Today's Presentation

MEMS Comb Drive Actuator to Vary Tension & Compression of a Resonating Nano-Doubly Clamped Beam for High-Resolution & High Sensitivity Mass Detection

GROUP D

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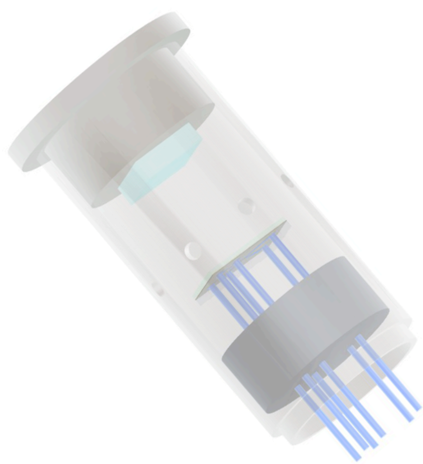
Overview

Contents
Theory & Design
Fabrication
Packaging

Today's presentation will cover the following:

- Application & Functionality
- Types of Actuators
- Theory behind selected Actuator
- Thermal Time Constant
- Fabrication
- Packaging
- Questions



NEMS Resonating Beam

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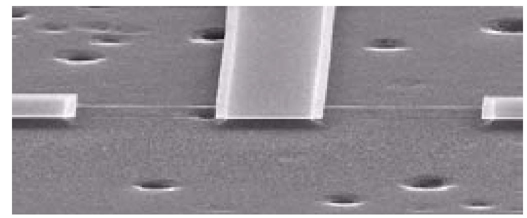
- **Applications**
  - Hyper-sensitive mass detector (hydrogen sensor)
  - Anti bio-terrorism (organic compound sensor)
  - Mechanical signal processing
  - Parametric Amplification



- **Functionality**
  - NEMS Doubly-clamped Au/Pd beam (10 microns x 80nm x 100nm)
  - Resonant frequency shifts as a result of mass loading
  - Detection of frequency shift through magneto-motive technique
  - Frequency shift corresponds to loading or beam dimension changes

MEMS Device for Adjusting Tension of NEMS Resonators

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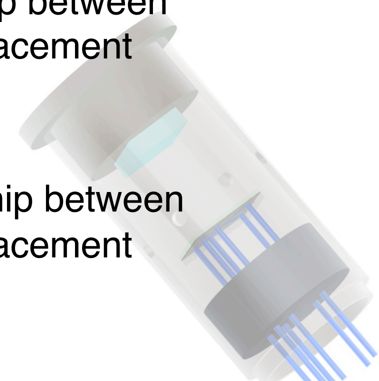
- **Motivation**
  - Residual tensile stresses in beam due to fabrication
  - Increased sensitivity under compressive loading
  - Desired loading +/- 200Mpa
- **MEMS Actuators**
  - Capacitance-driven electrostatic actuator
    - Advantage: Easy fabrication
    - Disadvantage: Non-linear relationship between input voltage and resultant force/displacement
  - Magneto-motive actuator
    - Disadvantage: Semi-linear relationship between input voltage and resultant force/displacement
  - **Comb drive electrostatic actuator**
    - Advantage: Linear relationship between input voltage and resultant force/displacement, simple fabrication



Proposed Comb Drive Design

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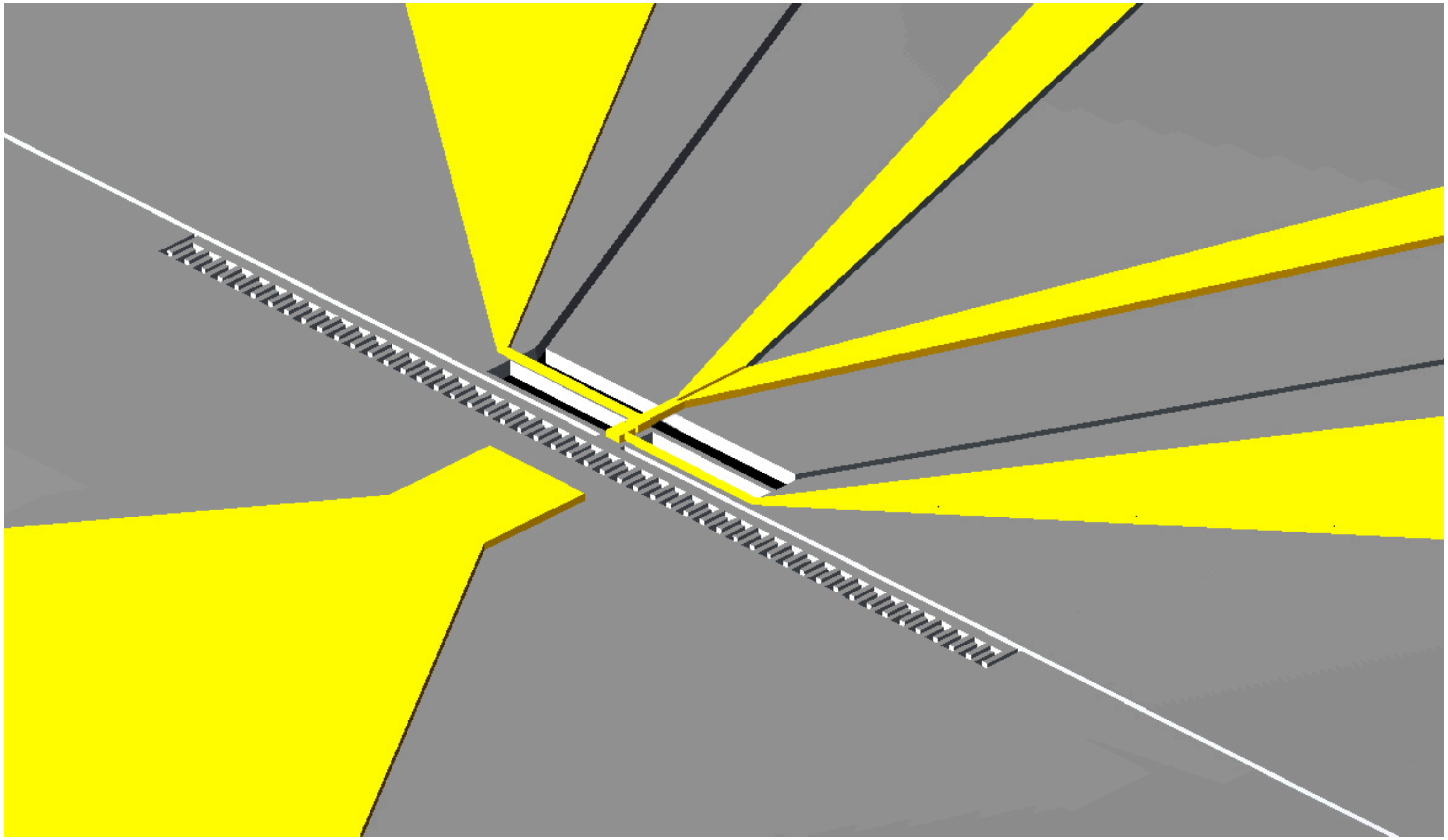

