Design choices: MEMS actuators

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With thanks to Prof. S. Mark Spearing, from whose work some of this material is obtained.

Outline

> **Sorting through design options**

> **Actuator characteristics, examples of actuators, and theoretical and practical limits**

- **Electrostatic**
- **Thermal**
- **Piezoelectric**
- **Magnetic**

Motivation

- We now have lots of domain knowledge that we can apply to decide whether a particular design is good enough for a particular application
- How do you develop your intuition about which approaches are likely to meet the needs of a given application?
  - Experience?
  - Literature search?
- One approach: borrow the concept of design charts, a tool commonly used at the macroscale for basic design choices (which material to choose?)
- D.J. Bell, T.J. Lu, N.A. Fleck, and S.M. Spearing, "MEMS Sensor and Actuator Selection: Database and Case Study", J. Micromechanics and Microengineering, v 15, p. S153, 2005.

Sample Materials Comparison Chart

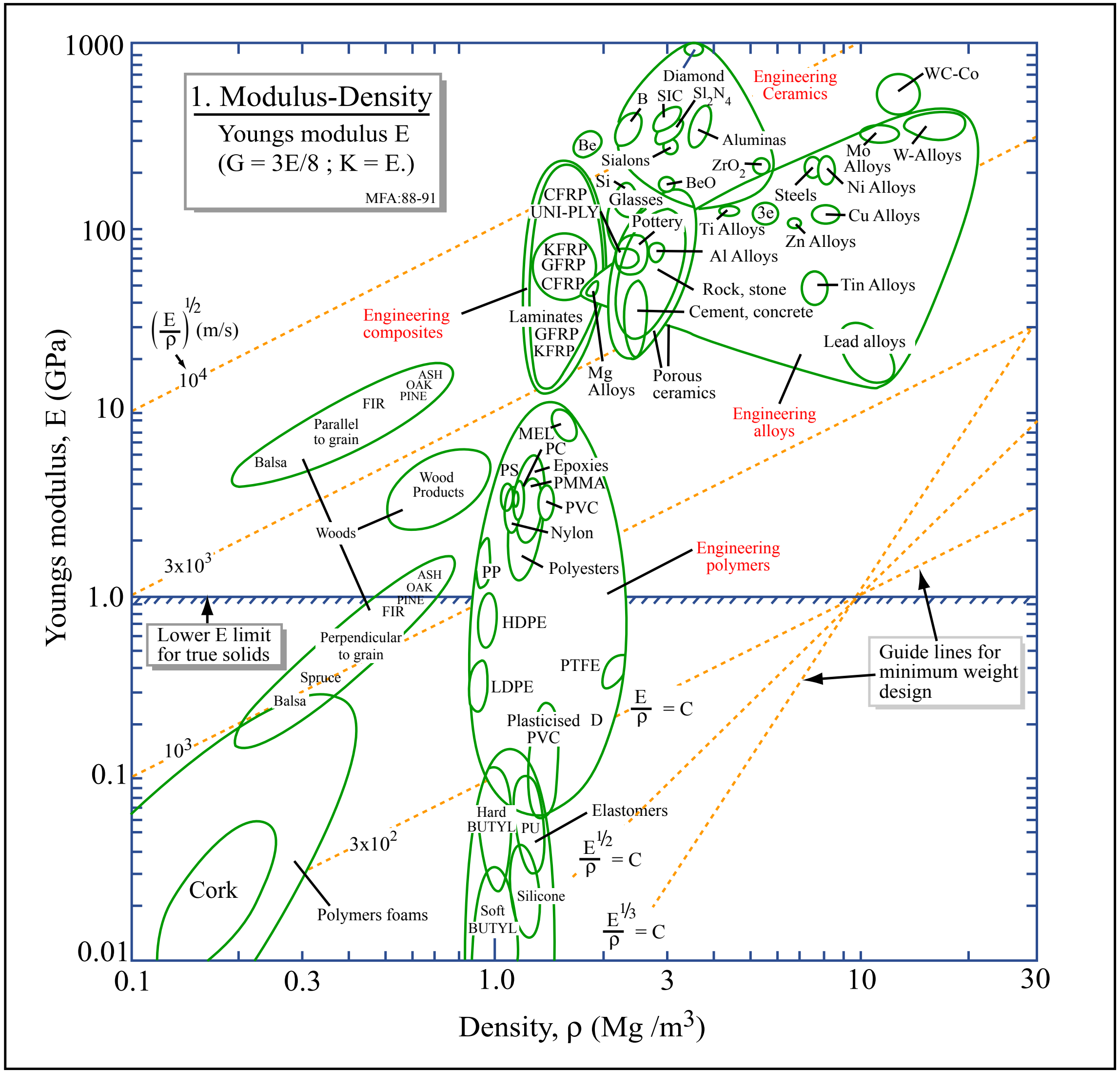


Image by MIT OpenCourseWare.

Adapted from Ashby, M. F. Material Selection in Mechanical Design. Boston, MA: Butterworth-Heinemann, 1995. ISBN: 9780750627276.

Material Selection in Mechanical Design, M.F Ashby, Pergamon Press, Oxford, 1995.

Different criteria for different actuator applications

> **Nanopositioners**

- **Speed, resolution, range, repeatability, robustness against disturbances, ability to sense as well as actuate…**

> **Micro mechanical testing apparatus**

- **Range of motion, force, ability to sense as well as actuate, speed…**

> **RF MEMS**

- **Speed, range of motion, force, power dissipation, voltage required, ability to sense as well as actuate…**

RF MEMS Approach

> **Active RF circuit components**
- **Implement through CMOS compatible circuits**

> **Reconfigurable system that allows multiple functionalities**
- **MEMS ohmic contact switches with low losses and good isolation and linearity**
- **MEMS variable capacitors (instead of CMOS capacitors)**

> **Integrate passive components in place, saving space in the overall system**

> **Some issues:**
- **Reliability can be an issue for MEMS switches (accumulated damage to contacting surface)**
- **Limited capacitance range for MEMS variable capacitors, though losses are low, and linearity and high power performance are good**

RF MEMS Components

- **Switches and relays open circuits, close circuits, or connect signals to ground**
  - **Includes RF signal electrodes and actuating electrodes**
  - **If the actuating signal and the RF signal exist on the same pair of electrodes, it's a switch**
  - **If the actuating signal and the RF signal exist on different sets of electrodes, it's a relay**
- **Variable capacitors can be tuned continually over their range**
- **Switchable capacitors can switch between two discrete capacitance values**
- **Resonators vibrate at a particular (often tunable) frequency and are useful for filters**
- **Components use a common set of actuation mechanisms**

The Wish List for RF MEMS

- **Low power operation**
- **Fast switching**
- **High force (especially for making electrical contact)**
- **Large analog-controllable actuator travel**
- **Simple fabrication**
  - **Few masks**
  - **Standard, CMOS-compatible processes and materials**
  - **Ability to be fabricated on the same chip as circuits**
- **Low voltage**
- **Robust operation, not prone to failures**
- **Ability to sense as well as actuate**

Outline

> **Sorting through design options**

> **Actuator characteristics, examples of actuators, and theoretical and practical limits**

- **Electrostatic**
- **Thermal**
- **Piezoelectric**
- **Magnetic**

Major Classes of MEMS Actuators

> **Electrostatic**

- **Attraction between oppositely charged conductors**

Figure 1 on p. 222 in Agrawal, V. "A Latching MEMS Relay for DC and RF Applications." *Electrical Contacts-2004: Proceedings of the 50th IEEE Holm Conference on Electrical Contacts; The 22nd International Conference on Electrical Contacts, Seattle, WA*. Piscataway, NJ: IEEE, 2004, pp. 222-225. ISBN: 9780780384606. © 2004 IEEE.

Image removed due to copyright restrictions. Figure 11 on p. 342 in Zavracky, P. M., N. E. McGruer, R. H. Morrison, and D. Potter. "Microswitches and Microrelays with a View Toward Microwave Applications." *International Journal of RF and Microwave Computer-Aided Engineering* 9, no. 4 (1999): 338-347.

> **Thermal**

- **Displacement due to thermal expansion**

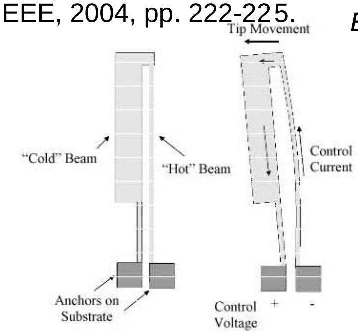


Image removed due to copyright restrictions. 4 actuators displayed side-by-side to show how small they are.

> **Piezoelectric**

- **Displacement due to strain induced by an electric field**

> **Magnetic**

- **Displacement due to interaction among various magnetic elements: permanent magnets, external magnetic fields, magnetizable material, and current-carrying conduct**

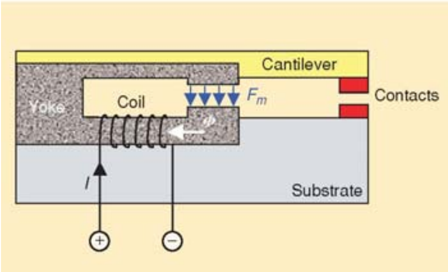
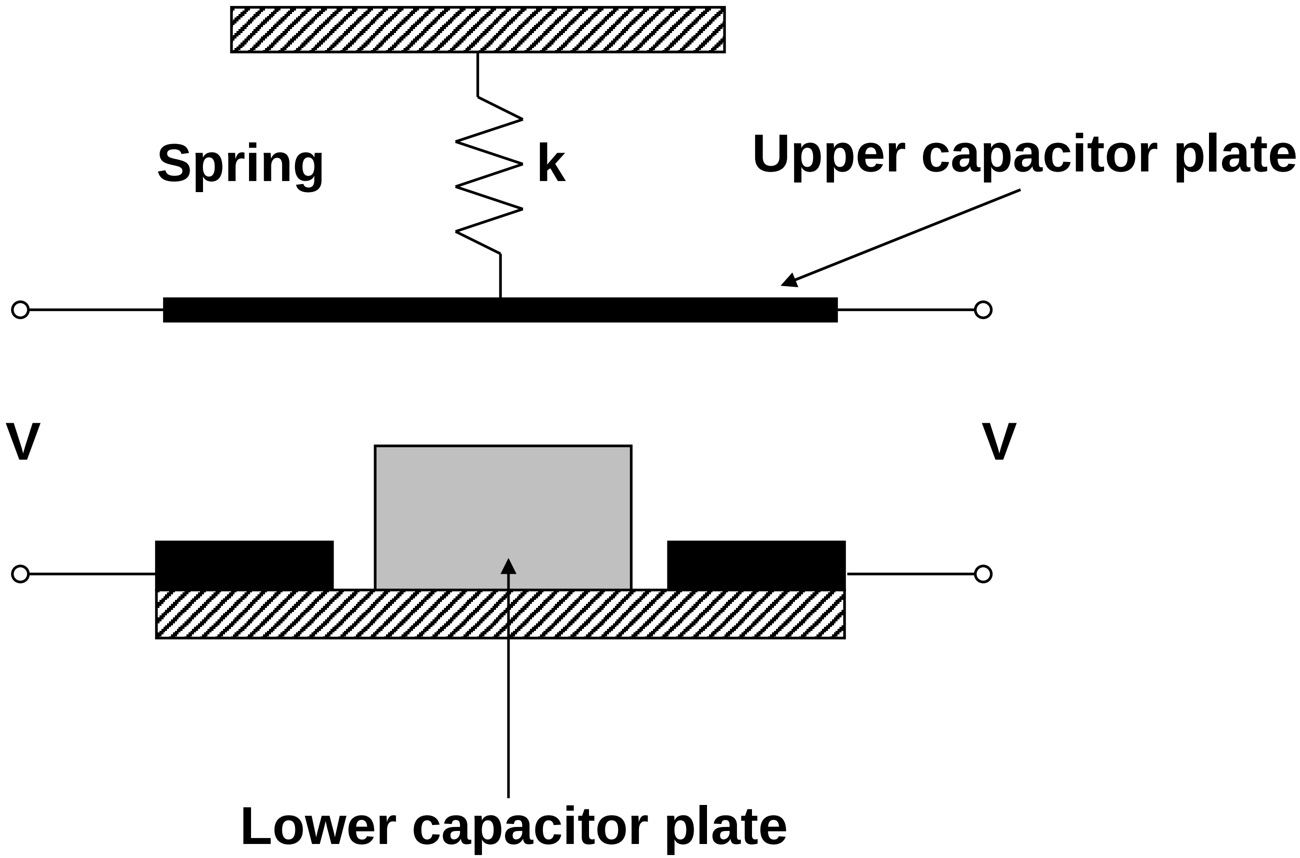


Figure 8 on p. 43 in De Los Santos, H. J., G. Fischer, H. A. C. Tilmans, and J. T. M. van Beek. "RF MEMS for Ubiquitous Wireless Connectivity. Part I. Fabrication." *IEEE Mirowave Magazine* 5, no. 4 (December 2004) 36-49. © 2004 IEEE.

