PARYLENE ELECTROTHERMAL VALVE FOR RAPID IN VIVO DRUG DELIVERY

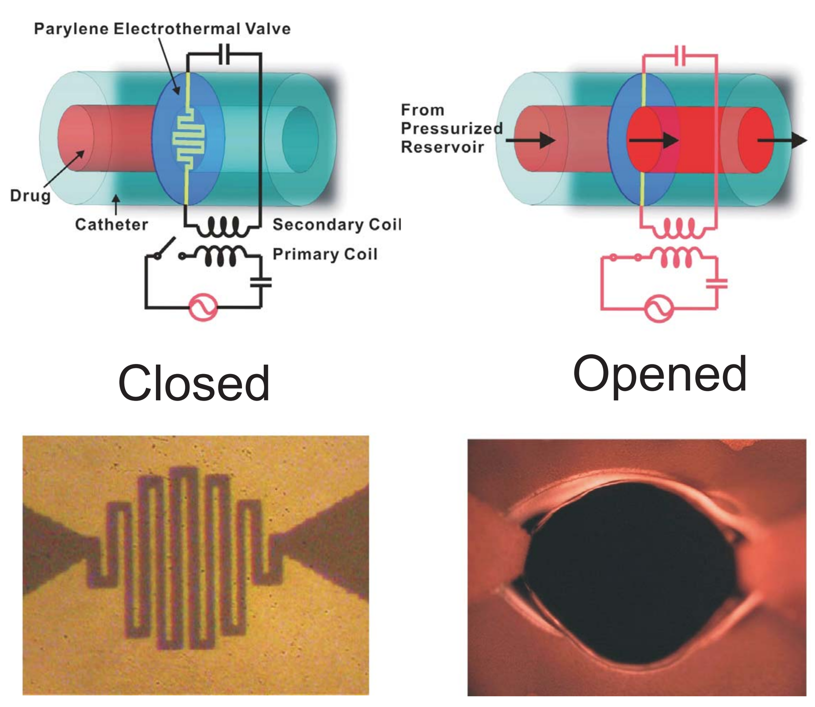
Po-Ying Li[1], Daniel P. Holschneider[2], Jean-Michel I. Maarek[3], and Ellis Meng[3]

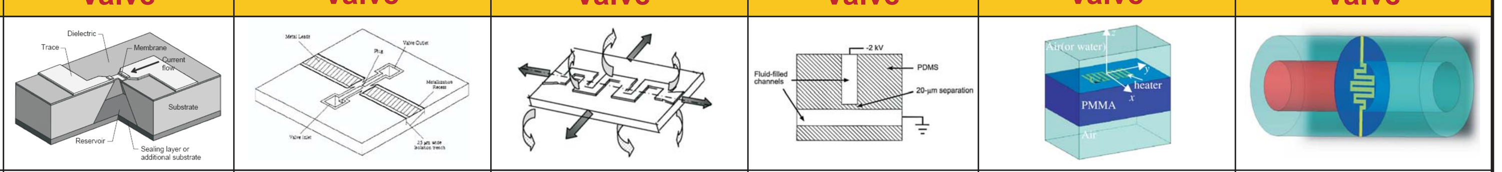
[1]Department of Electrical Engineering, University of Southern California, Los Angeles, USA
[2]Department of Neurology, University of Southern California, Los Angeles, USA
[3]Department of Biomedical Engineering, University of Southern California, Los Angeles, USA

USC UNIVERSITY OF SOUTHERN CALIFORNIA

Motivation for a Parylene as Valve Material[1]

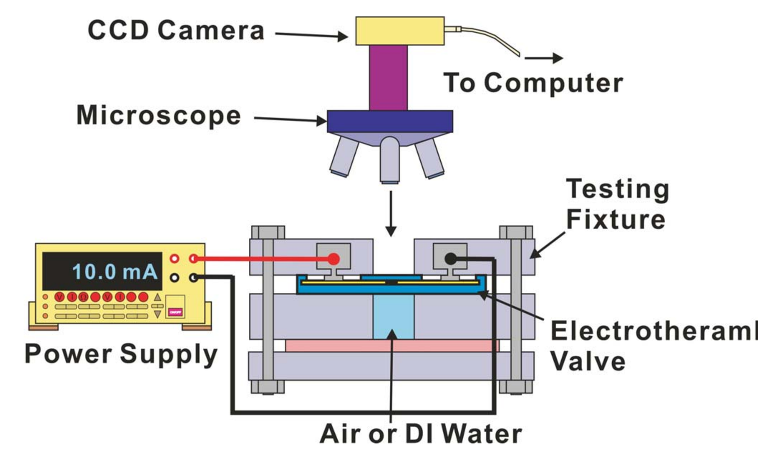
- **Electrothermal valve**
  - Thermal element: Pt, Au, Cu, Ni, ...
  - Membrane: Metal, Si, SiN, and Polymer
- **Previous valve required high power**
  - Pt: 2250 mW[2]
  - Si: 300 mW[3]
  - SiN_x: 16000 mW[4]
  - PDMS: 150 mW[5]
  - PMMA: 67 mW[6]
- **Parylene C as the valve material**
  - USP Class VI material
  - Well established MEMS mataerial
  - Good mechanical strength
  - Thermal properties allow low power consumption
    - ✓ Thermal oxidation temperature = 125 - 200°C
    - ✓ Melting temperature = 290°C
  - Low power consumption (25 mW)