Comb Drive Design

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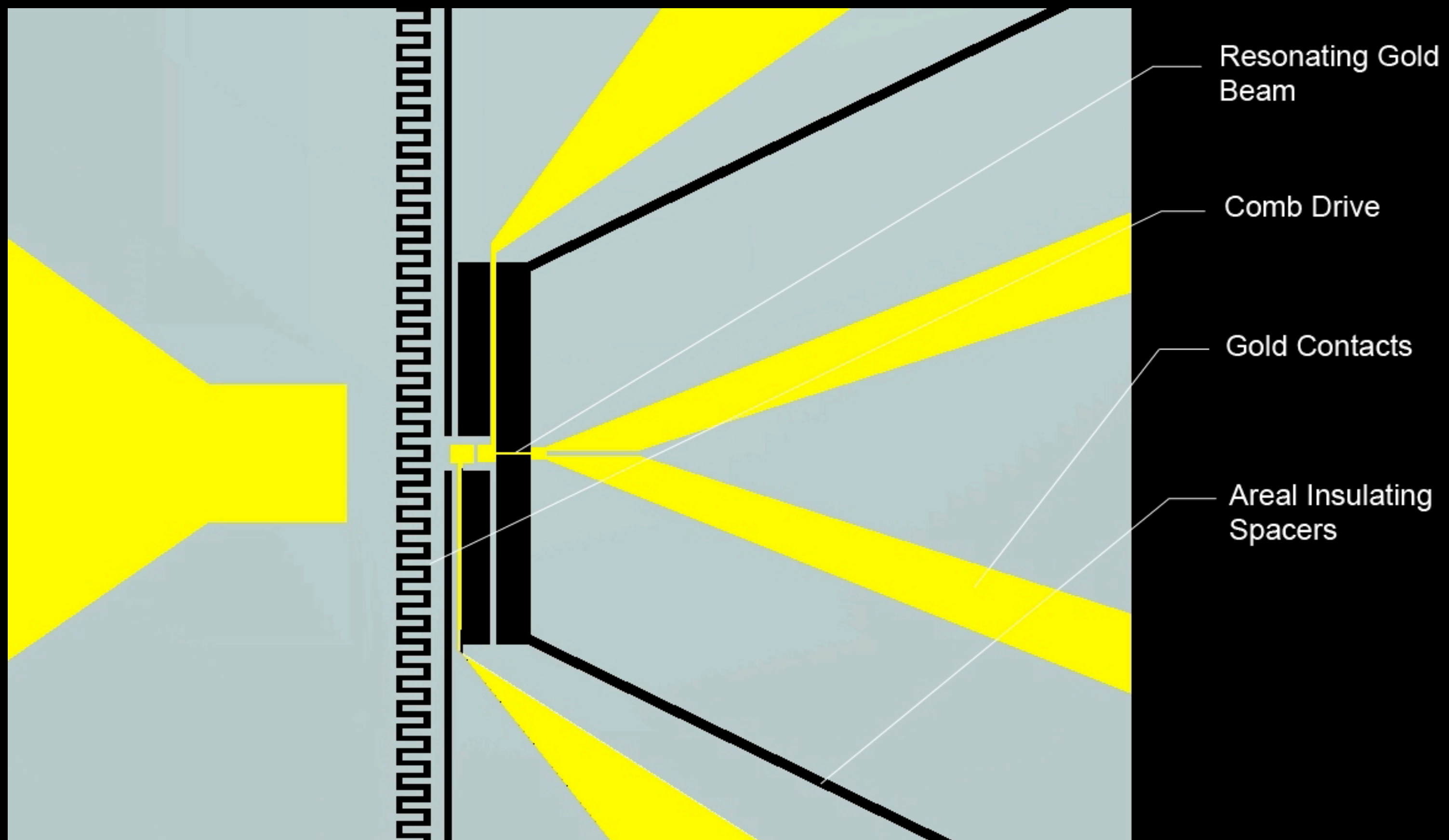

Theory & Design of Comb Drive Electrostatic Actuator

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Resonating Beam Equations:

Required Force on beam is given by: (P = +/- 200MPa)

$$P = \frac{F}{A_{Au/Pd}} \longrightarrow F = 1.6 \text{ micro N}$$

Beam axial deflection under +/- 200 MPa:

$$E_{eAu/Pd} = \frac{E_{Au}A_{Au} + E_{Pd}A_{Pd}}{A_{Au} + A_{Pd}}$$

$$\Delta L = \frac{\sigma}{E_{Au/Pd}} L_0 \longrightarrow L = 25.6\text{nm}$$

Theory & Design of Comb Drive Electrostatic Actuator

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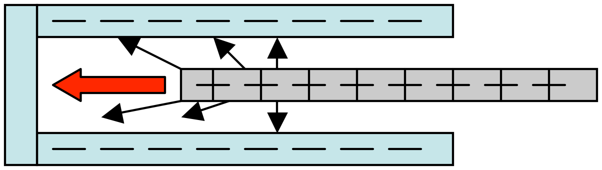
Comb Drive Equations:

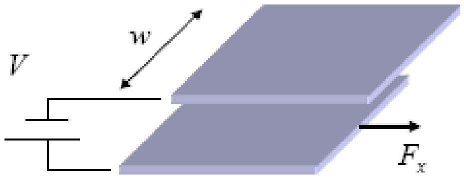
Energy in charged parallel plates:

$$U = \frac{1}{2}\frac{\varepsilon_r \varepsilon_0 A V^2}{d}$$



Differentiating with respect to x (lateral direction):

$$F_x = \frac{\varepsilon_r \varepsilon_0 w V^2}{d}$$



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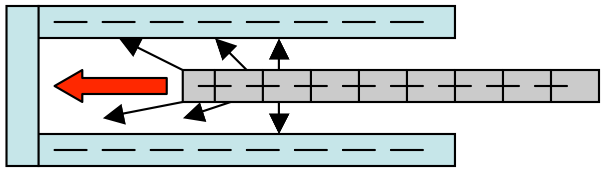
Comb Drive Equations:

Side Instability Voltage:

$$V_{SI} = \frac{d^2 k_y}{2\varepsilon_o bn}\left(\sqrt{2\frac{k_x}{k_y} + \frac{y_o^2}{d^2}} - \frac{y_o}{d}\right)$$



Beams supporting suspended comb drive resonator structure:

$$k_x = \frac{4E_e bh^3}{L^3} \qquad F_x = k_{eff} \cdot x \qquad v(x) = \frac{F}{6E_{eAu/Pd}I}(3x^2 L - x^3)$$

(Assumed to be cantilever beams)

Theory & Design of Comb Drive Electrostatic Actuator

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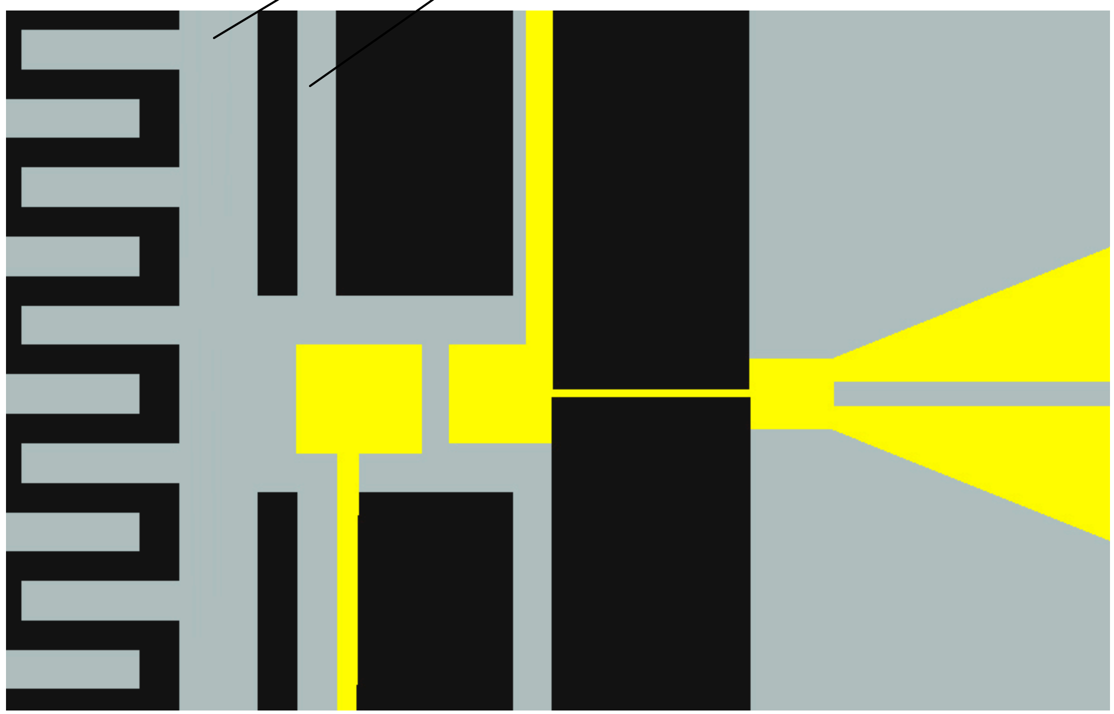
Critical Dimensions Based on Governing Equations:

Comb Drive (50 Fingers): 2 *μ*m x 5 μm x 8 μm

Cantilevered Support Beams: 2 *μ*m x 5 μm x 50 μm



Vertical Displacement due gravity (into page): 96.7pico-m

Side instability voltage: 1320V

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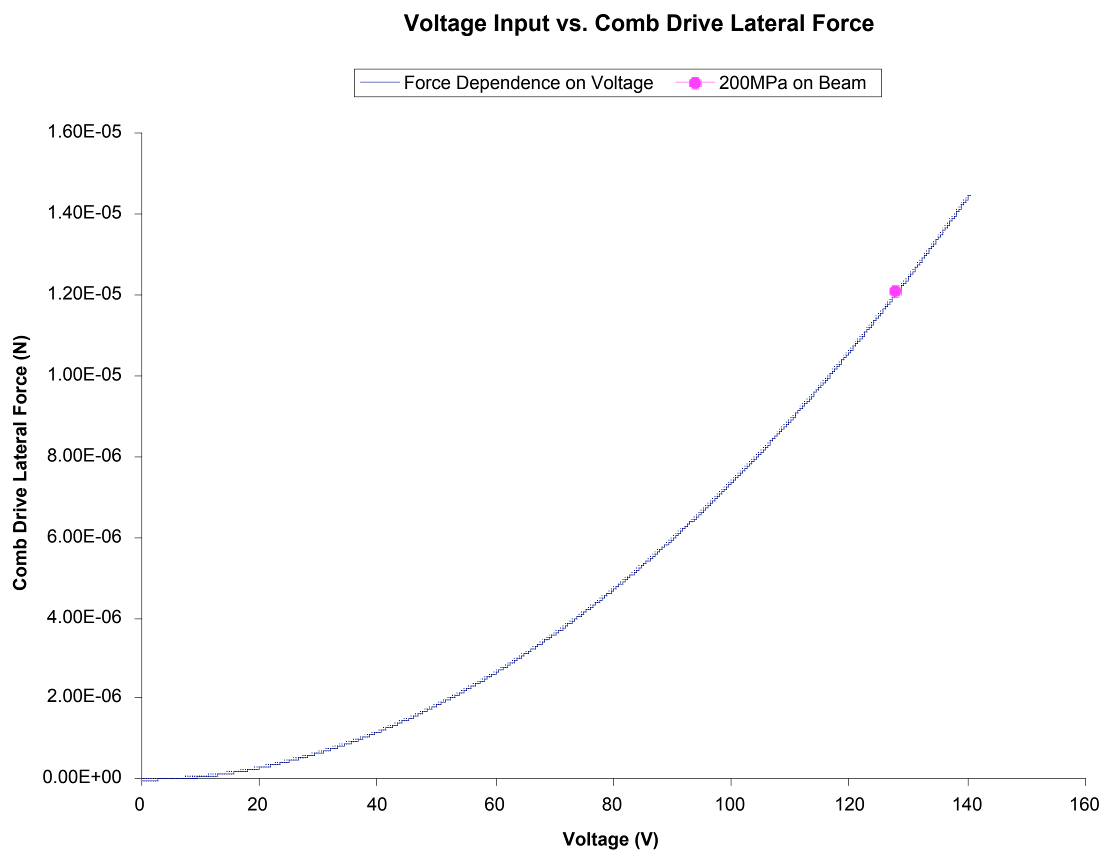
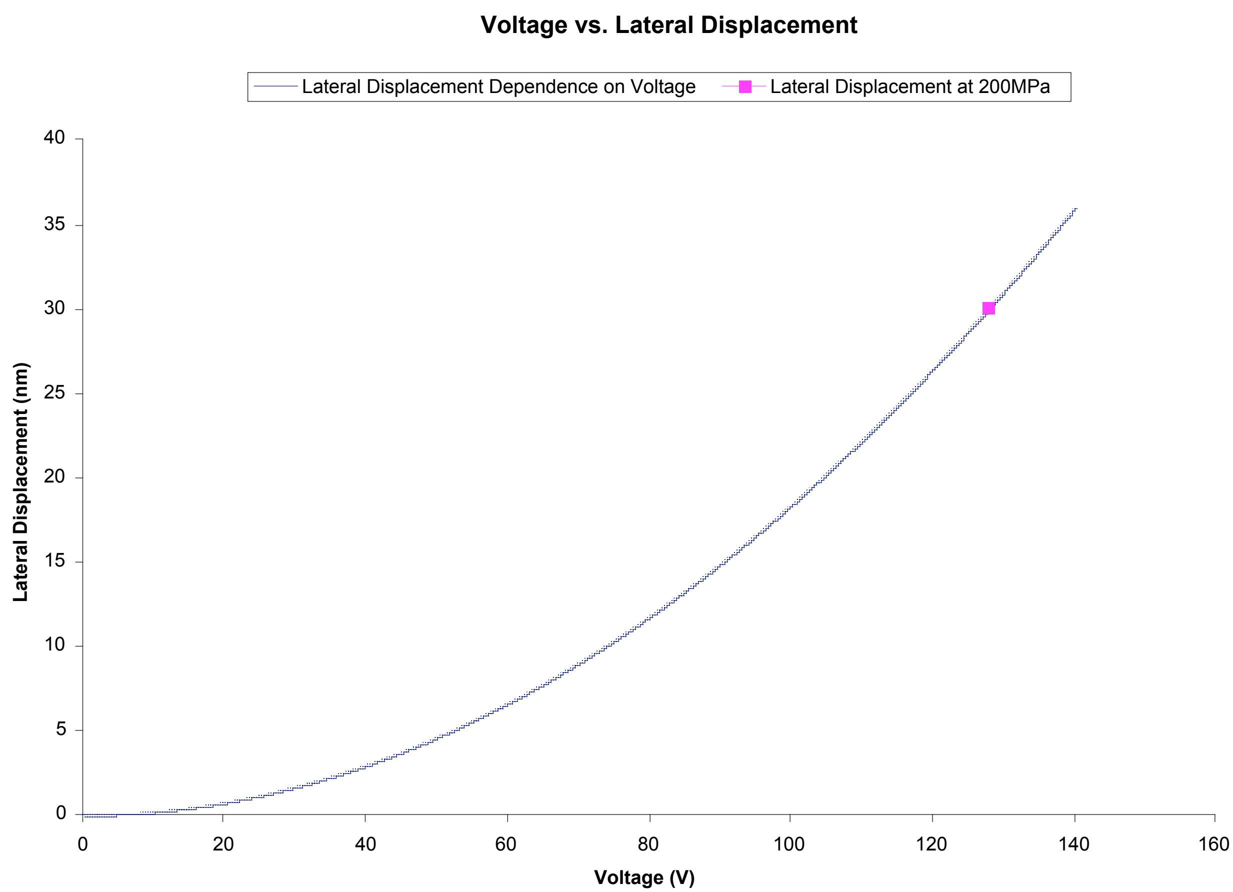
Voltage Input vs. Force:



Theory & Design of Comb Drive Electrostatic Actuator

Voltage Input vs. Lateral Displacement:



Theory & Design: Thermal Time Constant

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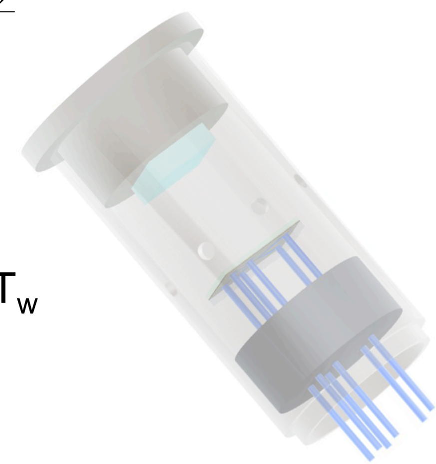
Thermal Time Constant:

• Thermal time constant of an actuator is the measure of time required for actuator to cool to ambient temperature following actuation.

• Speed at which frequency of the beam can be tuned is highly dependant on time constant.

