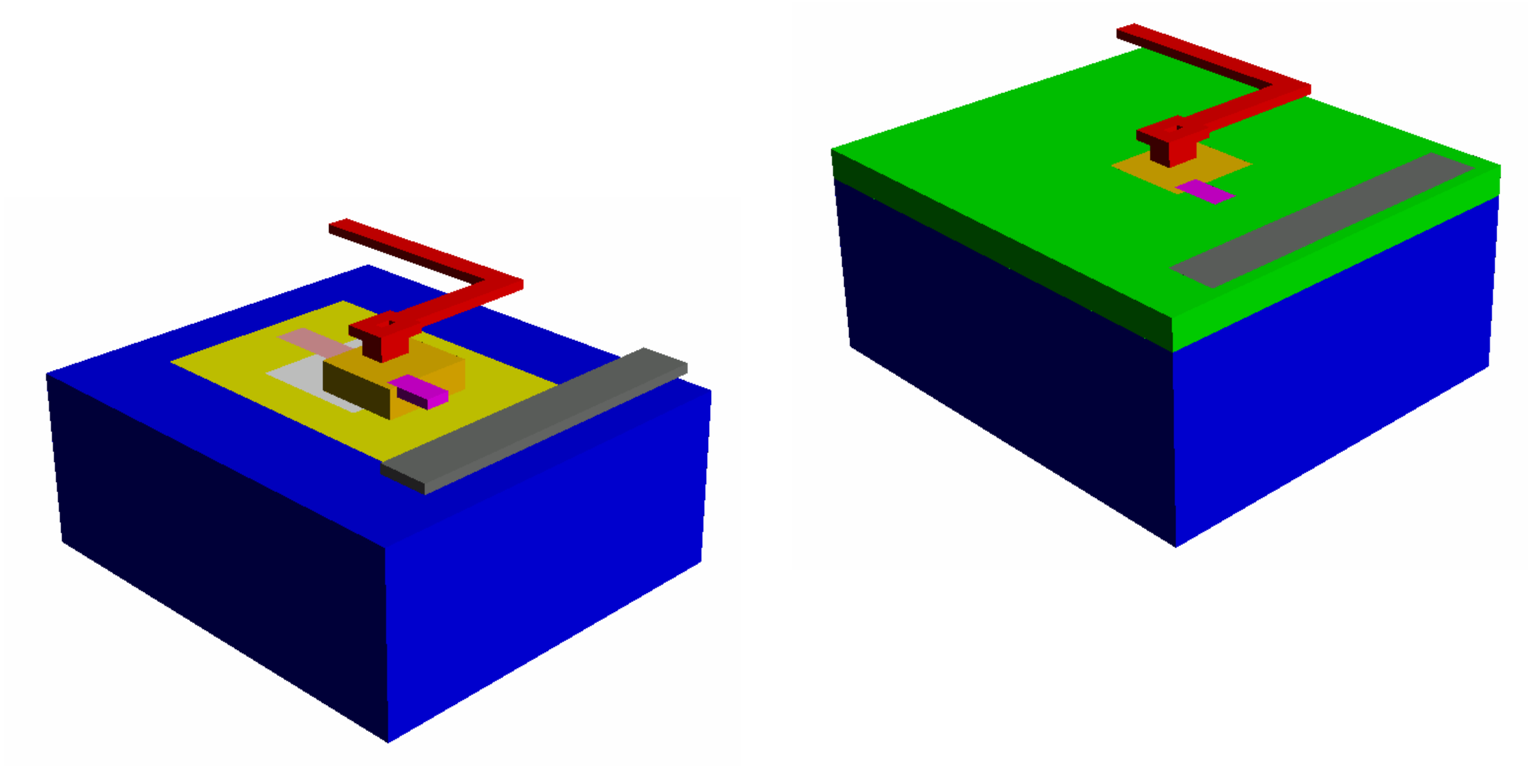
Surface conductor is made visible

Epi-layer is invisible

3D model building: expansion



(some layers invisible)