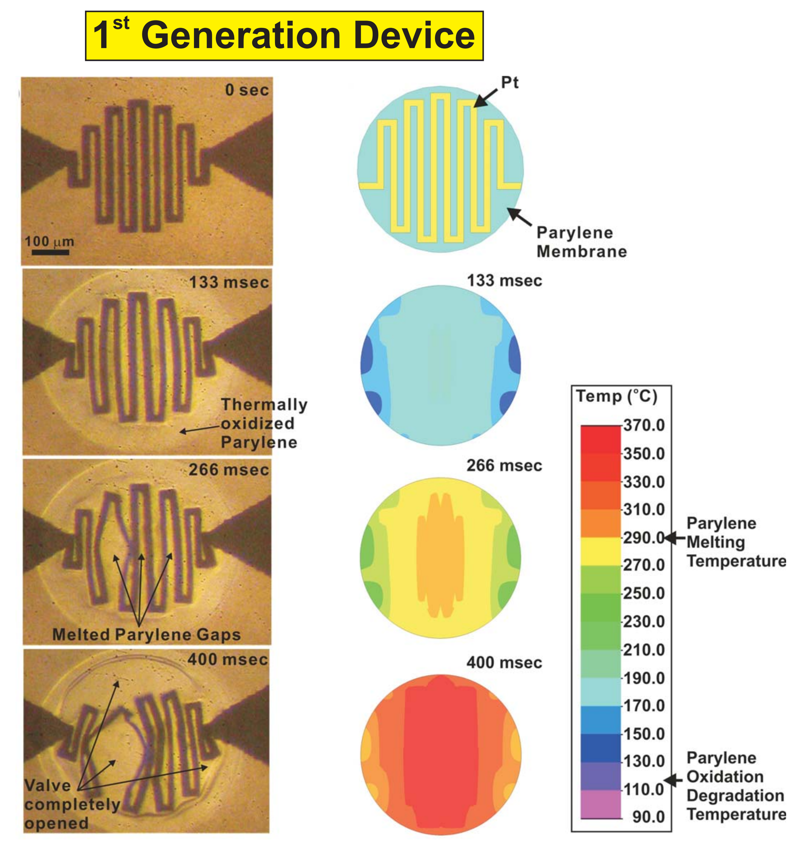


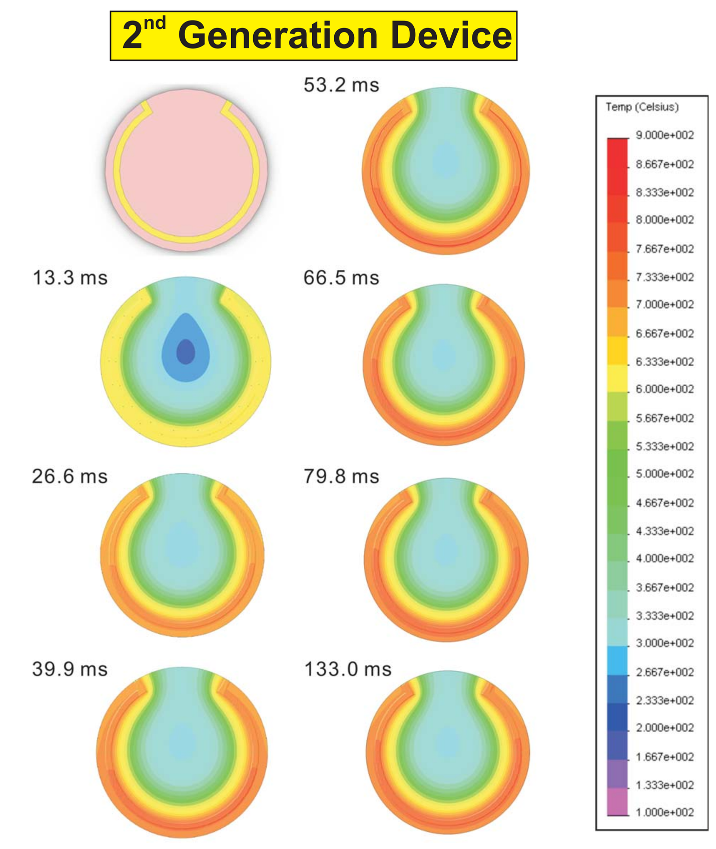
Research	Platinum Drug Reservoir Valve[2]	Silicon Micro Isolation Valve[3]	Nitride Micro Valve[4]	PDMS Channel Valve[5]	PMMA Microheater Valve[6]	Parylene Electrothermal Valve
						