- Heat Flow Equation: $\frac{\partial u}{\partial t} - k\frac{\partial^2 u}{dx^2} = \frac{Q(x,t)}{C_p}$
- Applied DC Current: $I = (Io)*(t)$; $I^2 = (Io)^2*(t)$
  Thus, $Q(x,t) = ((Io)^2*(t)*(R))/(h*w*L)$
- Boundary conditions (1-D): $u(0,t)=T_w$; $u(L,t)=T_w$
  Initial condition: $u(x,0)=T_w$

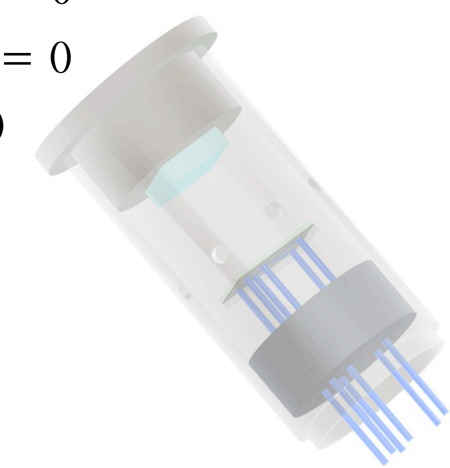


Theory & Design: Thermal Time Constant

- New function: $v(x,t)=u(x,t)-T_w$
  $v(0,t)=T_w-T_w=0$; $v(L,t)=T_w-T_w=0$;
  $v(x,0)=T_w-T_w=0$

- New Heat Flow Equation: $$\frac{\partial v}{\partial t} - k\frac{\partial^2 v}{dx^2} = Q(x,t)$$
  $$B.C.(1): v(0,t) = 0$$
  $$B.C.(2): v(L,t) = 0$$
  $$I.C.: v(x,0) = 0$$

- Eigen-function Expansion: $$v(x,t) = \sum_{n=1}^{\infty} a_n(t$$
  $$where\ \phi_n(x) =$$



Theory & Design of Comb Drive Electrostatic Actuator

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- Sturm-Liouville
- Eigenfunction Expansion<->Heat Flow equation → Generalized Fourier Series Q(x,t).
- Rules of orthogonally (to solve for Fourier coefficients):

$$\frac{da_n}{dt} + \lambda_n k a_n = \frac{\int_0^L Q(x,t)\,\phi_n(x)\,dx}{\int_0^L Q_n^2(x)\,dx} \equiv q_n(t)$$

$$where\ Q(x,t) = \sum_{n=1}^{\infty} q_n($$

- Orthogonally equation continuous. To make it integratable, use the *Integrating Factor:*

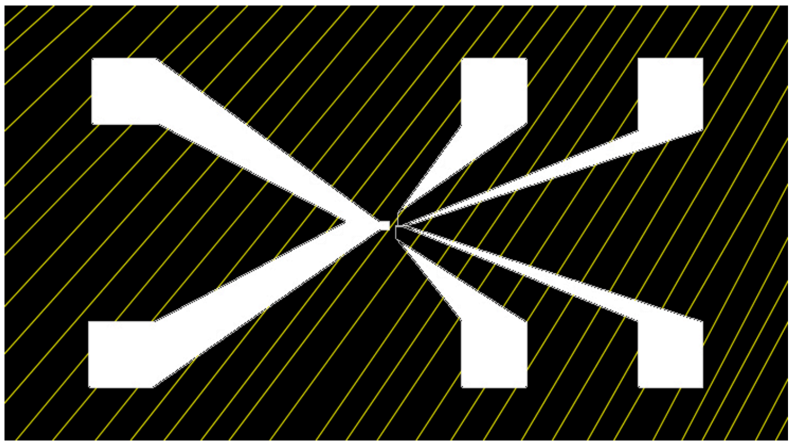
$$e_{-}^{nkt}$$

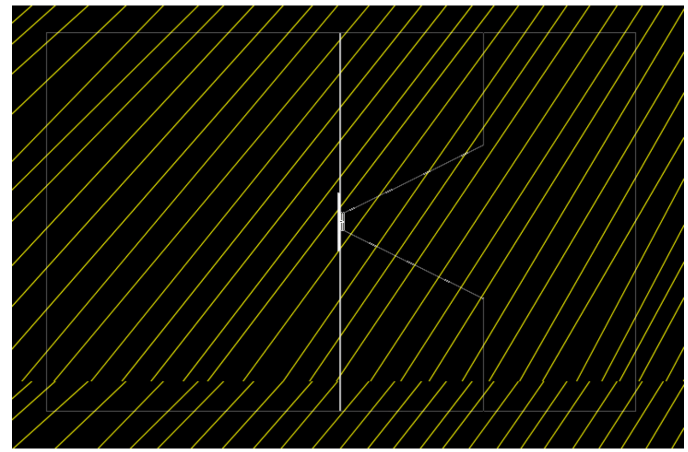
Fourier Coefficient solved →Longest time to reach steady state (n=1 eigenmode) →Thermal time constant = **0.169 micro-seconds**