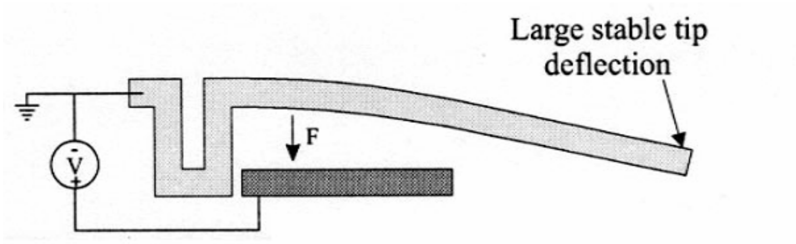
Recessed Actuation Electrodes



Gaining Additional Travel with Leveraged Bending

> **Pull-in is modified if the actuating electrodes are away from the point of closest approach**

1)



2)

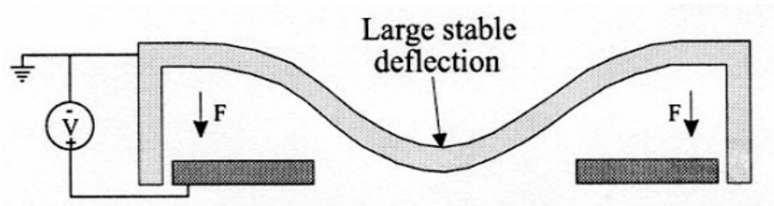
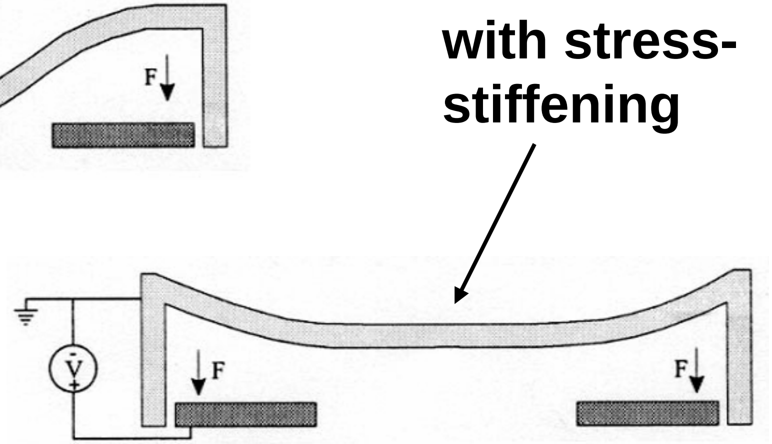


Figure 3 on p. 499 in Hung, E. S., and S. D. Senturia. "Extending the Travel Range of Analog-tuned Electrostatic Actuators." *Journal of Microelectromechanical Systems* 8, no. 4 (December 1999): 497-505. © 1999 IEEE.

3)



Zipper electrostatic actuators

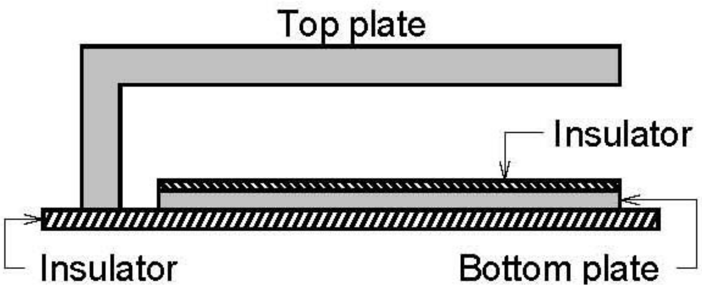
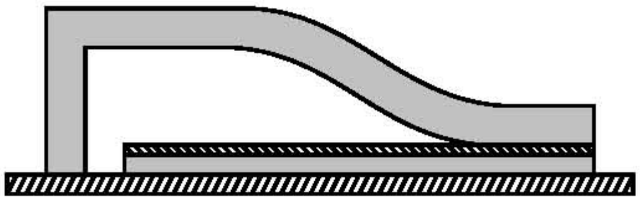
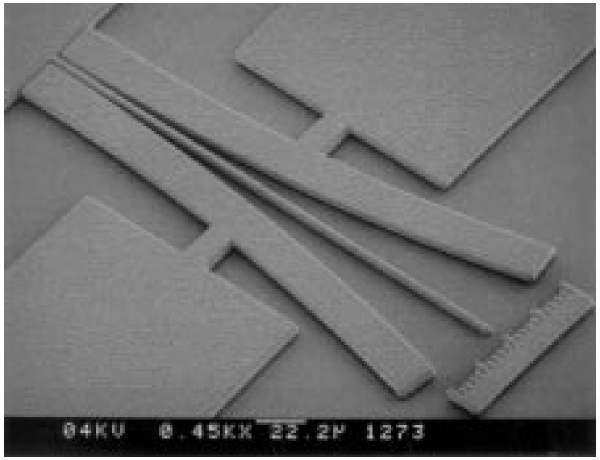


Figure 1 on p. 29 in Ionis, G. V., A. Dec, and K. Suyama. "A Zipper-action Differential Micro-mechanical Tunable Capacitor." *MEMS 2001: 2001 Microelectromechanical Systems Conference, Berkeley, CA, August, 24-26, 2001*. New York, NY: Institute of Electrical and Electronics Engineers, 2002. ISBN: 9780780372245. © 2002 IEEE.



Variable capacitor for RF

Figure 2 on p. 30 in Ionis, G. V., A. Dec, and K. Suyama. "A Zipper-action Differential Micro-mechanical Tunable Capacitor." *MEMS 2001: 2001 Microelectromechanical Systems Conference, Berkeley, CA, August, 24-26, 2001*. New York, NY: Institute of Electrical and Electronics Engineers, 2002. ISBN: 9780780372245. © 2002 IEEE.



Curved electrode actuators

Figure 10 on p. 263 in Legtenberg, R., J. Gilbert, S. D. Senturia, and M. Elwenspoek. "Electrostatic Curved Electrode Actuators." *Journal of Microelectromechanical Systems* 6, no. 3 (September 1997): 257-265. © 1997 IEEE.

Comb Drive Application: Variable Capacitor

Figure 2 on p. 126 in Yao, J. J., S. Park, and J. DeNatale. "High Tuning-ratio MEMS-based Tunable Capacitors for RF Communications Applications." *1998 Hilton Head Workshop on Solid-State Sensors and Actuators, Technical Digest 98TRF-0001*.

Area-tuning capacitor made by deep reactive ion etching. Tuning with area rather than gap promotes stability and tuning range, but fabrication is more challenging and expensive.

Electrostatic inchworm actuatorss

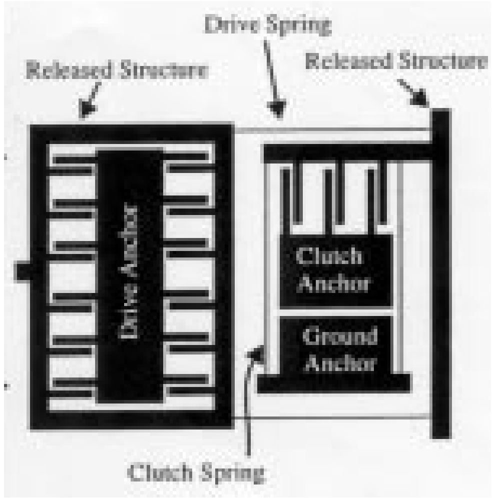


Figure 4d on p. 332 in Yeh, R., S. Hollar, and K. S. J. Pister. "Single Mask, Large Force, and Large Displacement Electrostatic Linear Inchworm Motors." *Journal of Microelectromechanical Systems* 11, no. 4 (August 2002): 330-336. © 2002 IEEE.

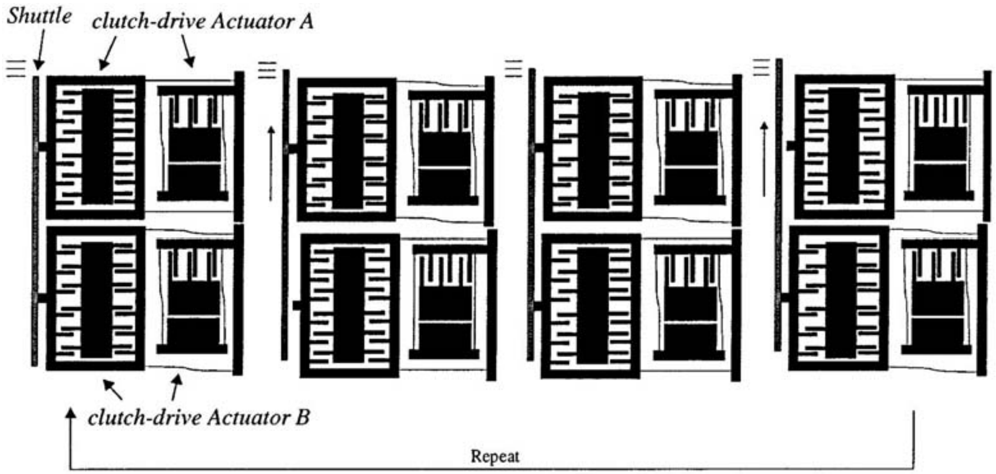


Figure 5 on p. 333 in Yeh, R., S. Hollar, and K. S. J. Pister. "Single Mask, Large Force, and Large Displacement Electrostatic Linear Inchworm Motors." *Journal of Microelectromechanical ystems* 11, no. 4 (August 2002): 330-336. © 2002 IEEE.

Inchworm (more travel by repeated motion)

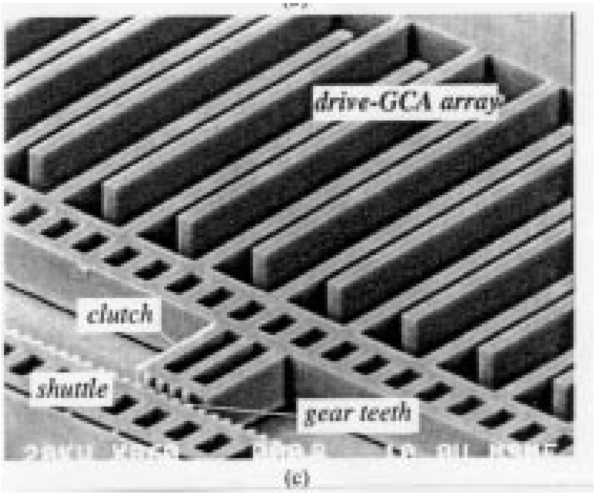


Figure 4c on p. 332 in Yeh, R., S. Hollar, and K. S. J. Pister. "Single Mask, Large Force, and Large Displacement Electrostatic Linear Inchworm Motors." *Journal of Microelectromechanical Systems* 11, no. 4 (August 2002): 330-336. © 2002 IEEE.