Biocompatible	Yes	No	Yes	No	No	Yes
Rapid delivery	No	Yes	Yes	No	Yes	Yes
Opening Temperature	High (1770°C)	High (1400 °C)	High (1900 °C)	Medium (675 °C)	Medium (490 °C)	Low (290 °C)
Power	High (2250 mW)	High (300mW)	High (16000mW)	Medium (150 mW)	Low (67mW)	Low (25mW)

Thermal Modeling

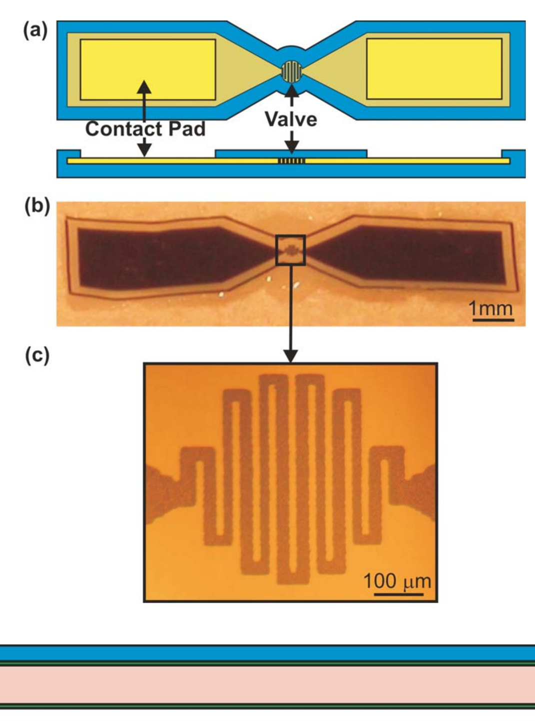
- **Thermal requirements**
  - Rapid valve opening with opening time < 1 sec
  - Uniform heat distribution over entire valve area
- **Transient FEM thermal analysis**
  - Time increment = 133 msec
  - Total run time = 400 msec
- **Valve opening experiment**
  - Time-sequence microscopic images
  - Applied current = 9 mA