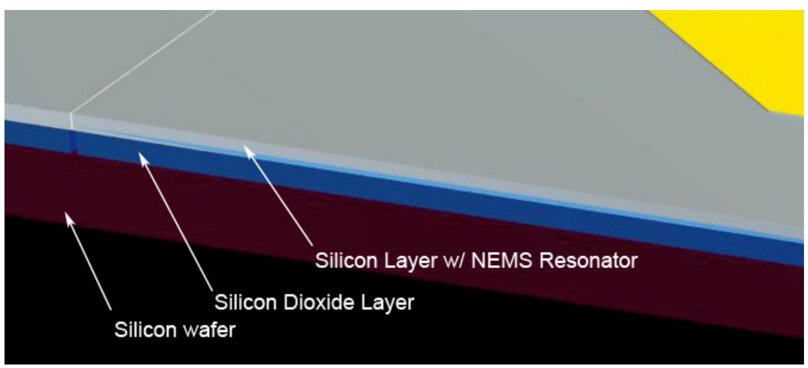
Fabrication

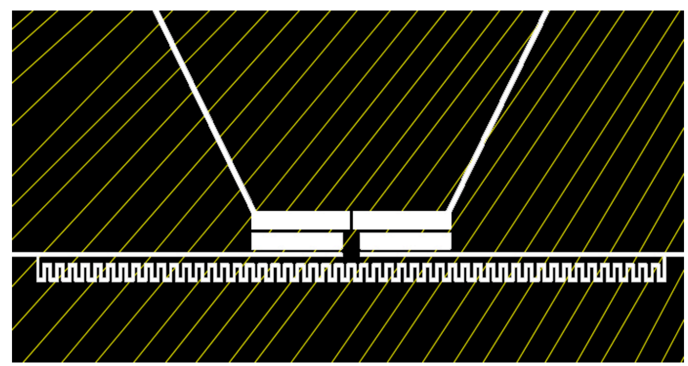
Mask #1: Au/Pd Contacts and Beam

Mask #2: RIE Comb Drives







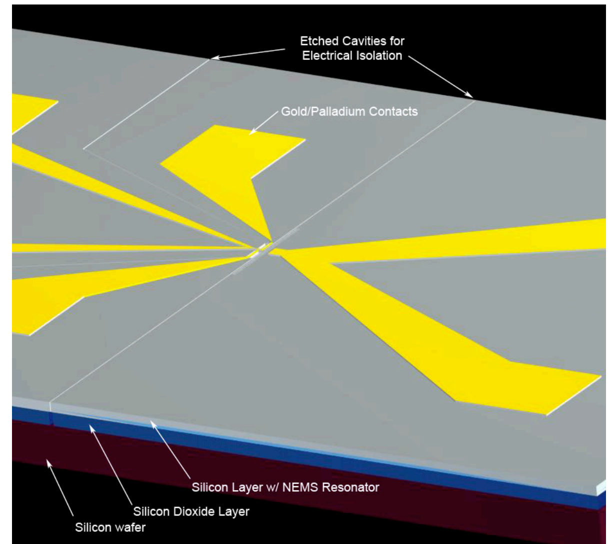


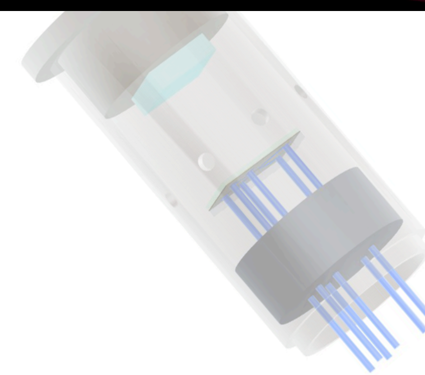
Close-Up View

Fabrication

Process Flow

Step	Description
Starting Materia[l]	SOI (5μm-1μm-125μm)
Clean	Standard RCA clean
Photo Resist	Spin on photoresist
Photolithography	Mask #1 (contacts)
develop	Remove area for contact and beam placement
clean	Standard RCA clean
E-beam evap.	Au/Pd e-beam evaporation to a depth of 80nm
strip	Remove photoresist
clean	Stardard RCA clean
Photo Resist	Spin on photoresist
Photolithography	Mask #2 (basic structure)
develop	Develop and remove used photoresist
etch	RIE to Silicon Dioxide surface
strip	Remove photoresist
clean	Standard RCA clean
Etch (optional)	Optional - if by using SEM we notice the the underside of the beam is not cut, we will purge the system with XeF2
clean	Standard RCA clean
Etch	5:1 BOE etch
Drying	Supercritical CO2 drying
Clean	Standard RCA clean
Contacts	Place contacts. Wire bond to package.
Test	Test structure
Mount	Pryrex mount
Test	Test structure





Proposed Comb Drive Design

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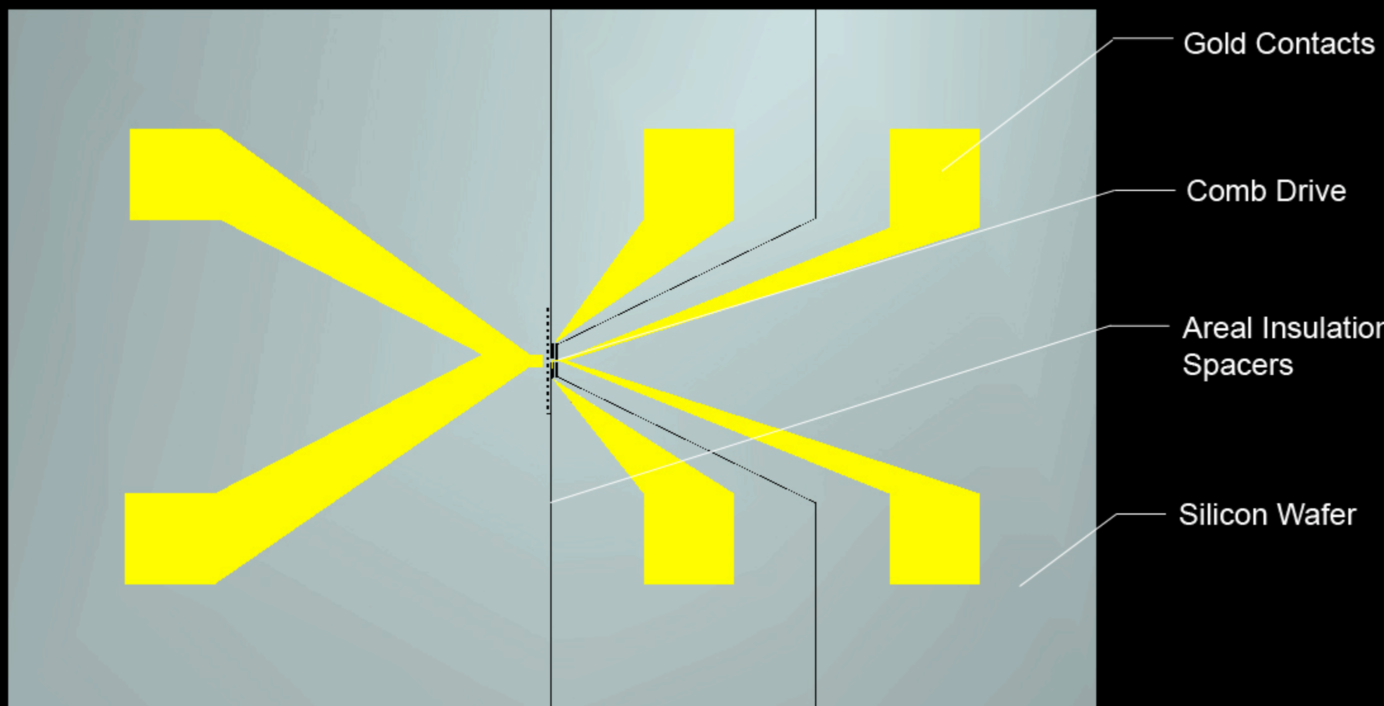