Electrostatic distributed actuators

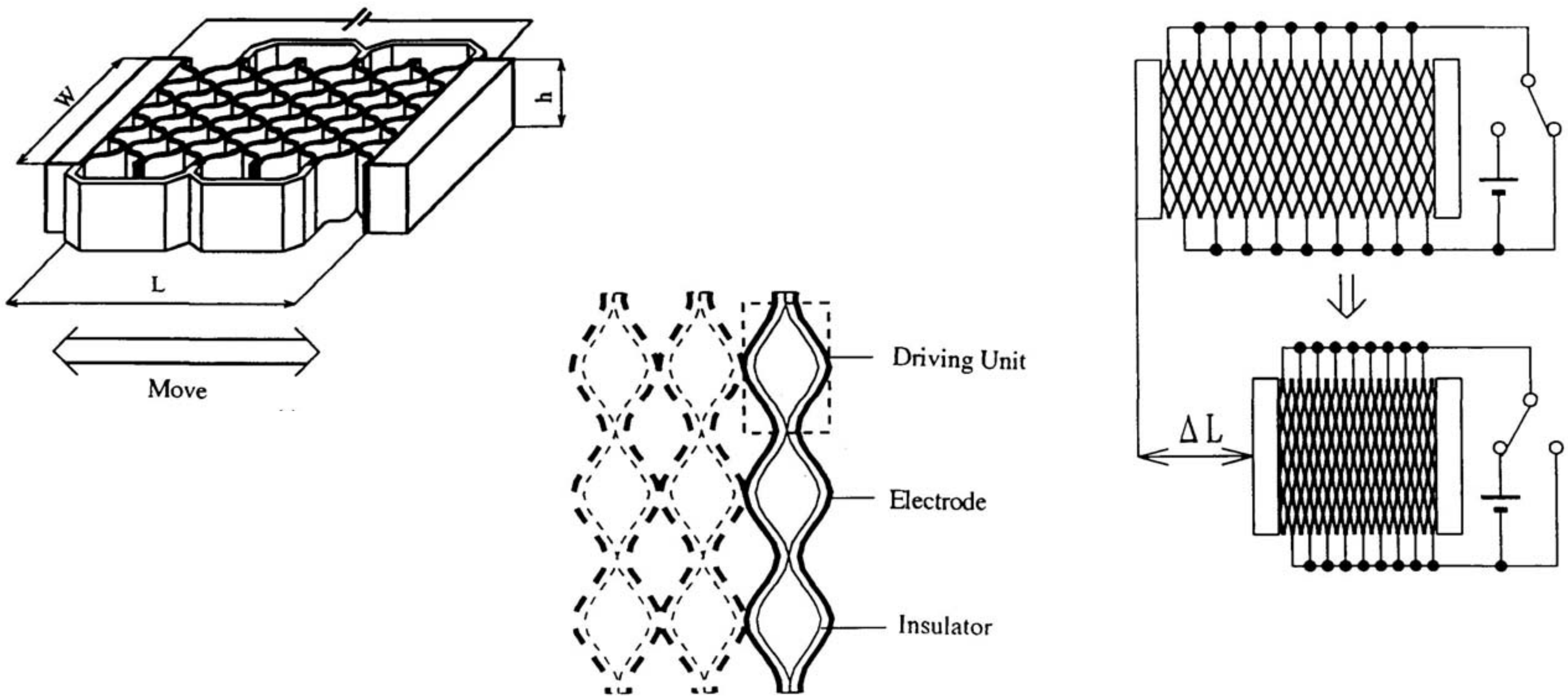


Figure 1 on p. 122 in Minami, K., S. Kawamura, and M. Esashi. "Fabrication of Distributed Electrostatic Micro Actuator (DEMA)." *Journal of Microelectromechanical Systems* 2, no. 3 (September 1993): 121-127. © 1993 IEEE.

Distributed actuators (more force and distance by series and parallel combination)

Electrostatic scratch drive actuators

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Figure 1 on p. 737 in Li, L., J. G. Brown, and D. Uttamchandri. "Study of Scratch Drive Actuator Force Characteristics." *Journal of Micromechanics and Microengineering* 12, no. 6 (November 2002): 736-741.

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Figure 4 on p. 738 in Li, L., J. G. Brown, and D. Uttamchandri. "Study of Scratch Drive Actuator Force Characteristics." *Journal of Micromechanics and Microengineering* 12, no. 6 (November 2002): 736-741.

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Figure 2 on p. 737 in Li, L., J. G. Brown, and D. Uttamchandri. "Study of Scratch Drive Actuator Force Characteristics." *Journal of Micromechanics and Microengineering* 12, no. 6 (November 2002): 736-741.

Limits on electrostatic actuators: Paschen's curve

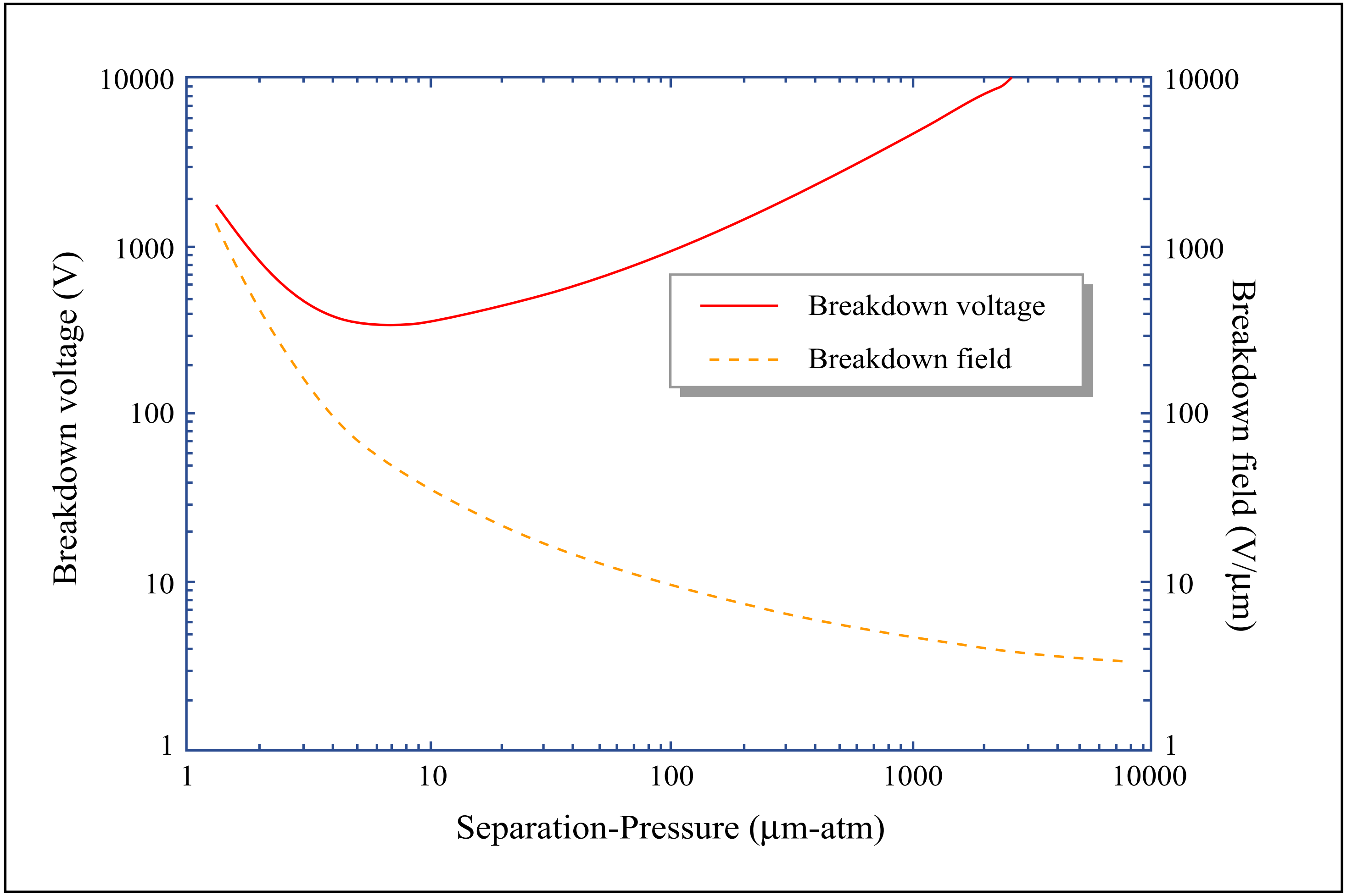
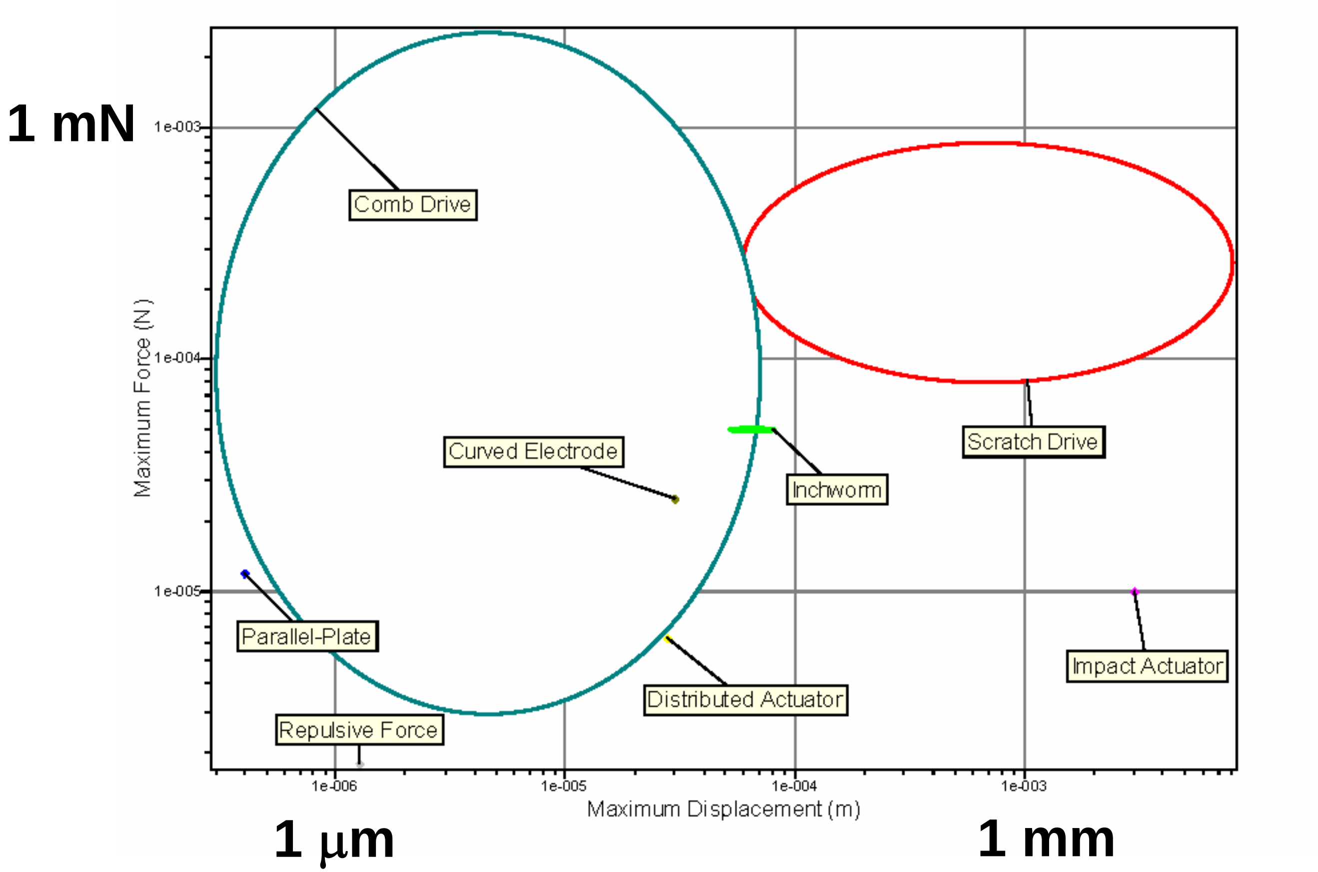


Image by MIT OpenCourseWare.

J. Judy, master's thesis, Berkeley.

Original reference: F. Paschen, Ann. Physik, 273 (1889) pp. 69-96.