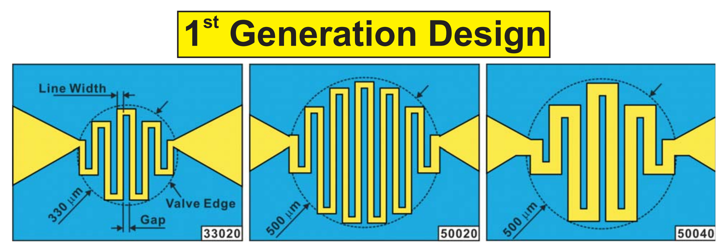


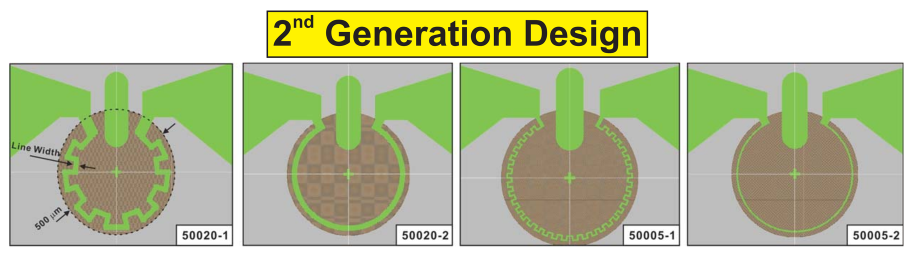


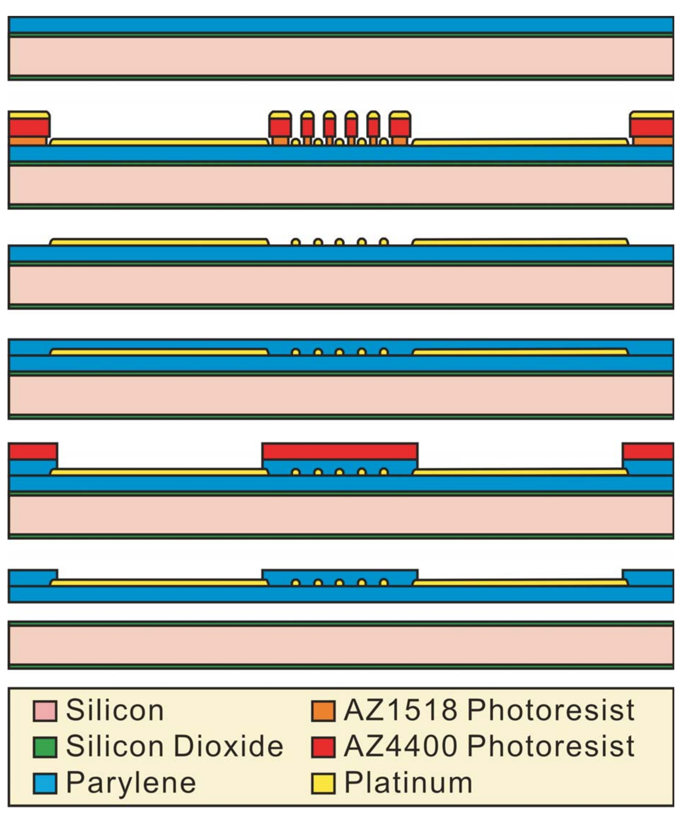


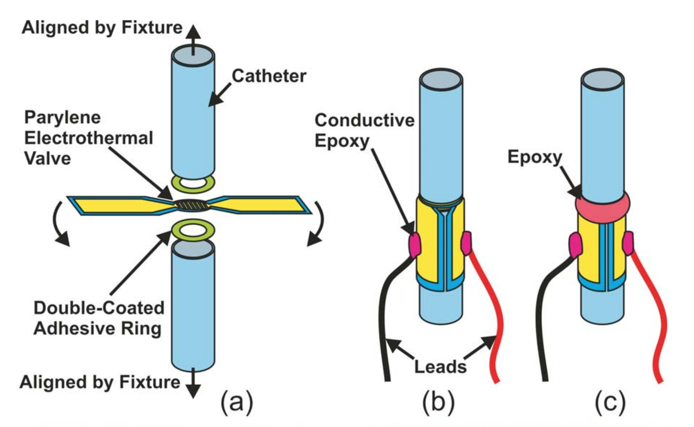
Design, Operation Principle, Fabrication, and Packaging

