Lecture 5: Scaling Benefits IV & Process Modules I

- Announcements:
- Make-up lecture (from last Friday) will be placed online soon on the course website
- HW#1 due next week on Wednesday morning
- Lecture Module 3 online
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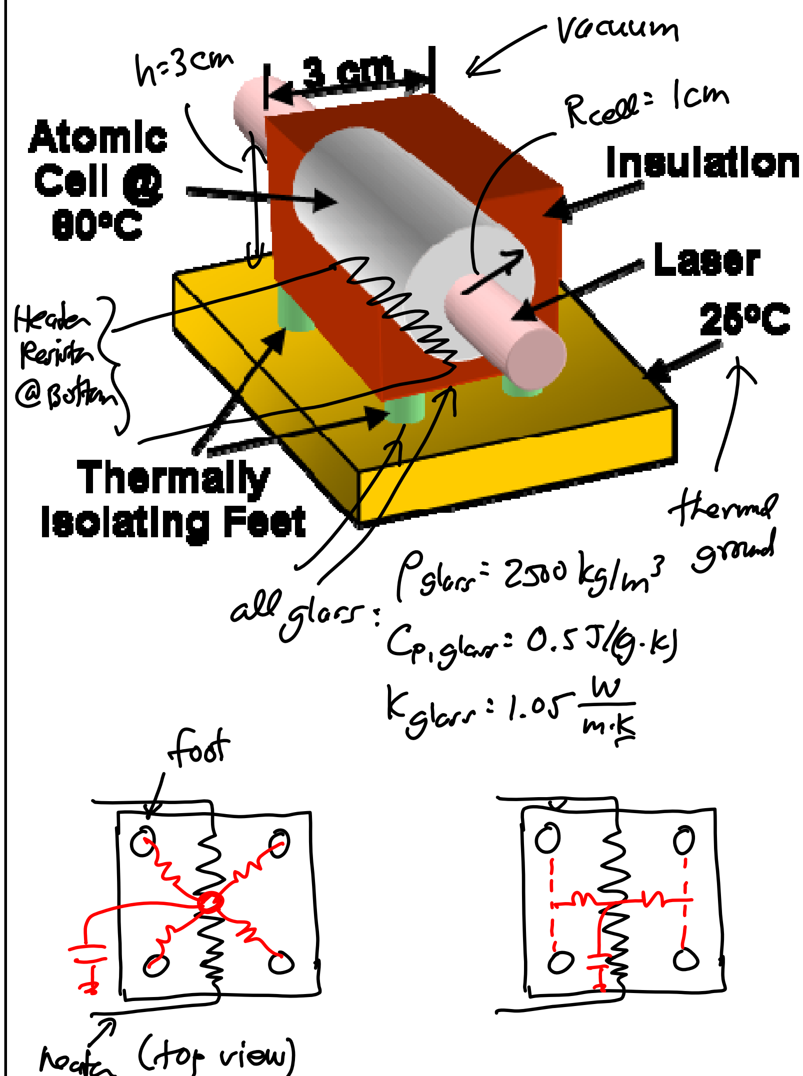
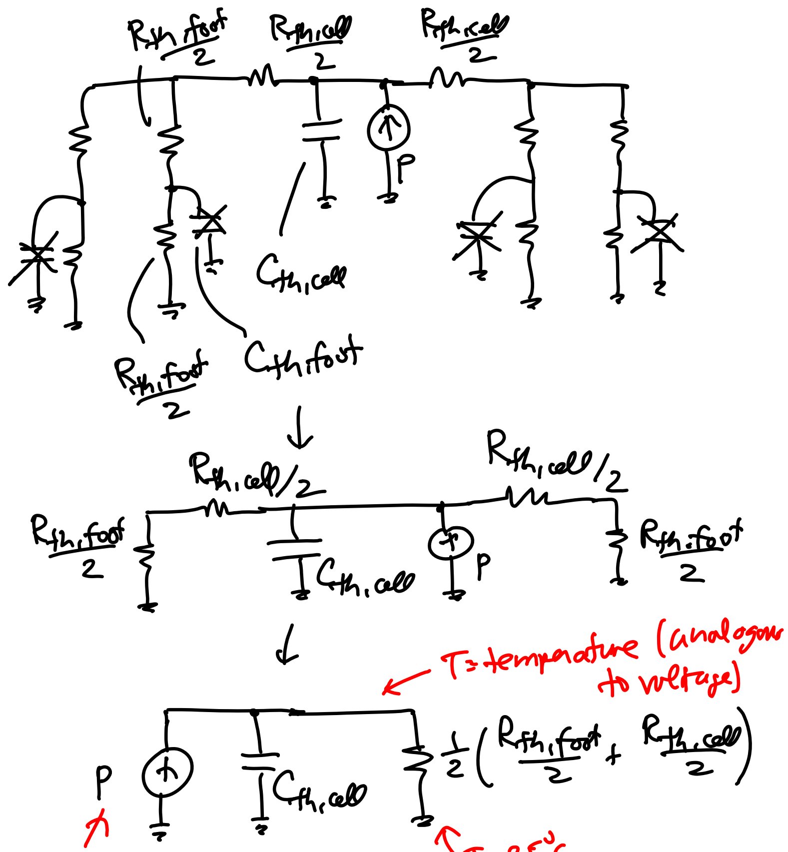
- Today:
- Reading: Senturia, Chapter 1
- Lecture Topics:
  - Benefits of Miniaturization
  - Examples
    - GHz micromechanical resonators
    - Chip-scale atomic clock
    - Thermal Circuits
    - Micro gas chromatograph
- Senturia, Chpt. 3; Jaeger, Chpt. 2, 3, 6
  - Example MEMS fabrication processes
  - Oxidation
  - Film Deposition
    - Evaporation
    - Sputter deposition
    - Chemical vapor deposition (CVD)
    - Plasma enhanced chemical vapor deposition (PECVD)
    - Epitaxy
    - Atomic layer deposition (ALD)
    - Electroplating
- -----------------------------------
- Last Time: Thermal circuit modeling