Electrostatic actuators: force and distance



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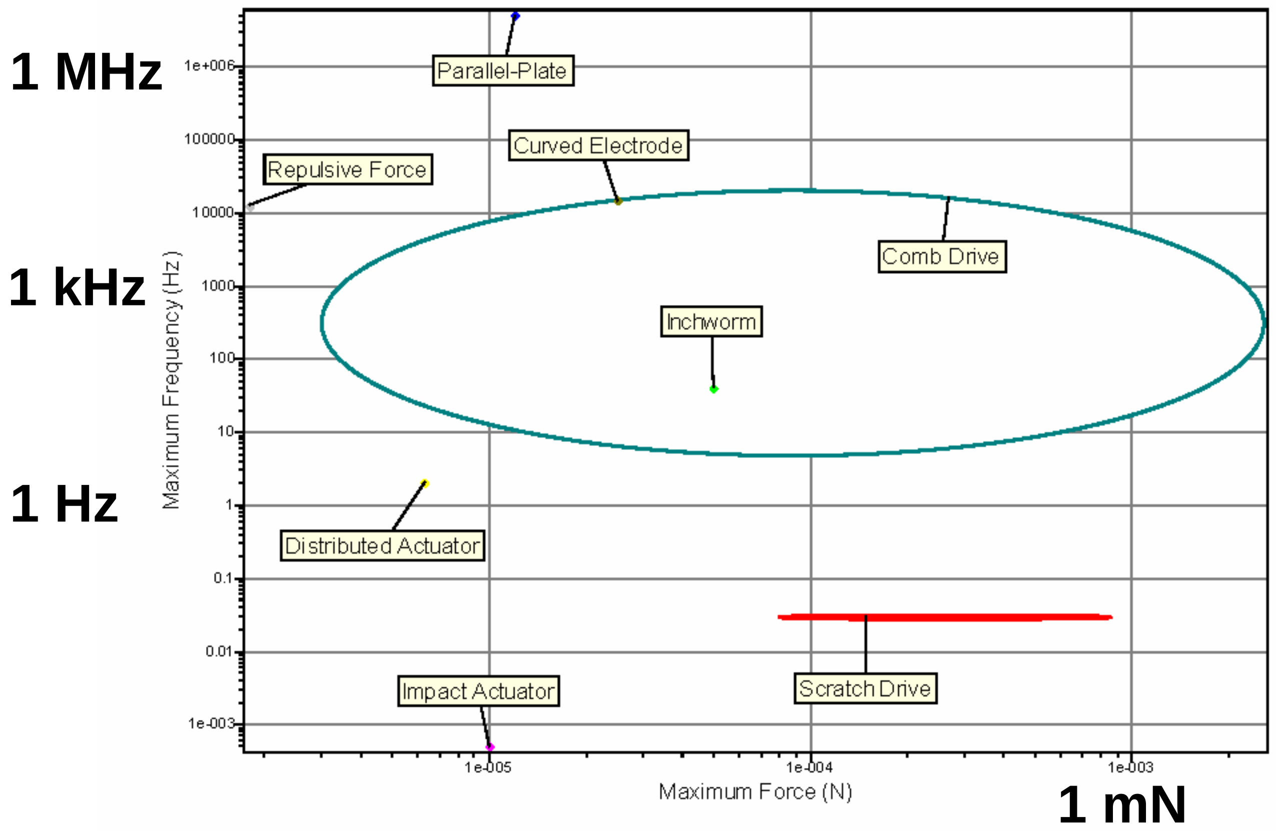
Electrostatic actuators: frequency and force



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Max frequency reflects reported values and resonant frequencies.

Electrostatic Actuators and the Wish List

- Low power operation ✓
- Fast switching (electrical RC times, maybe resonance) ✓
- High force (obtain μN to maybe mN if heroic) ✗
- Large analog-controllable actuator travel ✗
- Simple fabrication ✓
  - Few masks
  - Standard, CMOS-compatible processes and materials
  - Ability to be fabricated on the same chip as circuits
- Low voltage ✗
- Robust operation, not prone to failures (stiction, dust) so-so
- Ability to sense as well as actuate ✓

Thermal Actuation

- Heat up a moveable structure; when it expands, you get force and displacement
- A variety of different structures can take advantage of this type of actuation (example: thermal bimorph in a circuit breaker)
- Good features:
  - High force, moderate displacement
  - Lower actuation voltages
  - Relatively simple fabrication
- Not so good features:
  - Slower switching speeds (hundreds of microseconds)
  - Higher power dissipation: continuous current needed to maintain displacement unless structure latches

Thermal bimorph actuator

Figure 1 on p. 411 and Figure 4a) on p. 412 in Sehr, H., I. S. Tomlin, B. Huang, S. P. Beeby, A. G. R. Evans, A. Brunnschweiler, G. J. Ensell, C. G. J. Schabmueller, and T. E. G. Niblock. "Time Constant and Lateral Resonances of Thermal Vertical Bimorph Actuators." *Journal of Micromechanics and Microengineering* 12, no. 4 (July 2002): 410-413.

Buckle Beam Thermal Actuator

> **Concept:**
- **Run a current through a V-shaped beam**
- **Power dissipation heats beam and makes it expand**
- **Pre-buckled shape ensures that point of V moves outward**

> **Uniform heat dissipation in beam**

> **Center heats up more because it's more isolated from the supports**

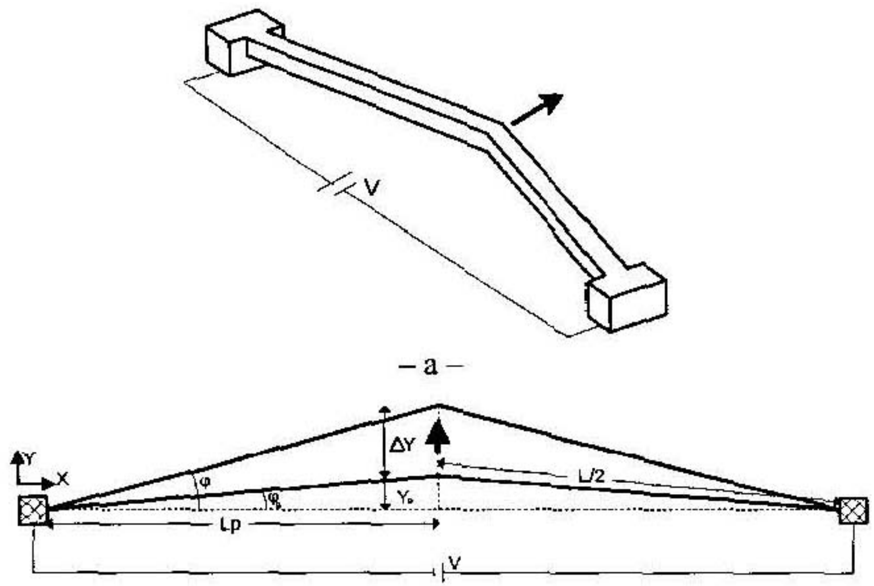


Figure 1 on p. 652 in Girbau, D., A. Lazaro, and L. Pradell. "RF MEMS Switches Based on the Buckle-beam Thermal Actuator." *33rd European Microwave Conference, 2003, Munich, Germany, October 7-9, 2003: Conference Proceedings* 2 (2003): 651-654. © 2003 IEEE.

Buckle Beam Thermal Actuator

- **Force increases linearly when actuators are connected in parallel**
- **Displacement is unchanged**
- **Used here to close RF switches in series and parallel configurations**
- **One consideration: it can be harder to get low contact resistance for contact between vertical sidewalls than for contact between horizontal surfaces**

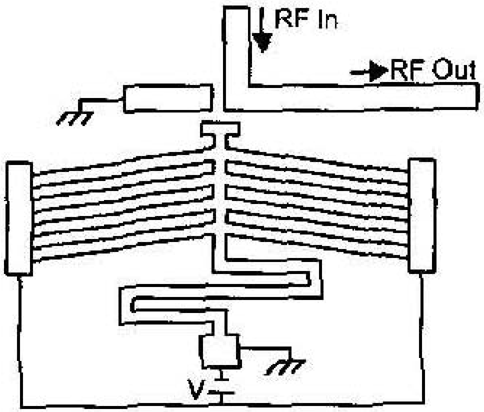


Figure 6. Schematic of the parallel switch.

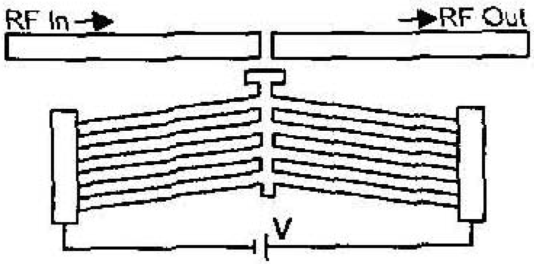


Figure 7. Schematic of the series switch.

Figures 6 and 7 on p. 653 in Girbau, D., A. Lazaro, and L. Pradell.“ RF MEMS Switches Based on the Buckle-beam Thermal Actuator.“ *33rd European Microwave Conference, 2003, Munich, Germany, October 7-9, 2003: Conference Proceedings* 2 (2003): 651-654. © 2003 IEEE.

Electrothermal Actuator: "Heatuator"

Basic heatuator with one wide and one narrow beam

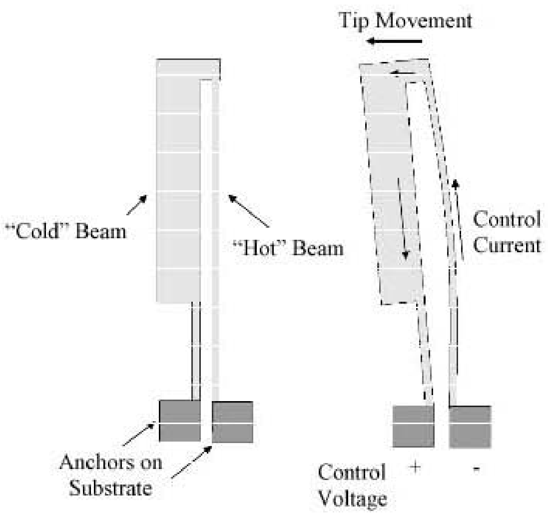


Figure 1 on p. 222 in Agrawal, V. "A Latching MEMS Relay for DC and RF Applications." *Electrical Contacts-2004: Proceedings of the 50th IEEE Holm Conference on Electrical Contacts; The 22nd International Conference on Electrical Contacts, Seattle, WA*. Piscataway, NJ: IEEE, 2004, pp. 222-225. ISBN: 9780780384606. © 2004 IEEE.

Modified heatuator: two narrow beams and one unheated signal beam

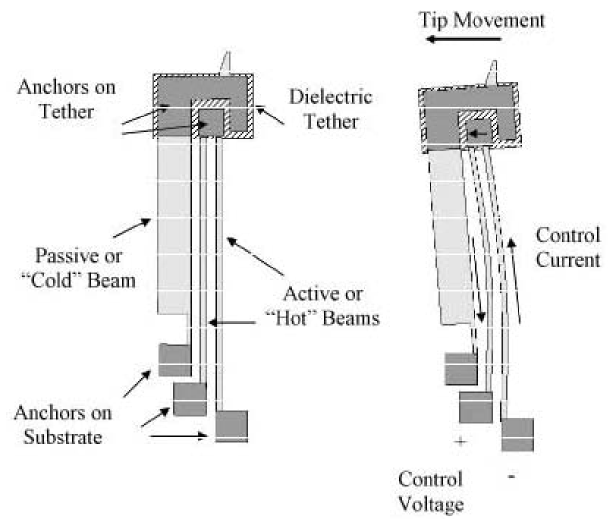


Figure 2 on p. 222 in Agrawal, V. "A Latching MEMS Relay for DC and RF Applications." *Electrical Contacts-2004: Proceedings of the 50th IEEE Holm Conference on Electrical Contacts; The 22nd International Conference on Electrical Contacts, Seattle, WA*, Piscataway, NJ: IEEE, 2004, pp. 222-225. ISBN: 9780780384606. © 2004 IEEE.

- **Analogous to a thermal bimorph, except bimaterial sandwich is replaced by a wide signal beam (cold) and narrow beams (hot).**

Electrothermal Relay with Mechanical Latch

Mechanical latch reduces power consumption after switching and closes the relay.