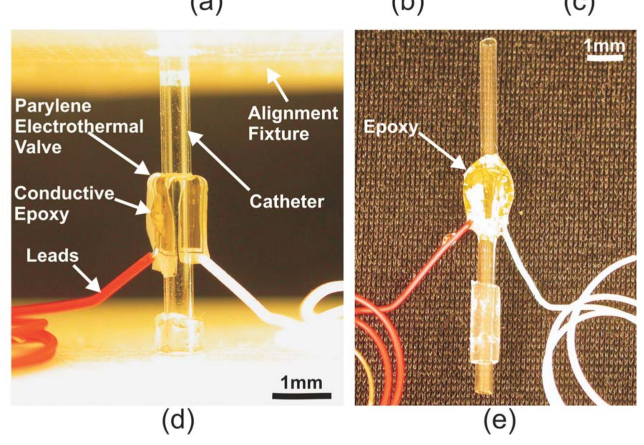




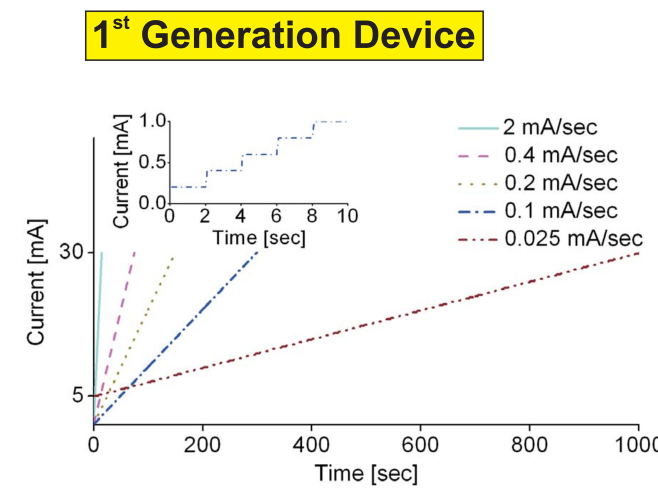


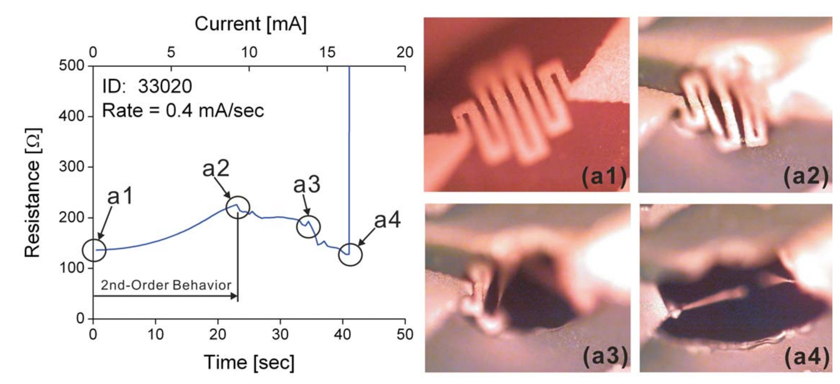




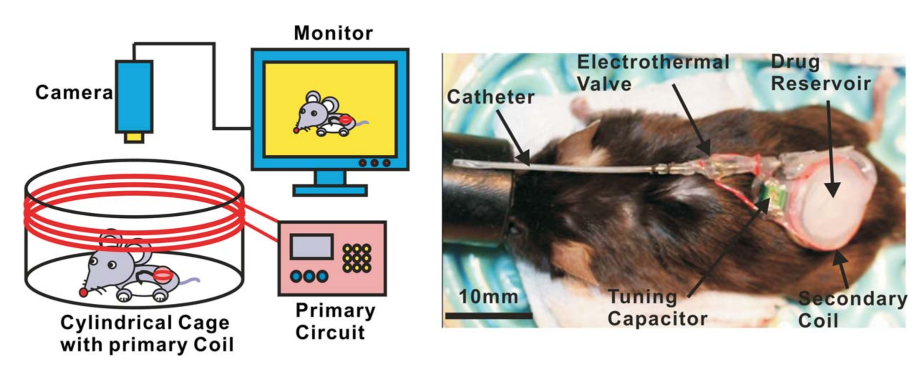


Benchtop and *In Vivo* Experiments





Ramping Rate (mA/sec)	33020	50020	50040
	Open or Not	Open or Not	Open or Not
0.025	O	O	O
0.1	O	O	O
0.2	X	X	O
0.4	O	X	X
2.0	X	X	X



Mechanical Modeling

- **Mechanical requirements**
  - Mouse blood pressure = 110 mmHg
  - Reservoir Pressure
    - ✓ Average = 200 mmHg
    - ✓ Instant = ~760 mmHg
- **Large deflection theory[7]**
  - Circular clamped thin plate
  - Uniform pressure
- **Nonlinear FEM analysis**
  - Nonlinear static module
- **Load-deflection experiment**
  - Pressure = 2.5 - 15 psi
  - Max deflection at center

Large deflection approximation [von Karman, 1910]

1. Nonlinear strain-displacement relations

$$\varepsilon_x = \frac{\partial u}{\partial x} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2$$
$$\varepsilon_y = \frac{\partial v}{\partial y} + \frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2$$
$$\gamma_x = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} + \frac{\partial w}{\partial x}\frac{\partial w}{\partial y}$$

2. Governing differential equations for large deflections of thin plates

$$\frac{\partial^4 \phi}{\partial x^4} + 2\frac{\partial^4 \phi}{\partial x^2 \partial y^2} + \frac{\partial^4 \phi}{\partial y^4} = E\left[\left(\frac{\partial^2 w}{\partial x \partial y}\right)^2 - \frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2}\right]$$
$$\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{t}{D}\left[\frac{p}{t} + \frac{\partial^2 \phi}{\partial y^2}\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 \phi}{\partial x^2}\frac{\partial^2 w}{\partial y^2} - 2\frac{\partial^2 \phi}{\partial x \partial y}\frac{\partial^2 w}{\partial x \partial y}\right]$$