Example: Thermal Ckt.

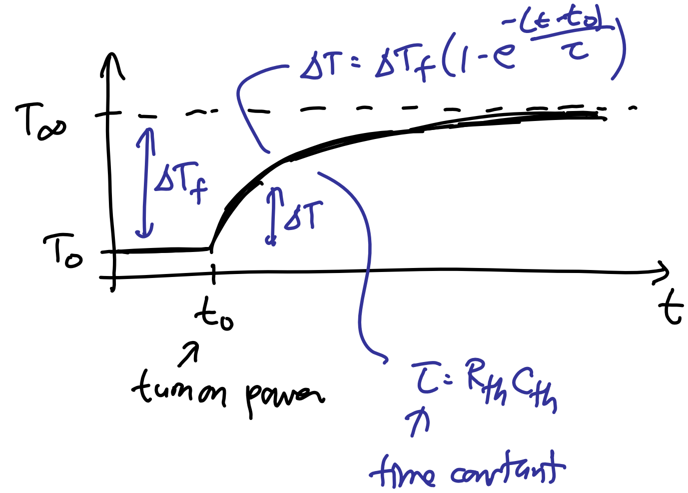
⇒ determine the power needed to get this atomic cell to 80°C (from RT) & how fast





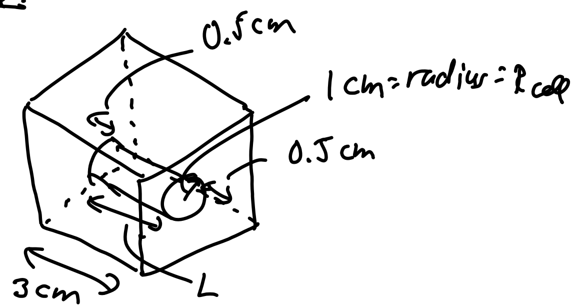
power → analogous to current

$\Delta T = T - T_0 = P R_{th}$ (in steady-state)



Find $C_{th,cell}$:

First, find the cell volume:

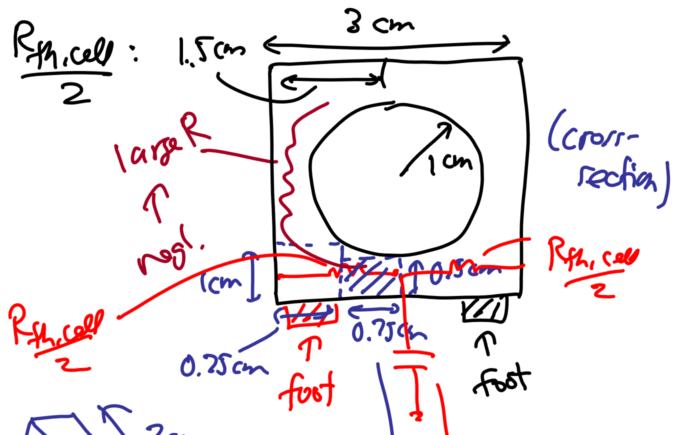


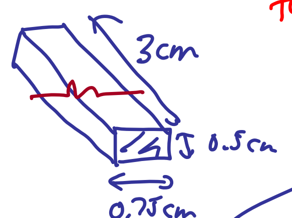
$$V_{cell} = hWL - \pi R_{cell}^2 \cdot L$$
$$= (3cm)(3cm)(3cm) - \pi(1cm)^2(2cm) = 20.7\ cm^3$$