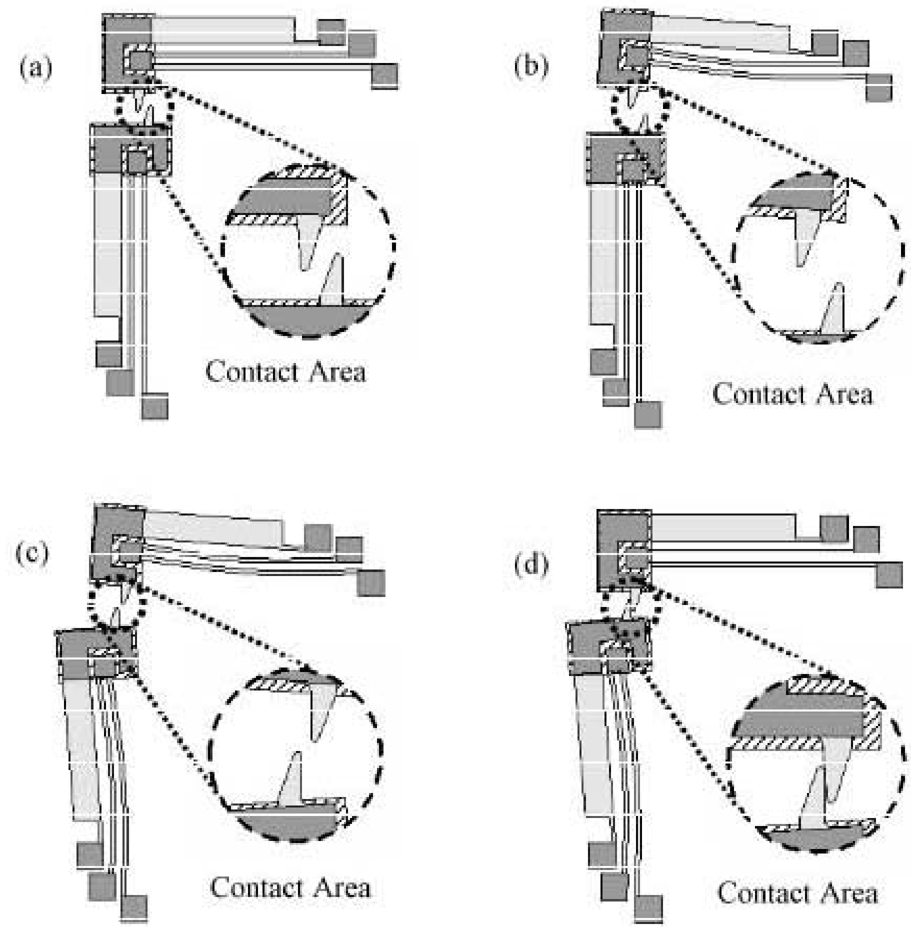
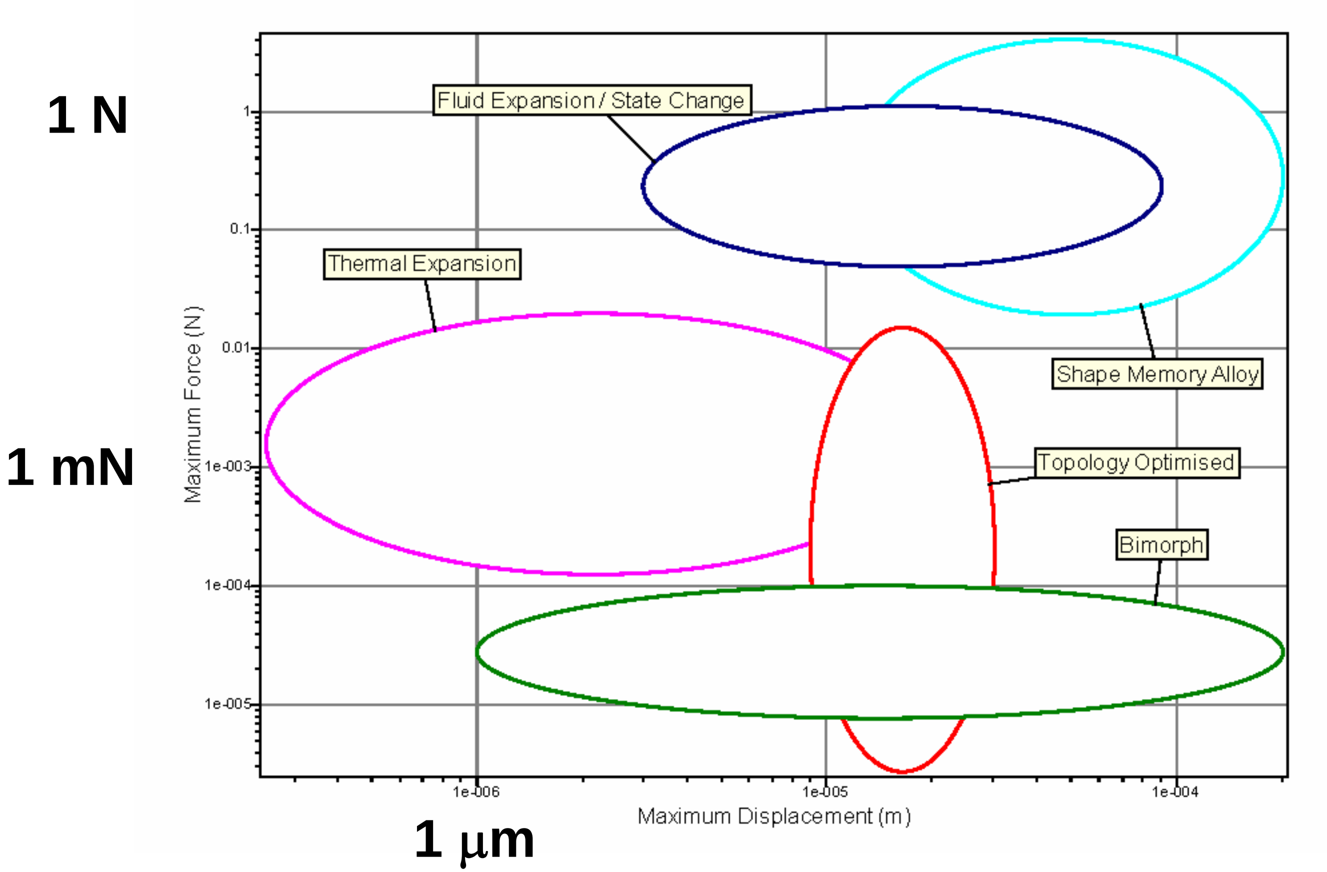


Figure 3 on p. 223 in Agrawal, V. "A Latching MEMS Relay for DC and RF Applications." *Electrical contacts-2004: proceedings of the 50th IEEE Holm Conference on Electrical Contacts; the 22nd International Conference on Electrical Contacts, Seattle, WA*. Piscataway, NJ: IEEE, 2004, pp. 222-225. ISBN: 9780780384606. © 2004 IEEE.

Thermal actuators: force and distance



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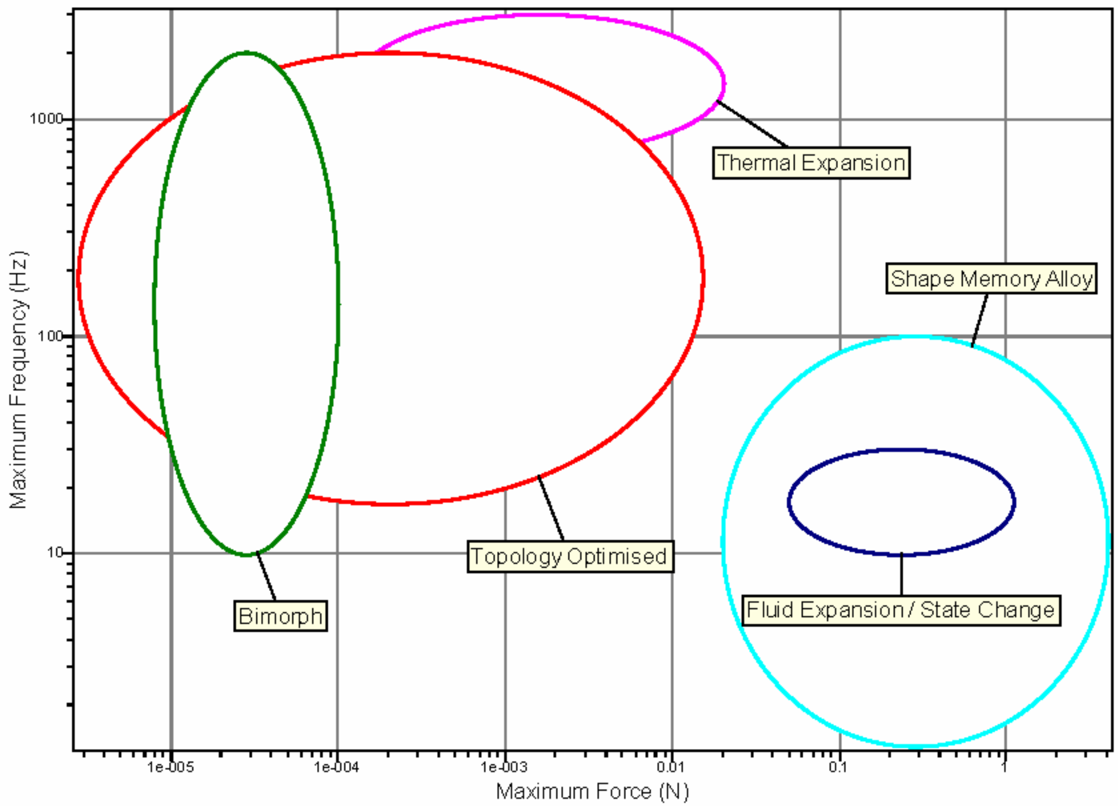
Thermal actuators: frequency and force

1 kHz



1 mN

1 N

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Max frequency reflects reported values and thermal time constants.

Thermal Actuators and the Wish List

> Low power operation ✗

> Fast switching so-so

> High force (μN to N, mN typical) ✓

> Large analog-controllable actuator travel (1-100 um) ✓

> Simple fabrication (is possible, at least) ✓
- Few masks
- Standard, CMOS-compatible processes and materials
- Ability to be fabricated on the same chip as circuits

> Low voltage ✓

> Robust operation, not prone to failures ✓

> Ability to sense as well as actuate ✗

Piezoelectric Actuation

- Apply an electric field across a piezoelectric material; deformation (strain) results, along with actuator deflection and force
- Different piezoelectric geometries are possible
- Good features:
  - High force
  - High switching speeds
  - Low power dissipation
- Not so good features:
  - Small strains must be engineered into useful displacements
  - Complex fabrication and nontrivial materials

Piezoelectric Actuators

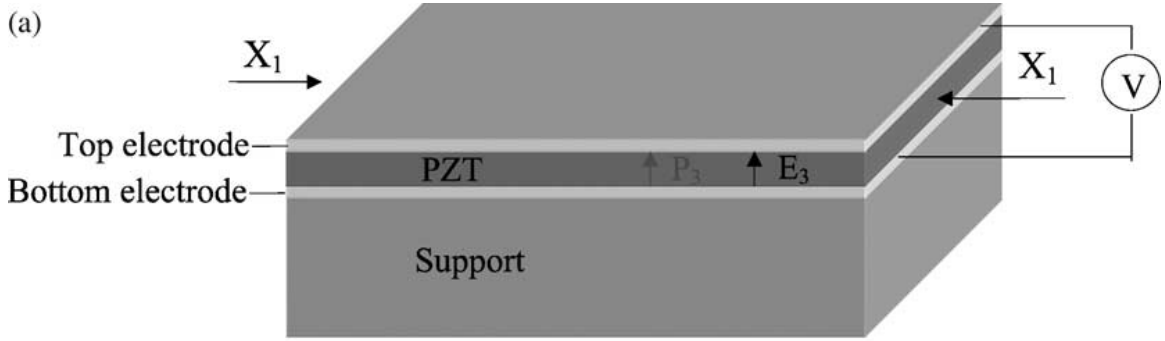
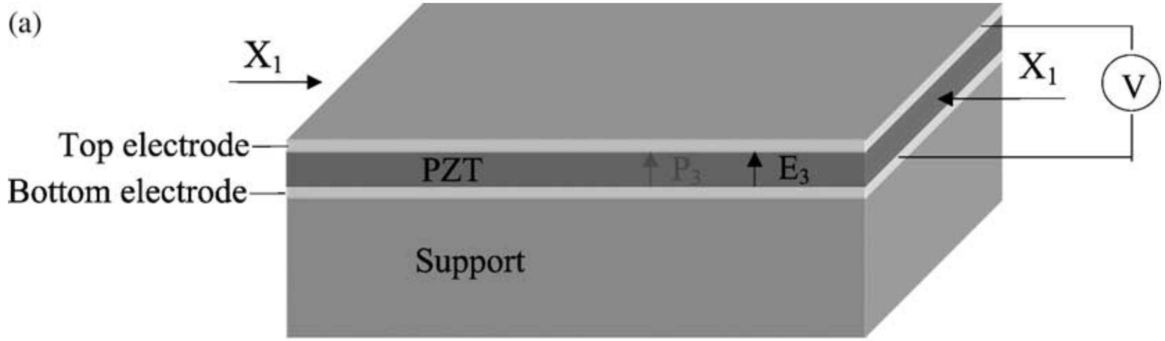


 Figure 1a on p. 92 in Zhang, Q. Q., S. J. Gross, S. Tadigadapa, T. N. Jackson, F. T. Djuth, and S. Trolier-McKinstry. "Lead Zirconate Titanate Films for d33 Mode Cantilever Actuators." *Sensors and Actuators A, Physical* 105, no. 1 (June 2003): 91-97.

