Lecture 5: Benefits of Scaling III

- Announcements:
- HW#1 issued today; due in two weeks
- Hopefully, you've watched the video lectures from last week; otherwise, you'll have a hard time understanding this lecture
- Quiz Thursday? yes / [✓ no]
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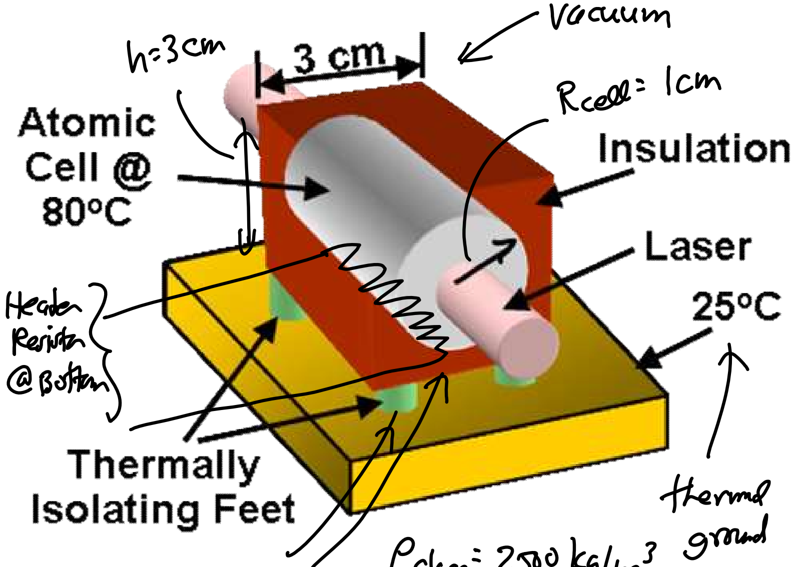
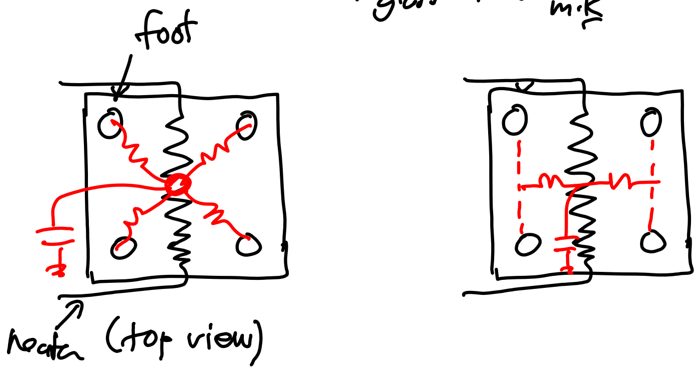
- Today:
- Reading: Senturia, Chapter 1
- Lecture Topics:
  - Benefits of Miniaturization
  - Examples
    - —GHz micromechanical resonators
    - —Chip-scale atomic clock
    - —Thermal Circuits
    - —Micro gas chromatograph
- Probably won't get to it, but next up is:
- Senturia, Chpt. 3; Jaeger, Chpt. 2, 3, 6
  - Example MEMS fabrication processes
  - Photolithography
  - Etching
  - Oxidation
  - Film Deposition
  - Ion Implantation
  - Diffusion
- ------------------------------------
- Last Time: Thermal circuit modeling