$$C_{th,cell} = \rho_{glass} V_{cell} C_{p,glass}$$
$$= \left(2500\ \frac{kg}{m^3}\right)\left(1000\ \frac{g}{kg}\right)\left(\frac{1}{100^3}\ \frac{m^3}{cm^3}\right) \times (20.7\ cm^3)\left(0.5\ \frac{J}{g \cdot K}\right)$$

$$\Rightarrow C_{th,cell} = 25.9\ J/K$$

Find $\frac{R_{th,cell}}{2}$:





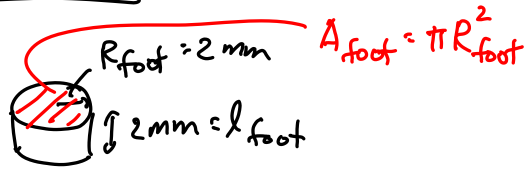
$$\frac{R_{th,cell}}{2} = \frac{\frac{3}{4}}{k(3)(\frac{1}{2})} + \frac{\frac{3}{4}}{k(3)(1)} = \frac{1}{k}\left(\frac{1}{8}+\frac{1}{4}\right) = \frac{3}{8}\frac{1}{k}$$

$\left[R_{th} = \frac{l}{kA}\right]$

$$\therefore \frac{R_{th,cell}}{2} = \frac{3}{8}\frac{1}{1.05} \times \left(100\,\frac{cm}{m}\right)$$

$$= \underline{35.7\ K/W}$$

Find $R_{th,foot}$:



$$\therefore R_{th,foot} = \frac{l_{foot}}{kA_{foot}} = \frac{2mm}{(1.05\frac{W}{m \cdot K})\pi(2mm)^2} = \underline{\underline{151.6\ \frac{K}{W}}}$$

Then:

$$R_{th} = \frac{1}{2}\left(\frac{R_{th,foot}}{2} + \frac{R_{th,cell}}{2}\right)$$

$$= \frac{1}{2}\left(\frac{151.6}{2} + 35.7\right) \Rightarrow R_{th} = \underline{\underline{55.8\ K/W}}$$

⇒ Find the power req'd to maintain $T_\infty = 80°C$ in steady-state:

$$P = \frac{T_\infty - T_o}{R_{th}} = \frac{(80-25)}{55.8} = 0.99W \sim \boxed{1W}$$

⇒ Find the time constant:

$$\tau = R_{th} C_{th,cell} = \boxed{24\,min.}$$

↳ If takes ~3τ to reach steady-state
∴ must wait 72 min. before using this atomic cell

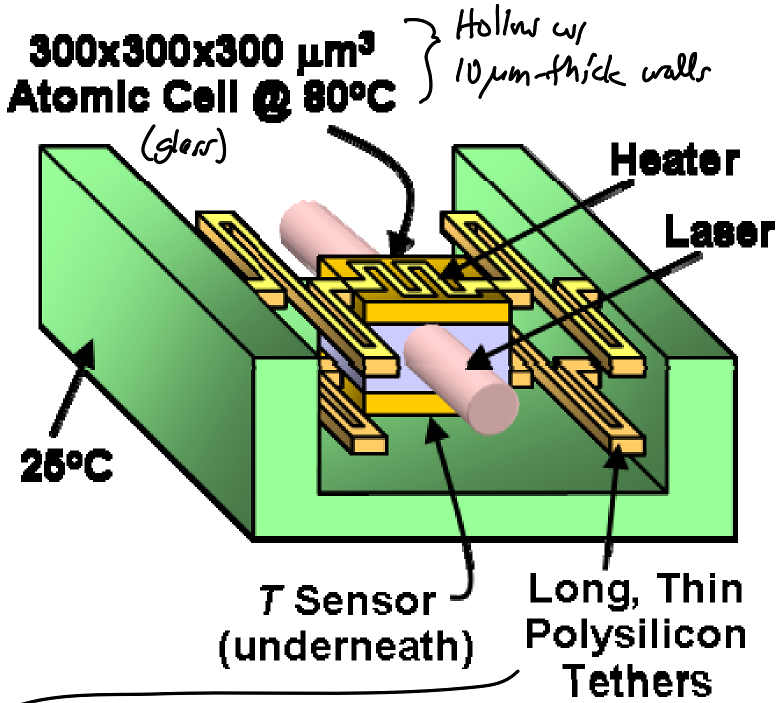
How about the MEMS case?