- **PZT layer is fabricated on top of cantilever, sandwiched between electrodes, and poled in the vertical direction**
- **Electric field is applied between top and bottom electrodes, parallel to polarization**
- **d_{31}: PZT develops a negative strain in the transverse direction; rest of cantilever does not**
- **Cantilever bends up**

Piezoelectric Actuators



Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission. Figure 1a on p. 92 in Zhang, Q. Q., S. J. Gross, S. Tadigadapa, T. N. Jackson, F. T. Djuth, and S. Trolier-McKinstry. "Lead Zirconate Titanate Films for d33 Mode Cantilever Actuators." *Sensors and Actuators A, Physical* 105, no. 1 (June 2003): 91-97.

- **If electric field is opposite to the polarization, the cantilever will deflect in the opposite direction, up to a point**
- **Consequence: stronger restoring forces and faster responses possible than with an unactuated return**
- **If antiparallel electric field is too large, PZT will repole in the other direction**

Piezoelectric Actuators

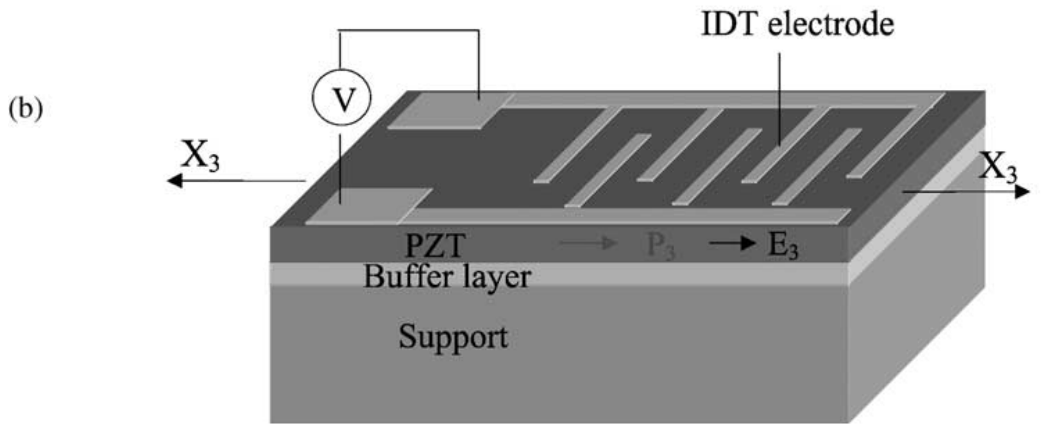


 Figure 1b on p. 92 in Zhang, Q. Q., S. J. Gross, S. Tadigadapa, T. N. Jackson, F. T. Djuth, and S. Trolier-McKinstry. "Lead Zirconate Titanate Films for d33 Mode Cantilever Actuators." *Sensors and Actuators A, Physical* 105, no. 1 (June 2003): 91-97.

- **PZT layer is fabricated on top of cantilever, under interdigitated electrodes**
- **Electric field is in the plane; PZT is poled in the plane**
- **d_{33}: With E parallel to poling, PZT develops a positive strain in the direction of its length; cantilever bends down**
- **Again, antiparallel E has opposite effect within limits**

Piezoelectric RF MEMS Switch

- Piezoelectric cantilever driven by interdigitated electrodes, d_{33}
- Cantilever is multilayer stack, both for film stress compensation (so the cantilever starts out flat) and for maximum actuation force and deflection
- Cantilever layers, from the bottom: 50 nm oxide barrier, 500 nm SiN structural layer, 50 nm oxide adhesion layer, 300 nm zirconia, 230 nm PZT, Cr/Au electrodes and contacts
- Few microsecond switching

Image removed due to copyright restrictions.

Figures 1a and 1b on p. 175 in Gross, S. J., S. Tadigadapa, T. N. Jackson, S. Trolier-McKinstry, and Q. Q. Zhang. "Lead-zirconate-titanate-based Piezoelectric Micromachined Switch." *Applied Physics Letters* 83, no. 1 (July 2003): 174-176.

Thin Film Bulk Acoustic Resonator (FBAR)

- Suspended structure: a sandwich of piezoelectric material between electrodes
- Apply an AC signal to electrodes at the proper frequency, and the piezoelectric resonates mechanically
- Air interfaces minimize acoustic losses into surrounding medium
- In commercial use (sold by Agilent for cell phones)

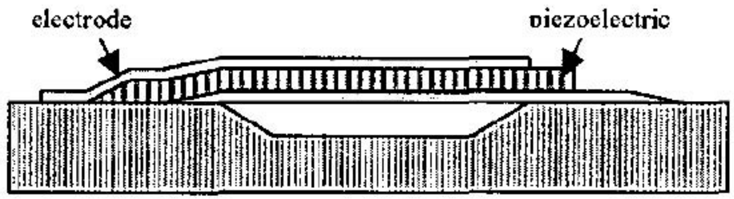


Figure 1 on p. 1687 in Wang, K., P. Bradley, and M. Gat. "Micromachined Bulk Acoustical-wave RF Filters." In *2004 7th International Conference on Solid-State and Integrated Circuits Technology proceedings, ICSICT 2004: October 18-21, 2004, Beijing, China*, edited by Ru Huang. Piscataway, NJ: IEEE Press, 2004, pp. 1687-1690. ISBN: 9780780385115. © 2004 IEEE.

Thin Film Bulk Acoustic Resonator (FBAR)

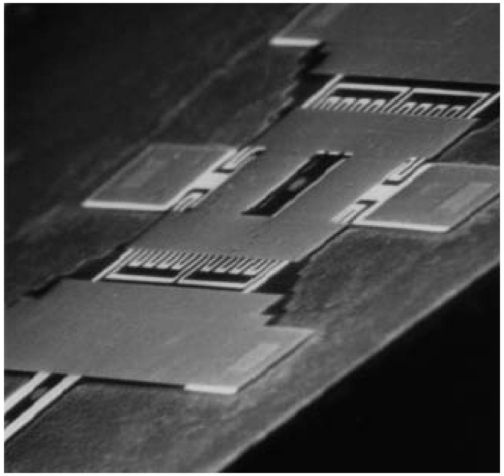


Figure 2 on p. 814 in Ruby, R. C., P. Bradley, Y. Oshmyansky, A. Chien, and J. D. Larson, III. "Thin Film Bulk Wave Acoustic Resonators (FBAR) for Wireless Applications." In *2001 IEEE Ultrasonics Symposium proceedings, an international symposium: October 7-10, 2001, Omni Hotel, Atlanta, Georgia*, edited by Donald E. Yuhas and Susan C. Schneider. Piscataway, NJ: IEEE, 2001, pp. 813-821. ISBN: 9780780371774. © 2001 IEEE.

- **Materials challenges:**
  - **Repeatability of piezoelectric's properties (choose AlN and work the process until it is repeatable)**
  - **Low acoustic losses and low electrical losses (choose molybdenum)**
- **Fabrication challenges:**
  - **Precise control of layer thickness**
  - **Process compatibility (with IC and piezoelectric)**
  - **Structure built over an oxide-filled cavity in the substrate; oxide removed at end to release**
  - **Packaging in the fab, by wafer bonding**

Image removed due to copyright restrictions.
4 actuators displayed side-by-side to show how small they are.

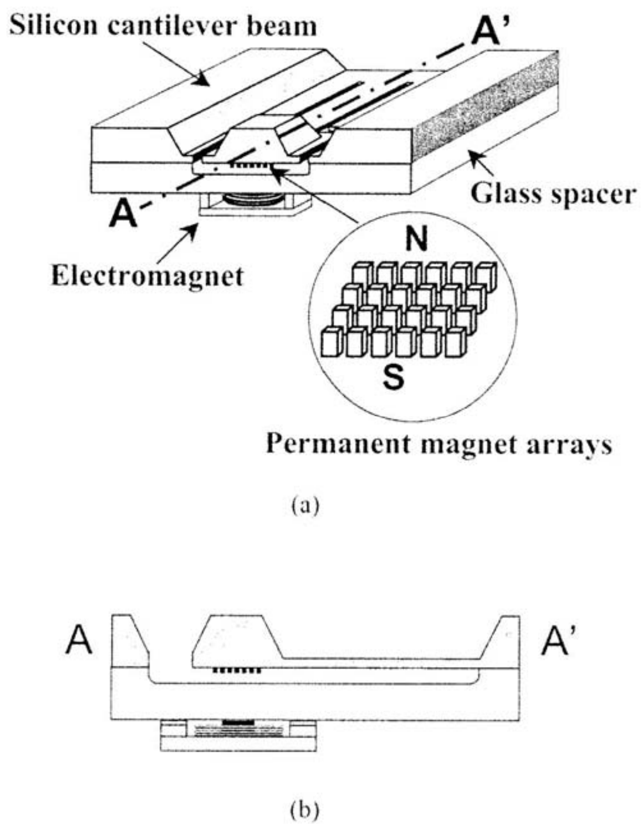
Piezoelectric Actuators and the Wish List

- > Low power operation ✓
- > Fast switching ✓
- > High force (10 μN to mN) ✓
- > Large analog-controllable actuator travel (<0.1 μm to mm) so-so
- > Simple fabrication ✗
  - Few masks
  - Standard, CMOS-compatible processes and materials
  - Ability to be fabricated on the same chip as circuits
- > Low voltage so-so
- > Robust operation, not prone to failures ✓
- > Ability to sense as well as actuate ✓

Magnetic Actuation

- **Many variations on the magnetic actuators theme**
  - **Permanent magnets interacting with an external field**
  - **Permanent magnets interacting with current-carrying coils**
  - **Current carrying conductors interacting with an external field**
  - **Variable reluctance devices**
- **An important good feature: high force**
- **Not so good features:**
  - **Current drive means high power dissipation**
  - **Fabrication complexity and severe materials challenges**

Electromagnetic actuators



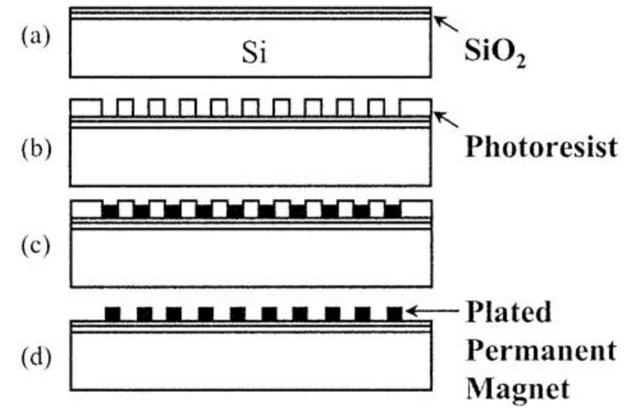


Figure 3 on p. 79 in Cho, H. J., and C. H. Ahn. "A Bidirectional Magnetic Microactuator Using Electroplated Permanent Magnet Arrays." *Journal of Microelectromechanical Systems* 11, no. 1 (February 2002): 78-84. © 2002 IEEE.

Figure 1 on p. 79 in Cho, H. J., and C. H. Ahn. "A Bidirectional Magnetic Microactuator Using Electroplated Permanent Magnet Arrays." *Journal of Microelectromechanical Systems* 11, no. 1 (February 2002): 78-84. © 2002 IEEE.

External magnetic field actuators

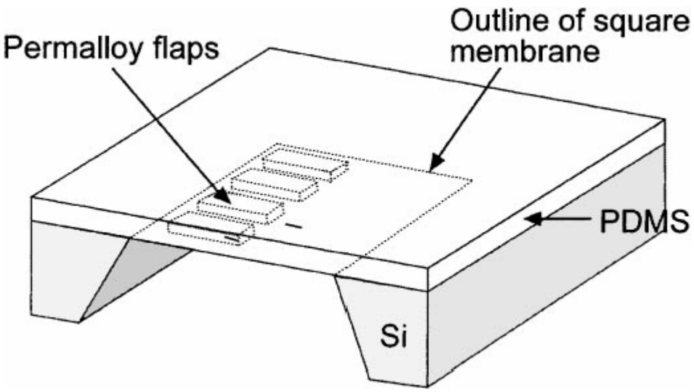


Figure 1 on p. 260 in Khoo, M., and C. Liu. "Micro Magnetic Silicone Elastome Membrane Actuator." *Sensors and Actuators A, Physical* 89, no. 3 (April 2001): 259-266.