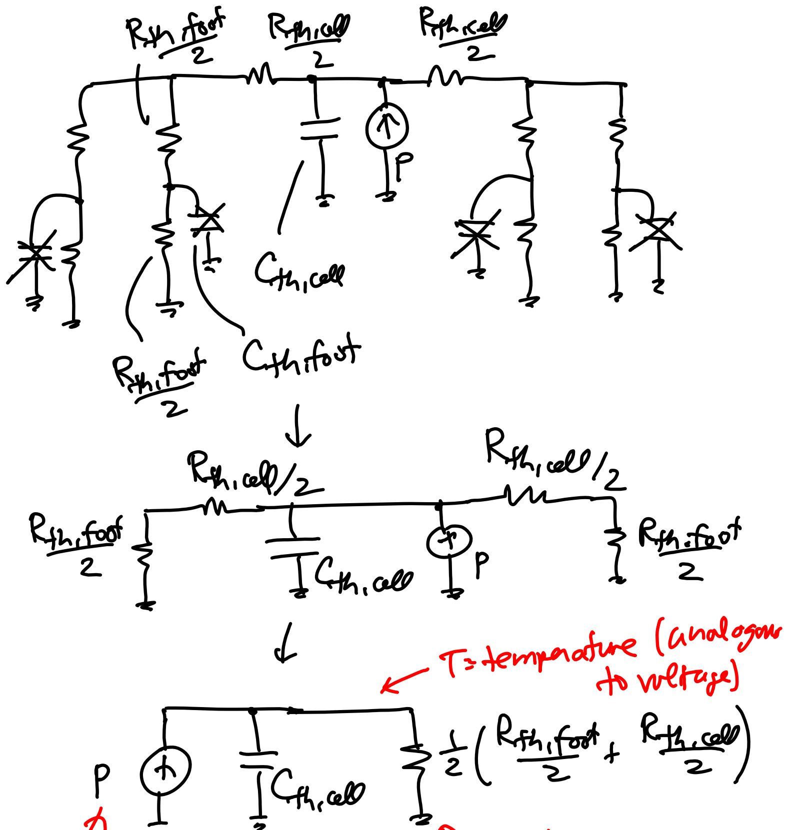
Example: Thermal Clock.

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



all glass:
$\rho_{glass} = 2500\ kg/m^3$
$C_{p,glass} = 0.5\ J/(g\cdot K)$
$K_{glass} = 1.05\ \frac{W}{m\cdot K}$



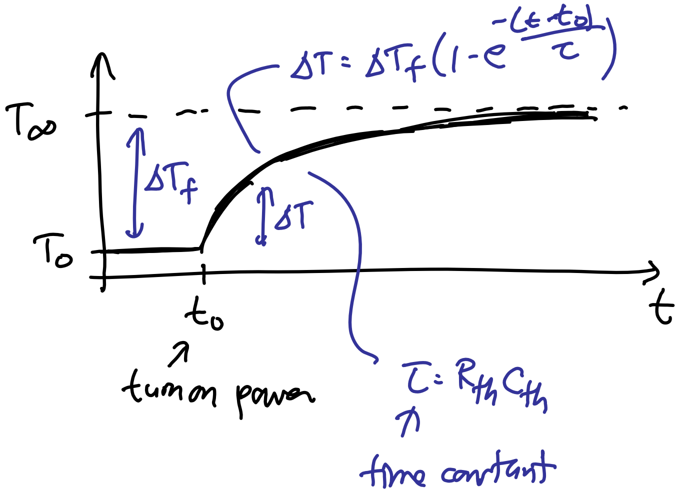


T = temperature (analogous to voltage)

$T_o = 25°C$

power → analogous to current

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



$\Delta T = \Delta T_f\left(1 - e^{\frac{-(t-t_o)}{\tau}}\right)$

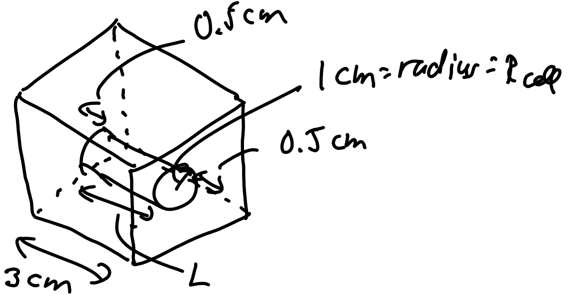
turn on power

$\tau = R_{th} C_{th}$

time constant

Find $C_{th,cell}$:

First, find the cell volume:



$V_{cell} = hWL - \pi R_{cell}^2 \cdot L$

$= (3cm)(3cm)(3cm) - \pi(1cm)^2(2cm) = 20.7\ cm^3$

$C_{th,cell} = \rho_{glass} V_{cell} C_{p,glass}$

$= \left(2500\ \frac{\cancel{kg}}{\cancel{m^3}}\right)\left(1000\ \frac{\cancel{g}}{\cancel{kg}}\right)\left(\frac{1}{100^3}\ \frac{\cancel{m^3}}{\cancel{cm^3}}\right)$