Fabrication to Packaging

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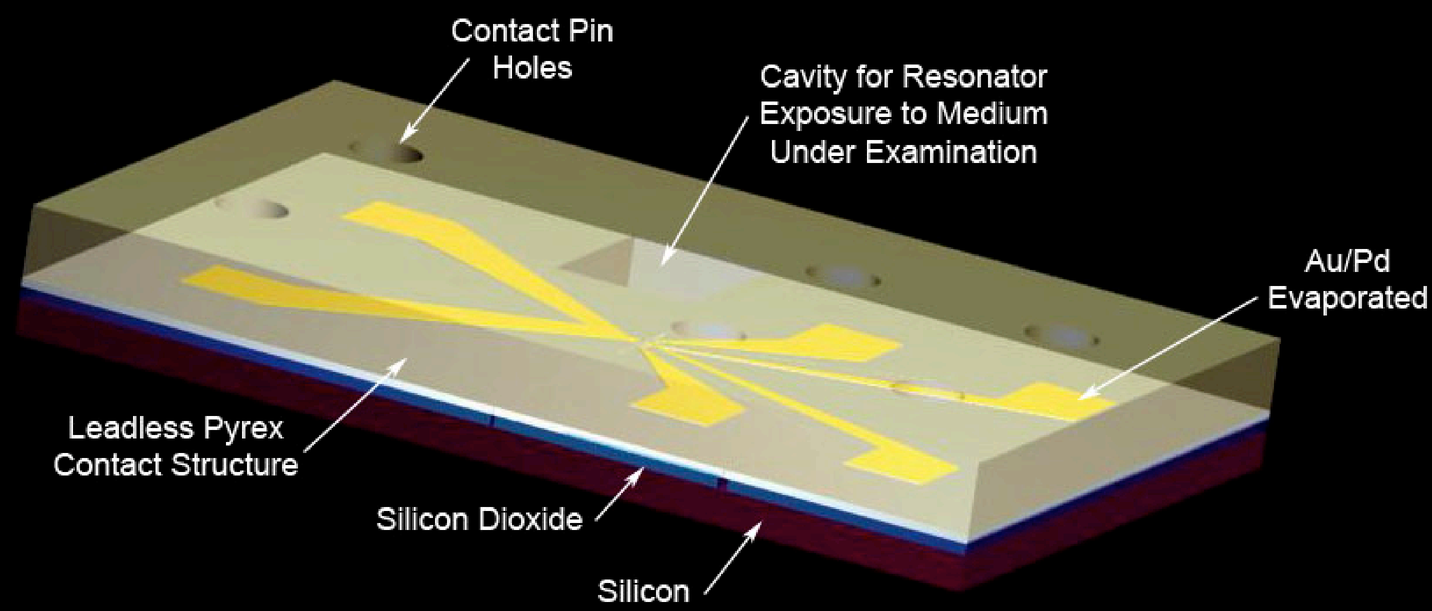