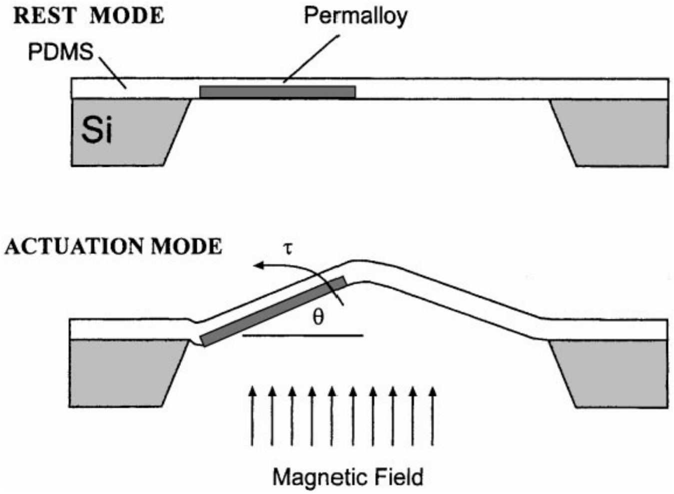


Figure 2 on p. 260 in Khoo, M., and C. Liu. "Micro Magnetic Silicone Elastome Membrane Actuator." *Sensors and Actuators A, Physical* 89, no. 3 (April 2001): 259-266.

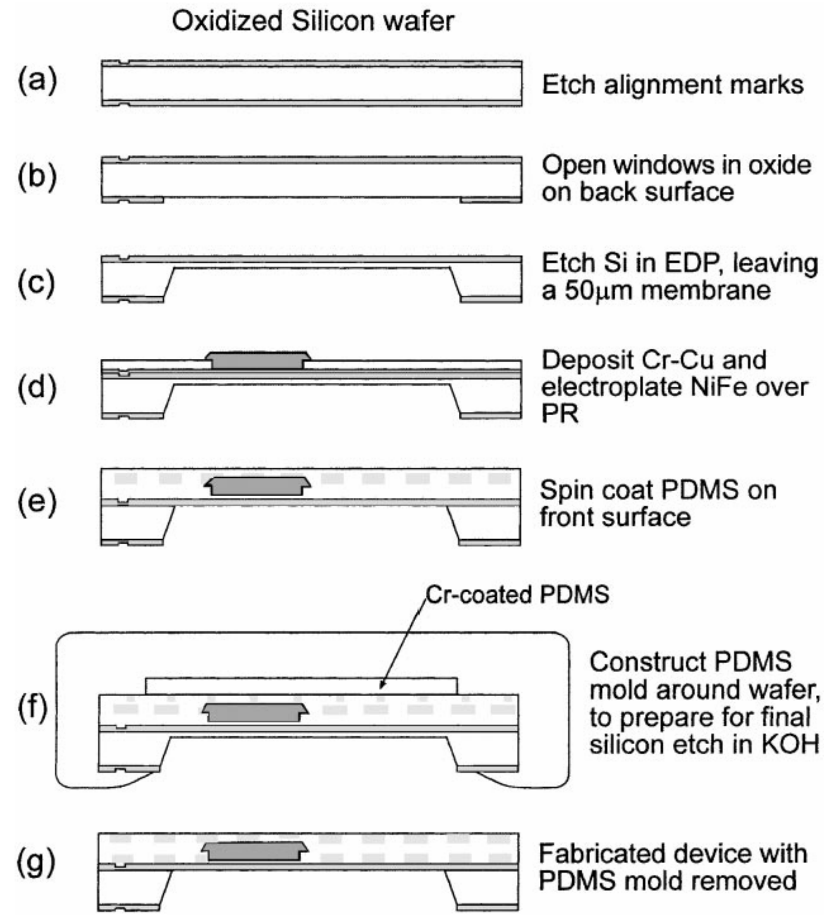


Figure 6 on p. 262 in Khoo, M., and C. Liu. "Micro Magnetic Silicone Elastome Membrane Actuator." *Sensors and Actuators A, Physical* 89, no. 3 (April 2001): 259-266.

External magnetic field actuator

Variable Reluctance Actuator Concept

- High permeability magnetic deformable and fixed structures form a magnetic circuit that flux penetrates
- Increasing current through coil increases magnetic flux
- Increasing magnetic flux through the circuit narrows actuator gap and draws structures together

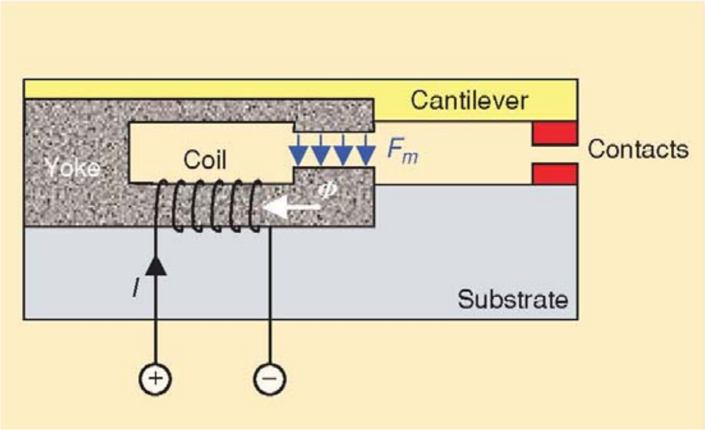


Figure 8 on p. 43 in De Los Santos, H. J., G. Fischer, H. A. C. Tilmans, and J. T. M. van Beek. "RF MEMS for Ubiquitous Wireless Connectivity. Part I. Fabrication." *IEEE Microwave Magazine* 5, no. 4 (December 2004): 36-49.

Variable Reluctance Relay

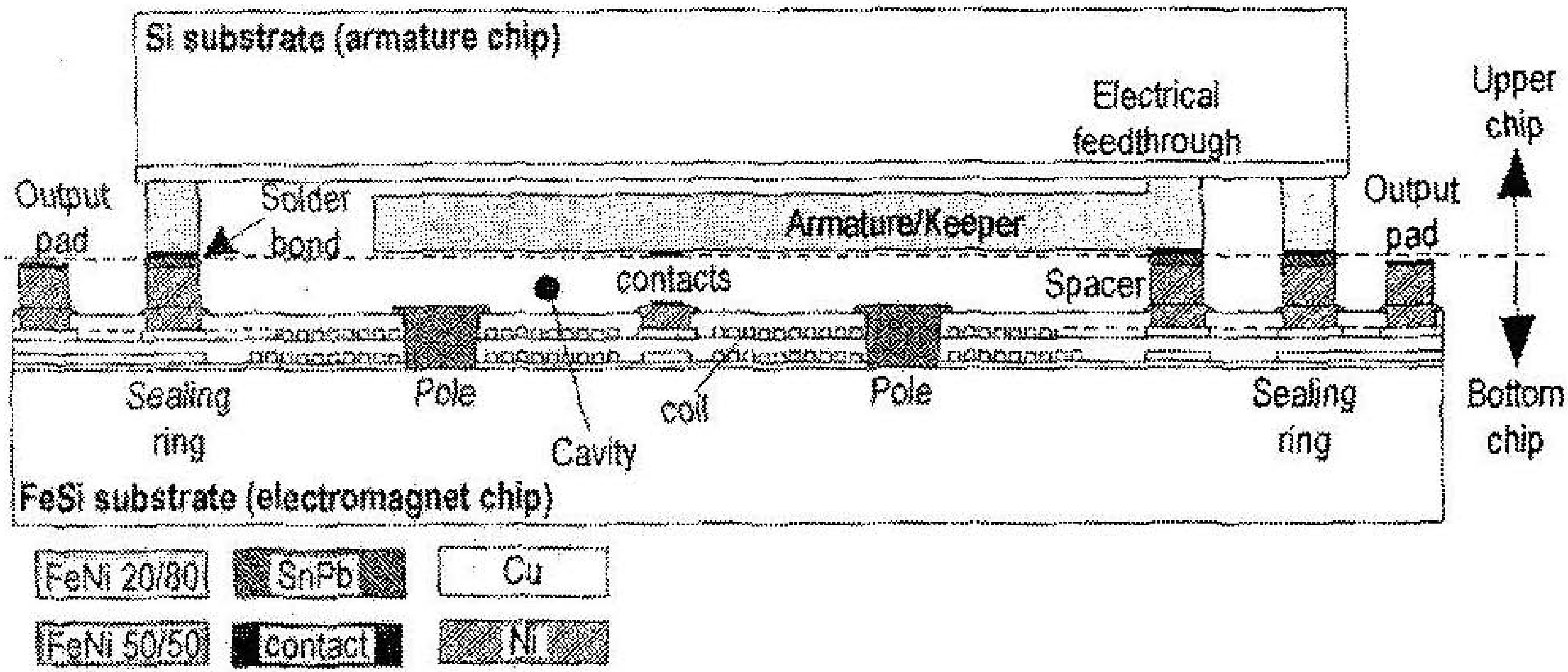


Figure 2 on p. 26 in Tilmans, H.A.C., E. Fullin, H. Ziad, M. D. J. Van de Peer, J. Kesters, E. Van Geffen, J. Bergqvist, M. Pantus, E. Beyne, K. Baert, and F. Naso. "A Fully-packaged Electromagnetic Microrelay." *MEMS '99: Twelfth IEEE International Conference on Micro Electro Mechanical Systems technical digest: Orlando, Florida, USA, January 17-21, 1999*. Piscataway, NJ: IEEE, 1999, pp. 25-30. ISBN: 9780780351943. © 1999 IEEE.

- **Two-wafer, flip-chip bonded implementation of variable reluctance concept; thick electroplated structures**
- **Switching speed > 500 Hz, operated at 2 V and 8 mA, 2 mN force**

Variable Reluctance Relay

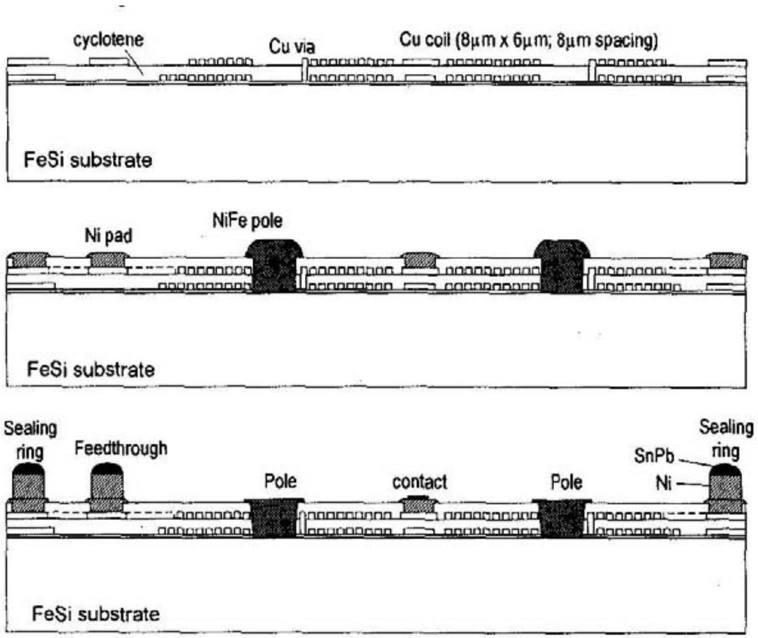


Figure 5 on p. 27 in Tilmans, H. A. C., E. Fullin, H. Ziad, M. D. J. Van de Peer, J. Kesters, E. Van Geffen, J. Bergqvist, M. Pantus, E. Beyne, K. Baert, and F. Naso. "A Fully-packaged Electromagnetic Microrelay.“ *MEMS '99: Twelfth IEEE International Conference on Micro Electro Mechanical Systems technical digest: Orlando, Florida, USA, January 17-21, 1999*. Piscataway, NJ: IEEE, 1999, pp. 25-30. ISBN: 9780780351943. © 1999 IEEE.