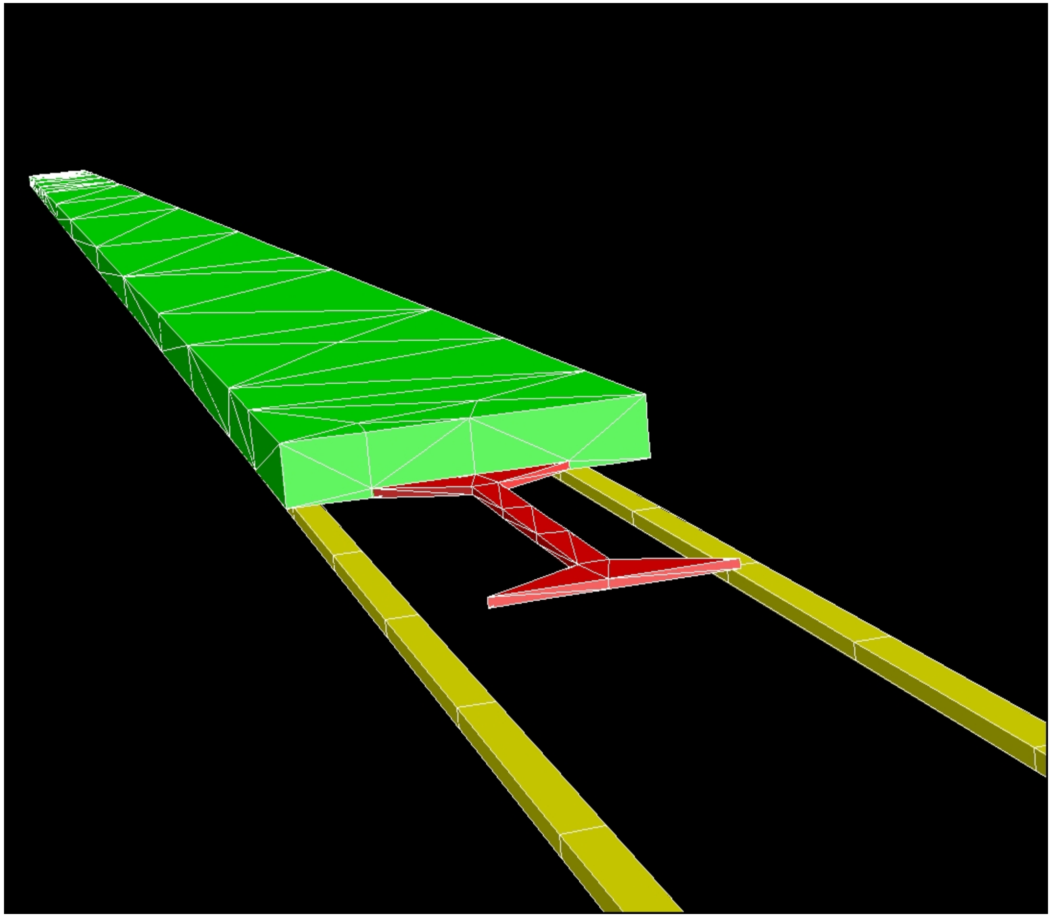


Complete structure with some layers made invisible

3D modelling procedure

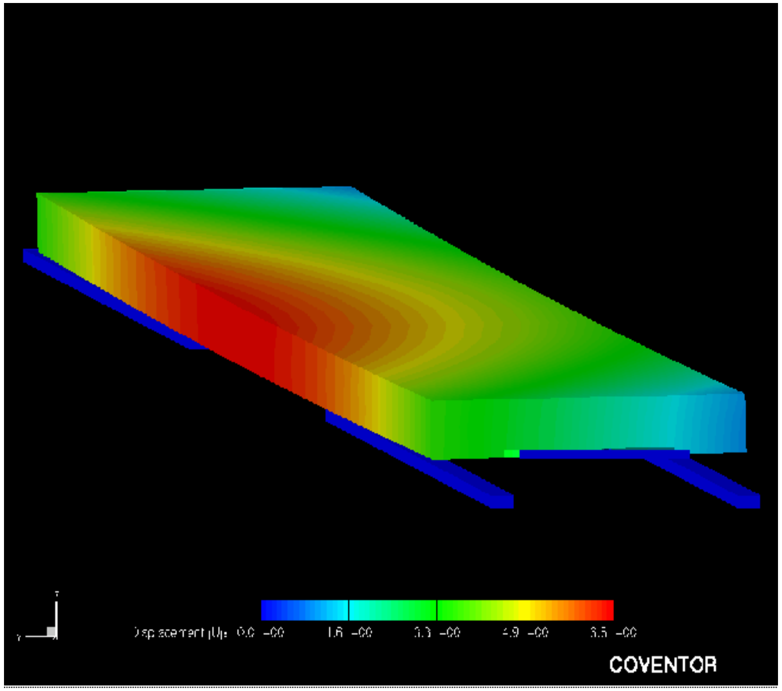
- To introduce one diffusion:
  - etch base material
  - fill in implanted material
    - **“deposit planar” with thickness = 0**
- To introduce multiple overlapping diffusions:
  - etch base material with all diffusion masks (the deepest first)
  - fill in the deepest implanted material
  - re-etch the remaining diffusion openings
  - fill in the next deepest implant etc.

Meshed model



- Mirror meshed by tetrahedrons
  - 23 µm, 3 µm
- Electrodes meshed by Manhatten bricks
  - 5 µm
- Rather coarse dim due to pull-in analysis

Mirror deflection, snapshot



Simulation: pull-in