$\times\ (20.7\ \cancel{cm^3})\left(0.5\ \frac{J}{\cancel{g}\cdot K}\right)$

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

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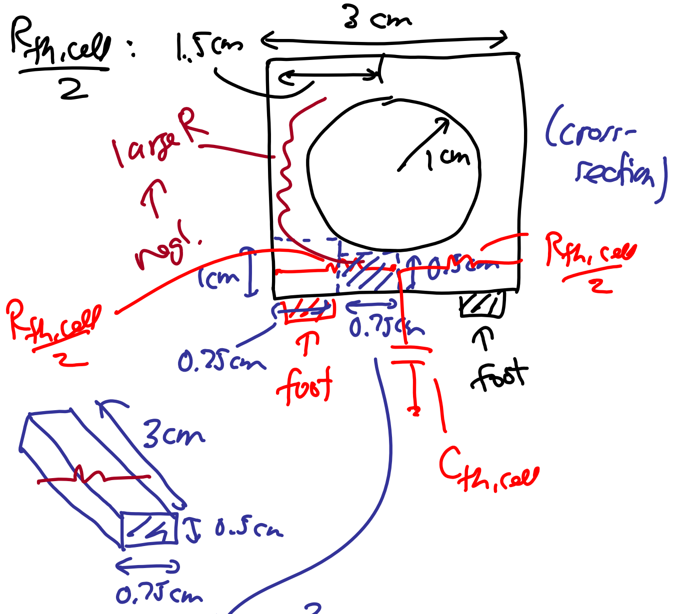
Lecture 5w: Benefits of Scaling III

CTN 1/31/17

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



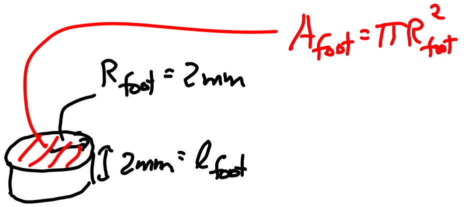
$$\frac{R_{th,cell}}{2} = \frac{\frac{3}{4}}{k(3)(\frac{1}{2})} + \frac{\frac{3}{4}}{k(3)(1)} = \frac{1}{k}\left(\frac{1}{8}+\frac{1}{4}\right) = \frac{3}{8}\frac{1}{k}$$

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

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

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

Find $R_{th,foot}$:



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

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:

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

⇒ Find the time constant:

$$\tau = R_{th}C_{th,cell} = (55.8\ K/W)(25.9\ J/K) = \boxed{24\,min.}$$

↳ It takes ~3τ to reach steady-state

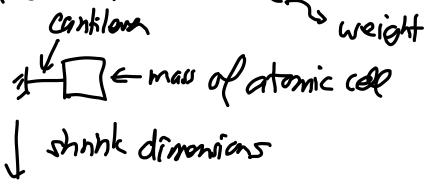
∴ must wait 72 min. before using this atomic cell

How about using MEMS, i.e., scaling down?

⇒ much smaller cell volume → s^3 → V↓ → C_{th}↓

↳ weight ↓

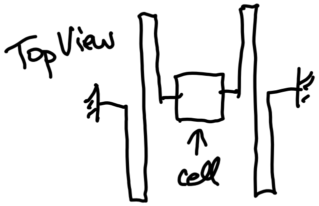
Macro:



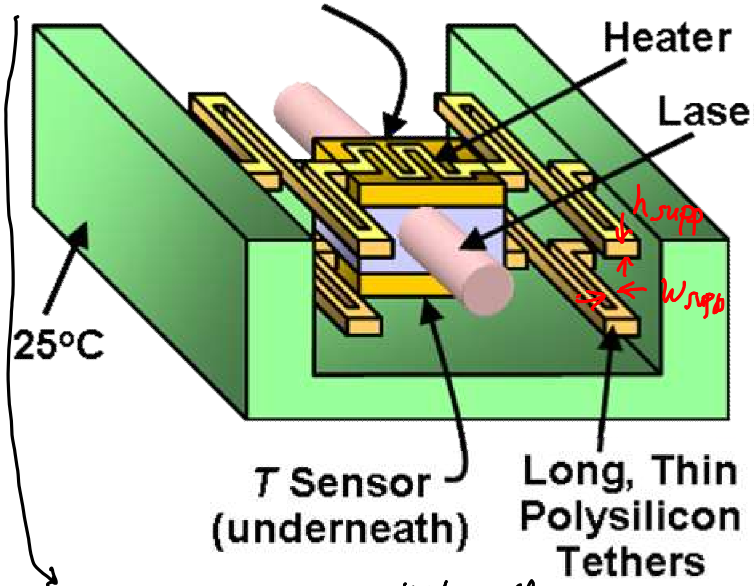
Micro:

can do this → use long-thin supports to suspend the cell

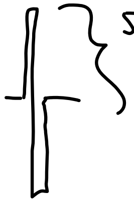
MEMS Atomic Cell



300x300x300 μm^3 Atomic Cell @ 80°C



Cell is hollow w/ 10μm-thick walls.