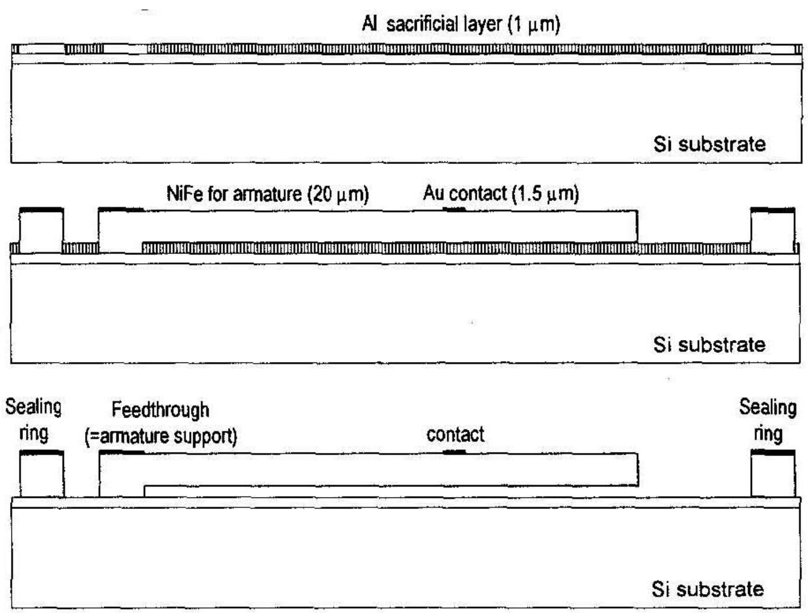


Figure 6 on p. 27 in Tilmans, H. A. C., E. Fullin, H. Ziad, M. D. J. Van de Peer, J. Kesters, E. Van Geffen, J. Bergqvist, M. Pantus, E. Beyne, K. Baert, and F. Naso. "A Fully-packaged Electromagnetic Microrelay.“ *MEMS '99: Twelfth IEEE International Conference on Micro Electro Mechanical Systems technical digest: Orlando, Florida, USA, January 17-21, 1999*. Piscataway, NJ: IEEE, 1999, pp. 25-30. ISBN: 9780780351943. © 1999 IEEE.

- **Wafer 1: a magnetic substrate with thick plated coils, poles, and infrastructure for flip-chip packaging**
- **Wafer 2: a silicon substrate with a plated armature and provision for electrical contact and packaging**

Issues with Magnetic Actuation

- **Fabrication challenges:**
  - **Thick conductors and magnetic features**
  - **Standard approach: plating into a mold**
  - **Plating often produces surfaces that are not flat – planarization required**
- **Material limitations:**
  - **Not all magnetic materials can be deposited with MEMS fabrication techniques**
- **Process limitations:**
  - **Not CMOS compatible**
  - **Minimize temperature during processing to avoid Curie temperature**
  - **Eliminates some process steps from consideration and modifies many others**

Magnetic Actuators and the Wish List

> Low power operation (but latching can help) ✗

> Fast switching so-so

> High force (approaching mN) ✓

> Large analog-controllable actuator travel (large gaps) ✓

> Simple fabrication ✗

- Few masks
- Standard, CMOS-compatible processes and materials
- Ability to be fabricated on the same chip as circuits

> Low voltage ✓

> Robust operation, not prone to failures ✓

> Ability to sense as well as actuate ✓

Force and distance

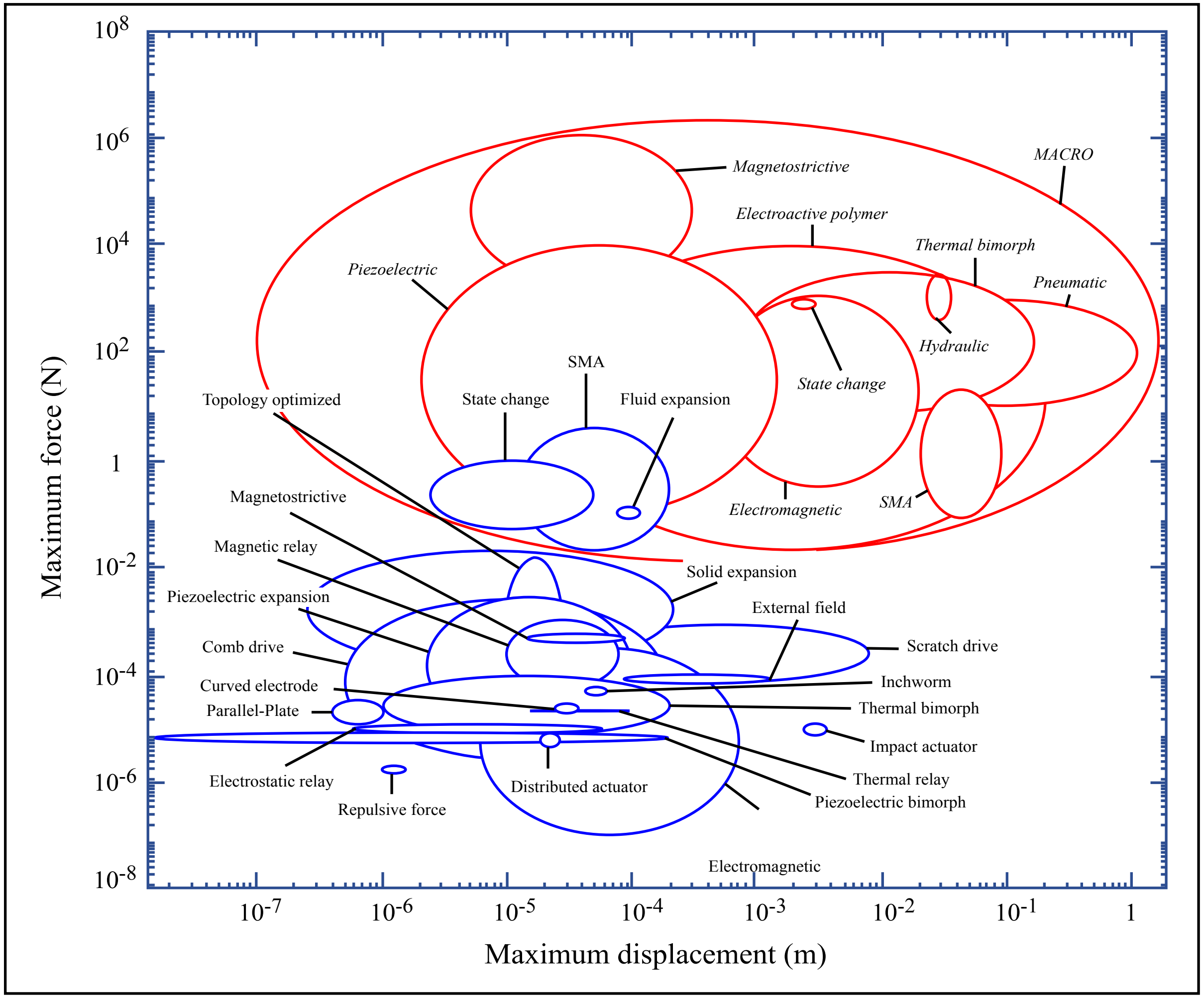


Image by MIT OpenCourseWare.

Adapted from Figure 1 on p. S155 in Bell, D. J., T. J. Lu, N. A. Fleck, and S. M. Spearing. "MEMS Actuators and Sensors: Observations on Their Performance and Selection for Purpose." *Journal of Micromechanics and Microengineering* 15 (June 2005): S153-S164.

Not all macro actuators have micro versions, and not all micro actuators have macro versions!

Frequency and displacement

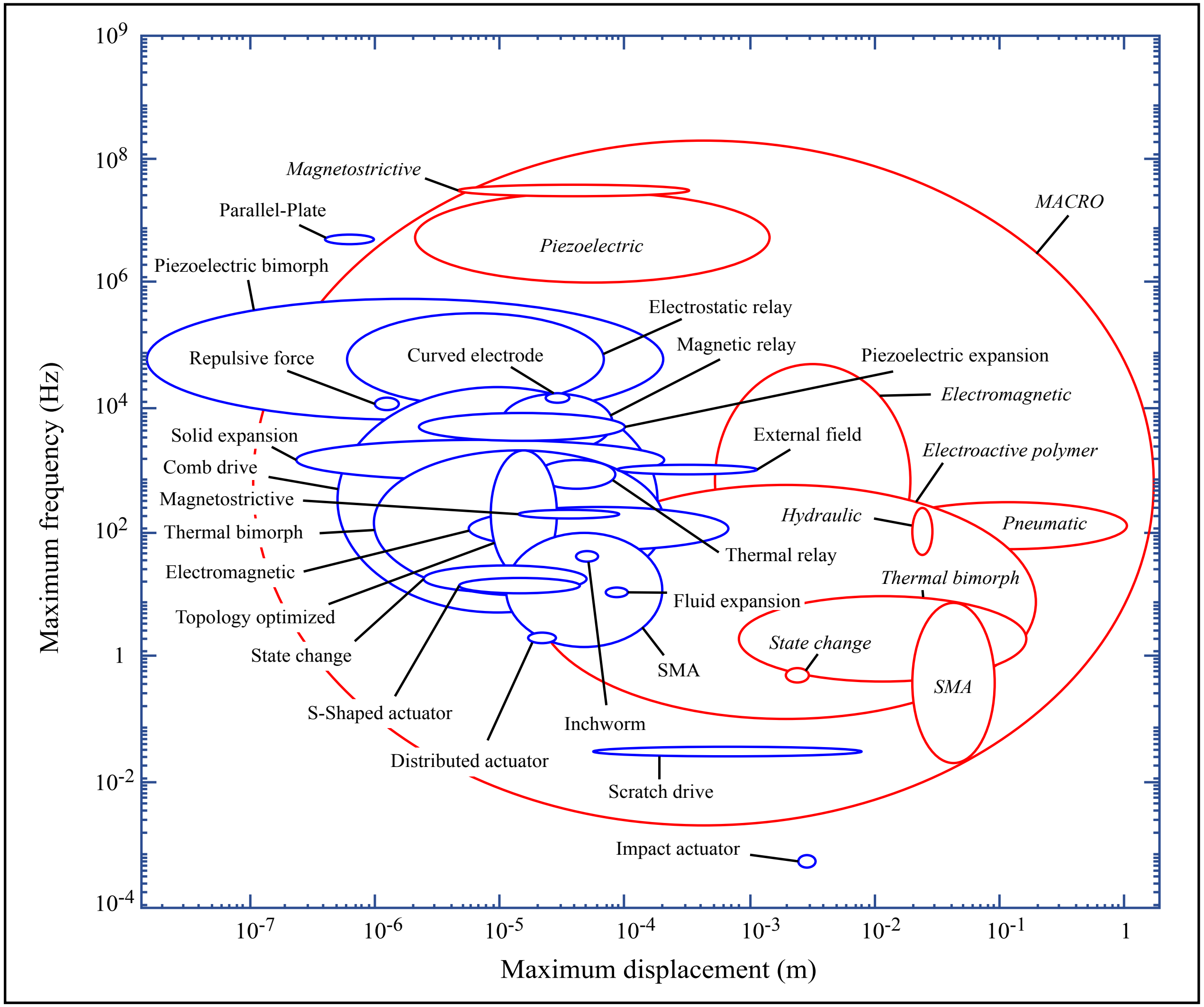


Image by MIT OpenCourseWare.

Adapted from Figure 3 on p. S157 in Bell, D. J., T. J. Lu, N. A. Fleck, and S. M. Spearing. "MEMS Actuators and Sensors: Observations on Their Performance and Selection for Purpose." *Journal of Micromechanics and Microengineering* 15 (June 2005): S153-S164.

Different Options Have Different Advantages

	Electrostatic	Thermal	Piezo	Magnetic
Low power	✓	✗	✓	✗
Fast switch	✓	~	✓	~
High force	✗	✓	✓	✓
Large travel	✗	✓	~	✓
Simple fab	✓	✓	✗	✗
Low voltage	✗	✓	~	✓
Robustness	~	✓	✓	✓
Sense/actuate	✓	✗	✓	✓

- **What is most important for your application?**
- **What suboptimal parameters can your application tolerate?**

Conclusions

- An awareness of the options can give you a head start in designing a device or process, and improve your device intuition
  - Literature awareness
  - Design charts
- Other factors come into play as well:
  - Ease of fabrication
  - Materials compatibilities
  - Resolution
  - Calibration
  - Robustness
  - Power consumption