

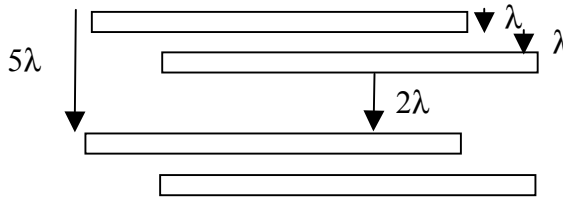
**Problem 1:** Calculate the energy density in Joules/kg of an Eveready AA alkaline battery (e.g. X-91) and a Tadiran extra high capacity AA battery (TL-5903):

$$3.6 V * 2.4 A * 3600 \text{ sec} / 0.0176 \text{ kg} = 1.8 \text{ MJ/kg}$$

**Problem 2: Actuator in DRIE process**

Assuming a DRIE aspect ratio  $S$ , a minimum feature size  $\lambda$ , a material density  $\rho$ , and a maximum voltage  $V$ ,

- a) calculate the force per unit area of an ideal gap-closing actuator array. (Use the zero-deflection force, not the force after pull-in; you may assume some magical sublithographic gap stop if you like).



$$F = \frac{1}{2} V^2 \frac{\epsilon_0 t l}{\lambda^2} \quad t: \text{thickness of film, } l: \text{length of actuator finger, } \lambda: \text{gap of actuator}$$

Area of an ideal gap-closing actuator array:  $5\lambda * l$

So: Force per unit layout area of an ideal gap-closing actuator array:

$$F/(5\lambda l) = \epsilon_0 t V^2 / (10\lambda^3)$$

- b) Calculate the force output per kilogram, assuming a film thickness  $t$ . Will micro robots with gap closing electrostatic actuators be able to lift themselves without massive gearing or levers?

$$F = \frac{1}{2} V^2 \frac{\epsilon_0 t l}{\lambda^2} \text{ and } m = 2\rho\lambda t l \text{ (assuming robots has minimum feature)}$$

$$F/m = \frac{\epsilon_0 V^2}{4\lambda^3 \rho} \quad \text{If } V=10 \text{ Volts, } \lambda=2\mu\text{m, } F/m=12000 > g, \text{ so micro robots can lift itself.}$$

- c) What is the optimum value for  $t$ , assuming we want to make minimum sized gaps and the maximum aspect ratio possible in our beams?

$$2t/\lambda \leq S, \text{ so the optimum value for } t = S\lambda/2.$$

- d) Calculate the maximum work done per cycle of the actuator against a constant force load (what is the load?).

$$\text{Maximum work: } F_{load} * \lambda = \frac{1}{2} V^2 \frac{\epsilon_0 t l}{\lambda}$$

- e) Calculate the electrical energy input per cycle, assuming that some smart control circuit limits the total charge on the capacitor plates to twice the charge applied initially to the actuator (the zero-deflection charge).

$$\text{Energy input per cycle: } Q * V = 2\epsilon_0 t l V^2 / \lambda$$

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f) What is the energy efficiency of this actuator?

*Energy efficiency: maximum work/energy input =  $2\epsilon_0 t l V^2 / \lambda / (\frac{1}{2} V^2 \frac{\epsilon_0 t l}{\lambda}) = 25\%$*

g) Assuming that you choose the support spring for your gap closing actuator such that when the gap closer has pulled in completely that the spring force is equal to the zero-deflection force of the electrostatic actuator, calculate the resonant frequency of your actuator in terms of only V, l, and r.

$$k_{spring} \lambda = \frac{1}{2} V^2 \frac{\epsilon_0 t l}{\lambda^2}, \text{ so we have } k_{spring} = \epsilon_0 t l V^2 / \lambda^3$$

$$\omega = \text{sqrt}(k_{spring}/m) = \text{sqrt}(\epsilon_0 t l V^2 / \lambda^3 / (\rho \lambda t l)) = \text{sqrt}(\epsilon_0 V^2 / (\rho \lambda^4))$$

*If V=10 Volts,  $\lambda = 2\mu\text{m}$ ,  $f = 25\text{kHz}$ .*

h) Ignoring damping, estimate the maximum power output per kilogram of an electrostatic gap closing actuator.

*Assume driving frequency is around 25kHz,*

$$\text{maximum power output} = \frac{\epsilon_0 V^2}{4 \lambda^3 \rho} \lambda * f_{driving} = 600 \text{W/kg, for } V=10 \text{Volts, } \lambda=2\mu\text{m}.$$

i) Insect flight muscle has a peak power density of 100W/kg, about as high as it gets for animals. Will micro robots based on gap closing electrostatic actuators ever fly?

*Yes.*