500μm-long, 10μm-thick, 20μm-wide

$$V_{cell} = (300\mu)(300\mu)(300\mu) - (280\mu)(280\mu)(280\mu)$$
$$= 5.048\times10^{-12}\ m^3$$

(much smaller than macro!)

$$C_{th,cell} = \rho_{glass} V_{cell} C_{p,glass}$$
$$= \left(2580\ \frac{kg}{m^3}\right)\left(5.048\times10^{-12}\ m^3\right)\left(500\ \frac{J}{g\cdot K}\right)$$
$$= 6.31\times10^{-6}\ \frac{J}{K} \leftarrow \text{4 million X smaller than macro!}$$

$$R_{th,supp} = \frac{l_{supp}}{K_{poly\,Si} W_{supp} h_{supp}} = \frac{500\mu}{\left(30\ \frac{W}{m\cdot K}\right)(20\mu)(10\mu)}$$

$$\Rightarrow R_{th,supp} = \underline{\underline{83{,}333\ K/W}}$$

↳ 548X larger than macro!

... and ...

$$P = \frac{4(80-25)}{83{,}333} = \boxed{2.64mW} \rightarrow \text{548X smaller}$$

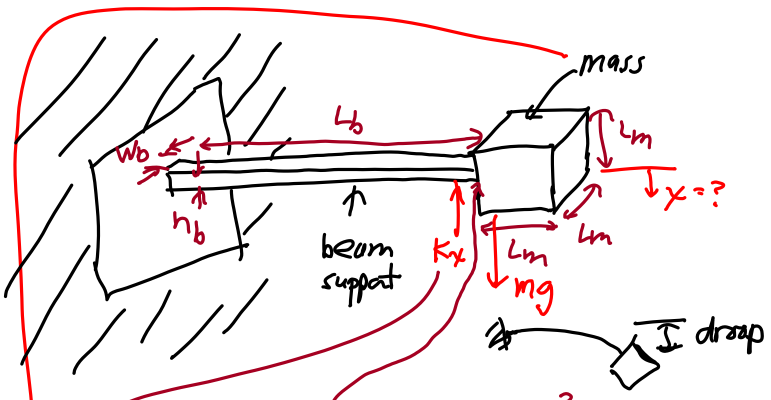
$$\tau = \boxed{0.13s} \leftarrow \text{7300X faster}$$

All Due to Scaling!

Remarks. (What makes this possible)

① Scaling reduces $C_{th} \sim l^3 \rightarrow s^3$
$\searrow s\downarrow \rightarrow C_{th}\downarrow\downarrow\downarrow$

② Scaling allows use of $\underbrace{\text{long, thin tether supports}}_{R_{th}\uparrow\uparrow}$



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

attachment pt. to mass

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

@ static equilibrium:

Force due to Gravity = Spring Force

acceleration due to gravity

$mg = kx$ *

displacement

$x = \frac{m}{k} g \sim \frac{s^3}{s} \sim s^2 \rightarrow$ as $s\downarrow \rightarrow x\downarrow\downarrow$

(less drop as this scales!)

can afford to lengthen support beam $\rightarrow L_b\uparrow$

Great! $R_{th} = \frac{L_b}{k W_b h_b}$

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

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

const.

$\sim R_{th}$

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

- Go through slides 30-31 and 37-48 in Module 2 to finish up Thermal Circuits and cover Micro Gas Analyzers

Process Module Overview:

- Lecture Topics:
  - ↳ Photolithography
  - ↳ Etching
  - ↳ Oxidation
  - ↳ Film Deposition
  - ↳ Ion Implantation
  - ↳ Diffusion
- As stated earlier, this is now assumed knowledge
- I will gloss over this material to review it a bit, but will not go over it in detail
- You can watch my lectures from EE245, Fall 2012, on the Webcast Berkeley site for more in depth coverage: Lectures 6-8
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Process Modules

⇒ there are actually only a few basic modules used for processing

↓

Combination of these in the correct sequence yields an integrated circuit technology that provides transistors, MEMS, nanodevices, etc.

⇒ For each module, need to understand:

① Physics and engineering of each module in detail.

② Interactions between modules.

③ The affect of each module on the finished device.