Packaging Solution

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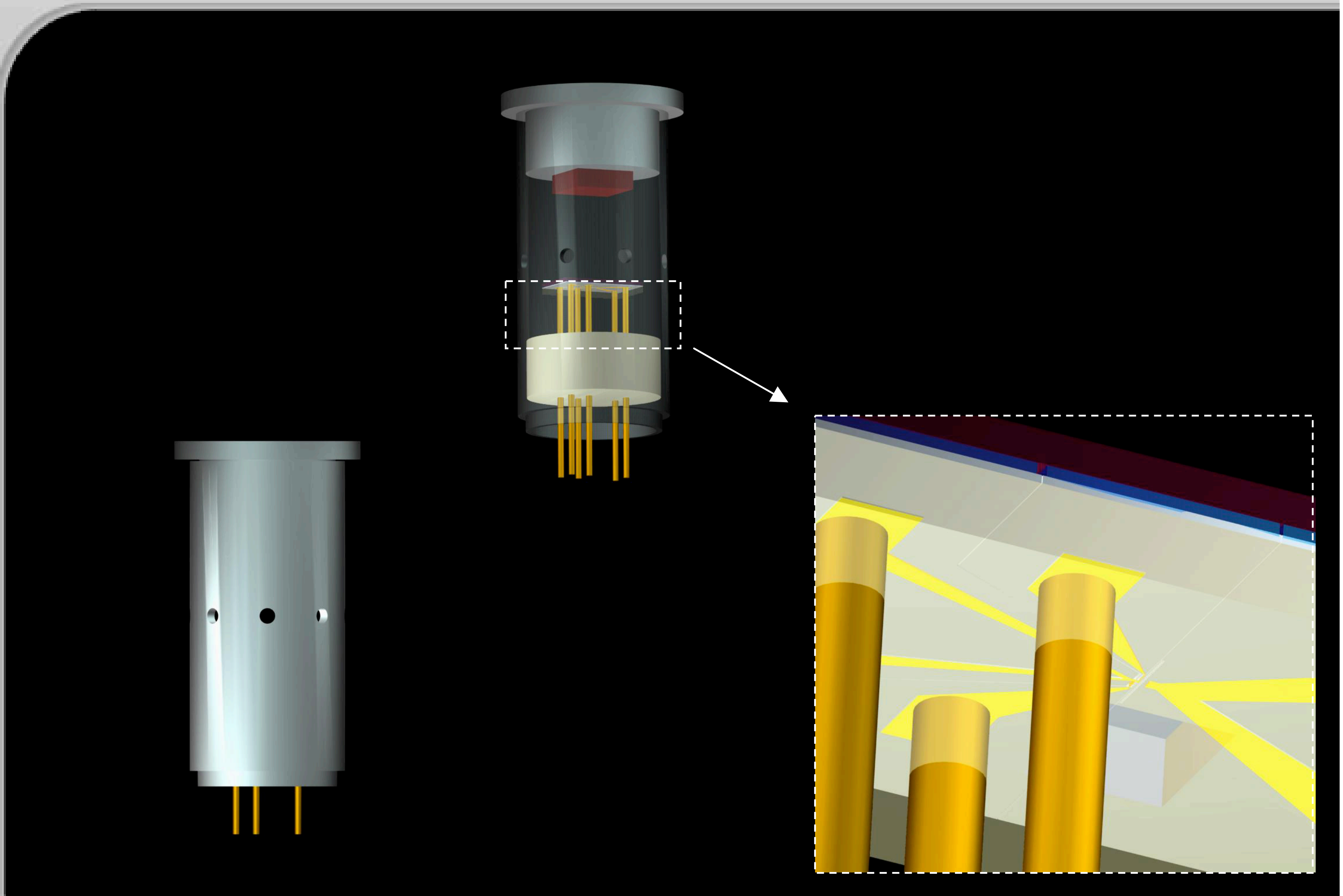
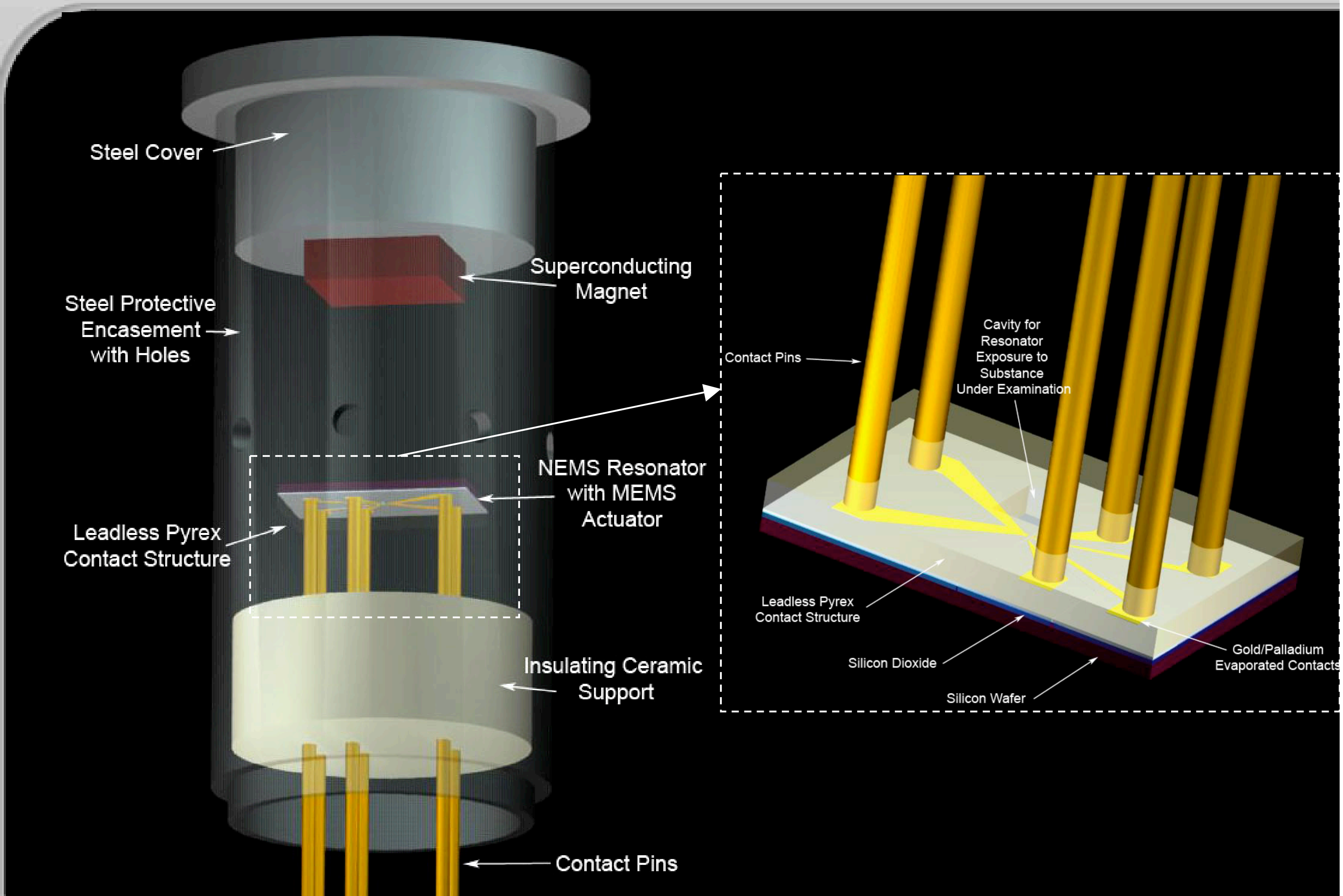
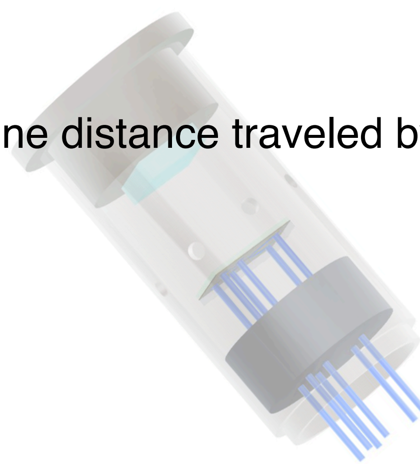


Packaging


Steel Cover
Superconducting Magnet
Steel Protective Encasement with Holes
NEMS Resonator with MEMS Actuator
Leadless Pyrex Contact Structure
Insulating Ceramic Support
Contact Pins
Contact Pins
Cavity for Resonator Exposure to Substance Under Examination
Leadless Pyrex Contact Structure
Silicon Dioxide
Silicon Wafer
Gold/Palladium Evaporated Contacts

Conclusion

- For this application, comb-drive actuator is superior to other mechanisms
- Design will allow accurate and feasible application
- Design will be relatively easy to fabricate using Columbia University resources
- Future Improvements: Feed back loop to determine distance traveled by block structure



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Questions

QUESTIONS?