$V\downarrow \to C_{th}\downarrow$

⇒ much smaller cell volume + weight↓

⇒ can use long, thin supports: $L\uparrow, A\downarrow \to R_{th}\uparrow$

MEMS Atomic Cell



→ 500µm-long, 10µm-thick, 20µm-wide

$V_{cell} = (300\mu)(300\mu)(300\mu) - (280\mu)(280\mu)(280\mu)$
$= 5.048\times10^{-12} m^3$
↳ of course, much smaller than macro!

$C_{th,cell} = \rho_{glass} V_{cell} C_{p,glass}$
$= (2500 \frac{kg}{m^3})(5.048\times10^{-12} m^3)(500 \frac{J}{kg\cdot K})$
$\rightarrow C_{th,cell} = \underline{\underline{6.31\times10^{-6}}} \frac{J}{K}$ ← 4 million x smaller than macro!

$R_{th,supp} = \frac{l_{supp}}{k_{polySi} W_{supp} h_{supp}} = \frac{500\mu}{(30 \frac{W}{m\cdot K})(20\mu)(10\mu)}$

$\Rightarrow R_{th,supp} = \underline{\underline{83,333\ K/W}}$
↑ 548X larger!

and...

$P = \frac{(80-25)}{83,333} = 2.64mW$ ← 548x smaller!

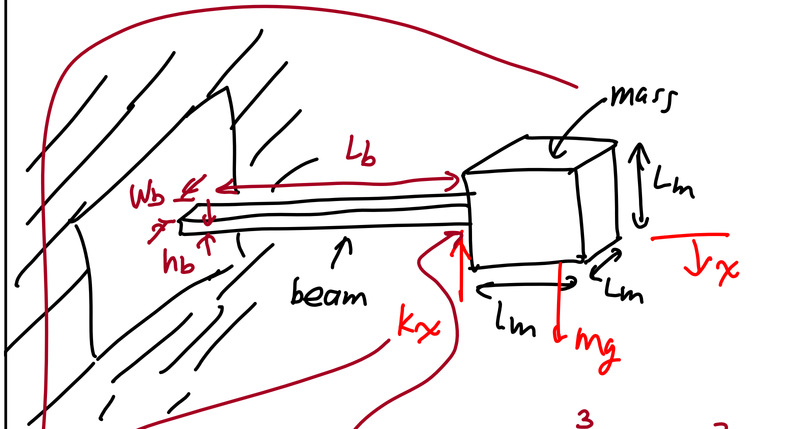
$\tau = 0.13s$ ← 7300x faster

All due to scaling!

What makes all of this possible?

① Scaling reduces $C_{th} \sim l^3 \rightarrow S^3$
↳ $S\downarrow \rightarrow C_{th}\downarrow\downarrow\downarrow$

② Scaling allows the use of long, thin tethers
⇓
$R_{th}\uparrow\uparrow$



$k \triangleq$ stiffness @ this pt. $= \frac{1}{4} E W_b \frac{h_b^3}{L_b^3} \sim S \frac{S^3}{S^3} \sim S$

mass $= \rho L_m^3 \sim S^3$

@ static equilibrium:

Force due to Gravity = Spring Force

$mg = kx$ ← displacement; acceleration due to gravity → g ; *

$x = \frac{m}{k} g \sim \frac{S^3}{S} \sim S^2$

as $S\downarrow \rightarrow x \downarrow\downarrow$

$R_{th} = \frac{L_b}{\kappa W_b h_b}$ → want to raise this (for lower power cons. atomic cell)
↓ but maintain the same droop x

* → $\rho L_m^3 g = \frac{1}{4} E W_b \frac{h_b^3}{L_b^3} x$

$\frac{L_b}{W_b h_b} = \frac{1}{4} E \frac{h_b^2}{L_b^2} x \frac{1}{\rho L_m^3 g} \sim \frac{S^2}{S^2} \frac{1}{S^3} \sim \frac{1}{S^3}$

($\sim R_{th}$; const.)

as $S\downarrow \rightarrow \frac{L_b}{W_b h_b} \sim R_{th} \uparrow\uparrow\uparrow$