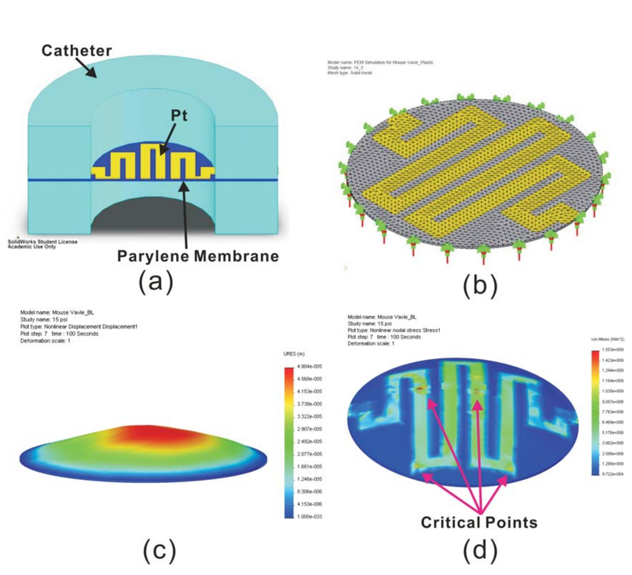
3. Strain energy method

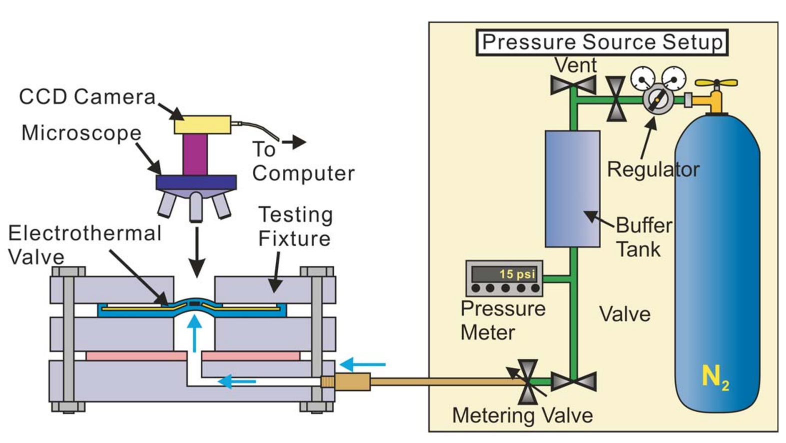
$$V = \frac{Et}{2(1-\nu^2)}\iint\left[\varepsilon_x^2 + \varepsilon_y^2 + 2\nu\varepsilon_x\varepsilon_y + \frac{1}{2}(1-\nu)\gamma_{xy}^2\right] dxdy$$

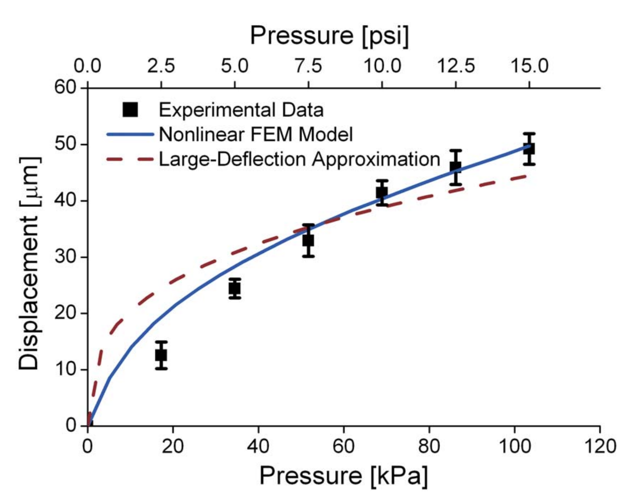
4. Solutions for clamped circular plate subject to a uniform load p_o

i. General $$\frac{p_o a^4}{64D} = w_{max}\left[1 + 0.488\left(\frac{w_{max}}{t}\right)^2\right]$$

ii. Very thin case $$\boxed{\frac{p_o a^4}{64\,Dt} = 0.488\left(\frac{w_{max}}{t}\right)^3}$$







Conclusion

- Developed two single-use, low power Parylene MEMS electrothermal valves for *in vivo* functional neuroimaging
- Second design optimized valve performance through simple geometry change
- Performed fabrication, packaging, modeling, and benchtop experiments
- Successfully performed preliminary *in vivo* study

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Acknowledgments

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